TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY
*Julkaisu 735 • Publication 735*

Jakub Marek Borkowski

# On Applicable Cellular Positioning for UMTS

Tampere 2008

Tampereen teknillinen yliopisto. Julkaisu 735
Tampere University of Technology. Publication 735

Jakub Marek Borkowski

# On Applicable Cellular Positioning for UMTS

Thesis for the degree of Doctor of Technology to be presented with due permission for public examination and criticism in Tietotalo Building, Auditorium TB109, at Tampere University of Technology, on the 23rd of May 2008, at 12 noon.

Tampereen teknillinen yliopisto - Tampere University of Technology
Tampere 2008

ISBN 978-952-15-1971-0 (printed)
ISBN 978-952-15-2016-7 (PDF)
ISSN 1459-2045

# On Applicable Cellular Positioning for UMTS

Jakub Marek Borkowski

April 29, 2008

# Abstract

Enabling the positioning of cellular handsets increases the safety level and at the same time opens exciting commercial opportunities for operators through providing location-based services. A major implementation obstacle, which prevents a wide deployment of cellular location techniques is the requirement of modifications of the existing network infrastructures and a need for the replacement of legacy terminals. Despite a significant amount of research on the mobile positioning problem, there are still unresolved aspects regarding applicable positioning solutions providing estimation accuracy sufficient for the majority of location-based services. Typically, the applicability of positioning technology in current networks and provided estimation accuracy yield for trade off.

The aim of the research performed in the frame of this thesis is to propose network- and mobile-based location techniques for UMTS networks that do not require any changes on the network side or in the user terminals and at the same time provide a reasonable estimation performance. This thesis provides a comprehensive overview of cellular mobile positioning with emphasis on applicable, practical approaches to the problem. The research results are mainly focused on the presentation of novel positioning techniques, performance assessment of the proposed techniques and evaluation of the impact of radio network planning on positioning accuracy.

Two applicable network-based positioning techniques (ECID+RTT and PCM) are proposed and evaluated. Consecutively, mobile-based location methods are presented that exploit signal strength measurements complemented by delay spread measurements or serving site information. Moreover, the thesis includes an extensive study on CID+RTT positioning. The performance of the proposed positioning methods is assessed through simulations and field measurements. In addition, this thesis introduces the influence of the topology planning process on the performance of the proposed positioning methods. The impact of capacity-oriented radio network planning on network-based positioning functionality and performance is evaluated in the context of numerous aspects of topology planning with emphasis on repeater deployment. The impact of the proposed network-based positioning on the network functionality and capacity is also studied.

# Preface

The research work for this thesis has been carried out during the years 2004-2008 at the Institute of Communications Engineering (ICE) of Tampere University of Technology, Finland in the frame of the "Advanced Techniques for Mobile Positioning" project.

First and foremost I would like to express my deep gratitude to my supervisor, Professor Jukka Lempiäinen, for his guidance, enthusiastic encouragement and constant support during the research work. I would also like to greatly acknowledge the thesis reviewers, Professor Torbjörn Wigren from the University of Uppsala and Ericsson, Sweden and D.Tech. Ville Ruutu from Nokia Siemens Networks, Finland for their constructive feedback and valuable comments.

During the years 2003-2006 I had the privilege of working with very talented, helpful, and friendly people in Institute of Communications Engineering, whose help is gratefully acknowledged. Special thanks are directed to Professor Markku Renfors, head of the institute for creating a pleasant and efficient working atmosphere and for his assistance in challenging situations.

Thanks are also due to my colleagues in the Radio Network Group with whom I had the pleasure to work on various interesting assignments: D.Tech. Jarno Niemelä; M.Sc. Tero Isotalo; M.Sc. Panu Lähdekorpi and M.Sc. Jaroslaw Lacki. Thank you for the many technical discussions, lots of unforgettable events, and your patience in assisting me with Latex. Moreover, I wish to thank all former and present personnel of ICE as well as from other institutes for making Tampere University of Technology a great place to study and work. In particular, I would like to thank D.Tech. Elena Simona Lohan, Docent Petri Jarske, and Professor Robert Piche for sharing their knowledge.

I would like to express special thanks to present and former colleagues from European Communications Engineering (ECE) for interesting technical discussions and their assistance in solving multiple technical challenges, in particular M.Sc. Jarkko Itkonen is greatly acknowledged. In addition, I wish to thank the following organizations and persons: former Nokia Networks (currently Nokia Siemens Networks) for providing Nokia NetAct Planner for research and for providing constructive feedback on various technical aspects of positioning platform and system functionality; NetHawk Oyj for providing RNC simulator for university indoor 3G network; uNav Microelectronics Finland Oy, especially M.Sc. Ilka Saastamoinen, for valuable comments regarding GPS handset implementation aspects; Elisa Oyj, especially M.Sc. Vesa Orava for allowing measurement campaigns in their network and providing repeater for measurements; Nemo Technologies for providing measurement equipment and technical support; FM Kartta Oy for providing digital maps; former Teleware Oy (currently KPMG Oy Ab), especially D.Tech. Harri Wihuri and B.Sc.,MBA Gregory Pierson, for enabling the continuation of my postgraduate studies while working in customer projects, and the city of Tampere for allowing repeater antenna installations in Tampere. In addition, I would like to thank John Shepherd from the Language Center, Tampere University of Technology for his effort on proofreading the thesis.

Special acknowledgments are directed to Tarja Erälaukko, Sari Kinnari, Ulla Siltaloppi, and Elina Orava for their kindness, patience, and efficiency in solving everyday practical matters. I am also truly thankful to D.Tech. Krzysztof Penkala from the Technical University of Szczecin, Poland and Professor Ireneusz Defee from Tampere University of Technology for helping me in the major arrangements related to study in Finland. Moreover, I would like to acknowledge all the personnel from Technical University of Szczecin, where I had the pleasure to begin my higher education.

Warm thanks are due to my friends from Tampere, especially to Kuba, Pawel with Sylwia, Jacek, and Ewelina for the enjoyable time we spent together. At the same time, I am very thankful to all my friends from Szczecin for our get-togethers, great trips, and keeping in touch despite the distance. Special thanks are directed to Rysiek with Ania, Ola, Anita, and Jacek with Dominika from Cracow.

I wish to express my deepest thanks to my family, my father Marek Borkowski, mother Alina Borkowska (rest in peace), and to my cousin Zofia Piekarska for their love, unconditional support, and guidance. Last but not least, I am very grateful to my girlfriend Katarzyna for her love, understanding, and patience.

April 2008, Bristol, United Kingdom

Jakub Marek Borkowski

# Table of Contents

# List of Abbreviations

| | |
|---|---|
| 2D | 2-Dimensional |
| 3D | 3-Dimensional |
| 3G | Third Generation |
| 3GPP | The Third Generation Partnership Project |
| AC | Admission Control |
| AIS | Automatic Identification System |
| AGPS | Assisted Global Positioning System |
| AOA | Angle of Arrival |
| AVM | Automatic Vehicle Monitoring |
| AS | Active Set |
| BCCH | Broadcast Control Channel |
| BS | Base Station |
| CAPEX | Capital Expenditure |
| CDF | Cumulative Distribution Function |
| CDMA | Code Division Multiple Access |
| CFN | Connection Frame Number |
| CN | Core Network |
| CRNC | Controlling Radio Network Controller |
| CERP | Circular Error Probability |
| CGALIES | Coordination Group on Access to Location Information by Emergency Services |
| CID | Cell Identification |
| CVB | Cumulative Virtual Banking |
| C/A | Coarse/Acquisition |
| DCH | Dedicated Channel |
| DL | Downlink |
| DCM | Database Correlation Method |
| DLL | Delay Locked Loop |
| DoP | Dilution of Precision |
| DPCCH | Dedicated Physical Control Channel |
| DPCH | Dedicated Physical Channel |
| DPDCH | Dedicated Physical Data Channel |
| DS | Delay Spread |
| ECID+RTT | Enhanced Cell Identification + Round Trip Time |
| EDT | Electrical Downtilt |
| EKF | Extended Kalman Filter |

| | |
|---|---|
| ETSI | European Telecommunications Standards Institute |
| FCC | Federal Communication Commission |
| FDMA | Frequency Division Multiple Access |
| FSHO | Forced Soft Handover |
| GLONASS | Global Navigation Satellite System (Russian) |
| GNSS | Global Navigation Satellite System |
| GPS | Global Positioning System |
| GSM | Global System for Mobile Communications |
| HSDPA | High Speed Downlink Packet Access |
| IC | Interference Cancelation |
| IPDL | Idle Period Downlink |
| I/Q | In phase / Quadrature |
| KPI | Key Performance Indicator |
| LBS | Location Based Services |
| LCS | Location Services |
| LMS | Location and Monitoring Services |
| LMU | Location Measurement Unit |
| LOB | Line of Bearing |
| LORAN | Long Range Aid to Navigation |
| LOS | Line of Sight |
| MDT | Mechanical Downtilt |
| MIMO | Multiple Input Multiple Output |
| ML | Maximum Likelihood |
| MUSIC | Multiple Signal Classification |
| NBAP | NodeB Application Protocol |
| NLOS | Non Line of Sight |
| Node B | 3GPP term for base station |
| OFDMA | Orthogonal Frequency Division Multiple Access |
| ODMA | Opportunistic Division Multiple Access |
| OPEX | Operational Expenditure |
| OTDOA | Observed Time Difference of Arrival |
| P | Precision |
| P-CPICH | Primary Common Pilot Channel |
| PCM | Pilot Correlation Method |
| PE-IPDL | Positioning Elements Idle Period Downlink |
| PRACH | Physical Random Access Channel |
| PRN | Pseudo-random Noise |
| QoS | Quality of Service |
| RF | Radio Frequency |
| RAN | Radio Access Network |
| RNC | Radio Network Controller |
| RNP | Radio Network Planning |
| RMS | Root Mean Square |
| RRM | Radio Resource Management |
| RSCP | Received Signal Code Power |
| RTD | Real Time Difference |

| | |
|---|---|
| RTT | Round Trip Time |
| SAS | Standalone Serving Mobile Location Center |
| SfHO | Softer Handover |
| SFN | System Frame Number |
| SHO | Soft Handover |
| SMLC | Serving Mobile Location Center |
| SOLAS | International Convention for the Safety of Life at Sea |
| SRNC | Serving Radio Network Controller |
| STD | Standard Deviation |
| TK | Teager-Kaiser |
| TA | Timing Advance |
| TA-IPDL | Time Alignment Idle Period Downlink |
| TCH | Traffic Channel |
| TDOA | Time Difference of Arrival |
| TOA | Time of Arrival |
| TX | Transmit |
| UE | User Equipment |
| UL | Uplink |
| UMTS | Universal Mobile Telecommunications System |
| U-TDOA | Uplink - Time Difference of Arrival |
| UTRA FDD | UMTS Terrestrial Radio Access Frequency Division Duplex |
| UWB | Ultra-Wideband |
| VM | Virtual Mapping |
| WCDMA | Wideband Code Division Multiple Access |
| WLAN | Wireless Local Area Network |

# CHAPTER 1

# Introduction

## 1.1 Background and motivation

Cellular communication and various value-added services launched in mobile networks play an important role in our daily activities. Currently, LBS (Location-based Services) are usually recognizable as car navigation systems based on GPS (Global Positioning System) technology. However, adequate applications accessible from mobile phones are not offered on a large scale yet, despite the presence of clear market opportunities increasing the operators' competitiveness. The range of LBS in a mobile world is certainly not limited to road assistance or car navigation, since together with the increased mobility of positioning-enabled devices, the opportunities are increasing accordingly [4],[5],[29], [31]. In fact, the research and development of mobile positioning was originally motivated by the issuance of the FCC (Federal Communication Commission) report in 1999 requiring cellular network operators to provide network-based positioning capabilities with certain performance requirements [22]. Naturally, the location information accessible by 112 (European) or 911 (North American) community and emergency service operators can significantly increase safety among mobile phone users [1],[23]. Enabling such a mechanism involves a definition of common positioning standards, but most of all, ensuring proper penetration of positioning-enabled networks and terminals. Moreover, the availability of location information can be exploited by radio network functionality procedures, improving the performance of mobility procedures in the idle mode and RRM (Radio Resource Management) algorithms in the connected mode [36]-[44]. On the other hand, the availability of positioning information could eventually lead abuse. Hence, 3GPP (Third Generation Partnership Project) standardized general privacy control mechanisms for location systems [28]. Nevertheless, due to the lack of a commonly adopted platform and absence of strict legal rules, there is right concern regarding privacy [5]-[9].

Enabling location-based services for cellular subscribers naturally requires implementation of technology that provides positioning information to the application. A major implementation obstacle which prevents the wide deployment of location techniques includes a requirement for performing modifications in the existing network infrastructure in order to support the positioning technology. Generally, positioning methods developed for GSM (Global System for Mobile Communication) could also be considered for CDMA (Code Division Multiple Access)-based cellular networks. Naturally, the actual implementation details vary to some extent through differences in the physical layer, system protocols definition, as well as in the overall functionality mechanisms. At the same time, the hardware limitations are system-dependent and hence most of the techniques originally developed for GSM but adopted to UMTS (Universal Mobile Telecommunications System) feature more accurate position estimation.

Typically, existing positioning solutions for cellular networks provide accurate location estimates, however at the cost of a significant increase of network and terminal complexity. At the same time, popular location techniques relying on pure cell identification are not complex, but neither are they accurate. Positioning technology is often referred to triangulation in time-biased methods or to techniques, which exploit the angle of signal arrival information [11],[72],[75],[159]. However, at the time of writing this thesis, such positioning systems are rarely deployed on a large scale in commercial cellular networks, with exception of time-based triangulation methods in North America. Due to lack of synchronization between adjacent base stations in UMTS, assurance of proper time-biased positioning functionality usually requires the deployment of LMU (Location Measurement Unit) [67]. These network elements perform timing measurements of all the local transmitters, based on which the actual relative time difference for each base station can be estimated. In a similar manner, enabling AOA (Angle of Arrival)-based estimation requires the implementation of adaptive array antennae, which can recognize the direction of the signal arrival [113]. At the same time, the terminal typically requires software modifications enabling positioning functionality. In turn, the most frequent necessary modifications to terminals include hardware and software upgrades providing GPS reception and processing features, which enable positioning at meter-level accuracy [16]. Consequently, the high deployment costs involved do not catalyze the deployment of the novel technology as revenues from LBS are expected over a relatively longer term. On the other hand, the majority of existing cellular location techniques, which are purely based on the standardized radio network architecture, do not typically provide the positioning accuracy at the wanted level by most LBS or other applications [P2],[98],[101],[152]. These methods estimate the location of the terminal mainly based on the dominance area of the serving cell or received signal strength through appropriate mapping of calculated path losses to the distances from the measured base stations. Certainly, it is challenging to meet the positioning performance expectations and at the same time keep the network and terminals free from modifications. Ideally, launching location-sensitive applications should not require major network and terminal modifications. In particular, enabling positioning services in legacy mobile terminals can maximize applicability and reduce time to market in the current competitive environment.

The major challenges of cellular positioning in meeting the performance requirements of LBS constitute multipath and NLOS (non line of sight) radio propagation, the unavailability of a sufficient number of base station needed for triangulation, limited resolution of terminal or base station measurements and geometrical dilution of precision. In the case of positioning methods exploiting GPS information, the scale of the multipath and NLOS problem is substantially reduced. However, additional challenges include the service availability, which is practically limited to the outdoor environment, and relatively long satellite acquisition time, especially during a ”cold start”. Naturally, the quantity and significance of these issues depend on the propagation environment, network topology, geographical position in the case of GPS-based methods, and the actual cellular communication system. In order to overcome these performance limitations, GPS terminal positioning is often assisted by the network in AGPS (Assisted GPS) solutions deployed in cellular networks [67].

The accuracy of the majority of cellular positioning systems strictly depends on the actual network topology as well. Hence, radio network planning and optimization aspects such as definition of the cell layout, cell overlapping, sectoring, antenna tilting, or multi layer and repeater deployment influence the performance of positioning [P3],[P8],[62]. Accordingly, the performed topology planning or optimization activities should take into account the performance of planned value-added services, including LBS, while naturally prioritizing network coverage and capacity.

## 1.2 Research objectives

The major objective of the research performed in this thesis is to study, develop, and finally to propose applicable cellular positioning methods for UMTS radio networks that do not require significant deployment investments. Specifically, the research focuses on the development of location techniques that effectively utilize existing network architecture and common 3G terminals without any or with only minor modifications enabling positioning. At the same time, the proposed techniques must meet the performance requirements of the majority of LBS.

At present, the techniques for mobile positioning in cellular networks either provide high positioning accuracy, but require major network and terminal infrastructure changes, or the methods are unable to meet performance requirements. Currently, the best positioning accuracy is provided by AGPS (Assisted GPS) [16],[67]. However, the majority of networks and terminals are not AGPS-enabled. The reduction of implementation complexity is essential in enabling positioning services in present cellular networks. Therefore, the research on positioning techniques concentrates on the development of methods that either do not require any modifications in the terminals or in the network. Techniques that utilize common UMTS terminals for positioning and perform the actual estimation process in the network (network-based methods) are attractive from the network operators’ and network hardware manufacturers’ perspective. In turn, other stake holders may be looking towards location techniques which allow modified terminals to be location-enabled in a wide range of networks (mobile-based). Hence, these two types of approaches to mobile positioning are considered in the frame of this thesis. The proposed methods are expected to be ready for direct deployment in current UMTS cellular networks due to minimum implementation complexity. In the long term, the availability of GPS-enabled mobile phones is likely to increase. Thus, the developed methods are expected to support AGPS positioning that significantly reduces latency and extends the positioning service availability to the indoor environment [P7].

## 1.3 Outline and main results of the thesis

This thesis introduces new network- and mobile-based location techniques for UMTS networks. The performance of the proposed positioning methods is assessed through extensive simulations and measurements. In addition, this thesis illustrates the influence of the topology planning process and selected aspects of optimization on the performance of the proposed positioning methods. The impact of capacity-oriented radio network planning on network-based positioning functionality and performance is evaluated in the context of numerous aspects of topology planning. Also studied is the impact of the proposed network-based positioning on network functionality and capacity.

The scope of the thesis is divided into three parts. The first part comprises a state of the art of the positioning area, the second part illustrates the proposed location techniques, and finally the third part presents a study on impact of radio network planning and optimization on positioning performance. The original results of the research are only generally reviewed in the thesis, as a comprehensive presentation can be found in the publications [P1]-[P9], attached as appendices to this thesis.

The thesis begins with a historical outline of positioning technical advances. Afterwards, Chapter 2 presents the motivation for mobile positioning in cellular networks and widely illustrates potential applications together with their performance requirements.

Chapter 3 presents the current state of the art in mobile positioning research, including a summary of standardization activities as well as an overview of existing research accomplishments in the field. In this context, the majority of cellular location techniques and satellite-hybrid methods are presented. Moreover, this chapter reviews the main technical and environmental challenges in meeting defined performance objectives.

The major part of the thesis (Chapter 4) presents the research results on network- and mobile-based cellular location methods for UMTS radio networks. In the scope of network-based techniques, the outcomes of study on CID+RTT positioning [P2] are included, and consequently, two network-based techniques - ECID+RTT and PCM originally presented in [P1],[P4],[P5],[112] are reviewed. The proposed techniques are entirely network-based, as enabling them in the current networks does not require any modifications in the terminals, only minor software updates in the network. At the same time, the conducted analyzes based on field measurements and simulations indicate that PCM and ECID+RTT positioning meet the accuracy requirements for most of the LBSs. In the scope of mobile-based techniques, two positioning approaches utilizing delay spread and propagation loss of the downlink signal are proposed and evaluated [P6]. Moreover, a technique that combines serving site information with signal strength measurements is proposed and compared with positioning based on pure signal strength measurements and adequate path loss-to-distance mapping [P7]. The considered mobile-based solutions do not provide as good accuracy as the proposed network-based techniques according to the results of the measurement campaigns [P6],[P7]. However, a higher level of accuracy than in signal strength-based methods can be achieved. Also, these positioning approaches can be utilized as effective assistance methods for mobile-based AGPS systems as evaluated in [P7] and summarized in Chapter 4.

Chapter 5, introduces the influence of the topology planning process and selected aspects of optimization on the performance of the proposed network-based positioning methods. In this scope, antenna site configuration, including sectoring and down tilting, as well as the impact of repeater deployment on radio capacity and positioning performance are studied [P2],[P3],[P8]. Moreover, the positioning accuracy is assessed on top of various network topology layouts including a recently proposed modified grid that features more controlled interference properties. Generally, the obtained results yield for a trade off between positioning performance and optimum radio topology from the capacity and coverage point of view. However, deployment of a repeater is an only example of topology optimization improving positioning performance while radio capacity is prioritized [P8],[P9]. In addition, in the frame of Chapter 5, the influence of proposed network-based location techniques on network functionality and radio capacity is evaluated [P1]. The performed study indicates that in practical scenarios, the proposed network-based positioning does not impact on radio performance. However, if a location is simultaneously requested by multiple terminals, the estimation processes should be scheduled in order to avoid interference peaks if ECID+RTT positioning is implemented [P1].

The general conclusions of the thesis and the remaining open aspects are presented in Chapter 6. A short summary of thesis publications [P1]-[P9], together with the author's contribution to the publications is given in Chapter 7.

## 1.4 List of publications

This thesis is a compilation of the following publications. In the text, they are referred to as [P1], [P2],. . ., [P9]. The publication [P9] is supplementary, because its main focus is on the topology planning of WCDMA radio networks. However, as topology planning and optimization clearly influence the performance of positioning, the problems considered in this paper complement the research on positioning.

[P1] J. Borkowski, J. Lempiäinen, "Practical Network-based Techniques for Mobile Positioning in UMTS", *EURASIP Journal on Applied Signal Processing, special issue on Wireless Location Technologies and Applications*, June 2006.

[P2] J. Borkowski, J. Niemelä, J. Lempiäinen, "Performance of Cell ID+RTT Hybrid Positioning Method for UMTS Radio Networks", *Proc. of 5th European Wireless Conf.*, February 2004.

[P3] J. Borkowski, J. Itkonen, J. Lempiäinen, "Impact of UMTS Topology Configuration on Cell ID+RTT Positioning Accuracy", *Proc. of 15th IST Mobile Summit*, June 2006.

[P4] J. Borkowski, J. Niemelä, J. Lempiäinen, "Enhanced Performance of Cell ID + RTT by Implementing Forced Soft Handover Algorithm", *Proc. of 60th IEEE Vehicular Technology Conf. (VTC)*, September 2004.

