LOCATION DETERMINATION TECHNIQUES USING TIMING AND SIGNAL CORRELATION FOR UNIVERSAL INTELLIGENT POSITIONING SYSTEM IN CELLULAR NETWORKS

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DECLARATION

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

8 May 2009                        KEERATPAL SINGH
                                      P28382
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ABSTRACT

The success factor of Location Based Services (LBS) is very much dependent on the accuracy of the Location Determining Techniques (LDT) to estimate mobile user’s location. Universal Intelligent Positioning System (UIPS) is proposed as the complete architecture of LBS server, located in Cellular Provider’s (Telco) network. The development of new LDTs for UIPS is the main emphasis of this research. Current available LDTs are Cell ID, Observed Time Difference of Arrival (OTDOA), uplink Time Difference of Arrival (uTDOA), Assisted Global Positioning System (A-GPS) and others. Time difference methods such as OTDOA and uTDOA require time measurements from at least three base stations (BS). Location servers in Telco network will then calculate these time differences as hyperbolic equations and thus estimating user’s location. In 3G, when UE (User Equipment) is too close to the serving BS (Node B), it may not be able to hear more than three Node Bs. Trilateration techniques based on time difference measurements using OTDOA or uTDOA will not work when hearability is less than three Node Bs. The main objective of this research is to develop novel LDTs and evaluate the performance under different hearability of BS, such as time measurement obtained from one BS, two BSs, three BSs and signal strength measurement obtained from one BS. The developed LDTs shall also meet US FCC E-911 location accuracy requirements for network based positioning. In situation where three Node Bs are hearable, two new methods called Close Circle Correlation for 3 Circles (CCC) and Newton Raphson’s 3 Circles (NR3C) are introduced to solve timing measurements. CCC is a geometric solver while NR3C is based on fast convergence. In situation where only two Node Bs are hearable, a method called Close Circle Correlation for 2 Circles (CCC2) is used along with genetic algorithm comparator to match road/walk-path in order to optimize location estimation. In situation where hearability is limited to one Node B, round trip time with road data or walk-path data are matched to estimate mobile’s location. Finally, a new technique called Signal Correlation Method (SCM) is introduced. Unlike fingerprinting technique, SCM only uses one BS’s received signal to be compared with stored signals in databases. Simulations of all the above new techniques were based on real data collected through drive test for urban, suburban and highway areas, within Klang Valley. Performances of all new LDTs except SCM in suburbs and rural, meet US FCC E-911 location accuracy requirements. NR3C produces the fastest processing time per estimate, in several milliseconds. SCM, using only one BS for urban, was able to predict 95% of location estimations within 298 m, better accuracy than techniques that uses two of BSs’ signal measurements. UIPS’s new LDTs effectively provide quality of accuracy for location estimation in different hearability conditions of 2G, 3G and beyond 3G networks.
ABSTRAK

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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>2G</td>
<td>Second Generation of Cellular Telephone System</td>
</tr>
<tr>
<td>3G</td>
<td>Third Generation of Cellular Telephone System</td>
</tr>
<tr>
<td>3GPP</td>
<td>Third Generation Partnership Project</td>
</tr>
<tr>
<td>4G</td>
<td>Fourth Generation of Mobile Network</td>
</tr>
<tr>
<td>A-GPS</td>
<td>Assisted Global Positioning System</td>
</tr>
<tr>
<td>ANN</td>
<td>Artificial Neural Network</td>
</tr>
<tr>
<td>AoA</td>
<td>Angle of Arrival</td>
</tr>
<tr>
<td>AP</td>
<td>Access Point</td>
</tr>
<tr>
<td>API</td>
<td>Application Programming Interface</td>
</tr>
<tr>
<td>ARFCN</td>
<td>Absolute Radio Frequency Channel Number</td>
</tr>
<tr>
<td>BCCH</td>
<td>Broadcast Control Channel</td>
</tr>
<tr>
<td>BRDT</td>
<td>Best Route Determining Technique</td>
</tr>
<tr>
<td>BS</td>
<td>Base Station</td>
</tr>
<tr>
<td>BSC</td>
<td>Base Station Controller</td>
</tr>
<tr>
<td>BSIC</td>
<td>Base Station Identity Code</td>
</tr>
<tr>
<td>BSS</td>
<td>Base Station Subsystem</td>
</tr>
<tr>
<td>BTS</td>
<td>Base Transceiver Station</td>
</tr>
<tr>
<td>CCC</td>
<td>Close Circle Correlation for 3 Circles</td>
</tr>
<tr>
<td>CCC2</td>
<td>Close Circle Correlation for 2 Circles</td>
</tr>
<tr>
<td>CDF</td>
<td>Cumulative Distribution Function</td>
</tr>
<tr>
<td>CN</td>
<td>Core Network</td>
</tr>
<tr>
<td>CP</td>
<td>Content Provider</td>
</tr>
<tr>
<td>CS</td>
<td>Circuit Switch</td>
</tr>
<tr>
<td>CPICH</td>
<td>Common Pilot Channel</td>
</tr>
<tr>
<td>DB</td>
<td>Database</td>
</tr>
<tr>
<td>DCM</td>
<td>Database Correlation Method</td>
</tr>
<tr>
<td>E-911</td>
<td>Enhanced 911 (emergency phone service in the USA)</td>
</tr>
<tr>
<td>ECNO</td>
<td>Energy per Chip divided power density in band</td>
</tr>
<tr>
<td>E-OTD</td>
<td>Enhanced Observed Time Difference (or EOTD)</td>
</tr>
<tr>
<td>ERXL</td>
<td>Enhanced Receive Level</td>
</tr>
<tr>
<td>ETSI</td>
<td>European Telecommunications Standard Institute</td>
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</tbody>
</table>
FCC  Federal Communications Commission
FDD  Frequency Division Duplex
GAC  Genetic Algorithm Comparator
GDOP  Geometric Dilution of Precision
GGSN  Gateway GPRS Support Node
GIS  Geographical Information System
GMLC  Gateway Mobile Location Center
GRNN  Generalized Regression Neural Network
GPRS  General Packet Radio Service
GPS  Global Positioning System
GSM  Global System for Mobile communications
GTD  Geometric Time Difference
HLR  Home Location Register
HSDPA  High Speed Downlink Packet Access
HTTP  Hypertext Transfer Protocol
ITU-R  International Telecommunication Union-Radiocommunication Sector
kLOS  known Line of Sight
LAC  Location Area Code
LAN  Local Area Network
LBS  Location Based Services
LBTP  Location Based Task Planner
LDT  Location Determining (or Determination) Technique
LEAN  Learn Another (used for SCM)
LMU  Location Measurement Unit
LOS  Line of Sight
MBRC  Minimum Best Road Comparator
MLP  Multi Layered Preceptron
MO  Mobile Originating
M-OCRAIA  Modified One Cell Road Angle Iteration Algorithm
MT  Mobile Terminating
MS  Mobile Station
MSC  Mobile Switching Center
<table>
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<th>Abbreviation</th>
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<tr>
<td>NB</td>
<td>Node B</td>
</tr>
<tr>
<td>NBAP</td>
<td>Node B Application Part</td>
</tr>
<tr>
<td>NBS</td>
<td>Navigation Based Services</td>
</tr>
<tr>
<td>NLOS</td>
<td>Non Line of Sight</td>
</tr>
<tr>
<td>NMR</td>
<td>Network Measurement Report</td>
</tr>
<tr>
<td>NN</td>
<td>Neural Network</td>
</tr>
<tr>
<td>NR2C</td>
<td>Newton Raphson 2 Circles</td>
</tr>
<tr>
<td>NR3C</td>
<td>Newton Raphson 3 Circles</td>
</tr>
<tr>
<td>OCRAA</td>
<td>One Cell Road Angle Algorithm</td>
</tr>
<tr>
<td>OCRAIA</td>
<td>One Cell Road Angle Iteration Algorithm</td>
</tr>
<tr>
<td>OTD</td>
<td>Observed Time Difference</td>
</tr>
<tr>
<td>OTDOA</td>
<td>Observed Time Difference of Arrival</td>
</tr>
<tr>
<td>OTDOA IPDL</td>
<td>Idle Period of Downlink Observed Time Difference of Arrival</td>
</tr>
<tr>
<td>PS</td>
<td>Packet Switch</td>
</tr>
<tr>
<td>PT</td>
<td>Processing Time</td>
</tr>
<tr>
<td>QoP</td>
<td>Quality of Positioning</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RLMN</td>
<td>Reference Location Measurement Node</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>RNC</td>
<td>Radio Network Controller</td>
</tr>
<tr>
<td>RRC</td>
<td>Radio Resource Control</td>
</tr>
<tr>
<td>RSCP</td>
<td>Received Signal Code Power</td>
</tr>
<tr>
<td>RSS</td>
<td>Received Signal Strength</td>
</tr>
<tr>
<td>RSSI</td>
<td>Received Signal Strength Indicator</td>
</tr>
<tr>
<td>RTD</td>
<td>Real Time Difference</td>
</tr>
<tr>
<td>RTT</td>
<td>Round Trip Time</td>
</tr>
<tr>
<td>RXL</td>
<td>Receive Level</td>
</tr>
<tr>
<td>SCM</td>
<td>Signal Correlation Method</td>
</tr>
<tr>
<td>SFN</td>
<td>System Frame Number for UMTS</td>
</tr>
<tr>
<td>SGSN</td>
<td>Serving GPRS Support Node</td>
</tr>
<tr>
<td>SMLC</td>
<td>Serving Mobile Location Center</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
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</tr>
<tr>
<td>SMS</td>
<td>Short Message Service</td>
</tr>
<tr>
<td>SMSC</td>
<td>Short Message Service Center</td>
</tr>
<tr>
<td>SMTTLU</td>
<td>Simple Mapping Technique Table Lookup</td>
</tr>
<tr>
<td>SS</td>
<td>Signal Strength</td>
</tr>
<tr>
<td>TA</td>
<td>Time Advance</td>
</tr>
<tr>
<td>TDOA</td>
<td>Time Difference of Arrival</td>
</tr>
<tr>
<td>Telco</td>
<td>Telecommunication Company</td>
</tr>
<tr>
<td>TOA</td>
<td>Time of Arrival</td>
</tr>
<tr>
<td>TU</td>
<td>Typical Urban</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>UIPS</td>
<td>Universal Intelligent Positioning System</td>
</tr>
<tr>
<td>uLOS</td>
<td>unknown Line of Sight</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunications System</td>
</tr>
<tr>
<td>URL</td>
<td>Uniform Resource Locater</td>
</tr>
<tr>
<td>US</td>
<td>Unique Samples (used for SCM)</td>
</tr>
<tr>
<td>USUC</td>
<td>Unique Samples Undefined Collection (used for SCM)</td>
</tr>
<tr>
<td>UTDOA</td>
<td>Uplink Time Difference of Arrival</td>
</tr>
<tr>
<td>UTM</td>
<td>Universal Transverse Mercator</td>
</tr>
<tr>
<td>URA</td>
<td>UTRAN Registration Area</td>
</tr>
<tr>
<td>UTRA</td>
<td>Universal Terrestrial Radio Access</td>
</tr>
<tr>
<td>UTRAN</td>
<td>UMTS Terrestrial Radio Access Network</td>
</tr>
<tr>
<td>VPN</td>
<td>Virtual Private Network</td>
</tr>
<tr>
<td>WCDMA</td>
<td>Wideband Code Division Multiple Access</td>
</tr>
<tr>
<td>WiMAX</td>
<td>Worldwide Interoperability for Microwave Access</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
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## LIST OF SYMBOLS