[P5] J. Borkowski, J. Lempiäinen, "Geometrical Transformations as an Efficient Mean for Reducing Impact of Multipath Propagation on Positioning Accuracy", *Proc. of 5th IEE International Conf. on 3G Mobile Communications Technologies*, October 2004.

[P6] J. Borkowski, J. Lempiäinen, "Novel mobile-based positioning techniques for UMTS", *Proc. of 9th IEEE International Symposium on Wireless Personal Multimedia Communications (WPMC)*, September 2006.

[P7] J. Borkowski, J. Niemelä, J. Lempiäinen, "Cellular Location Technologies Supporting AGPS Positioning in UMTS Networks", *Proc. of 62nd IEEE Vehicular Technology Conf. (VTC)*, September 2005.

[P8] J. Borkowski, T. Isotalo, P. Lähdekorpi, J. Lempiäinen, "Optimization aspects for cellular service performance and mobile positioning in WCDMA radio networks", *Proc. of 65th IEEE Vehicular Technology Conf. (VTC)*, April 2007.

[P9] J. Borkowski, J. Niemelä, J. Lempiäinen, "Applicability of Repeaters for Hotspots in UMTS", *Proc. of 14th IST Mobile Summit*, June 2005.

# Chapter 2

# Call for Positioning

In this chapter, the general motivation for positioning is briefly presented with emphasis on the need for positioning technology in cellular networks. The historical outline of the evolution of positioning radio techniques to present systems is also presented. Moreover, examples of the utilization of location awareness of mobile terminals in cellular networks with corresponding positioning performance requirements are illustrated.

## 2.1 Motivation for positioning

Our location has been always mysterious and despite rapid technological development and continuous enlargement of the observation area, the answer remains unknown. In addition to providing a solution for this constantly pervading philosophical question, the knowledge of position in the local dimension has been always critical for explorers and navigators.

Accurate location knowledge certainly improves the safety level, since numerous tragedies could be avoided with accessible location information [1]. Positioning is also crucial for military activities, which improve the overall safety of the country. Currently, the location of land line and wireless emergency callers in the majority of networks in developed countries is automatically provided for responsible organizations allowing a fast and accurate response. Furthermore, the tracking of children or disabled persons and the monitoring of vehicles or shopping items are other good examples showing that with positioning information safety can be improved and also the level of crime can be reduced. Properly managed positioning information undoubtedly improves the efficiency of organizations managing remote, distributed units, for instance, shipping or security companies. At the same time, the delivery of positioning information to portable devices opens an exciting range for new location-based services.

Typically, there are other viewpoints as well. The already mentioned priceless value of positioning information for military activities raises ethical questions [2],[3]. Additionally, the possibility of monitoring and tracking portable devices can be considered as attack on privacy that suggests the need for precise law adjustments to avoid abuse [4],[5],[6],[7],[8],[9].

### 2.1.1 History of positioning

Before the era of radio location techniques, people relied only on astronomical observations and magnetic features of the Earth in positioning. The approach changed radically in the early 1920s, when the first radio-based positioning technique was developed, known as LORAN-A (Long Range Aid to Navigation). Using this method, navigators were able to estimate the distance from shore-based transmitters based on TOA (Time of Arrival) [10]. Later, in the 1950s the US DoD (Department of Defence) developed the LORAN-C system through the utilization of artificial satellites. LORAN-C allowed more precise estimation based on the triangulation of pulsed, hyperbolic, low frequency (90-110 kHz) signal. This system offered selective coverage in the US and other countries [11],[12].

Following this, in 1959 TRANSIT was the first satellite-based radio location system, developed by The Johns Hopkins Applied Physics Laboratory (APL) [10]. This simple system consisting of 7 low-orbit polar satellites was initially intended to support the US Navy submarine fleet. However, the technology also constituted the groundwork for the revolutionizing positioning system - GPS (Global Positioning System). The system has plenty of drawbacks, including long acquisition time, two-dimensional estimation, coverage, and requirement of constant user velocity corrections, which makes it impractical for any rapidly moving users. However, it is still in use in some military applications. For civilian use, TRANSIT became available a few years later, in 1967 [13]. The Department of Defence was aiming to extend the existing system into a global, all-weather, continuously available navigation system for a broad range of users. The development continued in two parallel programs, TRANSIT and TIMATION. The system developed in the frame of the latter program consisted of only two experimental satellites to advance the research of mainly high stability clocks and time transfer [13]. In parallel, independent positioning research was carried out by The Aerospace Corporation, later supported by The US Air Force. By 1972, the outcome constituted a new type of satellite positioning based on PRN (Pseudo-random Noise) that was named System 621B. A consensus was reached in 1973, agreeing that research efforts would be united through combining the best features of the developed systems. The resulting concept emerged as NAVSTAR GPS, which is operational at present after various frequency and satellite volume modifications [10],[14]. Currently, this positioning system is simply referred as 'GPS'.

GPS provides global-wide, free, and accurate location information. The system relies on the constellation of 24 satellites transmitting on two frequency bands denoted as L1 - 1575.42 MHz and L2 - 1223.6 MHz. The signals are modulated by two PRN codes: P (Precision) and C/A (Coarse/Aquisition). On top of these, the GPS signal is modulated with a data message (GPS navigation message) in order to provide receiver information required for reliable position estimation from TOA measurements. The navigation message includes the position of the satellite - coarse and precise orbital parameters, the time of transmission of the PRN sequence, the coefficients needed to estimate the signal delay in the ionosphere and the coefficients needed to extract Universal Coordinated Time (UTC) from GPS system time [14]. The GPS receiver generates a replica of the PRN sequence and thus it is able to extract TOA information from shifting the locally generated sequence until a correlation is achieved with the received GPS signal. GPS satellites transmit on the same frequencies; however, CDMA (Code Division Multiple Access) is employed in the physical layer. Namely, each satellite uses unique ranging codes with low cross-correlation properties with each other.

In parallel with the activities in the United States, efforts towards an independent satellite navigation system were initiated in Russia, China, and the European Union. The Russian satellite positioning system, GLONASS (Global Navigation Satellite System) was developed to provide a similar performance to GPS in its final deployment stage. The major technical differences between GPS and GLONASS include frequency separation between satellites and synchronization aspects. However, GLONASS generally has many common technical features with GPS [17],[14]. In turn, the current stage of the Chinese satellite system (BEIDOU) comprises 4 geostationary satellites that provide limited coverage and application. However, China is aiming at developing BEIDOU to enable a truly global, all-weather satellite navigation system, consisting of 35 satellites. The outcome of satellite positioning activities in Europe comprises the development of GALIEO. Europe's own satellite system will operate on 1.1 - 1.6 GHz frequency employing CDMA transmission. GALILEO will transmit 10 different navigation messages enabling the provision of a wide range of services independently from other systems. It will be fully interoperable with existing GPS and GLONASS systems after the four first satellites are deployed, i.e., after 2009 [136]. However, according to current research and development progress, the estimated system launch will be postponed to 2013.

The development of a satellite-based system was not the only activity in the radio location field. Positioning systems using terrestrial radio transmitters was proposed already in 1969 motivated by the expected future need for vehicle monitoring [19],[20],[21]. A good example is represented by AVM (Automatic Vehicle Monitoring) systems providing positioning capabilities for a group of vehicles. These systems were introduced in North America in 1968. In 1995, the name was changed to LMS (Location and Monitoring Services), under which these systems are recognizable today. Typical applications of LMS include vehicle security, fleet management, and emergency services. The LMS in the US primarily operates in the spectrum of 902 - 928 MHz; however, it is also supported to a lesser extent in several bands below 512 MHz. The operating bands are shared with unlicensed devices, wireless phones, wireless area networks; hence interference between users of this spectrum is an issue [18].

### 2.1.2 Motivation for cellular positioning

Development activities of positioning technology applicable to cellular telephony was primarily motivated by the FCC (Federal Communication Commission) report stating that the calling party of all emergency calls (911) in the United States need to be located with a defined degree of accuracy [22]. Namely, the E911 Phase II report issued in 1999 stated that all cellular operators had to ensure location-enabled technology deployed by 10/2001. Moreover, cellular operators must have ensured that all subscribers in the United States use positioning-enabled terminals by 2005. In Europe, similar initiatives were taken by the EC (European Community). This organization appointed CGALIES (Coordination Group on Access to Location Information by Emergency Services) from a number of EU member states to define the positioning performance requirements for the E-112 wireless location system. The final report was issued in 2002 [23].

Certainly, the development of positioning technology is also driven by commercial opportunities in providing attractive LBS. Generally, LBS can be provided by any kind of independent network or fixed line telecommunications, however integrating cellular communications with location technology opens the door to very exciting areas of novel applications. These applications range from providing user location only, asset tracking and workforce management to interactive applications such as location-based games involving multi players or location-based dating services.

The availability of location information can potentially improve the efficiency of mobility procedures and overall RRM functionality in cellular networks. Good examples constitute location-based handover schemes that avoid the so called ping-pong effect or location explicit assignment to cell layers in hierarchical topology structures [24],[25],[26]. Moreover, location-sensitive billing provides the opportunity to introduce more flexible charging, for instance billing schemes with varying rates depending on whether the terminal is located in one's homebase, office, or on the road. Furthermore, based on location awareness, operators can encourage desirable behavior in network usage by employing location price disclamation [27]. Last but not least, mobile phone fraud can be potentially reduced through enabling accurate location tracking. According to [27], for some operators up to 1% of their subscribers experience fraud each month.

## 2.2 Cellular applications of location techniques and performance requirements

### 2.2.1 Location-based services

The combination of common cellular communication platform and location techniques opens an exciting range of new value-added applications. Location-based services can be defined as applications for cellular subscribers that utilize automatically determined location of the user.

3GPP (Third Generation Partnership Project) has standardized nine location-based services categories: public safety services, location-sensitive charging, tracking services, traffic monitoring, enhanced call routing, location-based information services, entertainment and community services and service provider specific services [28]. Location-based services can be classified in a number of ways. For instance, according to [4], three types of LBS are identified. These are namely pull, push, and tracking services. Pull type of applications generally require the user to send a request for location-sensitive information. Examples of such services include proximity information of PoI (Point of Interest), local weather forecast, location-sensitive yellow pages, etc. In turn, the push type of service provides location specific information automatically to subscribed users for such services. Examples include localized advertising, roadside assistance, or even interactive services involving multiple users such as location-based games or chat room. Similarly, emergency services can be classified as push-type applications as well. However, in this case, the calling user is not informed about the location, but naturally - the responsible organization. The services of the last category, tracking services, involve continuous positioning of the mobile terminal indicated by the customer on request. These applications include fleet management, workforce management, blind route guidance, location-based friend finders, and also services as fraud protection [5].

Four types of LBS are distinguished in the classification proposed in [29]. Services of type one provide the (generic) location information manually, for instance street number or post code in a similar way to popular applications such as MapQuest or ViaMichelin [30]. In turn, services of the second type are able to provide routing or proximity information, i.e., the most convenient route to the nearest PoI [31]. The third type of LBS can additionally provide push type of information, for example information about the event or traffic-specific alerts in the user location. Finally, a fourth type of these mobile applications feature location-aware application based on infrastructures, technologies and techniques that enable context aware information to be seamlessly offered to the end customer [32].

### 2.2.2 Location-sensitive network functionality

In cellular WCDMA-based networks, radio resources are simultaneously exploited by users transmitting in a single frequency band. The downlink power of the base station is shared among served users while every single power contribution in the uplink increases the interference level. Hence, the functionality of the radio resource algorithms is critical [33]-[35]. Utilization of location and mobility information of the subscribers allow the implementation of more accurate and efficient functionality of RRM algorithms [36]-[45]. For instance, admission control that takes into account the velocity of the terminal can make a more accurate estimation of the power increase due to admitting new user [36],[38],[41],[42]. In turn, location and mobility information allow for more efficient handover decisions that minimize the ping pong effect and improve the capacity of the network through allocation to the best available cell [37],[39],[40],[44]. Certainly, the benefits from location-based RRM algorithms are proportional to the network complexity. For instance, location-aware handover control can substantially improve the functionality of HCS (Hierarchical Cell Structures) [46],[47] or indoor systems [48]. In future, in cellular networks based on ODMA (Opportunistic Division Multiple Access), where coverage is enhanced by interconnecting users in an ad-hoc scheme [49],[50],[51], the location of the user can play an important role in connection-assignment and routing algorithms [52],[53],[54],[55].

Utilization of location information can improve the accuracy of radio planning and optimization activities. Namely, the uncertainties of coverage prediction models can be removed with location-assisted network planning. Then, the resulting dynamic distributive coverage maps represent the actual propagation conditions [56]. Assignment of antenna orientation or antenna down tilt in accordance with the density of users within a cell allows to minimize the transmission power and hence to minimize the interference and to increase the capacity [57],[58],[59],[60],[61],[62]. Certainly, the availability of precise terminal location improves the effectiveness of these optimization approaches.

### 2.2.3 Positioning requirements

The E911 Phase II report issued in 1999 requires that all cellular operators must have location-enabled technology providing accuracy of 100 m for 67% of calls and 300 m for 95% of calls (network-based), and correspondingly 50 m and 150 m for mobile-based solutions. The requirements for network-based are less tight as the FCC recognized these as applicable for immediate deployment. In turn, the participants of the European CGALIES group within the EC, did not reach apparent consensus on the precise accuracy requirements for 112 emergency calls. However, it was generally agreed that the mean location error should not be larger than 50 m in urban outdoor areas in order to provide an effective emergency service. The accuracy requirements are less strict in suburban areas (50 m - 100 m) and in rural areas (approximately 100 m), as presented in the final report in 2002 [23]. Unlike FCC, CGALIES did not define the accuracy requirements according to the positioning approach (network- or mobile-based).

The functional requirements including interoperability, performance, and security of LBS have been standardized by 3GPP (Third Generation Partnership Project) [28]. Generally, location systems must follow a flexible modular component framework with open interfaces in order to facilitate interoperability and evolution of service providing capabilities. In addition, OMA (Open Mobile Alliance) has standardized the location solution complementing the 3GPP approach. The defined SUPL (Secure User Plane Location Solution) is applicable for both 2G and 3G networks and involves a network-based server and terminal that communicates using IP (Internet Protocol) [66].

The location estimation process should intelligently combine diverse positioning methods and available local knowledge in order to provide optimal positioning request response in line with QoS (Quality of Service) parameters [28]. The QoS of LBS can be categorized into three layers: communication QoS, positioning performance QoS and location-related content QoS [63], while positioning performance is primarily defined by accuracy, availability and latency. The prioritization of the QoS parameters needs to be precisely defined individually for location services. For instance, the positioning response should be correlated with the defined priority of other performance requirements. In particular, if the accuracy requirement is prioritized, the location server answers when the estimated position meets the accuracy needs. On the other hand, if the response time has the highest importance, the server answers immediately, regardless of the accuracy of the available position estimate [28]. In most of the value-added location-based applications, a relatively fast response is desired with the location request (pull type of services), ranging from a few seconds to a few minutes, depending on the service. A similar response time, but with a constant interval applies to push type applications [63],[64]. From the other viewpoint, services such as AIS (Automatic Identification System) navigation for SOLAS (International Convention for the Safety of Life at Sea) vessels [65], require only a daily update of the position estimate [63].

The required accuracy of positioning for beneficial operation of most of the introduced push and pull LBS is at the level of 100 m for 67 % of estimates. However, there are services where much lower accuracy is needed, for instance location-based weather forecasts or location advertising. On the other hand, route guidance or specific location aware interactive games may require sub-meter positioning accuracy. The exploitation of positioning information to support location-aided planning and optimization improves the performance proportionally to the estimation accuracy. Certainly, the scale of improvement also depends on the cell size, for instance location aware handover might require positioning accuracy at the level of indoor/outdoor or velocity estimation with 10-20 km/h certainty, while location assisted dynamic network planning might require at least 100 m accuracy [39],[45],[48], [56].

There are no general requirements defined in terms of positioning service availability. However, as long as roaming agreements exist the positioning should be possible in either the home or visiting network. This functionality is crucial as the probability of using LBS (e.g., informative services) increases for roaming subscribers.

# Chapter 3

# Fundamentals of Location Techniques for UMTS

In this chapter, technical aspects of a mobile positioning technology are presented. Environmental and implementation challenges of positioning in meeting the LBS requirements are also described in this context. Location techniques are overviewed together with brief presentation of standardization activities in the positioning field.

## 3.1 Major positioning challenges

All positioning techniques are exposed on various environmental sources of error due to diverse and dynamic propagation characteristics in typical cellular scenarios. Moreover, a fundamental limitation or rather a major source of difficulty for any of the location techniques, which are based on time measurements is the speed of the wave propagation. Since radio waves propagate at a speed of light, hence in order to calculate the position within a rational accuracy frame, for instance, 100 m, the supporting time measurements need to be accurate within 328 nanoseconds. Naturally, achieving such performance is challenging in presence of all aggregated environmental and geometrical limitations. In addition, hardware limitation restricts the possible accuracy mainly due to the minimum separation ability of the RAKE receiver in case of time-biased methods or angular sensitivity of beam direction estimation in AOA (Angle of Arrival)-based approaches.

### 3.1.1 Environmental limitations

Multipath propagation appears due to the existence of various obstacles in the radio environment that are source of reflections, diffractions, and scattering of the radio signal. Multipath and NLOS (non-line of sight) propagation are the dominant sources of error for majority of positioning methods, as only a position estimation based on LOS component(s) provides true information. Unluckily, even in settings with existing LOS signal, it is challenging to correctly detect the LOS path in presence of multipath components, see subchapter 3.3.6. Therefore, all location technologies that involve distance estimation in positioning process are vulnerable to these phenomena.

Presence of obstacles in the propagation environment causes slow fading (or log-normal fading) with standard deviation of 6-10 dB depending on the propagation environment at UMTS frequency in typical cellular settings [128]. In turn, multiple components arriving at different incident angles and propagation time are constructively or destructively summed causing fast fading of the received signal. Undoubtedly, the fading phenomenon affects the location measurements and hence it degrades the estimation accuracy. Positioning based on signal strength measurements suffers directly from the fading phenomenon as the actual state of the radio propagation channel needs to be estimated before the calculated path loss is mapped to the distance. Naturally, averaging of the measurements and other statistical approaches can reduce the negative impact of the fading, see subchapter 3.3.2. In turn, an indirect influence of the fading phenomenon causes reduction and destabilization of the ratio between the desired and undesired signals arriving at the receiver that can lead to false LOS detection.

Multipath characteristics of the radio channel result in signal components spread over time and frequency. Such spreading causes interference in the UMTS downlink transmission as selected spreading codes for separating physical channels in the downlink are not fully orthogonal [129],[33]. Presence of downlink interference causes measurement corruption in the majority of the positioning methods, which require terminal to conduct certain measurements, hence this problem usually refers to mobile-based or mobile-assisted methods. Moreover, downlink interference reduces the hearability of the base stations that is typically a major coverage limiting factor of the positioning techniques requiring downlink measurements from at least 3 base stations, e.g., OTDOA (Observed Tome Difference of Arrival) method. The cell hearability is also limited in the uplink due to the influence of the cell load on the uplink cell range, which is commonly present in WCDMA systems. Hence, techniques requiring multiple uplink measurements such as most of AOA-based techniques (3.3.4) or derivative methods of recently standardized U-TDOA (Uplink-Time Difference of Arrival) technology (3.3.1) are affected.

### 3.1.2 Hardware limitations

One of the major sources of accuracy limitation in time-biased methods is a resolution of the receiver in separating multipath components. Of the utmost importance for mobile positioning is the ability of estimating the first arriving component from the subsequent multipaths. Typical RAKE receiver can separate the signal components with minimum one chip resolution, while multipaths arriving within intervals less then one chip are merged and thus cannot be distinguished. In the WCDMA physical layer, a chip rate of the spreading sequence is 3.84 MHz resulting in 0.26 $\mu s$ chip interval [129]. Therefore, in the worst case, the resulting positioning time error is in order of 0.26 $\mu s$ that translates to 78 m error in a range estimation. The performance of the RAKE receiver can be further improved in closely spaced scenarios if over sampling or interpolation-based methods are used. However, as the receiver complexity significantly increases with the over sampling rate, WCDMA receivers with the sampling rate higher than 4 times the chip rate are unusual in practical implementations. Alternatively, estimation accuracy of the receiver delay can

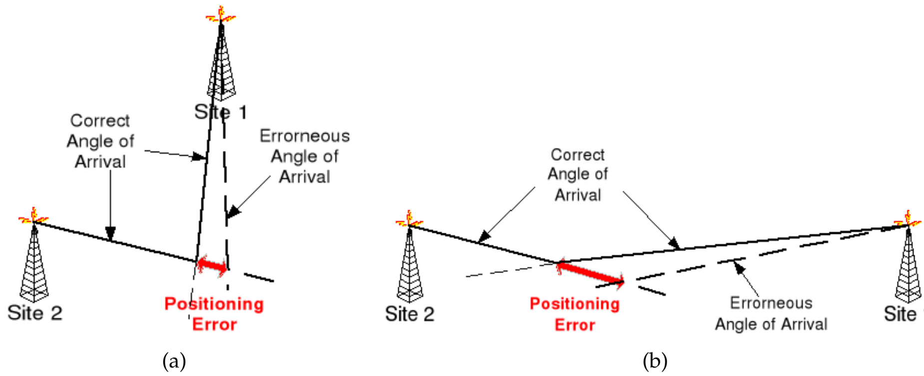



**Figure 3.1** Geometric dilution of precision; (a) - good geometry; (b) - bad geometry.

be enhanced with super-resolution algorithms combined with the RAKE receiver architecture, see subchapter 3.3.6. Due to size and cost constrains, deployment of complex mechanisms solving closely spaced path problems is more applicable for base stations than for mobile terminals. Hence, time-biased techniques exploiting uplink measurements, typically - network-based solutions, can potentially benefit from such enhancements. According to current performance requirements, the accuracy of the NodeB time measurements (RTT) is 0.5 chip that corresponds to 39 m range error, while the accuracy of the UE time measurements (Rx-Tx) is 1 chip [130]. In addition, time-biased methods suffer from an inaccurate time calibration of the framework elements as even small uncontrolled time offset can ruin the entire positioning process.

Other implementation-related limitations to positioning accuracy include filter mangnitude/group delay variations and I/Q magnitude imbalance. In addition to hardware constrains, positioning performance is limited by non ideal software-based processing. These may include fixed-point truncation, rounding errors, as well as limited data resolution.

### 3.1.3 Geometric limitations

The majority of the location techniques require simultaneous measurements of the signal from more than one transmitter, such techniques are also called as multilateral if the base station makes the measurements or unilateral if the UE performs measurements. In such techniques, the estimation accuracy is affected by the geometry of the network topology in cellular positioning or by the geometry of the satellite alignment in respect to the position of the terminal in satellite-based techniques. Precisely, geometric arrangement can increase a level of the accuracy degradation caused by the other sources. This phenomenon, known as a dilution of precision can be considered in horizontal and vertical plane and named accordingly. Good example illustrating geometrical degradation of positioning accuracy constitutes AOA technique, see Fig. 3.1.

Logically, the negative impact of geometric arrangement can be minimized by increasing a number of the reference points through, e.g., conducting measurements from larger number of base stations. Intuitively, in scenarios mainly consisting of 2-sectored base stations deployed in highway or rail link scenarios, the impact of the dilution of precision on the accuracy can be significant.

The geometric dilution of precision impacts the accuracy of satellite-based positioning as well. High latitude positions are especially vulnerable for geometrical accuracy reductions as in these locations, satellites are located at low angular altitudes beyond the horizon. This effect will be reduced in GALILEO positioning system as it is intended to provide better coverage than GPS especially for Northern or Southern locations.

## 3.2 Standardization

The ETSI (European Telecommunications Standards Institute) is responsible for the standardization of location techniques for UMTS within 3GPP (Third Generation Partnership Project). The 3GPP provides an overall service description and the core requirements for the LCS (Location Services) at the service level (Stage 1 LCS, ref. [28]) as well as standardizes the functional model, the LCS system architecture, and relevant message flows (Stage 2 LCS, [67],[68]). There are four standardized positioning methods supported by UTRAN (UMTS Terrestrial Radio Access Network) [67]. These are specifically, Cell ID (identification) - based methods including RTT (Round Trip Time) enhancement, OTDOA (Observed Time Difference of Arrival) that may be assisted by network configurable idle periods, network-assisted GNSS (Global Navigation Satellite System) methods, and U-TDOA (Uplink - Time Difference of Arrival) methods. The positioning methods will be reviewed in chapter 3.3 of this thesis.

The arrangement for implementing UE positioning functionality in UTRAN according to the 3GPP is presented in Fig. 3.2 [67]. The major functionality is concentrated within SRNC (Serving RNC (Radio Network Controller)), which has two standardized working modes - RNC centric and SAS (Standalone SMLC (Serving Mobile Location Center)) centric. Basically, the RNC in the centric mode manages the flow of positioning requests, selects the positioning technique, provides positioning assistance data if needed, and finally estimates the position. In case of the SAS centric mode, the major RNC positioning functionality is handed over to the SAS, however the SAS performs procedures only based on the requests from the SRNC. The SAS provides the GNSS assistance data and performs U-TDOA positioning. When timing assistance is needed, the SAS may rely on the associated LMU (Location Measurement Unit). In the SAS centric mode, the SRNC plays an active role in communication between the UE and the CN (Core Network) and delivers to the SAS information supporting location method selection. In turn, CRNC (Controlling RNC) determines involvement of the UTRAN elements and defines necessary measurements. The CRNC is responsible for managing impact of the UE positioning operations on the overall RAN performance, that includes an admission control of new location request and controlling idle periods for OTDOA positioning measurements. Moreover, the CRNC supports positioning by broadcasting necessary data.

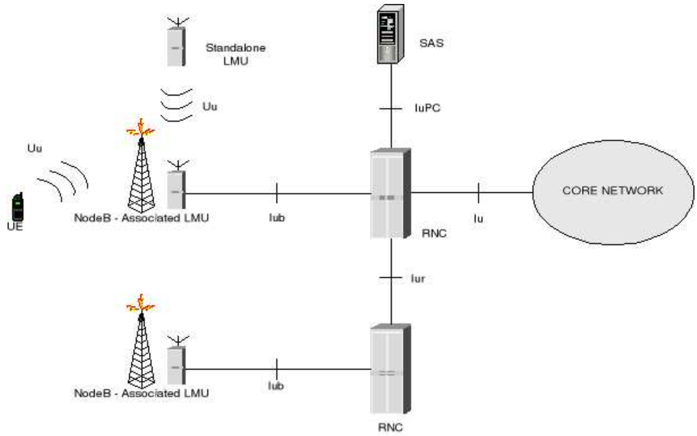



**Figure 3.2** General arrangement of UE positioning in UTRAN [67].

For instance, this might include broadcasting information of the timing difference between involved NodeBs based on the measurements provided by the LMU. The LMU role is to make continuously or on the CRNC request radio measurements and optionally to perform associated calculations and forward these to the CRNC. Typically, the LMU performs the GNSS measurements as well, which are for instance needed to report the timing offset calculated in a reference to the GNSS timing. In a similar manner, the UE performs measurements of the downlink signal and may transmit the needed signal for the uplink-based positioning. Delivery of the UE measurements to the network server for the location calculation is also part of OMA SUPL standards [66]. The UE either contains LCS application or accesses an LCS application over the network. Optionally, the UE can be equipped with GPS receiver and thus might be able to perform the entire positioning procedure without involvement of the UTRAN.

The physical layer measurements, which can be utilized for positioning are standardized in [69]. Depending on the location technology, the UE might be scheduled to measure and report Rx-Tx time difference, CFN-CFN (Connection Frame Number) or SFN-SFN (System Frame Number) observed time difference measurements, or pilot signal strength measurements - RSCP (Received Signal Code Power). Moreover, GPS-enabled terminals supporting AGPS positioning need to measure and report the GPS timing of the cell frames and the GPS code phase [69],[70]. In turn, the UTRAN standardized measurements include RTT and SFN-SFN observed time difference for selected time-biased positioning methods and the GPS timing of the cell frames when the AGPS is used.

## 3.3 Principles of cellular positioning

A number of basic technologies for mobile positioning has emerged over the last years. These techniques are traditionally classified as mobile- and network-based approaches depending on the involvement of network infrastructure in the positioning procedure and whether the final location is estimated in the UTRAN or in the UE. Technology-wise, the location techniques are basically grouped as time-biased methods, signal strength methods, database methods, and techniques that utilize adaptive antennas to estimate angle of arriving signal. In addition, network methods that exploit the GNSS information for accurate positioning in addition to the cellular radio measurements represent a separate category of the network-assisted satellite methods. Naturally, combinations of these basic methods are frequent, which result in hybrid positioning techniques aiming at improving performance of individual approaches. In majority of location techniques, the accuracy is limited due to NLOS and multipath propagation in typical radio environments. Hence, LOS detection and estimation technologies play an important role in the cellular positioning [15]. General presentations of the existing solutions for mobile positioning can be found in [11],[72],[75],[159].

### 3.3.1 Time-biased methods

Time-biased positioning methods exploit measurements of radio propagation time. These methods range from simple RTT-based [P2] methods where only distance(s) from single or multiple base stations are estimated, to TOA and TDOA methods exploiting propagation time measurements from or to at least three transmitters in order to estimate the set of the propagation distances. If the TOA positioning is used, the position of the UE is estimated in the intersection of the estimated ranges (3.1).

$$r_i = ct_i = \sqrt{(x_i - x)^2 + (y_i - y)^2} \tag{3.1}$$

In (3.1), $x_i$, $y_i$ are the coordinates of the $i$-th base station, $x$, $y$ are unknown coordinates of the UE, $r_i$ is the distance between the UE and the $i$-th base station based on the measured propagation time ($t_i$). In practice, $r_i \equiv (\tau_i - \tau)$, where $\tau_i$ is the measured TOA from the $i$-th base station and $\tau$ is a measurement error as observable TOA is enlarged due to multipath, NLOS, and hardware errors. The explicit solution can be found if at least three TOA measurements are known.

Alternatively, the position of the UE can be estimated through solving a set of equations illustrating time difference of arrival between a pair of measured base stations. Based on the single OTDOA measurement from two base stations a hyperbola with constant time difference can be derived along which the UE may be located. Hence, the position fix is based on the solution of set of the nonlinear equations representing at least two such hyperbolas, (3.2).

$$\begin{cases} c(t_1 - t_2) = \sqrt{(x_1 - x)^2 + (y_1 - y)^2} - \sqrt{(x_2 - x)^2 + (y_2 - y)^2} \\ c(t_1 - t_3) = \sqrt{(x_1 - x)^2 + (y_1 - y)^2} - \sqrt{(x_3 - x)^2 + (y_3 - y)^2} \end{cases} \tag{3.2}$$

In (3.2), $t_1$, $t_2$, and $t_3$ represent measured propagation time of signal from corresponding base station with coordinates $x_i$, $y_i$, while $x$ and $y$ stand for unknown coordinates of the UE and $c$ for speed of light. A set of the estimated hyperbolas forms a nonlinear set of equations, as the hyperbolas are shifted due to involved positioning errors. Commonly utilized numerical methods include nonlinear least-square, constrained least-square (timing error is always positive) [71], [72] or, e.g., linearization through expansion to Taylor series [14].

The OTDOA measurements are extracted from the UE physical layer SFN-SFN observed time difference measurements. Certainly, the OTDOA-based estimation process requires an information about the coordinates of the base stations as well as the RTD (real time difference) between the DL (downlink) transmissions as UTRAN base stations are not synchronized and hence the RTD is not constant. Required information can be provided by the LMU at fixed location, which timestamps the UTRAN cell frames according to the common GPS timing or performs the SFN-SFN observed time difference measurements of all the local base stations. Since the position of the LMU as well as the local base station is known, such measurements can be easily converted to the absolute RTD for every involved base station. Often, the positioning process is also supported by the RTT measurements from involved base stations. Depending on the working mode, the UE forwards all the measurements to the network where the SRNC or the SAS performs the actual position estimation (UE-assisted) or the required assistance data is delivered to the UE, which makes the final calculations (UE-based).

Naturally, the OTDOA-positioning is not an exception from exposure on harmful environmental conditions and hardware limitations. Hence, the OTDOA positioning typically aims at collecting time measurements of all visible transmitters in order to minimize the error. Practically, reasonable positioning accuracy is obtainable with more than 6 sites hearable at terminal location [165].

The major factors limiting applicability of the OTDOA include implementation and maintenance of the LMUs [73], terminals modifications, and mentioned restricted availability of the required number of pilots in typical cellular scenarios [74]. The standardized OTDOA optionally exploits IPDL (Idle Period Downlinks) technique. Accordingly, base stations synchronously cease their transmission in order to increase the availability of pilots at the UE location and thus to enable OTDOA positioning [74],[67],[75],[165]. Depending on the network topology, traffic, terminal SFN-SFN measurement sensitivity, and power dedicated for P-CPICH (Primary - Common Pilot Channel), the hearability improvement from the IPDL can be even triple-fold [74]. However, according to the results presented in [165], the OTDOA-IPDL estimation errors in the practical scenarios are expected to be quite large, as for 67% and 90% of measurements the positioning error is in order of 125 m and 400 m assuming the hearability of 6 sites and -30 dB Ec/Io sensitivity of the SFN-SFN measurements.

Additionally, numerous enhancements to the basic DL OTDOA aim at increasing the pilot hearability through cost of higher network and UE complexity. These mainly include TA-IPDL (time aligned - IPDL) [76],[77], PE-IPDL (positioning elements - IPDL) [78], and interference-based cancelation techniques: IC-IPDL [81] and software-based method CVB (Cumulative Virtual Blanking) [79],[80]. The TA-IPDL specifies a time-aligned configuration of idle periods ($\sim 30\ \mu s$) from different base stations that schedules each base station to transmit the pilot for 30% of the time allowing more distant base stations to be hearable by the UE. In turn, the PE-IPDL relies on additional network elements (PE), which synchronously transmit sequences that are exploited by the UE to perform the standardized OTDOA measurements. The accuracy of the OTDOA with PE-IPDL implementation strictly depends on the average distance between the UE and the measured PEs. Thus, a number of the deployed PE and the topology density have an impact on the positioning performance. Simulation results in [78] illustrate almost 15% accuracy improvement in comparison to the standardized OTDOA-IPDL in the heavy urban environment.

The other group of OTDOA enhancements exploits the interference cancelation and channel estimation techniques enabling undetectable signals to be measured. At the same time, as the idle periods in the transmissions are not needed any more, the network functionality is not invaded. This is clear benefit comparing to the standardized OTDOA-IPDL approach. Comprehensive simulation results of the IC-IPDL are presented in [81], where authors claim that the accuracy is slightly better then OTDOA-IPDL positioning. In turn, the performance assessment of the software-based method - CVB illustrates a significant accuracy improvement as the error is narrowed down to 12 m - 24 m for 67% of position estimates [79]. Time-biased positioning techniques that exploit the downlink measurements have been also proposed. Utilization of the time differences between the idle periods in transmission from the measured base station allows to simplify the hyperbolic equations and to estimate the position without exploiting the LMUs as claimed in [82]. In turn, the other method relies on the measurements of the relative timings of the network signals received by the UE for derivation and maintenance of the network synchronization map [83]. This information is exchanged between the users in the coverage area, and thus the need for LMUs is avoided as well. Method called Matrix provides the accuracy at a level of 50 m - 90 m for 67% of measurements, however required collection of measurements from multiple terminals might be challenging in practical realization [83].

On the contrary to the DL OTDOA-based approaches, the time-biased positioning can be applied in the UL (uplink) as well, hence avoiding idle periods in downlinks and a need for terminal modifications [84]. However, the U-TDOA (Uplink Time Difference of Arrival) requires measurement units in the network in addition to the LMUs, hence deployment cost is not low. The standardized U-TDOA method exerts a process similar to the downlink triangulation through estimating the difference of the signal arrival from the positioned UE at different LMUs [67],[85]. The time difference of the arriving signals at different LMUs is derived from the cross correlating and maximizing the correlation coefficient through shifting. In a similar manner to the DL positioning technique, resulting hyperbola defines the possible location of the UE. Hence, at least three hyperbolas are needed to obtain the unique position estimate. Naturally, as the resulting hyperbolas are erroneous, the accuracy increases with the number of cooperating LMU sites. According to [85], advertised U-TDOA-based product can exploit up to 50 sites for the single location measurements. Naturally, the availability is restricted in the practical scenarios, especially in sparse rural topology settings. Moreover, promising accuracy results were presented indicating 50 m accuracy not limited to outdoor environment [85]. In turn, the simulations results presented in [86] reveal that if the MUSIC algorithm is used for the TOA estimation, the DL-based TDOA positioning performs better.

### 3.3.2 Signal strength methods

The exploitation of radio propagation losses is one of the most straightforward techniques for mobile positioning as the signal strength measurements need to be obligatory supported by all radio-based communication systems. Signal strength-based positioning was one of the first radio location strategies proposed in 1969 for police vehicle location [20] and intensively studied in GSM [87],[88],[89],[90], [91],[92],[93], [94], [95]. Generally, the position is estimated from adequate path loss to propagation distance mapping according to the propagation model. Hence, at least three measurements of the signal from different transmitters are needed to find the explicit solution. Wide range of the propagation models is used, however the most often, estimation is based on COST-231-Hata model [96]. Certainly, the accuracy of the positioning based on direct implementation of the propagation model is very poor, therefore actual propagation parameters need to be estimated beforehand. There are numerous approaches for propagation parameters estimation that range from maximum-likelihood method [97] through statistical techniques [98],[99] to methods that combine signal processing with fuzzy logic [93],[94]. Again, estimated ranges are typically erroneous and do not intersect in a unique point, hence usage of appropriate optimization algorithms is needed.

The positioning accuracy primarily depends on density of the network topology and the propagation environment, but generally reported results of signal-strength-based methods illustrate much poorer accuracy than for instance time-biased techniques. Depending on the simulation environment and the estimation approach, reported mean error varies from over 150 m [90] and 300 m [100],[98] to even 1000 m [101]. The adaptation of the signal strength positioning to UMTS system is straightforward as the RSCP measurements of the P-CPICH are mandatory. In addition, a number of techniques basing on the same principle was proposed for WLAN (Wireless Local Area Network) [102],[103]. Moreover, signal strength measurements are commonly utilized in database correlation positioning methods, which are reviewed in the following subchapter.

### 3.3.3 Database methods

Numerous positioning estimation techniques are based on a database consisting of the most expected reports in the defined area. Simply, based on a priori knowledge of a particular measurement in the entire network, the position of the UE can be estimated in the region corresponding to the sample characterized by the highest degree of correlation with the actual measurement. For GSM, a fingerprinting method utilizing database with pre-measured signal strength samples was proposed in [104] and further intensively evaluated, e.g., in [105],[106],[107],[108]. Samples required for creation of the database can be collected by conducting measurements over the service area, but logically, they can also be gathered by performing simulations, as presented in [109]. The reported accuracy does not exceed 80 m for 67% of measurements. In turn, for UMTS networks the DCM (Database Correlation Method) was developed [110],[111]. This proposed technique uses measurements of multipath delay profile from the strongest cell. Moreover, complementary use of RTT information from the base stations further improves the accuracy. The simulation results have shown that in very dense network scenarios for urban deployment, 67% of users can be located with an error smaller than 25 m. In comparison, standardized OTDOA positioning evaluated in the same environment provided accuracy at the level of 97 m for 67% of measurements [110]. However, an extensive research on the fingerprinting concept in [166] reveals that the accuracy is typically deteriorated by the fact that terminals may be used in different positions against body and local scatters introducing substantial errors. Accordingly, in proposed database method relying on CID and path loss measurements, the positioning error can be reduced not more than to 20% of the original size of an urban cell since path loss may vary by 10-20 dB depending on the orientation of the user against the base station and local obstacles [166]. Naturally, the accuracy is strictly correlated with the network topology as highly overlapping sites provide a high level of the database diversification and hence improving the positioning accuracy [112],[106]. Alternatively, the database might be enhanced through utilization of both 2G and 3G measurement data thus improving the accuracy for dual system terminals [106].

Positioning methods based on the database correlation method principle are the most common approaches proposed to short-range networks such as WLAN or UWB (Ultra-Wideband).

### 3.3.4 Antenna array methods

A significant attention has also been gained by the positioning methods utilizing AOA (Angle of Arrival) information of the UL (uplink) signal at the base station antenna [72],[113]. In fact, positioning based on the AOA principle constitutes one of the earliest location methods used in radar and sonar devices. These techniques require base stations equipped in adaptive antennas for the accurate estimation of the direction of the incoming radio signal. Based on the measurements, a LOB (Line of Bearing) is estimated along which the location of the UE is restricted. According to the geometric, the uplink signal needs to be received by at least two base stations in order to have a unique location solution in the intersection of two resulting lobs, if the third dimension is neglected.

A cellular signal is generally exposed for multipath propagation affecting AOA positioning performance. However, macrocellular scenarios characterize with a relatively small angular spread of the received uplink signal, since scattering objects are usually located within small distance from the UE while base station antennas - above the surrounding buildings [114]. Naturally, significantly smaller positioning errors are expected in the microcellular environments than in the macrocellular. In any case, identification of the AOA and the LOB estimation is challenging due to presence of multiple replicas of the arriving signal waves at antenna connector. Many methods have been proposed ranging from approaches basing on linear prediction and maximum likelihood [115],[116] to subspace processing algorithms, e.g., MUSIC [117],[118],[119]. Due to presence of the multiple error sources, the estimated LOBs are basically always shifted. Hence, finding the unique location solution requires usage of numerical methods. A classical approach is based on the liberalization through expanding nonlinear location function to Taylor series and using the maximum likelihood (ML) estimator [120]. Later, non-iterative closed-form solutions to AOA estimation problems were also proposed [121],[122].

The AOA accuracy strictly depends on the network topology and propagation environment. Studies illustrated in [72],[123] reveal that the AOA estimation error can range from 200 m to 600 m depending on the scatters location and a number of the base stations involved in the procedure. Furthermore, lots of hybrid approaches involving the AOA measurements were proposed. For example, a conjunction of the TOA information with the AOA at the base station slightly improves the accuracy [124],[125]. Significantly larger improvement was reported in [126],[127], where the UE OTDOA measurements support the AOA measurements at the base station. This hybrid approach has revealed the accuracy at the level below 100 m for 67% of location estimates in most of the simulated scenarios for urban environment. However, the applicability in current UMTS networks is still at a low level as the implementation of the AOA recognition technology requires utilization of the adaptive array antennas, which are not frequently used.

### 3.3.5 Satellite-based and satellite-network hybrid methods

The satellite-based systems offer excellent positioning coverage and accuracy in open-space environment, significantly better than most of the network-based solutions. On the contrary, the satellite positioning systems do not work in indoor settings or even at street level in high-rise urban scenarios as due to very weak strength of the satellite signal, the LOS communication is required. Also, the acquisition time can be long especially for the first position fix, which is also called as a cold start [14]. Satellite hybrid or AGPS (Assisted GPS) method partly overcomes of these obstacles by assisting terminal through providing a satellite navigation message and optionally a rough position of the UE. Moreover, distributed positioning functionality in the AGPS solutions results in a lower terminal complexity. However, mobile phone manufacturers typically include also the UE-based AGPS in terminals. Basically, a network equipped with a reference GPS receiver located in the LOS with the satellite receives the navigation message and forwards the data to the UE over air interface using standardized dedicated signalling [67]. Provision of a rough terminal position together with the accurate reference time results in improved sensitivity (even 20 dB gain) [16]. In addition, information of a rough location of the terminal helps in more accurate selection of an initial point for optimizing satellite pseudo ranges and solving the location coordinates. Moreover, in environments where the GPS signal is unavailable, the position of the terminal can be solely estimated by network-assistance method [P7],[131] but naturally with a lower accuracy. Also, in case of the limited satellite hearability, satellite pseudo ranges can be complemented by cellular ranges estimated based on, e.g., the OTDOA principle [132]. Obviously, all kinds of satellite-hybrid method require integration of the GPS receiver to the user terminal that impacts manufacture costs, power consumptions, and size/weigth of the device. At the time of writing this thesis, mobile phone manufacturers seem reluctant in adapting GPS technology to the popular phones, as only top-shelf models appear to be GPS-enabled.

Network assistance methods for satellite positioning were studied and standardized already for the application in GSM networks [131],[133] and then adapted to 3G systems [67],[16],[134],[135],[132]. Moreover, as European satellite positioning system - GALIELO will be available in the future [136], adequate satellite-assisted location techniques are also studied. Namely, a method exploiting cellular assistance - Assisted GALILEO and a method that utilizes both GPS and GALILEO data (AGPS + Assisted GALILEO) for mobile positioning in UMTS [137] are considered. There are numerous developed commercial AGPS solutions for UMTS, for instance, gpsOne by Snaptrack (a Qualcomm company) [138] or Indoor GPS by Global Locate [139].