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<th>Symbol</th>
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<tbody>
<tr>
<td>$\Delta x$</td>
<td>Incremental correction for NR3C</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Weightage criteria for Best Comparator</td>
</tr>
<tr>
<td>$\tau_D$</td>
<td>Delay prediction error</td>
</tr>
<tr>
<td>$\tau_{RMS}$</td>
<td>RMS time delay spread</td>
</tr>
<tr>
<td>$a$</td>
<td>First constant for RSSI prediction model</td>
</tr>
<tr>
<td>$A_1$</td>
<td>First CCC2 output at first intersection</td>
</tr>
<tr>
<td>$A_2$</td>
<td>Second CCC2 output at first intersection</td>
</tr>
<tr>
<td>$Abwt$</td>
<td>Average Beamwidth</td>
</tr>
<tr>
<td>$a_{g_{ij}}$</td>
<td>Angle between BS$_i$ and BS$_j$</td>
</tr>
<tr>
<td>$b$</td>
<td>Bias for GRNN (SCM)</td>
</tr>
<tr>
<td>$B_1$</td>
<td>First CCC2 output at second intersection</td>
</tr>
<tr>
<td>$B_2$</td>
<td>Second CCC2 output at second intersection</td>
</tr>
<tr>
<td>$c$</td>
<td>Second constant for RSSI prediction model</td>
</tr>
<tr>
<td>$d$</td>
<td>Mobile distance from BS</td>
</tr>
<tr>
<td>$D_{PE}$</td>
<td>Delay Prediction Error constant</td>
</tr>
<tr>
<td>$dist$</td>
<td>Euclidean distance</td>
</tr>
<tr>
<td>$F$</td>
<td>Fitness Function for $A_1$, $A_2$, $B_1$ or $B_2$ of CCC2-GAC</td>
</tr>
<tr>
<td>$f_i(x,y)$</td>
<td>Function for NR3C</td>
</tr>
<tr>
<td>$G_{Error}$</td>
<td>CCC resolution error</td>
</tr>
<tr>
<td>$Gen$</td>
<td>Generation for GAC</td>
</tr>
<tr>
<td>$J(x)$</td>
<td>Jacobian matrix</td>
</tr>
<tr>
<td>$k_s$</td>
<td>Scale factor conversion for longitude and latitude</td>
</tr>
<tr>
<td>$L_1$</td>
<td>Output of BestGeo algorithm for angle checker</td>
</tr>
<tr>
<td>$L_g$</td>
<td>Output for distance checker</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of Hearable BS</td>
</tr>
<tr>
<td>$p_{ij}$</td>
<td>Variable in fitness function of GAC</td>
</tr>
<tr>
<td>$P(i)$</td>
<td>Input for SCM</td>
</tr>
<tr>
<td>$pop$</td>
<td>Population size for GAC</td>
</tr>
<tr>
<td>$RSSI_{Pred}$</td>
<td>RSSI prediction versus distance</td>
</tr>
<tr>
<td>$SL(i)$</td>
<td>Sample’s location for SCM</td>
</tr>
<tr>
<td>$spreading$</td>
<td>Spreading constant for GRNN (SCM)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>$T_A$</td>
<td>Time of Arrival</td>
</tr>
<tr>
<td>$T_{Approx}$</td>
<td>Approximate $T_A$ without delays</td>
</tr>
<tr>
<td>$T_D$</td>
<td>Time Delays</td>
</tr>
<tr>
<td>$T_E$</td>
<td>Timing Error</td>
</tr>
<tr>
<td>$T_G$</td>
<td>Geometric Time</td>
</tr>
<tr>
<td>$T_{Gpred}$</td>
<td>Predicted Geometric Time</td>
</tr>
<tr>
<td>$v$</td>
<td>Velocity of mobile</td>
</tr>
<tr>
<td>$w$</td>
<td>Weightage for GRNN</td>
</tr>
<tr>
<td>$x$</td>
<td>Horizontal axis of target</td>
</tr>
<tr>
<td>$y$</td>
<td>Vertical axis of target</td>
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1.1 INTRODUCTION

The success factor of Location Based Services (LBS) is dependant on the capabilities of Location Determining Techniques (LDT) to accurately estimate (predict) cellular (GSM or UMTS) user’s location. Once the location of the mobile user has been predicted, the location server could then provide the requested services, such as the nearest bookstore to the user. It is also important that location servers host a great deal of contents and varieties of services or information in order to provide the best match for the estimated user’s location. The total round trip time (from beginning of user’s request until the successful response of information from the location server) taken to receive the information is also of great importance in LBS. Mobile users will only evaluate the end result: if they can get what they need within acceptable location accuracy and the response time from the server is not slow enough to drive them away. There are certain services that are very time sensitive and requires ultimate accuracy (Zeimpekis et al. 2003) while certain services like area-group chatting may not demand high accuracy. Location server should segregate the quality of accuracy based on the requirements of location services offered. For Emergency Services, estimating user’s location is very critical at the instance of call establishment to the emergency center’s number (911 or 112 or 999). Accurate estimation of caller’s location would enable emergency operator to dispatch assistance to caller’s location even if the caller is unable to provide full address of his or her location. In the USA, Federal Communications Commissions (FCC) has requested network providers to comply with FCC E-911 location accuracy requirements for network based positioning (Anon 2005a). FCC requires that 67% of emergency callers’ estimated
location to be within 100 m of accuracy and 95% of emergency callers’ estimated location to be within 300 m of accuracy. Therefore, this accuracy can be used as a benchmark when comparing different LDT’s performances.

In Malaysia, LBS did not really make its first move until February 2004 (Anon 2004a) when Maxis launched its Friend Finder Service (Anon 2008a). The service enables user’s friends to locate the user by sending SMS to a designated short code number. Only friends that are in the user’s approved list could request for the user’s location. Other Telcos like Digi also followed and offered similar location service. But till date, Telcos have not gone full force to offer much LBS services even though Content Providers (CP) are ready to provide varieties of applications and contents. This is due to the fact that Telcos want to protect their subscribers’ privacy (subscriber’s information and profile) when information are being sent and received from third party CPs (Escudero-Pascual 2002). The other factor is Telco needs assurance that any new location services would not burden the extra resources of its voice’s signaling network. Voice is still Telcos’ major revenue generator. In Malaysia, 85.1 out of 100 population of Malaysia owns a mobile phone (MCMC 2007). With large numbers of phone user’s in Malaysia, tracking their locations would be advantages through the currently available cellular GSM (2G) and UMTS (3G) networks. To address the issues and concerns mentioned above, a new design called Universal Intelligent Positioning System (UIPS) is introduced.

1.2 UNIVERSAL INTELLIGENT POSITIONING SYSTEM

Figure 1.1 shows the architecture of UIPS in Telco’s network that is to interconnect Telco’s network to LBS contents. Located in the premises of Telco’s infrastructure, UIPS will be connected to the third party CPs via secure VPN (Virtual Private Network) tunnels. All CPs will have to follow an Application Programming Interface (API) like used by Google (Anon 2008b) for communication flows between UIPS and CPs’ servers. All communication between UIPS to CP will not reveal user’s identity, thus safeguarding user’s privacy. Figure 1.2 shows UIPS and its subsystems. Even though Telecommunication vendors like Nokia has produced their own Serving Mobile Location Center (SMLC) (Anon 2004b) for location estimation (3GPP 2001a),
but UIPS will cater for additional functionalities besides just being a location processing center/server.

Figure 1.1 Architecture of UIPS for GSM, UMTS and Beyond Network

Figure 1.2 UIPS and its components connected to Telco’s GSM and UMTS Networks
As was mentioned earlier, the purpose of UIPS is to provide flexibility for Telco’s to control their own LBS servers and subsystems, while maintaining subscribers’ privacy, and the ability to utilize LDTs that meet user’s requirements, such as providing Quality of Positioning (QoP) or level of accuracy. All the modules in UIPS have their own functionalities. The LDT module will hosts all newly developed LDTs which will be discussed in later chapters of this thesis. LDT module could also host all currently available LDTs (3GPP 2007a) such as Cell ID, Enhanced Observed Time Difference (EOTD) for GSM, Observed Time Difference of Arrival (OTDOA) for UMTS, uplink Time Difference of Arrival (uTDOA), Angle of Arrival (AoA), Assisted Global Positioning System (AGPS) (Anon 2003), and Database Correlation Method (DCM) (Laitinen et al. 2001b).

Billing module of UIPS is responsible to charge the LBS’s requester (mobile user) by sending charge transactions to Telco’s billing mediation platform. Billing Module will also be tied to QoS (Quality of Service) module, which is configured with all information related to LBS types of services, related pricing for each service (content or information) and the level of accuracy required for each service. As mentioned earlier the type of service plays a major role in determining which LDT to use, and UIPS is also capable to segregate which LDT performs faster as per the processing time (PT) taken to estimate one user’s location. Another intelligent aspect of UIPS is to distribute the processing of large LBS traffic requests between the LDTs if faster processing time is required at busy hour of the day. The information related to busy hour voice traffic, busy hour LBS request per area, base station’s coordinates, antenna information, environment conditions pertaining to survey data, area’s information, Location Measurement Unit (LMU) addresses, road data, maps and other information are stored in the Data module. Telco’s System Administrator can configure new information or update survey data (collected drive test data), road data, and collected signal strength information through the Administrator (Admin) module. This module will also be connected via LAN or router so administrators could even log on from remote terminal for ease of Operations and Maintenance tasks. From this module, administrators can view statistics of hourly, daily or monthly LBS requests and import the data for performing LBS analysis per service, per area, per user and other fields. Also through this module, any information on LMU clock drifts and
warnings would be alerted immediately to the system administrator. The Routing module will be used to communicate to UMTS Terrestrial Radio Access Network’s (UTRAN) Radio Network Controller (RNC) and Base Station Subsystem’s (BSS) Base Station Controller (BSC) through signaling protocol such as Radio Resource Control (RRC) (3GPP 2007b), which is used for UMTS. Routing Module is also connected to Mobile Switching Center (MSC), and Core Network (CN) elements such as Home Location Register (HLR), Serving GPRS Support Node (SGSN), Gateway GPRS Support Node (GGSN) and others (Holma & Toskala 2004). VPN module will make virtual private network connection through internet to all registered third party CP. Server module will be used by UIPS to communicate directly with UE through internet or data bearers, by-passing UTRAN and BSS communications. By-passing 2G and 3G layer protocols will help to reduce radio resources being used in heavy requests of LBS. UIPS clients will be installed on UE for easy menu-driven access to communicate with UIPS’s or LBS server. Permanent and temporary data will be stored in UIPS database through interfacing with the Data module. SMS module is used when LBS requests by UE are being sent to UIPS as text message: Short Message Service (SMS) Mobile Originating (MO). SMS module is also used to respond SMS Mobile Terminating (MT) message to UE through the Telco’s Short Message Service Center (SMSC).

Interfaces and signaling protocols for UIPS as used by location center to request RNC or BSS to obtain measurement reports from UE, Node B or LMU, will be based on specifications set by Third Generation Partnership Project (3GPP). Such as in 3GPP (2007a), signaling flows are described for currently defined LDT using Cell ID, OTDOA and uTDOA method. It is assumed for this research that the Location Measurement Unit (LMU) is built into Node B or also known as associated LMU. The signaling from RNC to associated LMU uses Iub interfaces with NBAP (Node B Application Part) signaling protocol (3GPP 2007c).

In UIPS, the originator of location request could be UE (user) or network. When UE requests for LBS, UIPS will request serving RNC to initiate signaling procedure to obtain OTDOA (time difference measurements from three Node B as observed by the UE) through OTDOA signaling operations as defined in 3GPP.
(2007a). UIPS will assume the role of location server in Core Network (CN). The fundamental of OTDOA and time based LDT will be discussed in Chapter 2. In general, when downlink or uplink time measurements are made from at least three Node B or Base Station (BS), trilateration or triangulation technique could be used to solve hyperbolic equations in order to estimate mobile locations. When less than three Node Bs or BSs are observed by UE, then other LDTs such as Cell ID may be used.

1.3 PROBLEM STATEMENT

In 3G, when UE is close to the serving Node B (BS), UE is unable to hear other neighboring BSs. This condition is called hearability problem. Time based methods such as EOTD, OTDOA and uTDOA only work when at least three BSs are hearable. The inability of UE to obtain three Node Bs’ measurements makes it impossible to estimate location within acceptable accuracy. In this situation when hearability of BSs is less than three, Cell ID method could be used. However if the cell size is too large, the estimation could be far off. Furthermore, using one cell’s information to estimate user’s location within a determined cell could not meet FCC E-911 location accuracy requirements as cell sizes could range from 50 m (picocell) in urban to more than 10 km in rural (Kupper 2005). In Malaysia, Cell ID (MCMC 2006) is still being used to determine emergency caller’s location, where the estimated location of user will always be the coordinate or the address of the serving cell.