### 3.3.6 LOS detection and estimation

Positioning accuracy of time-biased and AOA-derivative methods could be significantly enhanced if the LOS signal component could be detected or estimated from the arriving signal components. The LOS detection methods are mainly based on the history of distance measurements, which are assumed to consist of an actual distance plus an estimation noise, whose variance is assumed to be known. The measurement process is modeled as a high-order polynomial filter, Kalman filter or as a random process with exponentially decaying correlation and variable mean [140],[141],[142]. The LOS situation is then detected from the previous estimates based on certain assumptions of known measurement-noise variance. Other approaches exploit statistical data of the fading paths to estimate whether the LOS is present or not [143].

In settings with present LOS component, estimation of the first arriving path is challenging if subsequent signal components are overlapping, i.e., they arrive within the time instance shorter than a resolution of the RAKE receiver, which is duration of one WCDMA chip - 0.26 $\mu s$. Naturally, in time-biased positioning high delay estimation accuracy is desired as the time shift of 0.26 $\mu s$ corresponds to 78 m distance.

Approaches for estimating delay in closely-spaced scenarios include DLL-based methods [144], EKF (Extended Kalman filter) - structures [145], ML-based algorithms [146], pulse-subtraction techniques [147], deconvolution methods [148], introduced earlier subspace-based algorithms, quadratic-optimization algorithms [149], and TK (Teager-Kaiser) method [150]. In scenarios with unknown number of channel paths, the LOS delay can be estimated through 'thresholding', a technique that searches for the peaks of specially constructed correlation function that exceed a certain threshold [151]. A comprehensive overview of LOS detection and LOS delay estimation methods can be found in [15].

# CHAPTER 4

# Detailed Study on Mobile Positioning for UMTS

This chapter provides an overview of the research on cellular positioning for UMTS. Network- and mobile-based developed positioning methods are briefly presented and evaluated. A detailed description of the illustrated techniques and performance assessment together with an accurate presentation of measurement and simulation environment is provided in the publications attached to this thesis, [P1]-[P9].

## 4.1 Detailed study on network-based cellular positioning methods

A transfer of the positioning functionality to the network is a major principle of network-based positioning. The major advantage of these solutions is a minimization of the impact on terminal implementation. Thus, time to market of such positioning technology can be substantially improved through avoidance of the user terminal replacements. Logically, network-based positioning is preferred by network operators. Proposed methods in this chapter are entirely network-based, hence the implementation does not require any changes in the mobile terminals. Besides, the overall complexity is maintained at the minimum possible level through utilization of the standardized measurements and procedures. Therefore, the implementation of the proposed methods requires only slight software modification. In this subchapter, the developed network-based techniques will be overviewed and the performance results will be presented.

### 4.1.1 Cell ID + Round Trip Time

The cell based method, CID (Cell Identification) is the most basic and straightforward approach to the positioning [67]. The position of the UE is estimated on the cell level. Hence, depending on the network topology, the accuracy of the CID positioning can vary from few meters in picocellular or selected indoor scenarios to errors of kilometer-order in the sparse macrocellular settings [152],[P2],[153]. The accuracy of the network-based CID can be enhanced by combining information about the serving sector (CID) with the RTT measurement. Based on the RTT and corresponding

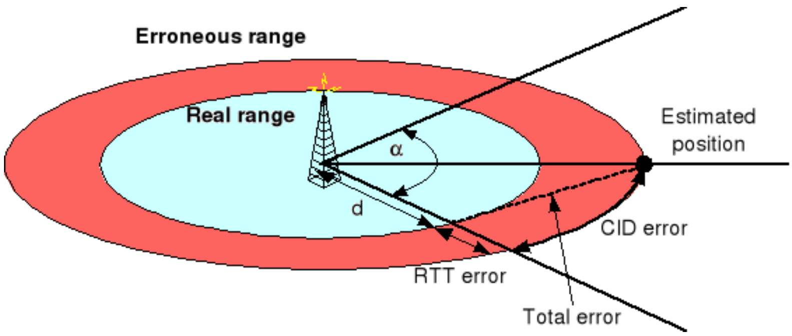



**Figure 4.1** Definition of the CID+RTT accuracy [P3].

UE Rx-Tx measurement, the distance between the UE and the serving cell can be estimated.

RTT is a standardized NodeB measurement that is performed on request on DPCH (Dedicated Physical Channel). Once measured, the RTT report is forwarded in the RL (radio link) measurement report to the SRNC using standardized NBAP (NodeB Application Protocol) dedicated message [154]. Then, the SRNC forwards the measurements to the SMLC for the position calculation process. NodeB defines RTT by observation of a time difference between the beginning of the DL DPCH frame transmission and reception of the beginning of the corresponding UL DPCCH/DPDCH (Dedicated Physical Control Channel) / (Dedicated Physical Data Channel) frame from the first detected path [69].

Naturally, reported RTT does not take into account the time offset on the dedicated channel that is introduced by the UE. In order to eliminate this ambiguity, the reported RTT is corrected by subtracting Rx-Tx time difference, which is measured by the UE and reported to the SRNC [69] as regular RRC (Radio Resource Control) signaling. The Rx-Tx measurement constitutes the time difference between the reception of the first detected path of the DL DPCH frame and transmission of the corresponding UL DPCCH/DPDCH frame. The SRNC forwards the received report to the SMLC for further position calculation. The accuracy of the CID+RTT depends on the range estimation error and the CID uncertainty [P2]. The RTT estimation ambiguity is defined by hardware limitations, multipath and NLOS propagation, while the CID inaccuracy is defined by the network topology, see Fig. 4.1. The hardware resolution of the RTT-based positioning is limited by the ability of estimating the first arriving path by the receiver in closely spaced scenarios, see subchapter 3.3.6. The precision of the RTT estimation depends on the deployed RAKE receiver in the NodeB, while hardware accuracy of the Rx-Tx depends on the terminal receiver implementation. According to the requirements [130], minimum accuracy of RTT measurements is at the level of 0.5 chip that translates to approximately 39 m range error in the worst case. In turn, the mandatory resolution (Type 1) of the Rx-Tx UE measurements is imposed by the 3GPP forum as 1 chip ($\sim$ 78 m range error) [130]. Moreover, optional Rx-Tx resolution (Type 2) is specified as 1/16 that corre-

**Table 4.1** Theoretical inaccuracies (in meters) of the CID+RTT for different radio network topologies [P2].

| Scenario | Type of area | Site spacing 0.75 km | Site spacing 1.0 km | Site spacing 1.5 km |
|---|---|---|---|---|
| 3-sectored/65° | Single | 240 | 320 | 480 |
| | SfHO | 22 | 29 | 44 |
| | SHO | 16-99 | 16-99 | 16-99 |
| 6-sectored/65° | Single | 65 | 87 | 131 |
| | SfHO | 32 | 44 | 65 |
| | SHO | 16-99 | 16-99 | 16-99 |
| 6-sectored/33° | Single | 90 | 120 | 180 |
| | SfHO | 8 | 11 | 16 |
| | SHO | 16-99 | 16-99 | 16-99 |

sponds to roughly 5 m distance ambiguity. Other sources influencing RTT accuracy naturally include NLOS and multipath propagation.

In scenarios with multiple radio links, e.g., SHO (soft handover) and SfHO (softer handover), a number of RTT reports is received by the SMLC as RTT is measured on each radio link [P2]. Logically, this has a direct impact on the accuracy, since in scenarios with more available RTT reports (2- or 3-way SHO), the position of the UE can be estimated based on the intersection of the estimated ranges. The positioning error of the CID+RTT for terminals under the single cell dominance area or in SfHO can be approximated by (4.1) assuming that position of the UE is always mapped in the middle of the sector or SfHO (softer handover) area, see Fig. 4.1, [P3]. Certainly, the accuracy for terminals located in SfHO regions is typically higher due to statistically narrow softer HO areas ($\alpha$), if these are properly defined in the SMLC.

$$PositioningError \approx 0.5\sqrt{4RTTerror^2 + (d + RTTerror)^2\alpha^2} \tag{4.1}$$

In (4.1), $RTTerror$ stands for the RTT measurement inaccuracy, $d$ represents the real UE-NodeB distance, and $\alpha$ is the outspread angle according to Fig. 4.1.

Theoretical accuracies calculated for typical UMTS topologies in hexagonal arrangements are illustrated in Table 4.1 derived with assumptions that for the single cell and SfHO areas, the accuracy is calculated in the middle of the cell range. Moreover, the distance is estimated in the LOS conditions and the RTT is measured with the resolution of 5 m (1/16 over sampling). Detailed definition of the simulation environment is provided in [P1] and [153]. The accuracy spread for SHO areas is due to geometry and undefined number of active radio links including 2- and 3-way SHO. Naturally, the accuracy is higher in 3-way SHO due to significantly smaller ambiguity and a lower impact of the geometry. In practical implementations, the position in 2- or 3-way SHO areas is estimated through utilization of numerical mechanisms. Thus, 3-way SHO allows for more accurate selection of the initial point for error optimization. In practice, terminals are not located in the middle of the cell range

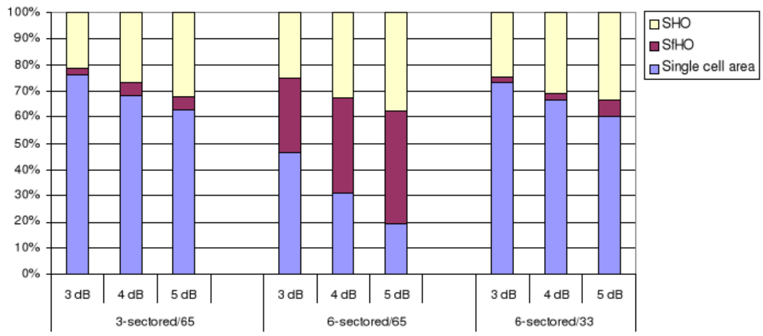



**Figure 4.2** The availability of different accuracy areas for different SHO window size and with different radio network topologies [P2].

and propagation environment is not free from obstacles causing RTT errors, hence the expectable values are on much lower level. Logically, the positioning error is smaller for more dense and 6-sectored topologies as shape of the dominance areas is statistically smaller restricting the ambiguity of the CID+RTT estimation. Directly, the overall CID+RTT accuracy can be improved through maximizing softer and SHO probability over the network and minimizing coverage of a single cell dominance. Impact of typical UMTS network topologies on distribution of areas with different degree of CID+RTT accuracy is presented in Fig. 4.2. The values are derived based on static Monte Carlo simulations performed on top of hexagonal grid with equal, 1 km site spacing in suburban macrocellular environment. Propagation was defined by COST-231-Hata model with constant propagation slope (35 dB/dec) while the average area correction factor was set to -6.7 dB. Detailed description of the simulation environment is provided in [P2]. Expectedly, higher cell overlapping in 6-sectored topologies with horizontally wide antennas provides the highest SHO probability. Naturally, commercial cellular networks are not deployed according to the hexagonal grid, hence presented results provide a relative comparison between the considered configurations. An impact of the network topologies on the overall CID+RTT positioning accuracy is studied more widely in [P2],[P3] and in Chapter 5 of this thesis.

The accuracy of the CID+RTT was evaluated through simulations performed for popular 3-sectored sites with $65^{\circ}$ horizontally wide antennas placed in a hexagonal arrangement with constant 1 km spacing [P3]. The position was estimated over 1000 times for terminals Poisson-distributed over the area of 36 $km^2$ consisting of 19 sites. NLOS propagation was modeled by a positive, distance-dependent additive error correlated with the expected mean excess delay and thus with root mean square delay spread ($\tau_{RMS}$) of the channel according to the studies presented in [155]. Distance dependency of ($\tau_{RMS}$) was defined based on [156]. The resulting NLOS bias in the range estimation is provided in (4.2):

$$NLOS^i(d) \approx k \cdot \tau^i_{RMS}(d) \approx k{\cdot}T_1(d^i)^{\epsilon} x^i \quad (4.2)$$

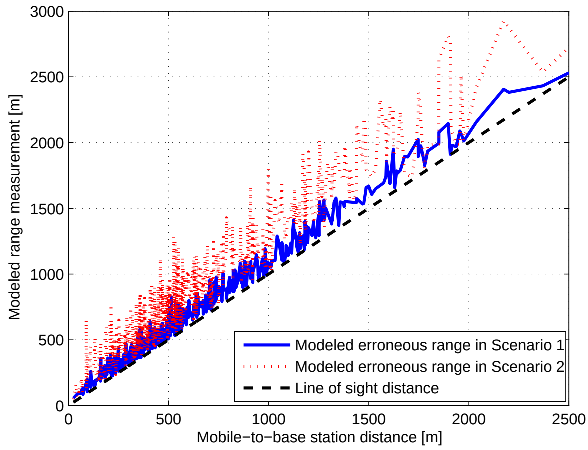



**Figure 4.3** Range additive error according to the model

In (4.2), $d$ is the UE - base station distance, $\epsilon$ is defined as 0.5 for studied environments, $k$ is the scaling factor, and $T_1$ is a median value of $\tau_{RMS}$ at $d = 1$ km selected according to measurement results published in [157] and [158]. In turn, $x$ is defined as $X = 10log(x)$, which represents Gaussian-distributed random variable with zero mean and standard deviation adequate to simulated environments. The accurate description of simulation environment and utilized multipath channel model is provided in [P3]. An example of generated NLOS error based on (4.2) is presented in Fig. 4.3, where Scenario 1 corresponds to the environment with light multipath while Scenario 2 represents the setting exposed for large multipath errors.

The overall CID+RTT accuracy in studied propagation environments is presented in Fig. 4.4. The results yield that even in scenario without multipath errors the accuracy of the CID+RTT (333 m) is practically not sufficient for majority of the location-based applications [P3]. Logically, the mean positioning error increases with larger multipath errors. Moreover, presented results are rather optimistic as the simulations were performed on top of the hexagonal grid with homogenous distribution of cell dominance areas. Also, assumed idealistic resolution of a RTT measurement (5 m) is rarely achievable in practical scenarios [130]. Therefore, numerous enhancements for basic CID+RTT positioning were studied. Considered methods include ECID+RTT [P1],[P4],[P5] and CID + Signal strength [P7], which are reviewed in the following subchapters.

### 4.1.2 Enhanced Cell ID + Round Trip Time

The accuracy of basic CID+RTT is on the highest level for terminals in SHO as presence of multiple dedicated radio links enables simultaneous RTT measurements. For GSM networks, forced handovers were proposed for corresponding Cell ID + TA (Timing Advance) method. During the procedure, TA is captured from subsequently

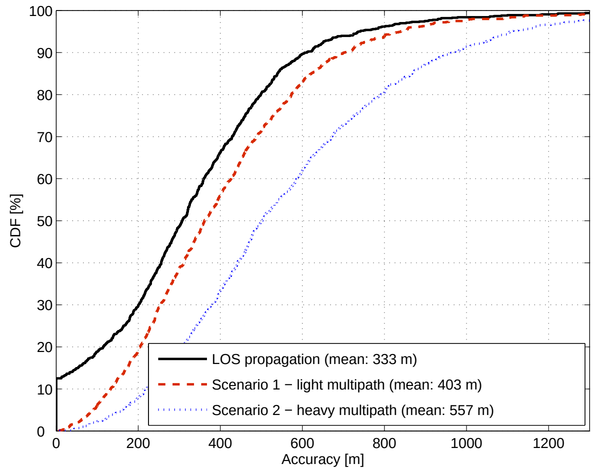



**Figure 4.4** CDF of the CID+RTT accuracy in various propagation environments according to the simulations [P3].

established radio links [159],[160],[161],[162]. Functionality of the WCDMA system allows for temporary increase of the SHO window, hence enabling RTT measurements from NodeBs included in the AS (Active Set). The idea of FSHO (Forced SHO) algorithm for improving performance of the CID+RTT was originally proposed in [P4]. Enhanced CID+RTT proposed in [P1] constitutes an enhancement to the basic CID+RTT positioning through the FSHO algorithm, numerical optimization, and VM (Virtual Mapping) techniques [P5].

Standardized SHO procedure relies on mobile-triggered event messages sent if measured $E_c/N_0$ (energy per chip over interference spectral density) of available CPICHs fulfils certain adding, removing, or replacing criteria. Namely, the radio link is added to the AS (active set), when the measured $E_c/N_0$ of the CPICH from the monitored cell is larger than $E_c/N_0$ of the best server lessened by the adding range. In a similar manner, the cell is removed from the AS. The forced SHO algorithm increases the SHO window for the positioned terminal, however for terminals located near the serving base station ($\leq$ 150 m), the forced HO algorithm is not executed as the accuracy of basic CID+RTT is assumed to be at the sufficient level according to (4.1) [P3]. For example, the accuracy of a single CID+RTT estimate at the distance of 150 m from the serving NodeB corresponds to 95 m - 99 m for terminals in sector dominance area and to 16 m - 57 m for terminals in softer HO in popular 6-sectored configurations if RTT errors are not present [P2].

The simplified procedure of the proposed algorithm is illustrated in Fig. 4.5. The algorithm is executed on the request generated by the SRNC after location task is received from the SMLC. The SHO window is gradually increased until three pilots from different sites will fulfil the criteria. The process of SHO window increase is executed by directing the SRNC to continuously update the SHO parameters and provide them to the UE according to the algorithm (Fig. 4.5) until $EventA$ message

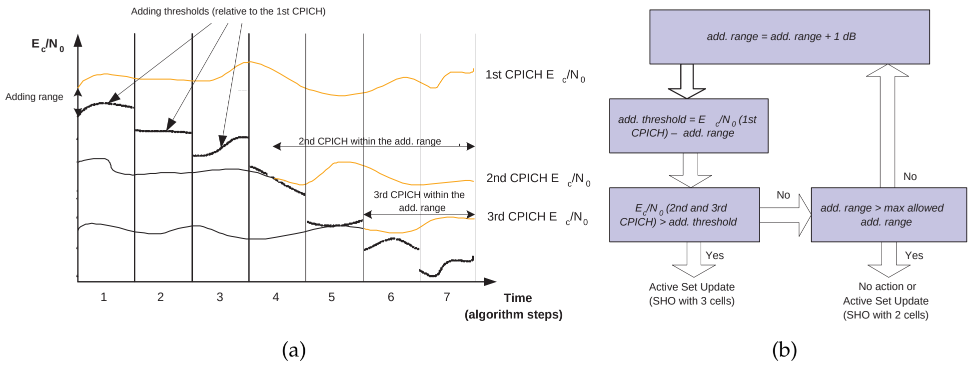


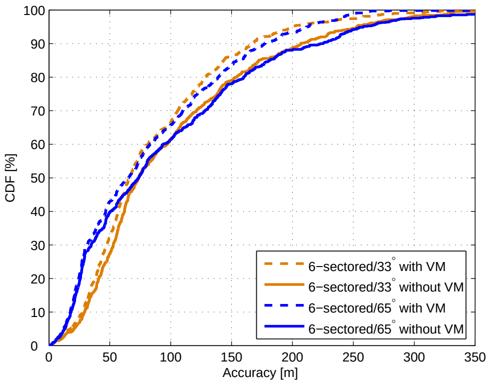

**Figure 4.5** Functionality of the Forced SHO algorithm; (a) - Illustration of the consecutive algorithm steps; (b) - simplified flow of the FSHO procedure.

is received by the RNC. Once triggering UL RRC messages are received by the RNC, the SHO is established and NodeBs are instructed to commence RTT reporting while the UE is requested to report Rx-Tx measurements. In order to minimize multipath and NLOS errors through averaging, multiple RTT and Rx-Tx measurements are captured from every radio link and reported to the SMLC for further processing. The initial position is estimated based on the constrained least square method, since the range error is always positive [P1]. The aim is to establish SHO with three different base stations. However, as such pilot availability is usually restricted to certain urban areas [74], the FSHO process is often finished with 2 pilots in the AS [P1].

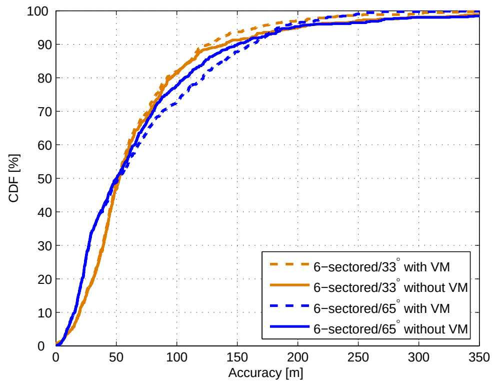
ECID+RTT (Enhanced CID+RTT) assumes further accuracy improvement through VM procedure, which is introduced and described in [P5]. The VM entirely relies on geometrical transformations of the initially estimated position towards higher accuracy. The procedure is performed through comparison of the CID of the positioned UE with the initially estimated position. Derived position based on pure RTT measurements is assessed to which sector area it geometrically belongs. If the corresponding CID does not match with the real sector ID of the UE, the VM shifts the estimated position to the nearest point that geometrically belongs to the area of the original sector ID of the UE. VM was originally proposed for 6-sectored topologies in [P5], however it could be easily extended for other network configurations.

Deployment of the presented method in commercial networks is naturally conditioned on expected impact of temporary widened SHO window on the overall network performance. Expectedly, network operators are reluctant to change RRM (Radio Resource Management) parameters, in particular the handover margins, as they might affect KPIs (Key Performance Indicators). This issue is widely studied in [P1] and summarized in subchapter 5.3 of this thesis. In addition, deployment of the VM requires definition of the sector dominance and the SHO areas, which could be obtained, e.g., from the coverage predictions. Undoubtedly, this issue might constitute a major factor limiting the VM applicability, especially in dense, irregular network topology scenarios.

Overall ECID+RTT accuracy is illustrated in Fig. 4.6. Simulation were performed




(a)




(b)

**Figure 4.6** Simulation results of the ECID+RTT accuracy in studied propagation environments; (a) - urban - heavy multipath; (b) - suburban - light multipath [P1].

on hexagonal grid of 19 equally spaced (1 km) 6-sectored sites with $65°$ and $33°$ horizontal beam width antennas. Multipath propagation was modeled by an additive distance-depended range error (4.2) described in [P1]. Dependence between errors of consecutive RTT measurements on each radio link together with remaining simulation parameters is presented in [P1] as well. For a randomly selected point in the simulation area, RTT measurements from three nearest sites were simulated. The accuracy was defined as a distance between the selected point and the ECID+RTT estimation.