Even when at least three BSs are hearable by the UE or MS, location estimation accuracy for OTDOA (UMTS) or E-OTD (GSM) LDT is between 50 m to 300 m (Kupper 2005). The location accuracy would further degrade when multipath time delay errors are present from Non Line of Sight (NLOS) BSs, and hearable BSs used for timing measurements are not in good geometry, such as on highways where BSs are placed parallel to the highways. UE is unable to obtain good triangulation paths from the hearable BSs when the BSs are in bad geometrical placements.

Determining user’s location within certain level of accuracy is not an easy task for Telcos. Even in the US, FCC is giving cellular providers up to year 2012 to meet the E-911 location accuracy requirements (Reed 2007). In estimating user’s location,
the more BSs involved in the measurement process, the more accurate the estimation becomes (Kupper 2005).

Therefore in this research, new or enhanced techniques and algorithms to estimate location based on time of arrival (TOA), OTDOA, uTDOA or EOTD measurements would be developed when hearability of BSs is three or less than three. In addition, actual BSs coordinates would be utilized to study geometric problems faced by Telco. Besides using time measurements from LMU, radio propagation measurements such as signal received from one serving BS would be used to estimate locations. Signal Correlation Method (SCM) would be developed to compare the signal received in worst condition of hearability where UE can hear from only one BS. This current received signal will be compared with stored signals (signals obtained during site survey) for the best correlation in order to estimate user’s location.

1.4 OBJECTIVE

UIPS was introduced to solve current LBS and location estimation problems faced by Telcos, by providing an intelligent location server that routes varieties of content between Telco and CPs, with various levels of QoS and QoP. The LDT module, which is also the central processor of UIPS, will host a collection of new or enhanced LDTs and predictors. LDT module will decide the best LDT to use for location estimation depending on network type (GSM, GPRS, UMTS or others), area classification (urban, high multipath, or others), type of location search (emergency, LBS, tracking), hearability of BSs (one, two or more), geometrical placements of BSs, QoP required (level of accuracy required), faster PT and other criteria. To implement the LDT module, the following research objectives must be met:

1) Develop and study the performance of timing technique LDTs in known and unknown multipath conditions when hearability is at least three.

2) Improve estimation technique for TOA and TDOA (Time Difference of Arrival) methods by studying the effect of geometrical problems related to BSs and UE.
3) Find or develop the best algorithm with the fastest PT to estimate user’s location.

4) Develop and study the performance of timing technique LDTs, predictors and road comparators in known multipath conditions when hearability is less than three.

5) Develop and study the performance of signal strength LDT when hearability is one and in unknown multipath delay conditions. Extend the study for phone assisted estimations to reduce Telco’s signaling from location measurements caused by huge LBS requests.

6) Integrate LDTs and predictors into LDT module by classifying their performances such as meeting FCC E-911 requirements, PT per estimate, QoP or accuracy achieved, hearability type and others.

1.5 METHODOLOGY

In order to meet the objectives of the research by developing timing and signal correlation methods in different hearability conditions, the following scope of study and methodology were formed for this research:

1) Review previous literature pertaining to available LDTs, numerical methods for solving timing equations, and radio propagation environments.

2) Perform drive test or data collections for different classification of areas in Klang Valley like metropolitan, urban, suburban, rural, and highways.

3) Analyze hearability, delay prediction error and geometrical placements of BSs based on Telco’s data: BS coordinates, directional antenna and other data provided by Telco. Analyze GSM and UMTS signal received from serving cell to predict a suitable Receive Signal Strength versus distance model.

4) Develop timing technique to estimate location for areas where multipath delays could be predicted based on survey data collected earlier. Develop
enhanced timing technique when Line of Sight (LOS) conditions are not known. Develop timing methods with using road matching techniques and sectorized cell’s information, when hearability is from one or two BS. Develop SCM of one cell to support timing method in urban where multipath is high.

5) Study the performance (in terms of accuracy and PT) of the timing techniques in known survey environment and unknown LOS. Extend the study of enhanced timing LDTs and predictors for selected drive test route collected earlier in Kuala Lumpur where UE faced hearability of less than three. Finally, study the performance on SCM in urban and less populated suburbs.

6) Analyze from performance results if modifications to estimation algorithms could further improve the accuracy of each LDT and observe the effects from geometric placements and other environment factors.

7) Develop and simulate an LBS application to verify LDT module’s selection criteria for selecting the best LDT that is appropriate for the service offered.

1.6 HYPOTHESIS

The hypothesis to develop timing and SCM LDTs for UIPS by studying location estimation performance as affected by the various placements of BSs in different classification of areas within actual Telco’s cellular network is formulated as:

*The collection of developed LDTs with predictors for timing techniques in various hearability situations, along with the collection of SCM LDTs, will form the complete UIPS’s LDT module that could intelligently provide desired level of QoP with desired PT pertaining to the QoS requested in different classification of environment and area, to solve current LBS and emergency location issues.*
1.7 THESIS OUTLINE

In this chapter the concept of UIPS was introduced for GSM (2G), GPRS, UMTS (3G) and beyond 3G cellular networks. The research objectives for developing UIPS’s LDT module and scope of work were defined. In Chapter 2, available LDT, hearability problems, existing time difference methods for solving timing equations, location estimation using received signal strength of cells, and radio propagation models will be reviewed. In Chapter 3, methodology, drive test data collection, data analysis and development of LDT with prediction models will be presented. Two new estimation techniques, Close Circle Correlation for 3 Circles (CCC) and Newton Raphson’s 3 Circle (NR3C) would be introduced to solve equations based on time or time difference such as EOTD, OTDOA or uTDOA, when UE could hear from three unique Node Bs. Enhanced averaging techniques for CCC and NR3C will be developed in situation where multipath delay information are not known. When hearability is from two BSs and the user is on a road or walking on walk-paths, Close Circle Correlation for 2 Circles (CCC2) will be used with road matching comparator such as Genetic Algorithm Comparator to further improve prediction accuracy. A prototype map is also discussed with some road path examples. The map will also aid navigation users to select the best route like functionalities provided by Global Positioning System (GPS) navigational tools (Anon 2008c). When measurements are only available from one Node B, Round Trip Time (RTT) will be used along with road data, to estimate user’s location. In Chapter 4, performance for both GSM and UMTS networks based on drive test data will be discussed in terms of accuracy and PT, when timing measurements are available (hearable) from one, two or three BSs. In Chapter 5, Signal Correlation Method (SCM) would be evaluated based on using new learning techniques called Learn Another (LEAN), Unique Samples (US) and Unique Sample Undefined Collection (USUC) to estimate user’s location by correlating current received signal of one cell to stored received signals in UIPS’s database. In Chapter 6, UIPS’s LDT module’s selection criteria to choose the best LDT pertaining to service offered, level of accuracy required, hearability conditions and other factors will be discussed along with examples of location services. Chapter 7 concludes the research work, describing the main contributions, and suggesting future work.
CHAPTER II

LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter, background information on GSM and 3G systems, radio network elements used for timing and signal measurements, outdoor and indoor cellular propagation models, will be presented. Available LDTs that have been specified or mentioned by GSM and 3G standards, followed by non specified LDTs such as fingerprinting technique of signal strengths (SS) of cells, will be described. In addition, other related research work using timing technique for location estimation, navigation, tracking service, location estimation with the aid of road maps, and signal measurements for location estimation, will be reviewed. In the final section of the chapter, the summary for each current LDT will be presented in terms of location accuracy level, PT for an estimate, and proposed type of location services.