As it appears from the figures, in simulated multipath scenarios, the ECID+RTT accuracy is at the sufficient level for current positioning needs. Namely, when RTT is repeated 4 times on each link, the accuracy is well below 100 m for 67% of estimates in scenario with light multipath (Fig. 4.6(b)). Expectedly, with larger multipath error, the CID+RTT accuracy decreases, however 67% $CERP$ (Circular Error Probability) does not exceed the barrier of 100 m significantly (Fig. 4.6(a)). As illustrated, the improvement from the VM is not outstanding, on average the accuracy is improved by 5-10%. Moreover, network topology does not seem to have a meaningful impact on the performance of the ECID+RTT. However, the accuracy is naturally better in networks with higher density of base stations. Moreover, mean accuracy is slightly better for positioning assessed on top of 6-sectored$/65°$ topology. Naturally, in topology scenarios with more dense site deployment, the ECID+RTT accuracy is expected to be higher as statistically smaller distances to the serving sites impose smaller multipath errors and more accurate estimation of the initial point for numerical optimization. According to the simulation results provided in [P1], when time measurements are repeated 10 times on each radio link, the accuracy for 67% of estimates decreases to 65 m in suburban and 40 m in urban multipath environments. Expectedly, the VM does not have an impact on the overall accuracy with higher number of RTT repetitions. Moreover, the ECID+RTT accuracy results illustrated in

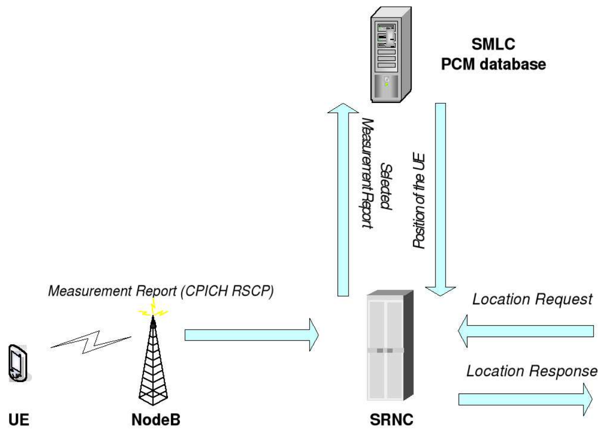



**Figure 4.7** Functionality of the Pilot Correlation Method [P1],[112].

[P4] yield for significant improvement in comparison to the basic CID+RTT positioning. In particular, in 6-sectored/$65°$ configuration, 67% $CERP$ was reduced from 120 m in traditional CID+RTT to 40 m with application of the FSHO algorithm. This accuracy results are obtained from simulations in the ideal environment, hence such positive results indicate rather best achievable performance bounds than expectable accuracy. Namely, the simulations were conducted on top of dense hexagonal grid set in macrocellular scenario free from multipath and NLOS propagation. Hence, resulting significant cell overlapping provided nearly continuous hearability of three sites for the entire simulation area [P4]. A duration of the positioning procedure is not noticeably extended in configuration with recurrent range measurements [P4]. The overall latency of the ECID+RTT procedure should not exceed 2 s, while a realization of RTT measurement with adequate reporting should be kept below 100 ms according to the maximum delay requirements [130],[163].

### 4.1.3 Pilot Correlation Method

PCM (Pilot Correlation Method) is based on a fingerprinting approach. This method was originally proposed in [112], but more accurate description is provided in [P1]. The PCM exploits a database containing the most probable CPICH levels of hearable sites for each defined positioning region. The position of the UE is estimated in the positioning region, which a priori measured pilot powers stored in the database have the highest correlation with the standardized measurement reported by the positioned UE. Basically, intended positioning service coverage area is divided into positioning regions that each of them has an individual representation in the database. The size and the shape of positioning regions naturally implies the resolution of the PCM estimation and volume of the database. Hence, positioning regions are arbitrarily selected according to the needs of planned location-sensitive applications.

The functional procedure of the PCM is presented in Fig. 4.7. Through utilization

**Table 4.2** Measurement accuracy results of the PCM positioning [P1].

| Scenario | Positioning accuracy 67% $CERP$ | 90% $CERP$ |
|---|---|---|
| Urban macrocellular | 70 m | 130 m |
| Suburban macrocellular | 170 m | 310 m |

of the standardized measurements, often the required information of pilots visibility and corresponding power levels of positioned UE is already in the network. This corresponds to the UE in the active state, when the UE provides measurement reports with required pilot information on DCCH that is sent either on PRACH (Physical Random Access Channel) ($Cell\_FACH$ state) or on DPDCH ($Cell\_DCH$ state). Depending on the vendor-specific network implementation, such reporting is performed continuously or it is event-triggered. Generally, once Location Request is received by the SRNC, the latest valid measurement reported by the positioned UE is selected from appropriate logs in the SRNC hard disk. According to practical limitations in current network implementations, such information can be buffered on the request every few tens of minutes. Afterwards, the logs are cleared and the storing process can be continued. However, in the case of event-triggered RAN (Radio Access Network) configuration, the most recent measurement report corresponding to the positioned UE can be expired. Then, the information needs to be updated through paging procedure, which insinuates the UL RRC reporting. The actual definition of buffered measurement expiration depends on the intended positioning accuracy as well on the expected average velocity of terminals in the service coverage area. Once the most valid measurement report is obtained, a vector containing corresponding pilot scrambling code IDs and RSCP (Received Signal Code Power) levels is generated and forwarded to the PCM database. The position of the UE is estimated based on the correlation of the provided vector with database entries containing pre-measured pilot power levels for each of the identified positioning region. Correspondingly, the position of the UE is estimated in the middle of the returned positioning region.

In PCM implementations optimized for high positioning accuracy, definition of the positioning regions logically increases probability of improper assignment of the UE to the positioning region. The accuracy can be improved through an assessment of the correlation degree. In scenarios, where the predefined correlation threshold is not reached, the vector with reported pilot levels is recreated using average of multiple consecutive terminal RSCP measurements. Towards more precise positioning, the PCM database and correlation vector can be complemented by information of visible GSM sites identified by BCCH frequencies, BSIC, and measured RxLev. Going further, the PCM accuracy can be also improved through adding to the database averaged, pre-measured RTT data for each positioning region. Naturally, the positioning procedure would then need to include NodeB RTT reporting and consequent

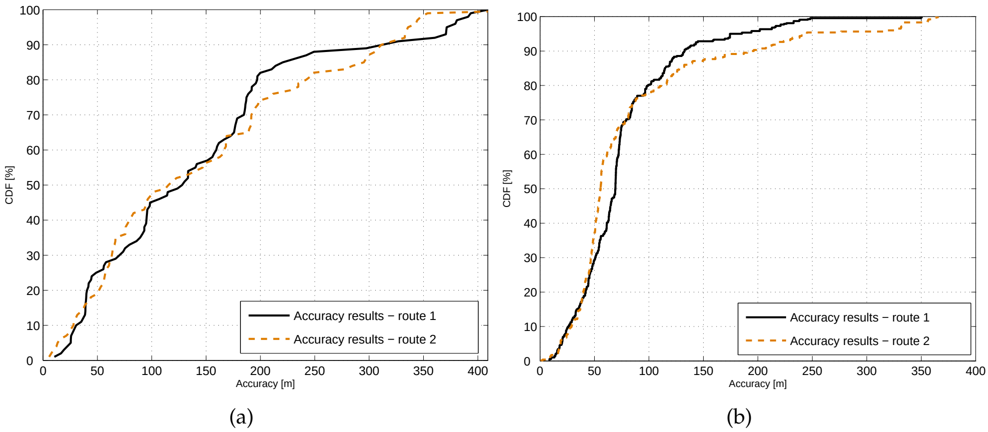



**Figure 4.8** CDF of the PCM accuracy based on the field measurements; (a) - urban environment; (b) - suburban environment [P1].

changes to creation of the correlation vector. The accurate description of the PCM functionality and proposed further evolution is provided in [P1] and [112].

The accuracy of the PCM positioning was assessed in urban and suburban environment of Tampere in Finland in live UMTS network [P1]. Network topology mainly consisted of 3-sectored sites with average 400 m in urban and 1.2 km in suburban site spacing distances. In the urban setting, site antennas were deployed on 20 m slightly exceeding the average rooftop level, while the suburban environment was a typical macrocellular scenario with antennas at 20 m - 25 m height. The average size of the positioning region was 100 m x 50 m in urban and 100 m x 100 m in the suburban environment. Power level samples required for the PCM database were collected from the considered service area by a measurement kit consisting of a laptop PC with UMTS air measurement software connected to a dashboard-mounted test UE and GPS receiver. The accuracy evaluation was performed by using the same measurement kit for continuous positioning of the user moving along two routes in each considered network environment [P1].

The PCM accuracy is presented in Table 4.2 and corresponding CDF plots in Fig. 4.8. The accuracy was defined as a difference between estimated position based on the PCM and GPS indication. The reference GPS locations were estimated with the accuracy below 10 m, however in selected positions in urban setting, the GPS error was at the level of 100 m due to obstructed sky view. The assessment in urban environment reveal promising accuracy results, as 67% $CERP$ is below 70 m for both measurement routes, Fig. 4.8(a). Evidently poorer accuracy outcomes from the Route 2 are due to more terminal locations at the cell edge, where dissimilarity between positioning regions is smaller leading to erroneous location assignment. As it appears from the measurement trial, site density has a direct impact on the PCM accuracy. Logically, smaller cell overlapping in macrocellular suburban setting with larger site spacing distances implies smaller differentiation of adjacent positioning regions. However, the accuracy for sparse suburban configuration is still within applicability range with error of 170 m for 67% of estimates, see Fig. 4.8(b). At the same time, it needs to be emphasized that the accuracy in practical use is likely to be slightly reduced as in the conducted field tests, the same measurement configuration was used for the positioning evaluation as for creation of the database. Instead, in practical application, different terminals are used with various accuracy of RSCP measurements and moreover the user terminal can be held in different position against head and other local scatters that might result to 10-20 dB errors in receivable signal level [166].

## 4.2 Detailed study on mobile-based cellular positioning methods

Mobile-based positioning aims at minimization of the network involvement in the position estimation process. Ideally, deployment of mobile-based location techniques should not require any hardware of software modifications in the network equipment as the entire positioning functionality is concentrated in the UE. However, changes to the user terminals in such approaches are basically inevitable in most of the cases. Mobile-based solutions are logically preferred by mobile phone manufacturers enabling their terminals for positioning in a wide range of networks. At the same time, deployment of such approaches is politically questionable, as mobile-based positioning typically requires network to provide information to the terminals with the base stations coordinates. Naturally, topology-related information are highly sensitive for operators, who usually are not willing to share this data. Moreover, in purely mobile-based positioning solutions, mobile terminated location requests cannot be supported, hence a residing location application is not able to obtain the terminal position. In this chapter, mobile-based location techniques are reviewed. The performance of proposed methods is assessed and benchmarked with the basic signal strength-based method.

### 4.2.1 Cell ID + Signal strength

The mobile-based CID + Signal strength method, introduced in [P7], exploits the information of the serving site configuration and the signal strength measurements. As proposed, required site information including sector configuration, antenna directions, and site coordinates is provided to the UE in frame of standardized assistance message. The UE estimates the distance from the serving base station based on the signal strength measurement and following estimated path loss-to-distance mapping according to COST-231-Hata model [96]. Combination of the calculated range with the relevant site information allows the UE to determine its position with better accuracy than based on pure signal strength-based positioning. Naturally, the CID + Signal strength method can easily be deployed as network-based solution as well, since mobile measurements are frequently reported to the network and site-related information is directly accessible.

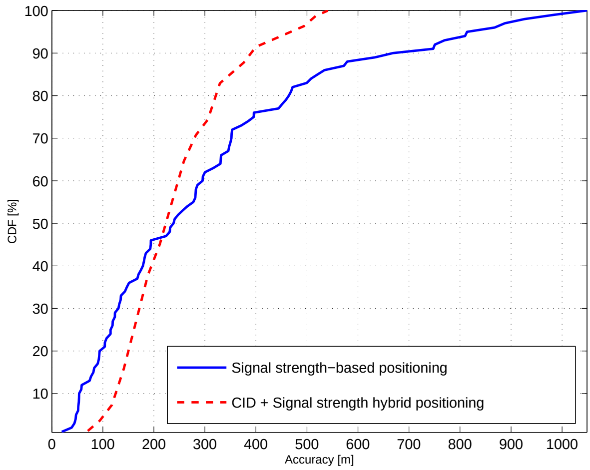



**Figure 4.9** Accuracy of CID + Signal strength method in comparison with basic signal strength - based positioning according to simulation results [P7].

Fig. 4.9 illustrates the accuracy of the proposed methods in comparison with basic signal strength-based positioning. Presented results constitute an outcome of simulations performed on top of hexagonal grid consisting of 3-sectored base stations with equal inter-separation of 2 km [P7]. As illustrated, the accuracy improvement from utilizing both the CID and the signal strength information ranges from 350 m to 270 m for 67 % of estimates. However, when the accuracy for 90% of measurements is compared, the gain from proposed hybrid method is more significant, see Fig. 4.9.

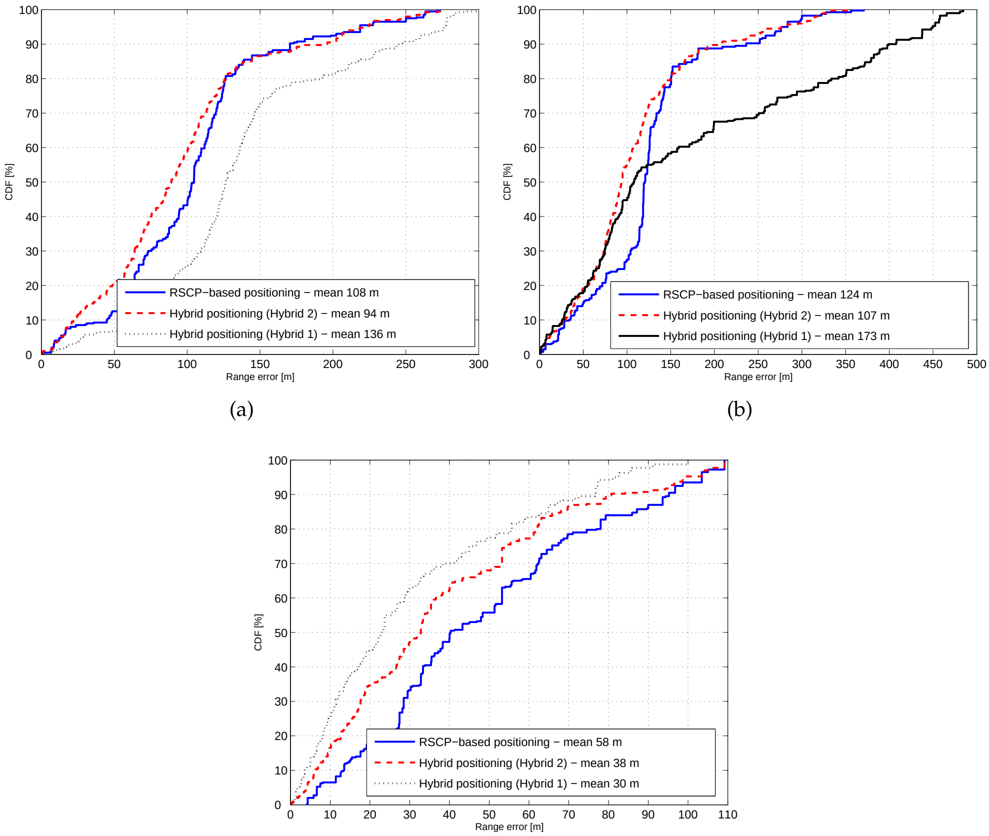
### 4.2.2 Delay spread-based hybrid method

Proposed hybrid method utilizes DS (delay spread) and signal strength measurements from available base stations. Two positioning algorithms that combine these measurements were proposed in [P6].

In the first proposed algorithm (Hybrid 1), the UE estimates the distances between measured sites independently from DS and RSCP measurements based on the implemented distance-based models. For RSCP-based range estimation, path loss is mapped to the distance according to COST-231-Hata model [164]. In turn, DS distance-dependent model was selected inline with [156], see (4.3).

$$d_{i,DS} = (\frac{\tau_{RMS,i}}{T_1})^2 \tag{4.3}$$

In 4.3, $\tau_{RMS,i}$ stands for RMS (root mean square) of the DS of the CPICH transmitted by the $i$-th NodeB, and $T_1$ is the mean value of $\tau_{RMS}$ measured at 1 km from the transmitter. An estimated pair of ranges for each of the measured NodeB are weighted and averaged [P6]. The average process exploits a phenomenon that at




(a) (b) (c)

**Figure 4.10** Simulation accuracy results of the proposed hybrid methods in comparison with basic signal strength - based positioning; (a) and (b) - macrocellular urban environment; (c) - small cell area in the microcellular urban environment.

small distances from the transmitter, the median of received power tends to decrease more sharply than RMS of the DS. In turn, at distances closer to the cell edge, propagation is exposed for significant influence enlarging time spread of multipath components while signal power levels appear to be more stable. The other proposed algorithm (Hybrid 2) takes an advantage of the correlation properties between RSCP and DS. Basically, in heavy multipath scenarios indicated by large delay spread, signal strength positioning is assumed to be erroneous. On the contrary, in locations with light multipath propagation indicated by a small delay spread of arriving components, positioning based on the signal strength measurement is much more reliable. The Hybrid 2 exploits these features through correcting RSCP-based estimated range according to measured RMS DS. Consecutively, the distance from the serving base station is estimated from the path loss to distance mapping model according to

COST-231-Hata [P6].

The performance assessment was carried out by extensive field measurements in urban micro and macro cellular environment as well as in the suburban/light urban macro cellular setting [P6]. An average distance between sites in studied scenarios was on average 400 m in microcellular urban, 600 m in macrocellular urban, and 1.2 km in suburban/light urban macrocellular environment.

The analysis indicates the pilot signal strength is correlated with its delay spread to some extent, hence results yield in favor of the Hybrid 2 approach. At the same time, an observable delay spread appears as not essentially correlated with the distance from the serving base station, thus Hybrid 1 does not improve the accuracy of pure RSCP-based range estimation Fig. 4.10(a), 4.10(b). However, in locations near the serving base station (mean distance to the serving base station - 140 m) in the microcellular urban scenario, the Hybrid 1 is performing the best, 4.10(c). In the regular urban macro cellular setting, the accuracy of the signal strength range estimation was improved from 108 to 94 m when the Hybrid 2 was applied, 4.10(a) or from 124 m to 107 m as illustrated in 4.10(b). The range error evaluation conducted in less dense macrocellular suburban setting revealed that proposed hybrid methods do not perform better than basic positioning based on the path loss to distance mapping [P6].

## 4.3 Cellular assistance for GPS positioning

The concept of providing assistance for GPS positioning dates back to 1977 [171],[172]. Generally, the assistance can be provided by any type of network, but as this thesis is focused on UMTS cellular positioning, only this assistance approach is considered. Basically, AGPS solutions can be categorized as network-based and mobile-based. In the network-based solutions, the function of the UE is limited to the measurement of the PRN (pseudo-random noise) signals and delivery to the location server. Logically, in the mobile-based approaches the position is estimated in the UE according to the measured satellite signals and the assistance provided from the network [16],[67],[70].

Applicable cellular location techniques improving latency and enhancing the service availability of satellite positioning are studied and evaluated in [P7]. As introduced earlier, a network assistance not only improves the performance of GPS functionality but also provides a back-up positioning solution for terminals outside of the GPS availability (e.g., indoor). For urban network environments, network-based PCM was proposed as an effective GPS assistance due to its overall functionality based on the standardized measurements and procedures. In turn, the delay spread hybrid method and the approach that relies on the CID and the signal strength measurement were evaluated as the mobile-based GPS assistance for rural settings. Naturally, if the network-based assistance aims only at providing timing assistance in addition to provision of the GPS navigation message, estimation of the UE-base station distance based on RTT measurement is sufficient. Then, a distance to the serving base station is estimated and provided to the terminal in the frame of the AGPS assistance message. Hence, the UE can roughly estimate the time of arrival, i.e., the code phases, of the satellite signal that results in improved acquisition time. In a similar manner, single RSCP measurement and adequate propagation distance estimation is sufficient for mobile-based solutions providing GPS assistance [P7].

The PCM accuracy was assessed in live UMTS network in urban environment with mean 400 m cell spacing distances, while the mobile-based solutions were evaluated in simulations on top of the hexagonal layout for rural setting with 2 km site spacing [P7]. The measurement results revealed that the mean accuracy is in order of 60 m, which is more than enough to provide effective AGPS assistance or sufficient functionality in a standalone mode. For comparison, the mean accuracy of the basic RSCP-based estimation for terminals in locations along the same measurement route was slightly below 250 m. In turn, the accuracy of the studied mobile-based assistance methods was evaluated from the simulations, which provided poorer outcomes. Namely, the mean accuracy of the proposed mobile-based method was at the level of 200 m - 250 m. However, the proposed methods significantly improve the accuracy of the basic signal strength positioning as 90% $CERP$ is improved from 800 m to 500 m (delay spread hybrid method) and further to 390 m for CID + Signal strength method [P7]. The complexity of the proposed solutions is kept at a minimum possible level. Therefore, these assistance methods are ready for implementation in current UMTS networks enabling LBS before AGPS will be commonly supported by terminals and networks. Subsequently, involved deployment expenditure will not be spoiled as methods will be efficiently utilized as AGPS assistance in the future.

# Chapter 5

# Cellular Radio Capacity and Functionality of Location Techniques

The second part of this thesis is devoted to the cellular network performance aspects when location techniques are considered. First, radio network planning process is overviewed and consequently, trade off between topology planning for radio capacity and positioning performance is briefly presented. In addition, impact of functionality of the positioning methods on the cellular network performance is assessed.

## 5.1 An overview of radio network planning process

The aim of the radio planning is to provide the required system coverage, capacity, and quality of service while minimizing needed equipment costs. Obviously, operators are willing to minimize CAPEX (capital expenditure). Adequately, reduced amount of the needed equipment for network roll out typically results in lower OPEX (operational expenditure).

Generally, the radio network planning process includes dimensioning, detailed planning, network monitoring, and optimization. Indicated radio network planning steps are universal regardless of the underlying radio system. However, detailed planning naturally depends on the radio interface technology of planned cellular network.

WCDMA (Wideband Code Division Multiple Access) selected for UMTS radio networks changes the planning principles adopted from GSM based on TDMA / FDMA (Time Division Multiple Access / Frequency Division Multiple Access) [35]. Universal frequency reuse in UMTS implies a consideration of expected system interference in the coverage planning, since the cell range depends on the traffic [34]. This phenomenon, called a cell breathing, indicates that in order to maximize the radio coverage and capacity, the interference needs to be minimized. Therefore, the performance of WCDMA-based networks closely depends on the topology planning as well as on the proper setting of parameters ensuring optimum network functionality. On the other hand, planning process for UMTS radio networks is partly simplified in comparison to GSM planning as a frequency planning is obviously not needed.

Instead, an uncomplicated code planning is performed.

### 5.1.1 Dimensioning

The aim of this initial phase of the planning process is to estimate an amount of the equipment needed to provide coverage, capacity, and quality of service according to the requirements. As an outcome of the dimensioning, the number of base stations as well as their average height is defined. Moreover, initial base station sectoring and antenna configurations is assumed for rough coverage and capacity estimations. In the dimensioning phase, the capacity requirements of different cells can be addressed through utilization of the standard load equation [33],[34],[35].

### 5.1.2 Detailed planning

During this phase, the entire network plan is specified. Generally, detailed planning can be divided into configuration planning, topology planning, code planning, and parameter planning. Once detailed planning is completed, the network is practically ready for the actual roll out process.

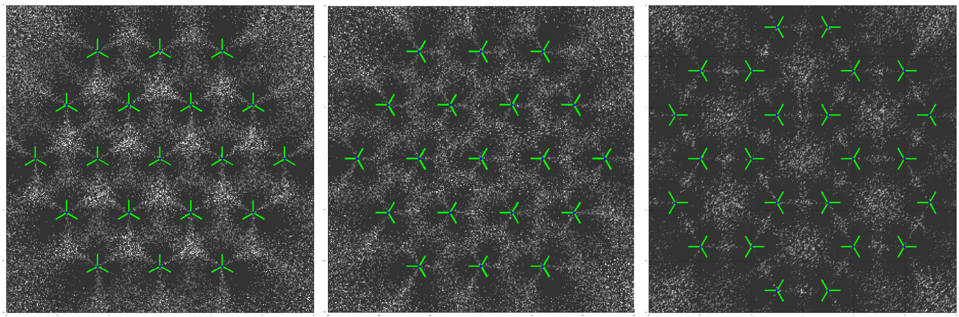
In the configuration planning, the base station and corresponding antenna line equipment is specified. When the RF (radio frequency) equipment is selected, radio power budget can be precisely calculated.

In the topology planning phase, the final configuration of the radio network elements, the base station configuration, and the network layout is defined. Typically, the base station site configuration includes definition of the site locations, antenna sectoring, and antenna orientations. Naturally, an optimum selection of the above parameters requires careful analysis of the radio environment as well as the system simulations, since the network coverage in WCDMA-based systems depends on the interference and thus on the user traffic.

Final, however equally crucial stage of detailed planning includes a definition of the scrambling codes and parameters for intended network functionality. Initially, recommended values of the parameters are assigned and consequently, the parameters are accurately adjusted during post-deployment, optimization stage. The code planning is straightforward, as a planning tool typically allocates the scrambling codes automatically.

### 5.1.3 Network monitoring and optimization

A cellular network requires careful performance verification prior to commercial launch, since conducted planning is based on system-level simulations with numerous assumptions and approximations. The performance of the network is typically verified using radio interface measurements and monitoring of KPIs (Key Performance Indicators) provided by the network management subsystem. Naturally, after the commercial launch, the network performance is continuously monitored as well. The optimization constitutes an outcome from monitoring and includes various planning-related tasks to ensure smooth and optimum network functionality and performance. The optimization often refers to the re-planning, since the entire



(a) (b) (c)

**Figure 5.1** Considered network topology layouts; (a) - Nominal hexagonal grid in North America; (b) - Nominal hexagonal grid in Europe; (c) - modified hexagonal grid.

planning process needs to be checked before any modifications can be implemented to the existing network plan [34],[35].

## 5.2 Topology planning and location techniques

In this section, the selected topology planning and optimization methods are reviewed. Performed analyzes illustrate the impact of the considered planning aspects on the radio capacity, system functionality and on the performance of selected mobile positioning techniques.

### 5.2.1 Network topology layout

The most popular layouts for cellular network topology are formed by equally spaced base stations placed in corners of an imaginary hexagon with constant antenna directions [114]. Two hexagonal grids consisting of 3-sectored sites with different antenna orientations gained a considerable attention, Fig. 5.1(a), 5.1(b). In Europe, the most popular layout appears to have antennas directed at $30°$, $150°$, and $270°$. In turn, a topology that consists of 3-sectored sites with horizontal orientation of $0°$, $120°$, and $250°$ is often referred to the nominal grid in North America. In addition, recently proposed modified layout assumes that all sites are pointing towards the center of a hexagon [167], [168]. In order to fulfil this requirement, the modified grid exploits two different antenna orientation schemes, namely $30°/150°/270°$ and $90°/210°/330°$, Fig. 5.1(c).

According to the studies published in [167], [168], the modified hexagonal configuration provides more controlled radio performance features through directing main lobes of base station antennas towards each other. Therefore, a high level of an interference can be theoretically concentrated in the selected regions. In practical deployments, the interference could be aggregated on areas not planned for high radio capacity, e.g., lakes, mountains, forests. On the contrary, in the nominal hexagonal topologies, the interference is spread all over the cell boundaries.

The CID+RTT performance analyzes presented in [P3] reveal that studied network topologies do not have a significant impact on the positioning accuracy. Expectedly, the modified grid as well as North American nominal layout provide slightly higher SHO probability, hence improving the overall positioning accuracy. Moreover, the modified hexagonal configuration features statistically smaller dominance areas, thus the positioning ambiguity for terminals served by a single base station is minimized. Based on the performed simulations, mean accuracy of the CID+RTT estimation was improved from 320 m (nominal North American grid) and 330 m (nominal European grid) to 298 m when the modified topology was used in the ideal LOS environment [P3]. Naturally, when modeled NLOS errors are added to estimated ranges, the overall positioning accuracy is reduced. However, the topology impact remains, as the modified hexagonal grid provides the best support for the studied positioning technique.

### 5.2.2 Sectoring and antenna beam width

A deployment of directional antennas at a base station in a sectorized configuration is an efficient method for increasing capacity of cellular system [34],[36],[169]. Logically, antennas should be selected according to the planned site division into sectors, as the sector overlapping needs to be kept at a reasonable level for optimum performance [170].

Expectedly, the accuracy of positioning based on the CID+RTT is directly influenced by the size of dominance areas. As indicated in subchapter 4.1.1, site configurations providing larger cell overlapping result in larger coverage of softer and soft HO, where the accuracy of the CID+RTT is on the highest level. At the same time, larger sector overlapping typically results in smaller cell dominance areas that in turn minimizes the CID positioning ambiguity for terminals served by a single site. Correspondingly, the overall accuracy of the CID+RTT positioning is improved by over 50% in 6-sectored topology with horizontally wide antennas ($65^{\circ}$) [P2], Fig. 5.2 due to over 40% SHO probability according to Fig. 4.2.

Mobile positioning based on the PCM theoretically benefits from topology evolution towards higher order sectoring schemes. Directly, topology with higher cell overlapping provides better diversification between adjacent positioning regions. Hence, the estimation accuracy can be improved through narrowing area of positioning regions. However, highly overlapping site configurations result in reduced network performance. Generally, deployment of horizontally wide ($65^{\circ}$) antennas in 6-sectored configuration reduces radio capacity by approximately 30-35% in comparison to optimum narrow beamwidth antennas ($33^{\circ}$) [P2],[170]. Additionally, the proportion of pilot polluted areas is naturally more significant when horizontally wide antennas are used. This results in a higher level of the interference and thus reduction of the radio capacity.

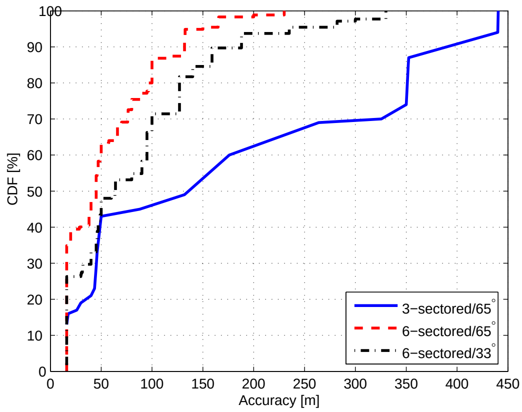



**Figure 5.2** Simulation results illustrating accuracy of the CID+RTT for various network topologies.

### 5.2.3 Antenna down tilting

The antenna down tilting is the final topology optimization method. Through electrical (EDT) or mechanical down tilting (MDT), the antenna radiating footprints can be more accurately defined for each cell. Hence, the cell dominance can be emphasized while harmful pilot pollution can be reduced resulting in a lower inter-cell interference [34],[35]. According to the studies published in [61], the capacity was improved by 17% in 3-sectored topology when optimum down tilt angle was used. Larger gains were observed in 6-sectored topologies with optimized antenna configuration through down tilting, which were namely 18.8% for MDT and 27.5% when EDT was used.

The topology optimization through antenna down tilting yields for a compromise when the ECID+RTT performance is considered. Generally, cell area modifications through antenna down tilting do not influence positively CID+RTT positioning as SHO probability tends to decrease. Namely, the SHO overhead is reduced from 30.9% in 0° tilt configuration to 25.3% (3°) and 21.7% (7°) [61]. However, at the same time, the dominance of the first pilot is improved that results in a smaller positioning ambiguity for terminals under a single cell coverage area. Nevertheless, the mean CID+RTT accuracy drops from 190 m in the studied non-tilted antenna configuration to 207 m with 3° EDT and to 220 m with 7° EDT [P8]. Moreover, in properly configured topology for radio capacity, hearability of the third pilot is significantly minimized directly impacting ECID+RTT availability and accuracy.

Positioning based on the proposed PCM method is not significantly influenced by this topology modification as long as the database is updated accordingly. Naturally, smaller cell overlapping might decrease the ability to keep the database resolution on the intended level. However, when the database does not follow with topology changes, expectedly the PCM accuracy can clearly fall. According to [P8], the positioning error was increased from 111 m to 168 m when MDT was removed from majority of the sites and the database was not updated.

### 5.2.4 Repeater deployment

Traditionally, repeaters are considered as easy to deploy and efficient topology enhancement for extending coverage in hardly accessible locations, e.g., underground, indoor, etc. [173],[174],[175],[176],[177]. Recently, an exploitation of repeaters is also considered for improving capacity in CDMA-based networks through reducing base station transmit power [178],[179],[P9],[180]. Undoubtedly, an inevitable increase of the uplink noise reducing the base station receiver sensitivity constitutes a drawback in repeater applications for hot spot capacity.

The actual capacity gain from repeaters depends on the user traffic distribution between the repeater mother cell and the repeater serving area (hot spot). The simulation results illustrated in [179] reveal that the capacity in the downlink is improved by 75% when hot spot was 6 times more loaded than remaining cell area. In turn, in scenario with the homogenous load distribution, the downlink cell capacity was enhanced by 38%.

Deployment of repeaters in antenna line introduces additional signal processing delays (5 - 6 $\mu$s), which need to be accounted in time-biased positioning methods including CID+RTT or ECID+RTT. Generally, the dominance area of the cell enhanced by repeaters becomes larger that reduces the CID+RTT accuracy. However, terminals served by a repeater can be recognized from excessive value of reported RTT. Thus, the positioning accuracy can be improved if repeater serving area is properly defined and the repeater coordinates are known [P8],[P9].

The outcomes from conducted measurement trial indicate that the mean accuracy of the CID+RTT is improved from 190 m to 154 m when the repeater is used [P8]. Moreover, deployment of repeaters results in a better LOS condition in the cell, hence contributing to further improvement of positioning accuracy [P9]. Repeaters do not have impact on the performance of PCM, obviously if new propagation characteristics are introduced to the database [P8]. Concluding, deployment of repeaters constitutes an uncommon example when the benefit is on both sides: the radio capacity and the positioning performance.

## 5.3 Impact of positioning on network performance

Positioning based on the CID+RTT or PCM does not affect the network performance. These techniques are based on the standardized measurements and the procedures and hence extra signalling is often not needed in UTRAN interfaces. When the positioned UE is in the active state, the CID+RTT requires only single RTT report, which loads transmission interface practically invisibly. Similarly, positioning based on the PCM does not introduce any signalling as long as the latest measurement report stored in the SRNC is not expired. When the positioned UE is not in the dedicated state or the measurement data in the SRNC is not valid, a single inter exchange of the signalling messages involved in the paging procedure has a negligible load as well.

However, positioning based on the ECID+RTT increases an interference level in the network through addition of radio links. Especially, an establishment of the dedicated connections from adjacent base stations can result in significant transmission power increase in locations under strong dominance of a single base station. Hence, network operators could be averse to deployment of this method in their commercial networks as it could potentially impact KPIs. However, conducted analysis in [P1] reveals that the negative impact is not meaningful in practical situations. Nevertheless, instantaneous capacity drops might be significant. The assessment results illustrate that the cell capacity drops from 1350 kbps to 200 kbps when the terminal is forced to SHO with cells having 10 dB of the path loss difference at the location. However, the duration of the ECID+RTT procedure is below 2 sec and moreover in practical scenarios, location requests do not arrive continuously for terminals in a single cell. For instance, if the location requests are considered to arrive every 30 sec, 1 minute, or 5 minutes, the mean cell capacity during an hour is correspondingly reduced by 8.5%, 4.2%, and 0.8% [P1].

The indicated capacity losses do not have practical impact on the network functionality. However, if the position of multiple terminals is requested at the same time, the ECID+RTT applies scheduling approach for positioning estimation that prevents simultaneous execution of the multiple FSHO procedures in the same cell. Hence, potential negative consequences could be minimized while keeping high positioning performance, as resulting additional delays are insignificant [P4].

# CHAPTER 6

# Conclusions

## 6.1 Concluding summary

This thesis provided a comprehensive overview of cellular mobile positioning aspects with focus on applicable, practical approaches to the problem.

In this context, positioning applications in UMTS networks, existing research accomplishments, and the main challenges in meeting positioning requirements were reviewed. Background research clearly indicates that it is challenging to enable positioning with sufficient accuracy for the majority of LBS while keeping existing network infrastructure and terminals free from modifications. The aim of the proposed network- and mobile-based positioning solutions was to combine minimum technical complexity with good positioning accuracy. The development of new network-based methods was motivated by the poor accuracy of basic CID+RTT positioning in practical scenarios: based on simulations, 67% $CERP$ was over 400 m. Similarly, poor performance of pure signal strength-based positioning (67% $CERP$ at a level of 350 m) motivated the research on mobile-based hybrid methods.

For network-based positioning, an extensive study of CID+RTT positioning and two new applicable methods were presented - ECID+RTT and PCM. The complexity of the developed methods is maintained at a minimum level in order to provide immediate support for location-based services in current UMTS networks without requesting subscribers to change terminals. Both techniques are entirely network-based, as the positioning process is concentrated on the network side and only minor network modifications are needed to enable positioning. The ECID+RTT comprises standardized CID+RTT positioning enhanced by Forced SHO algorithm, enabling multiple RTT measurements regardless of the terminal location. In addition, the application of Virtual Mapping further improves accuracy through the geometrical shift of estimated position in case of erroneous initial positioning. In turn, the proposed PCM positioning is based on the database concept with a priori measured signal strength samples. However, the utilized measurements are standardized, frequently reported by terminals and readily accessible in the network. Therefore, the impact on the network architecture is minimized and the introduced signalling load is insignificant. The simulation results revealed that the ECID+RTT accuracy for 67% of estimates is in the range of 70 m to 100 m in the studied suburban and urban propagation scenarios when RTT is measured 4 times on each established radio link. The harmful impact of multipath and NLOS propagation can be minimized through averaging the multiple RTT measurements on each radio link. Correspondingly, if RTT is measured 10 times on each radio link, the 67% $CERP$ decreases to 40 m and 65 m in the considered suburban and urban environments. The accuracy of the PCM method was assessed through field measurements in selected urban and suburban areas of the macrocellular live UMTS network. Promising results were achieved, as the accuracy for 67% of measurements did not exceed 70 m in urban topology with 400 m mean site spacing, and 170 m in suburban settings with 1.2 km average site-to-site distance. However, the accuracy could be further improved by increasing the resolution of the database and through utilizing other measurements to provide higher diversification between positioning regions.

For mobile-based positioning, a technique that utilizes serving site information (CID) in combination with receivable signal strength and two hybrid techniques exploiting delay spread and signal strength measurements were proposed. The introduced hybrid methods combine the terminal measurements based on potential correlation properties between propagation loss and delay spread due to multipath and dependency of delay spread from the propagation distance. Extensive analysis based on field measurements indicated that the method exploiting correlation between delay spread and path loss improves the accuracy of pure signal strength-based positioning. However, in the considered scenarios the improvement was not significant, as for instance, the 67% $CERP$ was improved from 130 m to 110 m when the hybrid positioning was used in an urban macrocellular setting with 600 m average site spacing distances. At the same time, the results yield poor delay spread dependency in a function of signal propagation distance with the exception of dense microcellular environments. On the contrary, the CID + Signal strength method substantially outperformed basic signal strength-based positioning. Specifically, in the studied sparse topology configuration (2 km site-to-site distances), the accuracy for 67% of measurements was improved from 350 m to 270 m. Moreover, the error for 90% of the estimates was reduced from 700 m to 400 m when the proposed method was used.

In this thesis, the impact of the topology modifications on the positioning performance was also studied. The conducted study disclosed that the optimization techniques aiming at emphasizing cell dominance areas yield for tradeoff between CID+RTT or ECID+RTT accuracy and radio capacity. These techniques include, for instance, antenna down tilting or sectoring. In turn, topology optimization through repeater deployment positively influences the performance of the considered network-based location methods. This is mainly caused by the more dense locations of the positioning reference points (base stations, repeaters) resulting in smaller dominance areas and, on average, smaller distances to the serving base station, which directly improves the positioning accuracy. The study on the impact of the topology layout on positioning accuracy showed that CID+RTT accuracy is slightly improved when evaluated on top of the modified grid featuring more controlled radio interference properties. However, the overall impact is insignificant. The considered planning and optimization aspects do not influence the PCM accuracy as long as the database is updated according to the performed topology modifications. However, topology upgrade through repeater deployment results in more diverse radio conditions, potentially allowing for better database resolution.

In summary, the presented performance results reveal that the proposed cellular network-based techniques enable positioning with the accuracy required by the majority of location-based services, i.e., mean accuracy below 100 m. Hence, these methods could be directly deployed in the current networks, enabling a wide range of LBS, while in the longer term they could be exploited as effective assistance for AGPS positioning. On the other hand, performance evaluation of the mobile-based solutions indicated much poorer accuracy figures, which are below the typical LBS requirements. However, the proposed mobile-based techniques could be utilized as assistance for AGPS in future UMTS networks.

## 6.2 Future research work

The promising simulation results of the ECID+RTT positioning revealed a further need for research on the practical implementation aspects. Moreover, extensive performance assessment of this method through field measurements in diverse topology and propagation scenarios remains an open aspect. Further development of the PCM positioning towards better estimation accuracy includes study on improving resolution of the database, while keeping a high degree of correlation in the positioning process. This comprises research on complementing the database by RTT samples, 2G RxLev data, and evaluation of the most applicable correlation procedures.

Further research on mobile-based positioning includes considerations of efficient exploitation of correlation properties between delay spread and signal propagation loss towards higher positioning accuracy. Moreover, penetration of GPS-enabled networks and terminals will substantially increase in the coming years. Therefore, worth considering are mobile-based techniques that exploit a self-learning database updated according to position estimates of GPS-enabled terminals and their corresponding CIDs. Online access to such a database allows for non-GPS-enabled terminals to estimate the position based on the CID, but obviously with some location ambiguity; although, sufficient for some of the applications. A major benefit of such an approach is the possibility for the terminal to find its location without requiring the operators to forward sensitive topology information such as, e.g., base station coordinates. Utilization of such a self-learning database approach with existing location methods might result in interesting ideas for applicable cellular positioning.

The role of the cellular positioning of devices in next generation networks based on OFDMA (Orthogonal Frequency Division Multiple Access) [181] is expected to converge with providing assistance for AGPS/Assisted-GALILEO positioning. Therefore, adequate research and development will be needed.

# Chapter 7

# Summary of Publications

## 7.1 Overview of publications and major thesis results

The positioning research conducted in the frame of this thesis focuses on the research and development of applicable cellular positioning solutions for UMTS, providing performance that is sufficient to meet practical application requirements [P1]-[P7]. Moreover, the impact of selected topology planning and optimization aspects on the positioning performance was considered in [P3],[P8],[P9].

A study on network-based positioning methods was conducted in [P1]-[P5]. In frame of these publications, two new network-based cellular location techniques (ECID+RTT and PCM) are proposed and evaluated. The proposed methods provide accuracy sufficient for the majority of applications and at the same time do not involve any changes in the terminals but only minor software upgrades of the network equipment.

The functionality and performance of the basic CID+RTT was studied in [P2] and further developed in [P4]-[P5] as the simulation outcomes presented in [P2] revealed that the estimation accuracy does not meet the needs of LBS. Enhancements to the CID+RTT including Forced SHO algorithm and Virtual Mapping procedure were proposed in [P4]-[P5]. Publication [P4] also includes performance assessment based on the simulations of proposed ECID+RTT, however only an ideal LOS environment free from multipath propagation was considered. In turn, multipath propagation effect was taken into account in [P5], where performance of the ECID+RTT comprising VM procedure was evaluated. Finally, publication [P1] includes solid performance analysis of the ECID+RTT positioning conducted in various multipath environments which confirmed the applicability of this method.

Pilot Correlation Method was presented and evaluated based on field trials in [P1], although originally the technique was proposed in [112]. The measurement results revealed that the PCM is an applicable technique as the accuracy is at a sufficient level for most of the practical applications. At the same time, the complexity of the method is kept at a minimum level through the utilization of standardized measurements and procedures.

Mobile-based positioning techniques were studied in [P6]-[P7]. Two hybrid approaches exploiting delay spread and signal strength measurements were presented and assessed in [P6]. The proposed hybrid solutions rely on the correlation properties between the propagation loss and delay spread of the received signal and delay spread dependence on the propagation distance. The measurement results showed that the delay spread of the signal is not essentially correlated with the propagation distance. However, through utilization of the dependence between the observable delay spread and propagation loss, the accuracy of pure signal strength-based positioning can be improved. In addition, a distance-dependent model of the error in range estimation based on RSCP measurements with subsequent COST-231-Hata distance mapping was proposed in [P6].