2.2 GSM AND UMTS SYSTEMS

GSM also commonly referred to as the second generation (2G) of digital cellular systems was designed to provide efficient voice communications compared to analog systems in the first generation. With the evolution of data services such as General Packet Radio Services (GPRS) or 2.5G, UMTS or the third generation (3G) system provides higher efficiency in data services of up to 2 Mbps (Holma & Toskala 2004). 3G system supports voice, data service and also integration to GSM, GPRS, packet networks, and other IP (Internet Protocol) networks in order to provide various QoS and high quality of multimedia service.
2.2.1 LDTs in GSM and UMTS

To determine (estimate) the location (position) of 2G, 2.5G or 3G cellular users, LDTs are used. The currently specified LDTs for cellular network providers are Cell Identification (Cell ID), E-OTD for GSM, OTDOA for UMTS, uTDOA, Angle of Arrival (AoA), and AGPS. Basically there are two categories of LDTs: network based or phone based. Network based LDTs may request the assistance of mobile phone to perform measurements but the bulk of the calculations to estimate user’s location is done at location server. Phone based LDT such as using GPS receiver built on the phone, could measure and estimate location through the guidance of satellites, while phone based LDT using Cell ID could estimate user’s proximity to the serving cellular base station’s location.

European Telecommunications Standards Institute (ETSI) produces standards related to GSM, such as for Location Services Functional description (ETSI 2004). At the same time the same standards are also available in 3GPP with a different reference number (3GPP 2004a). The standard describes various combinations of signaling flow initiated either from Serving Mobile Location Center (SMLC) to Mobile Station (MS) or from MS to SMLC. As mentioned in the previous chapter, UIPS will assume the roles of SMLC, Gateway Mobile Location Center (GMLC), and Location Server. In fact there are a few Location Services specifications within 3GPP pertaining to different segments of cellular network and interfaces, such as for BS, MS, LMU, Base Station Controller (BSC), signaling flow, signaling layers and the various LDTs’ message flow (3GPP 2008). In this thesis, a separate remark will be highlighted if a specific LDT could only work for either GSM or UMTS. With the convergence of 2G, 3G and beyond 3G, same LDTs are generally used on both 2G and 3G systems. For example, Cell ID is specified for both GSM and 3G.

2.2.2 Network Architecture

As in Figure 1.2, within GSM network, Base Transceiver System (BTS) is referred to as Base Station and mobile phone is referred to as Mobile Station (MS). Several BTS are controlled by BSC and this whole radio network is termed as Base Station
Subsystem (BSS). If MS moves to another location area, the serving BSC will handover its control to a new eligible BSC, which has its own cluster of BTSs. Mobile Switching Center (MSC) will route and handle all cellular switching within an area. For example, there could be a few MSCs within a state or region and a few BSCs within a city. For packet (data) services in GSM, GPRS network is used. All packet data communications will flow from BSC to Serving GPRS Support Node (SGSN), Gateway GPRS Support Node (GGSN), and to Telco’s internal data network or externally to the internet. Location update for each MS connecting to new serving BTS/BSC/SGSN/MSC will be stored in Home Location Register (HLR).

In UMTS, BS is referred to as Node B, MS is referred to as UE, BSC as RNC and BSS is referred to as UTRAN (UTRAN Frequency Division Duplex is generally used). The core network (CN) is divided to Circuit Switch (CS) and Packet Switch (PS). MSC and Gateway MSC will be handling all CS (voice) switching, while SGSN and GGSN are used as PS networks for both GPRS and 3G data services. HLR would also be storing the location updates of UE. In cities there could be several RNCs and in state level, only a couple of MSCs. In 3G, the modulation scheme is called QPSK which represents 2 bits per symbol of signal. The chip modulation rate is 3.8 Mcps. Each Frame carries 38,400 chips and has 10 ms duration. Each Frame is serially referred to as System Frame Number (SFN) from 0 to 4095. SFN will be used as reference for timing of Base Station (Kupper 2005). Broadcast Control Channel (BCCH) would be used in both GSM and UMTS for all MSs to listen to serving BS and neighboring BSs. Another channel specified in 3GPP which is of interest for location estimation is Common Pilot Channel (CPICH). It is used by UE for signal strength measurement, timing measurement, for handover decisions and feedback power control (Kupper 2005).

### 2.2.3 Cellular Radio Propagation

A brief overview of the cellular radio propagation characteristics will provide some insight of how to use radio signal’s parameters to estimate mobile user’s whereabouts. Several models are available by Sizun (2005) that provides theoretical, empirical using statistical analysis of experimental measurements or semi-empirical using
statistical analysis of experiments and combining signal reflections, scattering and other loss properties, in order to determine (predict) signal path loss calculations with respect to BS height, MS distance from BS, frequency of cellular system and others. Once the path loss model is determined, the power received versus distance (BS to MS) could be obtained. The power received, $P_r$ in dB is defined as:

$$P_r = P_T + G_T + G_R - L - L_{other} \tag{2.1}$$

where, $P_T$ is power transmit in dB (dBW), $G_T$ is gain of BS transmit antenna in dB (or in dBi), $G_R$ is gain of mobile/UE receive antenna in dB (or dBi), $L$ is path loss in dB, and $L_{other}$ is other losses caused by fading in dB.

$P_r$ measurements could be obtained as described in 3GPP’s specification (3GPP 2007d), from measuring received power of the CPICH by UE (RSCP), wideband receive power (RSSI) of UE, and CPICH $E_b/N_0$ of UE. For measurements of power obtained in dBm, the conversion factor is $P_r$ (in dBm) = $P_r$ (in dB) + 30. When $Pr$ could be measured, then from Equation (2.1), $L$ could be calculated. Therefore, we can calculate $L$ from $P_r$ or vice versa when either of the variables is known. Theoretical formula to obtain Free Space Propagation Loss, $L$ when there is no obstruction between BS and MS in Line of Sight (LOS) is defined as:

$$L = 32.44 + 20\log(f) + 20\log(d) \tag{2.2}$$

where, $f$ is the operating cellular frequency in MHz, and $d$ is the distance between BS and MS in km. Other widely used propagation models for GSM and UMTS are Okumura-Hata (Hata 1980), Walfisch-Ikegami, COST 231 Okumura-Hata, and others. Okumura-Hata model is based on empirical prediction (Laiho et al. 2006), and for Loss, $L$ in dB is defined as:

$$L = A + B\log(f) - 13.82\log(b_h) - a(m_h) + [C - 6.55\log(b_h)]\log(d) \tag{2.3}$$

where,

$$a(m_h) = 3.2[\log(11.75m_h)]^2 - 4.97,$$

is mobile antenna gain function for large cities,
A is constant used for GSM with value of 69.55 and for 3G with value of 46.3,
B is constant used for GSM with value of 26.16 and for 3G with value of 33.9,
b_h is BS antenna height in meters between 30 to 200 m (typical value is 30 to 35 m),
m_h is MS antenna height in meters between 1 to 10 m (typical value is 1.5 m),
f is GSM or UMTS frequency in MHz,
d is distance in km between 1 to 20 km, and
C is tuning constant between 44 to 47 based on best fit (typical value is 44.9).

In general, Okumura-Hata model has been widely used as reference for
comparison to latest improved prediction models for outdoor cellular environment.
Even then, prediction of coverage and losses has to be carefully planned with using
more detailed parameters such as NLOS information, actual coordinates including
altitude, signal reflections and others dealing with specific geometrical conditions of
BSs that could influence each unique area’s coverage prediction.

For site specific indoor propagation model, Chevallier et al. (2006) proposes
Motley-Keenan model, an extension of the free space propagation model to be used in
order to determine the path loss $L_0$ in dB as below:

$$L_0 = P_o + 20 \log(d) + (p \times WAF) + (K \times FAF)$$  (2.4)

where,

- $P_o$ is $20 \log \left( \frac{4\pi f}{c} \right)$ in dB, $f$ is cellular frequency in MHz, $c$ is the speed of light, $d$ is
distance in meters from transmitter to receiver, $p$ is number of walls from transmitter
to receiver, $K$ is number of floors from transmitter to receiver, $WAF$ is Wall
Attenuation Factor in dB (modern office wall 3 dB and brick wall 10 dB), and $FAF$ is
Floor Attenuation Factor in dB (between 13 dB to 18 dB). References by Aguirre et
al. (1994), Rappaport & Siedel (1989), Rappaport et al. (1990), Motley & Keenan
(1988), Motley & Keenan (1990) and Siedel et al. (1992) provide additional
information on $WAF$, $FAF$ and indoor propagation.
It could be observed from indoor and outdoor propagation models that the further MS range (distance) from BS, the higher is the MS/UE signal loss, or the lower received signal strength value. When measured signal strength value is known, mobile user’s distance from the serving base station could be roughly estimated.