A mobile-based positioning method, which relies on the Cell ID information and signal strength measurement was proposed in [P7]. Outcomes from the conducted measurement trial indicated that a conjunction of serving site information with terminal signal strength measurements significantly outperforms the basic estimation based on pure signal strength measurements. Moreover, publication [P7] studied the applicability of the proposed network- and mobile-based methods for assistance in future AGPS positioning solutions.

The impact of the network topology layout on the accuracy of basic CID+RTT positioning was studied in [P3]. In this context a novel modified topology grid featuring controlled radio interference properties was considered. An evaluation of the impact of other radio network planning aspects on the performance of positioning was illustrated in [P8]. In part, the impact of base station antenna configuration on the CID+RTT performance was studied in [P1]. The conducted study indicated the need for a general compromise if both radio capacity and positioning performance are optimized. Special attention was paid to capacity optimization through repeater deployment [P8] and [P9]. The results of the measurement trials revealed that performance of the network-based positioning does not suffer if repeaters are deployed for higher radio capacity [P9].

## 7.2 Author's contribution to the publications

The research work for this thesis was conducted at the Institute of Communications Engineering, Tampere University of Technology, in the frame of the "Advanced Techniques for Mobile Positioning" project. During the project work, the author participated in the research activities of the Radio Network Group (RNG) related mainly to mobile positioning, including satellite-based location technology, radio network planning, and topology optimization. Naturally, many of the presented ideas have emerged from intensive discussions between colleagues, especially D.Tech. Jarno Niemelä, M.Sc. Tero Isotalo, M.Sc. Panu Lähdekorpi, and M.Sc. Jaroslaw Lacki. Moreover, all the publications were guided by the thesis supervisor Prof. Jukka Lempiäinen who provided plenty of valuable input into the research. Thus, it is somewhat problematic to separate precisely the input of each of the co-authors to the publications, however the author's own contribution was substantial.

In publication [P1] the author proposed two network-based techniques and conducted the relevant simulations and field measurements. Jarno Niemelä helped in defining the database implementation details for the PCM. Moreover, the idea of assessing impact of the FSHO on radio capacity originated from extensive discussions with Jarno Niemelä. In turn, the definition of indoor network configuration for performance measurements was done with the great help of Tero Isotalo.

In publication [P2] the theoretical analysis and simulations were carried out by the author. However, the definition of the simulation methodology was done together with Jarno Niemeä and Jukka Lempiäinen. Moreover, Jarno Niemelä and Jukka Lempiäinen provided valuable input related to the final appearance of the paper.

In publication [P3], the positioning accuracy analysis was conducted by the author. Jarkko Itkonen performed the topology studies and provided a modified hexagonal site layout for the simulations.

In publication [P4], the author came up with idea of the FSHO implementation for the CID+RTT positioning. However, Jarno Niemelä helped in performing the positioning accuracy analysis of the enhanced location technique. Moreover, Jarno Niemelä helped in improving the final appearance of the paper.

Positioning research in the frame of [P5] was solely prepared by the author, but it goes without saying that the ideas originated from numerous informal discussions with colleagues.

In publication [P6], the author proposed hybrid mobile-based location methods and conducted the performance analysis. However, the field measurements assessing the technique applicability were done together with Jarno Niemelä. Performance analyzes of positioning techniques were carried out by the author while Jarno Niemelä provided very useful guidelines in defining the measurement scenario and also helped in the execution of the field measurements themselves.

The development of the mobile-based hybrid method as well as the measurements performed in the frame of the research in publication [P7] were done by the author. However, [P7] partly relies on outcomes from the PCM measurement trial originally presented in [112]. The presented analysis in [P7] was made with the help of Jarno Niemelä. However, the author's contribution was substantial.

In publication [P8], the evaluation of optimization aspects on positioning performance was carried out by the author while the assessment of the impact on radio capacity was made by the co-authors. Specifically, performance analyzes of antenna down tilt were conducted by Tero Isotalo and repeater deployment aspects were studied by Panu Lähdekorpi. Moreover, Tero Isotalo and Panu Lähdekorpi helped in the preparation of the camera-ready paper.

For publication [P9], repeater deployment in live network as well as the field measurements were performed together with Jarno Niemelä. The analysis of repeater impact on the radio capacity was conducted by the author and Jarno Niemelä. However, evaluation of the positioning performance and preparation of the paper was carried out by the author.

# Bibliography


[1] Website " Wirelss E911-Tragedies",
Available: $http://www.nena.org/Wireless911/Tragedies.htm.$

[2] B. A. Clark, "GPS military land navigation and strategy impacts", *Proc. of Position Location and Navigation Symposium*, April 1996, pp. 381-384.

[3] A. Pouttu, M. Raustia, H. Saarnisaari, P. Lilja, P. Leppanen, T. Tuukkanen, H. Rompainen, "New tactical radio systems in Finland", *Proc. of Military Communications Conf. (MILCOM)*, October 2005, vol. 2, pp. 1231-1237.

[4] I.K. Adusei, K. Kyamakya, F. Erbas, "Location-Based Services: Advances and Challenges", *Proc. of Electrical and Computer Engineering*, May 2004, vol. 1, pp. 1-7.

[5] H. Koshima, J. Hoshen, "Personal locator services emerge", *IEEE Spectrum magazine*, February 2000, vol. 37, pp. 41-48.

[6] Katina Michael, Andrew McNamee, MG Micheal, "The Emerging Ethics of Humancentric GPS Tracking and Monitoring", *Proc. of Intl Conf. on Mobile Business (ICMB)*, June 2006, pp. 34-46.

[7] R. P. Minch, "Privacy issues in location-aware mobile devices", *Proc. of Hawaii Intl Conf. on System Sciences*, January 2004, pp. 1-10.

[8] L. Perusco, K. Michael, "Control, trust, privacy, and security: evaluating location-based services", *IEEE Technology and Society Magazine*, Spring 2007, vol. 26, pp. 4-16.

[9] M. Gruteser, Liu Xuan, "Protecting privacy in continuous location-tracking applications", *IEEE Security and Privacy Magazine*, March-April 2004, vol. 2, issue 2, pp. 28-34.

[10] Scott Pace, Gerald P. Frost, Irving Lachow, David R. Frelinger, Donna Fossum, Don Wassem, Monica M. Pinto, "The Global Positioning System Assessing National Policies", Appendix B: GPS History, Chronology, and Budgets", 1995, Available at: $http://rand.org/pubs/monograph\_reports/MR614.$

[11] T. S. Rappaport, J. H. Reed, B. D. Woerner, "Position location using wireless communications on highways of the future", *IEEE Communications Magazine*, October 1996, vol. 34, issue 10, pp. 33-41.

[12] Cyrus E. Potts, "Loran-C: Yesterday, Today and Tomorrow", *Proc. of OCEANS Conf.*, 1977, pp. 493-497.

[13] Bradford W. Parkinson, "GPS Eyewitness: The Early Years", *GPS World Magazine*, September 1994, no. 5, pp. 32-45.

[14] Elliott D. Kaplan, Christopher J. Heqarty, "Understanding GPS: Principles and Applications", Artech House, 2005.

[15] Simona Lorena Lohan, "Multipath Delay Estimators for Fading Channels with Applications in CDMA Receivers and Mobile Positioning", Doctoral Thesis, Tampere University of Technology, Finland, 2003.

[16] Jari Syrjärinne, "Studies of Modern Techniques for Personal Positioning", Doctoral Thesis, Tampere University of Technology, Finland, 2001.

[17] N. Ivanov, V. Salishchev, "The GLONASS system - An overview", *Journal of Navigation"*, May 1992, col. 45, no. 2, pp. 175-182.

[18] R. Zhen et al, "Capacity and Interference Resistance of Spread Spectrum Automatic Vehicle Monitoring Systems in the 902-928 MHz Band", Virginia Tech., Mobile and Portable Radio Research Group (MPRG), MPRG-TR-94-26, September 1994.

[19] S. Riter and J. McCoy, "Vehicle Location - An Overview", *IEEE Transactions on Vehicular Technology*, February 1977, vol. 26, issue 1, pp. 7-11.

[20] W. G. Figel, N. H. Shepherd, W. F. Trammell, "Vehicle location by a signal attenuation method", *IEEE Transactions on Vehicular Technology*, November 1969, vol. 18, issue 3, pp. 105-109.

[21] G. L. Turin, W. S. Jewell, T. L. Johnston, "Simulation of urban vehicle-monitoring systems", *IEEE Transactions on Vehicular Technology*, February 1972, vol. 21, issue 1, pp. 9-16.

[22] FCC publications, "FCC Acts to Promote Competition and Public Safety in Enhanced Wireless 911 Services",
Available: $http://www.fcc.gov/Bureaus/Wireless/News\_Releases/1999/nrwl9040.doc$.

[23] Coordination Group on Access to Location Information for Emergency Services (CGALIES), "Final report. Report on implementation issues related to access to location information by emergency services (E112) in the European Union",
Available: $http://ec.europea.eu/environment/civil/pdfdocs/cgaliesfinalreportv1\_0.pdf$.

[24] S. Naghian, "Hybrid predictive handover in mobile networks", *Proc. of IEEE Vehicular Technology Conf. (VTC)*, October 2003, vol. 3, pp. 1918-1922.

[25] Hsin-Piao Lin, Rong-Terng Juang, Ding-Bing Lin, ”Improved location-based handover algorithm for mobile cellular systems with verification of GSM measurement data”, *Proc. of IEEE Vehicular Technology Conf. (VTC)*, September 2004, vol. 7, pp. 5170-5174.

[26] A. Markopoulos, P. Pissaris, S. Kyriazakos, E. Sykas, ”Optimized handover procedure based on mobile location in cellular systems”, *Proc. of IEEE Personal Indoor and Mobile Radio Communications Conf. (PIMRC)*, September 2003, vol. 3, pp. 2490-2494.

[27] J. J. Caffery, G. L. Stuber, ”Overview of radiolocation in CDMA cellular systems”, *IEEE Communications Magazine*, April 1998, col. 36, issue 5, pp. 38-45.

[28] 3GPP TS 22.071, ”UMTS; Location Services (LCS) Service description; Stage 1”, ver. 7.4.0, Release 7.

[29] Telematica Institute, Business models for Innovative Telematics Applications (BITA), ”Overview of Mobile Information and Entertainment Services”, technical report, project deliverable D1.1.3,
Available: $http://doc.telin.nl/dscgi/ds.py/Get/File-27217$.

[30] Website Via Michelin,
Available: $http//www.viamichelin.com$.

[31] G. Retscher, ”Pedestrian navigation systems and location-based services”, *Proc. of IEE Intl Conf. on 3G Mobile Communications Technologies*, October 2004, pp. 359-363.

[32] I. Koeppel, ”What are location services? - From a GIS perspective”, Technical report, 2000, Sun Microsystems,
Available: $http://lbs360.directionsmag.com/LBSArticles$
$/ESRI.What\%20are\%20LS\%20Whitepaper.pdf$.

[33] H. Holma, A. Toskala, ”WCDMA for UMTS”, Third Edition, John Wiley and Sons, Ltd, 2004.

[34] J. Laiho, A. Wacker, T. Novosad, ”Radio network planning and optimization for UMTS”, John Wiley and Sons, Ltd, 2002.

[35] J. Lempiäinen, M. Manninen (ed.), ”UMTS Radio Network Planning, Optimization and QoS Management”, Dodrecht Kluwer Academic Publishers, 2003.

[36] J. Perez-Romero, O. Sailent, R. Agusti, ”Impact of user location in W-CDMA downlink resource allocation”, *Proc. of IEEE Intl Symposium on Spread Spectrum Techniques and Applications*, September 2002, vol. 2, pp. 420-424.

[37] Hsin-Piao Lin, Rong-Terng, Ding-Bing Lin, ”Improved location-based handover algorithm for mobile cellular systems with verification of GSM measurement data”, *Proc. of IEEE Vehicular Technology Conf. (VTC)*, September 2004, vol. 7, pp. 5170-5174.

[38] J. Sanchez-Gonzalez, J. Perez-Romero, O. Salient, R. Agusti, "An admission control algorithm for WCDMA considering mobile speed and service characteristics", *Proc. of IEEE Vehicular Technology Conf. (VTC)*, June 2005, vol. 3, pp. 1860-1864.

[39] S. Naghian, "Hybrid predictive handover in mobile networks", *Proc. of IEEE Vehicular Technology Conf.(VTC)*, October 2003, vol. 3, pp. 1918-1922.

[40] Ming-Hsing Chiu, M. A. Bassiouni, "Predictive schemes for handoff prioritization in cellular networks based on mobile positioning", *IEEE Journal on Selected Areas in Communications*, March 2000, vol. 18, issue 3, pp. 510-522.

[41] L. Badia, M. Zorzi, S. Fini, "On the estimation of user mobility for improved admission control algorithms in WCDMA systems", *Proc. of IEEE Vehicular Technology Conf (VTC)*, April 2003, vol. 2, pp. 1193-1197.

[42] Sunghyun Choi, K. G. Shin, "Exploiting path/location information for connection admission control in cellular networks", September 2000, vol. 3, pp. 935-940.

[43] J. Niemelä, T. Isotalo, J. Borkowski, J. Lempiäinen, "Sensitivity of optimum downtilt angle for geographical traffic load distribution in WCDMA", *Proc. of IEEE Vehicular Technology Conf. (VTC)*, September 2005, vol. 2, pp. 1202-1206.

[44] A. Markopoulus, P. Pissaris, S. Kyriazakos, E. Sykas, "Optimized handover procedure based on mobile location in cellular systems", *Proc. of IEEE Personal Indoor and Mobile Radio Communications Conf. (PIMRC)*, September 2003, vol. 3, pp. 2490-2494.

[45] H. Laitinen, Suvi Ahonen, Sofoklis Kyriazakos, Jaakko Lhteenmki, Raffaele Menolascino, Seppo Parkkila, "Cellular network optimisation based on mobile location, CELLO", Technical report, no. CELLO-WP2-VTT-D03-007-Int, Available: $http://www.telecom.ntua.gr/cello/documents/CELLO-WP2-VTT-D03-007-Int.pdf$.

[46] M. O Droma et al. "Always Best Connected,Enabled 4G Wireless World", *Proc. of IST Summit on Mobile and Wireless Communications*, June 2003, pp. 710-16.

[47] D. Bultman, M. Siebert, M. Lott, "Performance evaluation of accurate trigger generation for vertical handover", *Proc. of IEEE Intl Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, September 2005, vol. 3, pp. 2034-2039.

[48] J. Lacki, "Optimisation of Soft Handover Parameters for UMTS Network in Indoor Environment", M.Sc. Thesis, Tampere University of Technology, Finland, December 2006.

[49] S. Frattasi, H. Fathi, F.H.P. Fitzek, R. Prasad, M.D. Katz, "Defining 4G technology from user perspective", *IEEE Network magazine*, January-February 2006, vol. 20, issue 1, pp. 35-41.

[50] H. Hinkasalo, K. Pehkonen, M.T. Niemi, A.T. Leino, "WCDMA and WLAN for 3G and beyond", *IEEE Personal Communications*, April 2002, vol. 9, issue 2, pp. 14-18.

[51] P.W.C Chan, E.S. Lo, R.R. Wang, E.K.S. Au, V.K.N. Lau, R.S. Cheng, Wai Ho Mow, R.D. Murch, K.B. Lataief, "The evolution path of 4G networks FDD or TDD", *IEEE Communications Magazine*, December 2006, vol. 44, issue 12, pp. 42-50.

[52] Ha Duyen Trung, W. Benjapolakul, "Location-Aided Multipath Routing Method for Mobile Ad Hoc Wireless Networks", *Proc. of First Intl Conf. on Communications and Electronics (ICCE)*, October 2006, pp. 7-12.

[53] Liu Hueying, Li Yiyung, "A location based QoS routing protocol for ad hoc networks", *Proc. of Intl Conf. on Advanced Information Networking and Applications (AINA)*, March 2003, pp. 830-833.

[54] Taejoon Park, K.G. Shin, "Optimal tradeoffs for location-based routing in large-scale ad hoc networks", *IEEE/ACM Transactions on Networking*, April 2005, col. 13, issue 2, pp. 398-410.

[55] L. Blazevic, J.Y. Le Boudec, S. Giordano, "A location-based routing method for mobile ad hoc networks", *IEEE Transactions on Mobile Computing*, March-April 2005, vol. 4, issue 2, pp. 97-110.

[56] S. Sharma, A.R. Nix, "Dynamic W-CDMA network planning using mobile location", *Proc. of Vehicular Technology Conf. (VTC)*, September 2002, vol. 2, pp. 1182-1186.

[57] J. Niemelä, T. Isotalo, J. Borkowski, J. Lempiäinen, "Sensitivity of optimum downtilt angle for geographical traffic load distribution in WCDMA", *Proc. of Vehicular Technology Conf. (VTC)*, September 2005, vol. 2, pp. 1202-1206.

[58] M. Pettersen, L.E. Brten, A.G. Spiling, "Automatic antenna tilt control for capacity enhancement in UMTS FDD", *Proc. of Vehicular Technology Conf. (VTC)*, September 2004, vol. 1, pp. 280-284.

[59] W. C. Drach, "Using continuously adjustable electrical down-tilt (CAEDT) antennas to optimize wireless networks", RFS World: Detailed White Papers, Available: $http://www.rfsworld.com$.

[60] S. C. Bundy, "Antenna downtilt effects on CDMA cell-site capacity", *Proc. of IEEE Radio and Wireless Conf. (RAWCON)*, August 1999, pp. 99-102.

[61] J. Niemelä, T. Isotalo, J. Lempiäinen, "Optimum Antenna Downtilt Angles for Macrocellular WCDMA Network", *EURASIP Journal on Wireless Communications and Networking*, October 2005, vol. 5, issue 5.

[62] J. Niemelä, "Aspects of Radio Network Topology Planning in Cellular WCDMA", Doctoral Thesis, Tampere University of Technology, Finland, 2006.

[63] L. Busic, "Positioning Reporting Frequency for Location-Based Services", *Proc. of Intl Conf. on Applied Electromagnetics and Communications*, October 2005, pp. 1-4.

[64] Lidija Busic, Renato Filjar, "The Role of Position Reporting Frequency in LBS QoS Establishment", *Proc. of Intl Conf. on Software in Telecommunications and Computer Networks SoftCOM*, September-October 2006, pp. 209-213.

[65] International Convention for the Safety of Life at Sea, Department of Foreign Affairs Canberra, Australian Government Publishing Service, 1983, no. 2, Available: $http://www.austlii.edu.au/au/other/dfat/treaties/1983/22.html$.

[66] Open Mobile Alliance, SUPL 1.0 Requirements Document, OMA-RD-SUPL-V10,
Available: $http://www.openmobilealliance.org$.

[67] 3GPP TS 25.305, "UMTS, User Equipment (UE) positioning in Universal Terrestrial Radio Access Network (UTRAN)", Stage 2, ver. 7.3.0, Release 7.

[68] 3GPP TS 23.271, "UMTS; Functional stage 2 description of location services (LCS), ver. 7.8.0, Release 7.

[69] 3GPP TS 25.215, "UMTS; Physical layer; Measurements (FDD)", ver. 7.2.0, Release 7.

[70] 3GPP TS 25.171, "UMTS; Requirements for support of Assisted Global Positioning System (A-GPS); FDD", ver. 7.1.0, Release 7.

[71] G. Beveridge and R. Schechter, "Optimisation: Theory and Practice", New York: Mc Graw Hill, 1970.

[72] J. Jr. Caffery, G. L. Stuber, "Subscriber location in CDMA cellular networks", *IEEE Transactions on Vehicular Technology*, vol. 47, issue 2, May 1998, pp. 406-416.

[73] Project report Emily IST 2000-26040 deliverable D18, "Business Models Report", 2002,
Available: $http://www.emilypgm.com/acrobat/emily\_d18.pdf$.

[74] C. Johnson, H. Joshi, J. Khaleb, "WCDMA radio network planning for location services and system capacity", *Proc. of Intl Conf. on 3G Mobile Communications Technologies*, May 2002, pp. 340-344.

[75] Yilin Zhao, "Standardization of mobile phone positioning for 3G systems", *IEEE Communications Magazine*, vol. 40, issue 7, July 2002, pp. 108-116.

[76] 3GPP TSG-RAN WG1 doc. no R1-99b79, "Time Aligned IP-DL positioning technique", 1999,
Available: $http://www.3gpp.org/ftp/tsg\_ran/WG1\_RL1/TSGR1\_07/Docs/Pdfs/R1-99b79.pdf$.

[77] B. Ludden, L. Lopes, "Cellular based location technologies for UMTS: a comparison between IPDL and TA-IPDL", *Proc. of IEEE Vehicular Technology Conf.*, vol. 2, May 2000, pp. 1348-1353.

[78] 3GPP TSG-RAN WG1 doc. no R1-00-1186, "Initial Simulation Results of the OTDOA-PE positioning method", 2000,
Available: $http://www.3gpp.org/ftp/tsg\_ran/WG1\_RL1/TSGR1\_16/Docs/PDFs/R1-00-1186.pdf$.

[79] Cambridge Positioning System Ltd company white paper, David Barlett, Paul Morris, "CVB A technique to improve OTDOA positioning in 3G networks", 2002.

[80] P. J. Duffett-Smith, M. D. Macnaughtan , "Precise UE positioning in UMTS using cumulative virtual blanking", *Proc. of Intl Conf. on 3G Mobile Communication Technologies*, May 2002, pp. 355-359.

[81] Kim Sangheon, Jeong Yangseok, Lee Chungyong, "Interference-cancelation-based IPDL method for position location in WCDMA systems", *Transactions on Vehicular Technology*, vol. 54, issue 1, Jan 2005, pp. 117-126.

[82] J. Stefanski, "Method of Location of a Mobile Station in the WCDMA System without Knowledge of Relative Time Differences", *Proc. of Vehicular Technology Conf.*, September 2005, pp. 674-78.

[83] Cambridge Positioning Systems Ltd. company white paper, P. J. Duffett-Smith, P. Hansen, "Precise Time Transfer in a Mobile Radio Terminal",
Available: $http://www.cursor-system.com/cps/pdf/EGPSwhitepaper.pdf$.

[84] M. Cadervall, "Mobile positioning for third generation WCDMA systems", *Proc. of IEEE Intl Conf. on Universal Personal Communications*, vol. 2, October 1998, pp. 1373-1377.

[85] TruePosition company white paper, "An Examination of U-TDOA and Other Wireless Location Technologies: Their Evolution and Their Impact on Today's Wireless Market", 2004,
Available: $http://www.trueposition.com/trueposition\_wp\_us.pdf$.

[86] Wrya. Muhammad, Emmanuele Grosicki, Karim Abed-Meraim, Jean Pierre Delmas, Francois Desbouvries, "Uplink versus Downlink Wireless Mobile Positioning in UMTS Cellular Radio Systems", *Proc. of EURASIP EUSIPCO Conf*, paper no 364, 2002,
Available: $http://www.eurasip.org/content/Eurasipco/2002/articles/paper364.pdf$.

[87] M. Hata, T. Nagatsu, "Mobile location using signal strength measurements in a cellular system", *IEEE Transactions on Vehicular Technology*, vol. 29, issue 2, May 1980, pp. 245-252.

[88] M. Hellebrandt, R. Mathar, M. Scheibenbogen, "Estimating position and velocity of mobiles in a cellular radio network", *IEEE Transactions on Vehicular Technology*, vol. 46, issue 1, February 1997, pp. 65-71.

[89] C. L. C. Wong, M. C. Lee, R. K. W. Chan, "GSM-based mobile positioning using WAP", *Proc. of IEEE Wireless Communications and Networking Conf.*, vol. 2, September 2000, pp. 874-878.

[90] Zhu Liangxue, Zhu Jinkang, "Signal-strength-based cellular location using dynamic window-width and double-averaging algorithm", *Proc. of IEEE Vehicular Technology Conf.*, vol. 6, September 2000, pp. 2992-2997.

[91] M. Aso, T. Saikawa, T. Hattori, "Mobile station location estimation using the maximum likelihood method in sector cell systems", *Proc. of IEEE Vehicular Technology Conf.*, vol. 2, September 2002, pp. 1192-1196.

[92] K. W. Cheung, H. C. So, W. K. Ma, Y. T. Chan, "Received signal strength based mobile positioning via constrained weighted least squares", *Proc. of IEEE Intl Conf. on Acoustics, Speech, and Signal Processing*, vol. 5, 2003, pp. 137-140.

[93] Han-Lee song, "Automatic vehicle location in cellular communications systems", *Proc. of IEEE Transactions on Vehicular Technology*, vol. 43, issue 4, November 1994, pp. 902-908.

[94] Xuemin Shen, J. W. Mark, Jun Ye, "Mobile location estimation in cellular networks using fuzzy logic", *Proc. of IEEE Vehicular Technology Conf.*, vol. 5, September 2000, pp. 2108-2114.

[95] B. C. Liu, J. C. Wu, "A novel estimation method based on received signal strength difference for GSM moble positioning", *Proc. of Intl Conf. of Informatics, Cybernetics, and System*, Taiwna, R.O.C, December 2003, pp. 1402-1407.

[96] Digital Mobile Radio Towards Future Generation Systems, COST-231 Final Report,
Available: $http://www.lx.it.pt/cost231/final\_report.htm$.

[97] J. K. Ng, S. K. Chan, K. K. An, "Location estimation algorithms for providing location services within a metropolitan area based on a mobile phone network", *Proc. of 5th Intl Workshop on Mobility Databases and Distributed Systems*, September 2002, pp. 710-715.

[98] T. Roos, P. Myllymaki, H. Titti, "A statistical modelling approach to location estimation", *IEEE Transactions on Mobile Computing*, vol. 1, issue 1, January-March 2002, pp. 59-69.

[99] K. M. K. Chu, K. R. P. H. Leung, J. K. -Y. Ng, Chun Hung Li, "Locating mobile stations with statistical directional propagation model", *Proc. of 18th Intl Conf. on Advanced Information Networking and Applications AINA*, vol. 1, 2004, pp. 230-235.

[100] Bo-Chieh Liu, K. -H. Lin, Jieh-Chain Wu, "Analysis of hyperbolic and circular positioning algorithms using stationary signal-strength-difference measurements in wireless communications", *IEEE Transactions on Vehicular Technology*, vol. 55, issue 2, March 2006, pp. 499-509.

[101] K. Y. Kabalan, J. L. Mounsef, "Mobile location in GSM using signal strength technique", *Proc. of IEEE Intl Conf. on Electronics, Circuit, and Systems*, vol. 1, December 2003, pp. 196-199.

[102] V. Lang, C. Gu, "A locating method for WLAN based location service", *Proc. of IEEE Intl Conf. on e-Business Engineering ICEBE*, October 2005, pp. 427-431.

[103] Wilson M Yeung, K. Joseph, "Wireless LAN Positioning based on Received Signal Strength from Mobile device and Access Points", *Proc. of IEEE Intl Conf. on Embedded and Real-Time Computing Systems and Applications*, August 2007, pp. 131-137.

[104] H. Latinen, J. Lahteenmaki, T. Nordstrom, "Database correlation method for GSM location", *Proc. of IEEE Vehicular Technology Conf.*, vol. 4, May 2001, pp. 2504-2508.

[105] O. Sallent, R. Augusti, X. Calvo, "A mobile location service demonstrator based on power measurements", *Proc. of IEEE Vehicular Technology Conf.*, vol. 6, September 2004, pp. 4096-4099.

[106] P. Kemppi, S. Nousiainen, "Database Correlation Method for Multi-System Positioning", *Proc. of IEEE Vehicular Technology Conf.*, vol. 2, 2006, pp. 866-860.

[107] Clause Takenga, C. Takenga, K. Kyamakya, "A Hybrid Neural Network-Data Base Correlation Positioning in GSM Network", *Proc. of IEEE Intl Conf. on Communication Systems*, October 2006, pp. 1-5.

[108] R. Haeb-Umbach, S. Peschke, "A Novel Similarity Measure for Positioning Cellular Phones by a Comparison With a Database of Signal Power Levels", *IEEE Transactions on Vehicular Technology*, vol. 56, issue 1, January 2007, pp. 368-372.

[109] D. Zimmermann, J. Baumann, A. Layh, F. Landstorfer, R. Hoppe, G. Wolfle, "Database correlation for positioning of mobile terminals in cellular networks using wave propagation models", *Proc. of IEEE Vehicular Technology Conf.*, vol. 7, September 2004, pp. 4682-4686.

[110] S. Ahonen, H. Latinen, "Database correlation method for UMTS location", *Proc. of IEEE Vehicular Technology Conf.*, vol. 4, April 2003, pp. 2986-2700.

[111] S. Ahonen, P. Eskalinen, "Performance estimations of mobile terminal location with database correlation in UMTS networks", *Proc. of Intl Conf on 3G Mobile Communication Technologies*, June 2003, pp. 400-403.

[112] J. Borkowski, J. Lempiäinen, "Pilot Correlation Positioning Method for Urban UMTS Networks", *Proc. of European Wirelees Conf.*, April 2005, pp. 465-469.

[113] S. Sakagami, S. Aoyama, K. Kuboi, S. Shirota, A. Akeyama, ”Vehicle position estimates by multibeam antennas in multipath environments”, *IEEE Transactions on Vehicular Technology*, vol. 41, issue 1, February 1992, pp. 63-68.

[114] W. C. Jakes, ”Microwave Mobile Communications”, New York IEEE Press, 1994.

[115] M. Wax, T. Kailath, ”Optimum localization of multiple sources by passive arrays”, *IEEE Transactions on Acoustic, Speech, and Signal Processing*, vol. 31, issue 5, October 1983, pp. 1210-1217.

[116] J. Bohme, ”Estimation of source parameters by maximum likelihood and nonlinear regression”, *Proc. of IEEE Intl Conf. on Acoustics, Speech, and Signal Processing*, vol. 9, part 1, March 1984, pp. 271-274.

[117] M. Coker, E. Ferrara, ”A new method for multiple source location”, *Proc. of IEEE Intl Conf. on Acoustics, Speech, and Signal Processing*, vol. 7, May 1982, pp. 411-415.

[118] G. Bienvenu, ”Eigensystem properties of the sampled space correlation matrix”, *Proc. of IEEE Intl Conf. on Acoustics, Speech, and Signal Processing*, vol. 8, April 1983, pp. 332-335.

[119] H. Wang, M. Kaveh, ”Estimation of angles-of-arrival for wideband sources”, *Proc. of IEEE Intl Conf. on Acoustics, Speech, and Signal Processing*, vol. 9, part 1, March 1984, pp. 279-282.

[120] D. J. Torrieri, ”Statistical Theory of Passive Location Systems”, *IEEE Transactions on Aerospace and Electronic Systems*, vol. AES-20, issue 2, March 1984, pp. 183-198.

[121] A. Pages-Zamora, J. Vidal, D. H. Brooks, ”Closed-form solution for positioning based on angle of arrival measurements”, *Proc. of IEEE Intl Symposium on Personal, Indoor, and Mobile Radio Communications*, vol. 4, September 2002, pp. 1522-1526.

[122] A. Urruela, A. Pages-Zamora, J. Riba, ”Divide-and-Conquer Based Closed-for Position Estimation for AOA and TDOA Measurements”, *Proc. of IEEE Intl Conf. on Acoustics, Speech, and Signal Processing*, vol. 4, May 2006, pp. 921-924.

[123] S. Sakagami, S. Aoyama, K. Kuboi, S. Shirota, A. Akeyama, ”Vehicle position estimates by multibeam antennas in multipath environments”, *IEEE Transactions on Vehicular Technology*, vol. 41, issue 1, February 1992, pp. 63-68.

[124] P. Deng, P. Z. Fan, ”An AOA assisted TOA positioning system”, *Proc. of Intl Conf. on Communication Technology*, vol. 2, August 2000, pp. 1501-1504.

[125] S. Venkatraman, J. Jr. Caffery, ”Hybrid TOA/AOA techniques for mobile location in non-line-of-sight environments”, *Proc. of IEEE Wireless Communications and Networking Conf.*, vol. 1, March 2004, pp. 274-278.

[126] Li Cong, Weihua Zhuang, "Hybrid TDOA/AOA mobile user location for wideband CDMA cellular systems", *IEEE Transactions on Wireless Communications*, vol. 1, issue 3, July 2002, pp. 439-447.

[127] N. J. Thomas, D. G. M. Cruickshank, D. I. Laurenson, "Performance of a TDOA-AOA hybrid mobile location system", *Proc. of Intl Conf. on 3G Mobile Communication Technologies*, March 2001, pp. 216-220.

[128] J. Parsons, "Mobile radio propagation channel (second edition)", John Wiley and Sons Ltd, 2000.

[129] 3GPP TS 25.201, "UMTS; Physical layer - General description", ver. 7.4.0, Release 7.

[130] 3GPP TS 25.133, "UMTS, Requirements for support of radio resource management (FDD)", ver. 7.9.0, Release 7.

[131] D. Drakoulis, S. Kyriazakos, G. Karetsos, "Improving subscriber position using a hybrid satellite-assisted and network-based technique", *Proc. of Vehicular Technology Conf.*, September 2000, vol. 3, pp. 1887-1893.

[132] Hyung Chul Son, Jang Gyu Lee, Gyu In Jee, "Mobile station location using hybrid GPS and a wireless network", *Proc. of Vehicular Technology Conf.*, April 2003, vol. 4, pp. 2716-2720.

[133] ETSI TS 101 723 V 7.0.0, "Digital Cellular Telecommunications Systems, Location Services (LCS), Functional Description (Phase 2+)", August 1999.

[134] D. Kothris, M. Beach, B. Allen, P. Karisson, "Performance assessment of terrestrial and satellite based position location systems", *Proc. of Intl Conf. on 3G Mobile Communication Technologies*, March 2001, pp. 211-215.

[135] G. Heinrichs, P. Mulassano, F. Dovis, "A hybrid positioning algorithm for cellular radio networks by using a common rake receiver architecture", *Proc. of IEEE Intl Symposium on Personal, Indoor and Mobile Radio Communications*, September 2004, vol. 4, pp. 2347-2351.

[136] European Commission, Directorate-General Energy and Transport, "GALILEO European Satellite Navigation System",
Available: $http://ec.europa.eu/dgs/energy\_transport/galileo/index\_en.htm$.

[137] 3GPP TR 23.835, "Technical Specification Group Services and System Aspects, Location Services (LCS); Study into Applicability of GALIELO in LCS", ver. 1.0.0, Relase 6.

[138] S. Soliman, P. Agashe, I. Fernandez, A. Vayanos, P. Gaal, M. Oljaca, "gpsOne: a hybrid position location system", *Proc. of IEEE Intl Symposium on Spread Spectrum Techniques and Applications*, September 2000, vol. 1, pp. 330-335.

[139] Global Locate Inc. company whitepaper, Dr Frank van Diggelen, "Global Locate Indoor GPS Chipset Services",
Available: *http://www.globallocate.com/GlobalLocateIndoorGPS.pdf*.

[140] M. P. Wylie and J. Holtzman, "The non-line of sight problem in mobile location estimation", *Proc. of IEEE Intl Conf. on Universal Personal Communication*, October 1996, vol. 2, pp. 827-831.

[141] M. P. Wylie-Green and S. S. Wang, "Robust range estimation in the presence of the non-line-of-sight error", *Proc. of Vehicular Technology Conf.*, October 2001, vol. 1, pp. 101-105.

[142] N. J. Thomas, D. G. M. Cruickshank, D. I. Laurenson, "A robust location estimator architecture with biased Kalman filtering of TOA data for wireless sytems", *Proc. of IEEE Intl Symposium on Spread Spectrum Techniques*, September 2000, vol. 1, pp. 296-300.

[143] A. Lakhzouri, E. S. Lohan, R. Hamila, M. Renfors, "EKF Channel Estimation for LOS Detection in WCDMA Mobile Positioning", *EURASIP Journal on Applied Signal Processing*, 2003, issue 13, pp. 1268-1278.

[144] G. Fock, J. Baltersee, P. Shulz-Rittich, H. Meyr, "Channel tracking for RAKE receivers in closely spaced multipath environments", *IEEE Journal on Selected Areas in Communication"*, 2001, vol. 19, issue 12, pp. 2420-2431.

[145] R. A. Iltis, "Joint estimation of PN code delay and multipath using the extended Kalman filter", *IEEE Transactions on Communications*, 2001, vol. 38, issue 10, pp. 1677-1685.

[146] E. Ertin, U. Mitra, S. Siwamogsatham, "Maximum-likelihood-based multipath channel estimation for code-division multiple-access systems", *IEEE Transactions on Communications*, February 2001, vol. 49, issue 2, pp. 290-302.

[147] E. S. Lohan, M. Renfors, "Feedforward approach for estimating the multipath delays in CDMA systems", *Proc. of Nordic Signal Processing Symposium (NORSIG)*, June 2000, vol. 1, pp. 125-128.

[148] M. D. Hahm, Z. I. Mitrovski, E. L. Tilebaum, "Deconvolution in the presence of Doppler with application to specular multipath parameter estimation", *IEEE Transactions on Signal Processing*, September 1997, vol. 45, issue 9, pp. 2203-2219.

[149] E. S. Lohan, R. Hamila, A. Lakhzouri, M. Renfors, "Highly efficient techniques for mitigating the effects of multipath propagation in DS-CDMA delay estimation", *IEEE Transactions on Wireless Communications*, January 2005, vol. 4, issue 1, pp. 149-162.

[150] E. S. Lohan and M. Renfors, "Subchip multipath delay estimation for downlink WCDMA system based on Teager-Kaiser operator", *IEEE Communications Letters*, January 2003, vol. 7, issue 1, pp. 1-3.

[151] J. Vidal, M. Najar, R. E. Jativa, ”High resolution time-of-arrival detection for wireless positioning systems”, *Proc. of Vehicular Technology Conf.*, September 2002, vol. 4, pp. 2283-2287.

[152] E. Trevisani, A. Vitaletti, ”Cell-ID location technique, limits and benefits: an experimental study”, *IEEE Workshop on Mobile Computing Systems and Applications*, December 2004, pp. 51-60.

[153] J. Borkowski, J. Niemelä, J. Lempiäinen, ”Location Techniques for UMTS Radio Networks”, *Proc. of Mobile Venue Conf.*, May 2004.

[154] 3GPP TS 25.433, ”UTRAN Iub Interface Node B Application Part (NBAP) signalling”, ver. 7.6.0, Release 7.

[155] J. Yangseok, Y. Heungryeol, L. Chungyong, ”Calibration of NLOS error for positioning systems”, *Proc. of Vehicular Technology Conf.*, May 2001, vol. 4, pp. 2605-2607.

[156] L. J. Greenstain, V. Erceg, Y. S. Yeh, M. V. Clark, ”A new path-gain/delay-spread propagation model for digital cellular channels”, *IEEE Transactions in Vehicular Technology*, May 1997, vol. 46, issue 46, pp. 477-485.

[157] E. S. Soussa, V. M. Jovanic, C. Daigneault, ”Delay spread measurements for the digital cellular channel in Toronto”, *IEEE Transactions on Vehicular Technology*, November 1994, vol. 43, issue 4, pp. 837-847.

[158] J. van Rees, ”Measurements of the wide-band radio channel characteristics for rural, residential, and suburban areas”, *IEEE Transactions on Vehicular Technology*, February 1987, vol. 36, issue 1, pp. 2-6.

[159] J. H. Reed, K. J. Krizman, B. D. Woerner, T. S. Rappaport, ”An overview of the challenges and progress in meeting the E-911 requirements for location service”, *IEEE Communications Magazine*, April 1998, vol. 36, pp. 30-37.

[160] C. Drane, M. Macnaughtan, C. Scott, ”Positioning GSM tepephones”, *IEEE Communications Magazine*, April 1998, vol. 36, pp. 46-54.

[161] M. Pettersen, R. Eckhoff, P. H. Lehne, T. A. Worren, E. Melby, ”An experimental evaluation of network-based methods for mobile station positioning”, *Proc. of IEEE Intl Symposium on Personal, Indoor, and Mobile Radio Communications*, September 2002, vol. 5, pp. 2287-2291.

[162] M. I. Silventoinen and T. Rantalainen, ”Mobile station emergency locating in GSM”, *Proc. of IEEE Intl Conf. on Personal Communications*, February 1996, pp. 232-238.

[163] 3GPP TR 25.853, ”UMTS; Technical Specification Group Radio Access Network; Delay Budget within the Access Stratum”, very 4.0.0, Release 4.

[164] Digital Mobile Radio Towards Future Generation Systems COST-231 Final Report,
Available: $http://www.lx.it.pt/cost231/final\_report.htm$.

[165] 3GPP TSG-RAN WG1 doc. no R1-040567, "Expected performance of OTDOA-IPDL positioning - initial indications based on live measurements", 2004, Available: http://www.quintillion.co.jp/3GPP/TSG_RAN/TSG_RAN2004/TSG_RAN_WG1_RL1_5.html.

[166] T. Wigren, "Adaptive Enhanced Cell-ID Fingerprinting Localization by Clustering of Precise Position Measurements", *IEEE Transactions on Vehicular Technology*, September 2007, vol. 56, issue 5, pp. 3199-3209.

[167] J. Itkonen, N. Rahmani, J. Lempiäinen, "A Novel Network Topology for CDMA Networks Based on Modified Hexagonal Grid", *Proc. of IEE Intl Conf. on 3G and Beyond*, November 2005, pp. 1-5.

[168] J. Itkonen, B. P. Tuzson, J. Lempiäinen, "A Novel Network Layout for CDMA Cellular Networks with Optimal Base Station Antenna Height and Downtilt", *Proc. of Vehicular Technology Conf.*, May 2006, vol. 2, pp. 688-692.

[169] C. Braithwaise and M. Scott, Eds., "UMTS Network Planning and Development: Design and Implementation of the 3G CDMA Infrastructure", Elseview Newses, 2003.

[170] J. Niemelä and J. Lempiäinen, "Impact of the Base Station Antenna Beamwidth on Capacity in WCDMA Cellular Networks", *Proc. of Vehicular Technology Conf.*, April 2003, vol. 1, pp. 80-84.

[171] F. H. Raab, G. W. Board, S. D. Arling, J. D. Dobbs, S. C. Smrdel, J. R. Waechter, "An Application of Global Positioning System to Search and Rescue and Remote Tracking", *Navigation, Journal of the Institute of Navigation*, Fall 1977, vol. 24, no. 2, pp. 216-228.

[172] R. E. Tayvlor, J. W. Sennott, "Navigation System and Method", US Patent No. 4,445,118, 1984, 20 p.

[173] W. C. Y. Lee, D. J. Y. Lee, "The impact of repeaters on CDMA system performance", *Proc. of IEEE Vehicular Technology Conf.*, May 2000, vol. 3, pp. 1763-1767.

[174] S. Park, W. W. Kim, B. Kwon, "An analysis of effect of wireless network by a repeater in CDMA system", *Proc. of IEEE Vehicular Technology Conf.*, May 2001, vol. 4, pp. 2781-2785.

[175] H. Jeon, Y. Jung, B. Kwon, J. Ihm, "Analysis on coverage and capacity in adoption of repeater systems in CDMA2000", *Proc. of Intl Zurich Seminar on Broadband Comm.*, February 2002, pp. 33-1 - 33-6.

[176] W. Choi, B. Y. Cho, T. W. Ban, "Automatic on-off switching repeater for DS / CDMA reverse link capacity improvement", *IEEE Communications Letters*, 2001, Issue 4, vol. 5, pp. 138-141.

[177] Qualcomm company whitepaper, ”Repeaters for Indoor Coverage in CDMA Networks”, April 2003,
Available: $http://www.qualcomm.com/repeaterone/pdf/80-31576-1\_RevB.pdf$.

[178] M. Rahman, P. Ernström, ”Repeaters for Hotspot Capacity in DC-CDMA Networks”, *IEEE Transactions on Vehicular Technology*, 20004, Issue 3, vol. 53, pp. 626-633.

[179] P. Lähdekorpi, ”Effects of Repeaters on UMTS Network Performance”, Master of Science Thesis, Tampere University of Technology, Finland, March 2006.

[180] J. Borkowski, J. Niemelä, T. Isotalo, P. Lähdekorpi, J. Lempiäinen, ”Utilization of an Indoor DAS for Repeater Deployment in WCDMA”, *Proc. of IEEE Vehicular Technology Conf.*, May 2006, vol. 3, pp. 1112-1116.

[181] 3GPP TR 25.912, ”Requirements for Evolved UTRA (E-UTRA) and Evolved UTRAN (E-UTRAN)”, ver. 7.3.0, Release 7.