2.3 LDT

This section describes each LDT that are specified or mentioned by 3GPP for GSM and UMTS.

2.3.1 Cell ID (GSM and UMTS)

In omni directional cell, where the antenna of BS is covering the entire cell, only one Cell ID number is required to identify the cell. Figure 2.1 illustrates the concept of a cell in a densely populated area and the Cell ID number associated with the cell. The

Figure 2.1 Concept of Cell ID in 2G and 3G network

Source: Zhu 2006

BS or Node B is located in the center of the cell with x, y position of coordinate. For this example, it has a 3 sector cell and with direction of its antennas at 0° (North) for
sector 1, 120° for sector 2 and 240° for sector 3. The beam width of each sector’s antenna is 120°. Sometimes Telco uses BS of three sectors with beam width of 60° and at different antennas’ direction. Examples of antenna sectorization in UMTS are presented by Niemela & Lempiainen (2003a and 2003b). Theoretically, only cells with 6 sectors will be divided into 60° of coverage area within the cell. Another point to note is, the cell labeled b in Figure 2.1 shows BS’s location with respect to a cell. The cluster of cells labeled a in Figure 2.1 is grouped into seven cells of network (2G or 3G) coverage. Bigger area could be covered by several of the same frequency reusable clusters: N=7 allow sufficient distance for repeated clusters to reuse same arrangements of original cluster’s frequencies. In theory, cells are represented as hexagon (hexagon representation of a cell makes a better filling/continuation of the entire cluster of cells compared to circles which leaves smaller gaps of uncovered area between one circle cell to another circle), but in reality it could almost be a shapeless combination between an hexagon and a circle. In general three types of cell categories are frequently mentioned: macrocells, microcells and picocells. Macrocells cover larger outdoor areas (antenna mounted on transmission tower or above rooftop), microcells provide small coverage suited for urban areas with antenna below rooftop levels, and picocells are suited for covering small indoor areas.

In Figure 2.1, if for example, MS moves from previous cell towards the new cell’s sector 3 as shown, BSC will compare from handover parameters’ of all the surrounding BSs, such as looking for the best received signal strength and signal quality. Based on the best handover parameters, decision for a new serving cell for the MS would be made, such as sector 3 as shown in the figure. In sectorized cell, each sector carries a Cell ID number. The last digit of the Cell ID represents the sector number, for example Cell ID 10003 (last digit indicates sector 3 of the cell). This Cell ID number is always updated in the Home Location Register (HLR) corresponding to each mobile user’s location update. In terms of location estimation based on Cell ID, when UIPS or location server requests from the serving RNC to provide the Cell ID of MS, it could then be estimated based on the Cell ID that the MS in the example was nearer to sector 3’s coverage area of the new cell called 10003. For omni cell, where the direction is covered 360° throughout the cell, the estimation to locate MS could be anywhere around the cell.
2.3.2 Round Trip Time (RTT)

In order to improve estimation of locating UE within the Cell ID, one hybrid approach is to use timing measurement of Round Trip Time (RTT) between the UE and the BS. RTT is the round trip time (total travelling time between the first measured transmitted downlink frame from the BS until receiving the same first uplink frame from the UE), so one way trip time (one way distance) is just simply dividing by 2. In UMTS, RTT could be used when UIPS or Location Server requests RNC to measure the serving Node B’s RTT (3GPP 2007d) for the UE. If UE is in idle mode, RNC will enforce state transition by paging the UE. With the availability of the Node B’s position coordinates within UIPS’s database, the distance could be estimated from the time-distance relationship at the speed of light, \( c \). With hybrid RTT and Cell ID, the estimation could be narrowed down within the Cell ID area and estimated MS’s distance from the Node B’s sectorized antenna station. Study on RTT is presented by Borkowski et al. (2004). In GSM, this feature is already built in as a timing buffer between each GSM channels and is also known as Timing Advance (TA). TA when used can only give estimation within 550 m (or multiple of 550 m) (Laitinen et al. 2001a) of distance between MS and the serving BS with the condition that the MS must be in busy mode (not idle).

2.3.3 Time of Arrival (ToA)

Figure 2.2 shows the time of arrival (TOA) from three base stations as observed by UE or MS. The distance, \( d_i \) from MS to \( BS_i \) (Kaaranen et al. 2001) is as following:

\[
d_i = c \cdot t_i + e
\]  

(2.5)

where, \( t_i \) is the time of arrival from \( BS_i \) to MS, \( c \) is the speed of light, and \( e \) is the measurement error caused by signal reflections, fading and shadowing of Non-line of Sight (NLOS) signal path from BS to MS. To minimize uncertainty and error margins, at least three or more BSs (solving three of the TOA equations to estimate location) are required to participate in the triangulation/trilateration of TOA method. TOA
requires accurate synchronization between all three hearable BS. That is why time
difference of arrival (TDOA) from BSs such as EOTD or OTDOA is sometimes
preferred (Kupper 2005) to TOA to minimize synchronization errors by acquiring the
differences of time between BSs rather than acquiring individual BS’s time
measurements.

2.3.4 Enhanced Observed Time Difference (E-OTD) for GSM

EOTD is an LDT based on trilateration of timing measurements obtained from at least
three BS as observed by the MS. In order for time measurements between the BSs’
difference of time measurements) to be synchronized, Location Measurement Units
(LMU) has to be installed within GSM networks. LMU can be dimensioned based on
grouping of a few BS to one LMU. LMU could also be a stand alone unit or

![Diagram of TOA, E-OTD and OTDOA location estimations](source: 3GPP 2004a)

Figure 2.2 TOA, E-OTD and OTDOA location estimations

associated within a BS. Standalone LMU will have different signaling protocols than
associated LMU. In this research we will assume that each LMU is associated within
each BS. Abis interface (BSC to BTS in Figure 1.2 uses this interface) is used
between BSC to the associated LMU or also referred to as type B LMU (ETSI 2004).
The interconnections of various technologies in Telco’s network such as microwave
networks, fiber networks, 2G, 3G and 4G requires synchronization between clocks at
every layer of transport components. Hence, a superior internal clock at each base station could further translate and serve as reference to MSs’ internal clocks.

There are two types of EOTD as defined by 3GPP (2004a): circular type and hyperbolic type. Circular type uses the concept of TOA, where timing from each BS is measured separately, and the estimated location of MS will be at the intersection of the three BSs’ radii, $d_i$. At least three hearable BSs with associated LMU, forming three TOA equations, are required to estimate MS’s location. In hyperbolic type of EOTD as shown in Figure 2.2, hyperbolic equations (Spirito 2001) are used to solve EOTD measurements within GSM network. Implementation for both type of EOTD is similar except the timing measurement error will be different. In EOTD (generally referred to hyperbolic type), Observed Time Difference (OTD) is the observed time difference of arrival at the MS from two BTSs. For example, the first pair of observe time difference, $OTD_1 = t_a2 - t_a1$, is between BTS1 and BTS2, and the second pair of observe time difference, $OTD_2 = t_a3 - t_a1$, is between BTS1 and BTS3, where $t_ ai$ is the arrival time from each BS. But the difference will be 0 if both BTSs’ transmission burst arrive at the same instant of time at MS. Real Time Difference (RTD), is the transmission time difference from two BTS to the MS as observed by LMU. For example, the first pair of real time difference, $RTD_1 = t_t2 - t_t1$, is between BTS1 and BTS2, and the second pair of real time difference, $RTD_2 = t_t3 - t_t1$, is between BTS1 and BTS3, where $t_ ti$ is the transmission time of BS $i$. If the BTSs pair transmits at the same time, then the real time difference is 0, $RTD = 0$. Geometric Time Difference (GTD) is the physical time (physical geometric distance of locations) difference at MS between the two different BTSs. For example, the first hyperbolic pair of geometric time difference, $GTD_1 = t_2 - t_1$, is the difference between $d_1$ of BTS1 and $d_2$ of BTS2, and the second pair of geometric time difference, $GTD_2 = t_3 - t_1$, is the difference between $d_1$ of BTS1 and $d_3$ of BTS3. If the distance (each $t_i$ multiply with $c$) between the two BTS is exactly the same from the MS, then $GTD = 0$. The relationship between $GTD$, $OTD$ and $RTD$ is as following:

$$GTD = OTD - RTD$$ (2.6)
where, $OTD$ is the observe time difference between two BSs, and $RTD$ is the real time difference between two BSs. Since $GTD$ represents the real equation of physical locations, with two pair of hyperbolic equations (ETSI 2004), the intersecting point as shown in Figure 2.2 could be determined as the estimated location of the MS. The hyperbolic equation is represented as following:

$$d_j - d_1 = c(OTD_{j,1} - RTD_{j,1})$$  \hspace{1cm} (2.7)

where, $d_j$ is the distance between $BTS_j$ to MS, $d_1$ is the distance between $BTS_1$ to MS, $OTD_{j,1}$ is the observe time difference between $BTS_j$ and $BTS_1$, and $RTD_{j,1}$ is the real time difference between $BTS_j$ and $BTS_1$. If more than two pairs of hyperbolic equations are formed, or more than three BSs participate in time difference measurements, the accuracy of E-OTD’s location estimation will improve.

### 2.3.5 Observe Time Difference of Arrival (OTDOA) for UMTS

OTDOA in UMTS (3G) follows the same concept of EOTD and it is also used for downlink time difference of arrival as observed by UE. At least three Node Bs are required for the OTDOA based hyperbolic equations to be solved, in order to estimate user’s location. Again, associated LMU will be focused here. The Iub interface will be used between RNC to associated LMU (RNC to Node B in Figure 1.2 uses this interface), and Node B Application Part (NBAP) will be used as the signaling protocol. LMU, which gets its clock source from GPS, could measure the observed timing frame difference between each Node Bs or also known as SFN-SFN observed time difference measurements. UIPS or location server can request OTDOA measurements from the serving RNC which is able to directly interrogate the UE using the Radio Resource Control (RRC) protocol. RNC could also request UE for periodic measurement through the RRC protocol until a stop command is sent to the UE. All Radio Interface Timing (RIT) from Node Bs are reported to the serving RNC, which will pass to UIPS (or SMLC) for checking synchronization status between Node Bs, clock drifts at Node B, GPS clock status and CPICH information of measured signal. In 3GPP (2007d), physical layer measurements for Frequency Division Duplex (FDD) that are of interest for LBS are UE SFN-SFN observed time
difference represented by the relative time difference between time of CPICH slot arrival at UE from Node B₁ and time of CPICH slot arrival at UE from Node B₂, CPICH Received Signal Code Power (RSCP), GSM RSSI (Receive Signal Strength Indicator), UTRA RSSI, CPICH Ec/No (receive energy per chip divide by power density), UE Rx-Tx time difference (time difference between UE uplink DPCCH/DPDCH frame and the beginning of the first DPCH frame in the measurement link observed), RTT measurement from Node B (time difference between the first downlink DPCH frame to UE and the first uplink of the same DPCCH/DPDCH frame from the UE), LMU SFN-SFN observed time difference (relative time difference between time of LMU receives the first primary CPICH frame from Node B₁ and the same LMU receive the first primary CPICH frame from Node B₂), PRACH/PCPCH propagation delay, UE GPS Timing of Cell Frames for UE (timing between cell i with SFN as observed by UE), and GPS Time of Week.

Once the LMU has determined the RTD, and the UE has reported to RNC via Uu interface the OTD result, similar process by solving hyperbolic equations to obtain estimated location as in E-OTD follows. With two GTD hyperbolas, where one hyperbolic equation is represented by Equation (2.7), UIPS could then solve the two equations to estimate mobile location.

In UE phone, Rake receiver (Holma & Toskala 2004) assists in detecting multipath signals from Node B. Installing OTDOA software could assist UE in obtaining detailed measurements by comparing (cross correlation) Node B’s signal with a reference signal within the mobile, and detecting the highest peak signal’s time of the Node B. The process is repeated for all the participating Node Bs’ pilot signal. The difference in time of arrival between two Node Bs provides one hyperbolic equation as discussed earlier. Two hyperbolic equations are required. These information is sent to RNC, SMLC and finally to Location Server to further estimate and calculate the UE location.

If more than three Node Bs participate (active and monitored Node Bs observed by the UE), the better the accuracy of the OTDOA method. Inaccuracy could also be reduced if RTD is synchronized down to less than 10 nanoseconds (10 nanoseconds of time error can cause 3 m of location estimation error), drifts of clocks
at Node B is measured regularly and compared to RTD constants as recorded in databases, and Node Bs used during OTDOA (Kupper 2005) are observed by UE from different angles (directions) in order to avoid or reduce Geometric Dilution of Precision (GDOP).

2.3.6 Idle Period of Downlink OTDOA (OTDOA IPDL) in UMTS

As mentioned in OTDOA method, at least three Node Bs are required for trilateration to work. Two hyperbolic equations obtained from three Node Bs enable the calculation for location estimation. When UE is too close to the serving cell, UE may not be able to hear other neighboring Node B’s signals due to the dominant stronger signal from its serving Node B. This problem is referred to as hearability problem. In terms of location estimation, inability to obtain sufficient measurements from unique Node B’s would degrade the accuracy of location estimation. According to Holma & Toskala (2004) for OTDOA measurements, the estimation of location could be up to several tens of meters when three or more Node Bs participate, when more different directions of Node Bs’s pilot transmission towards UE are obtained, and when there is good LOS between Node Bs and UE. Holma & Toskala (2004) also reports that in simulation of UMTS network, about 31% probability of pilot signals from at least three Node Bs are hearable for OTDOA measurements and 74% probability of hearability of at least three Node B’s pilot signals are hearable for OTDOA IPDL. Therefore, 3GPP has included OTDOA IPDL as one of UMTS positioning method. In UMTS, the duration of one frame is 10 ms, and every 10 downlink frames one IPDL slot occurs (every 100 ms burst mode of IPDL). Even though this method requires extra network usage in terms of signaling, but it increases the probability of getting measurements from at least three Node Bs. The main role of OTDOA IPDL (Bartlett & Morris 2002) compared to OTDOA is during the idle period, the serving Node B stops transmission for very short period, allowing UE to be able to hear other Node Bs’ signals. Under instructions of SMLC, the serving RNC will control the idling of Node B via NBAP protocol and RRC signaling is used (via Uu interface) to inform UE about the IPDL process. SMLC controls the process until at least three Node Bs are able to be measured by the UE. Another benefit of OTDOA IPDL is when
downlink idle period slot occurs, other nearby UEs requesting for LBS could also take advantage of this facility.

### 2.3.7 uplink Time Difference of Arrival (uTDOA)

Figure 2.3 illustrates the uplink lateration method. In this method, UE pilot signals are observed by three Node Bs. A special LMU is required at Node Bs to detect the uplink arrival of multipath signals from UE. Multipath occurs when there is no direct LOS of signal travelling from source to destination or when the signal is reflected along the way, it will travel in various paths with longer time period to reach destination. For GSM, 3GPP (2008) Technical Specification 43.059 states that the terminal must be in busy mode for uTDOA to operate and there should be enough LMU surrounding the MS to estimate the MS’s location. In 3GPP (2007e), the location request messages between SMLC and BSS is called Base Station System Application Part LCS (Location Services) Extension (BSSAP-LE). UIPS will also use this message format between the same Lb interface to BSS. SMLC (or UIPS) will request BSS for uTDOA measurements in GSM network.

![Figure 2.3 uTDOA method](Source: Kupper 2005)

In UMTS, LMU will cross-correlate the signals received from the UE for two BS as in Figure 2.4, by comparing and matching two signals peak by peak, and
matching the peaks occurrence and their time intervals, the time difference of arrival, $t_d$ between Node B1 and Node B2, could be obtained. It is also required that the site with the highest attenuated signal power (or serving BS) be chosen as the reference site for signal comparator (3GPP 2007a). When three pairs of hyperbolas are obtained from three time difference of arrivals (four Node Bs participate in the process), the accuracy of estimating MS or UE increases. When Location Server or UIPS request a Radio Access Network Application Part (RANAP) Location Reporting Control Message to RNC via Iupe interface (3GPP 2007f), RNC will check if UE is connected or in idle mode. If UE is in idle mode, RNC will change its state to Forward Access Channel state (Cell_FCH) mode from UTRAN Registration Area paging channel (URA_PCH) or cell level paging channel (Cell_PCH) mode. Then serving RNC (SRNC) will force UE through RRC protocol to transmit data, for uTDOA measurements to be completed. Once SRNC gets the complete measurements, instructions to UE to stop transmission will be made. Location Server would then use these measurements to solve the hyperbolic equations.

![Figure 2.4 Cross-correlation between two Node Bs’ signals](Source: 3GPP 2007a)
2.3.8 Angle of Arrival (AoA)

Based on the pilot signal from UE or MS, antenna array receiver is required in each Node B to measure the angle of arrival (AoA) from UE as shown in Figure 2.5. The angle of arrival, $\theta_i$ from UE as observed by Node B$_i$ is defined as:

$$\theta_i = \arctan\left(\frac{y_i - y}{x_i - x}\right)$$

(2.8)

where, $x_i$ and $y_i$ are the coordinates of Node B$_i$, while $x$ and $y$ are the estimated coordinates of UE. With two Node Bs measurements, and by solving two AoA equations, the position of the UE could be estimated at the intersecting lines of the two Node Bs. Due to NLOS or wave reflections, inaccuracy could be introduced. When more than two Node Bs are used, the accuracy increases. Even though AoA could also be measured by the phone, but the complexity required for receivers to be installed on UE or MS may be impractical compared to installing specialized receiver antenna at a central point for measurement, such as at Telco’s stations.

![Figure 2.5 AoA technique](source: Kupper 2005)
2.3.9 Global Positioning System (GPS) as a phone based LDT

GPS is a satellite based positioning that requires at least four satellite’s pilot signals to arrive (same concept as TOA) at the GPS receiver (or UE integrated with GPS receiver) from a range of 5 to 10 visible satellites. GPS only work in LOS environments. Firstly, the receiver will identify the visible satellites available. When the GPS receiver does not have orbital information of satellite (almanac) or its previous locations, the receiver will do a cold start-up to listen to all the satellites around it. When the following information is available, it could start the rough estimation of user’s location estimation. This process is called warm start-up. When all satellites locations are updated and accurate, with precise ephemeris (Anon 2008d), it could start estimating user’s locations without identifying coarse acquisition codes to choose from. This process is called hot start-up. In general start-ups takes up receiver’s processing time to select the best four satellites based on their visibilities and their GDOP, so that the best estimation of location could be made. Kupper (2005) states that for a low cost GPS receiver, the cold start-up takes between 40 s to 60 s, warm start-up takes between 30 s to 40 s and hot start-up takes between 5 s to 15 s. GPS receivers are able to calculate and display directly to users the longitude, latitude, altitude (height) and in fact the speed of the users if used with commercial navigation based software packages (Anon 2008c), installed on the receivers.

2.3.10 Assisted Global Positioning System (A-GPS) as network based LDT

To reduce the longer processing time of acquiring code from satellites by the GPS receiver, assistance of the latest information such as visible satellites, satellite ephemeris, clock corrections, satellite doppler, and reference data are sent from the serving BS and thus eliminating the complex calculations at the mobile terminal. Figure 2.6 illustrates the A-GPS concept. When the UE or MS is able to calculate and estimate its location, it is referred to as UE/MS based A-GPS. All assistance information are transmitted in the downlink from the serving Node B (serving BTS).
Figure 2.6 Assisted GPS as a network based LDT in GSM and UMTS

Source: 3GPP 2004a

The nearest reference or serving Node B should be equipped with latest information pertaining to the satellites around the area, and will transmit immediately (through protocols controlled by serving RNC or serving BSC) in the downlink when requested (3GPP 2007g) by the UE. In UE (phone) assisted A-GPS, only partial feature of GPS receiver is installed within the mobile device. Therefore Kaaranen et al. (2001) mentioned only limited assistance data are sent to UE to enable it to make pseudorange measurements. UE will send the measurements as uplink response to the serving BS so that the location server in the network could calculate and estimate the final position based on UE’s measurements and Node B satellite receiver station’s latest information. According to Holma & Toskala (2004), A-GPS’s reference receiver if installed in all BS, could improve accuracy of estimation to 10 m for outdoors and several tens meters for indoors. A-GPS is also able to support indoor positioning due to the assistance data received through the cellular network, unlike the basic GPS receivers that must receive time of arrival from at least least four LOS satellites (fourth satellite is required as clocking reference to improve accuracy even though three satellites could provide the intersection point from TOA method as similarly achieved from cellular based TOA technique). Assistance data will not only reduce the code acquisition process and provide fast processing Time to First Fix (TTFF) to estimate location, but will also reduce the GPS power consumption of the UE/MS since UE does not have to monitor the satellites frequently.
2.3.11 Hybrid Techniques

When an accurate estimation of the user’s location is required, combination of Cell ID, TDOA (OTDOA/E-OTD/uTDOA), RTT, AoA and, A-GPS could be performed together. For instance, in the following situation where the user’s phone is in idle mode and does not have GPS and does not have the capability to perform OTDOA, an accurate positioning is required to estimate user’s location in order to provide emergency services. For this case, AoA, Cell ID and RTT could then be used to estimate the location of the UE. uTDOA also could have been used since no software or hardware changes are required at UE/MS, but specialized LMU to measure uplink signals must be installed at BSs. Laitinen et al. (2001a) mentioned that hybrid signaling are not fully standardized yet and the cost of using it is very high. Other estimation methods that could be combined with current standards of 2G/3G LDT are Received Signal Strength (RSS) or RSSI matching technique that matches stored signal strengths from surveyed BSs to current BSs’ signal strengths. This type of pattern matching is sometimes referred to as fingerprinting technique and will be covered in the next section. The only drawback to signal parameters’ type of comparison is that stored BSs’ configurations are never permanent. Telcos could change the configuration of antennas’ direction and other BSC/BS radio parameters that could affect the RSSI levels in the area of request. The process of changing BSCs’ configuration is part of Telco’s radio network optimization routine, but could really affect pattern matching or fingerprinting type of location estimation techniques when stored parameters are no longer updated.

2.4 NON SPECIFIED 3GPP/ETSI LDTs FOR GSM AND UMTS

Other current LDTs that are not specified in 3GPP are fingerprinting of signal strengths or DCM (Laitinen et al. 2001b) and pattern matching of signals. Pattern matching from camera or optical images of stored location areas (landmarks or scenery) is also being introduced by researchers (Laitinen et al. 2001a) but not practical to be carried out in cellular environment, unless cameras within UE can automatically capture the surrounding when LBS request is being made. However
optical pattern matching could be integrated as part of cellular navigation in vehicular technology.

2.4.1 Fingerprinting of Received Signals

Matching received signal levels of base stations with captured stored signals are referred to as RF fingerprinting (Rao & Siccardo 2001). Firstly, site survey is conducted to collect signal strength levels from as many BSs as possible at specific points of location coordinates. Each point will represent a small bin of area (grid area), for example 20 m by 20 m. During the actual usage of LBS, the user’s signal levels with respect to all the surrounding BSs will be measured. Then the result will be sent to a location server so that the measured signal levels could be compared to the sets of fingerprints in the database. Based on current BSs’ signal matching to the stored fingerprint samples, the grid location with the best matching is the estimated location of mobile phone. Few methods could be used for deciding the best pattern matching such as Euclidean Distance’s weightage factor (Kaemarungsi & Krishnamurthy 2004) of all current signal levels to all fingerprint sets of stored BSs’ signal levels, or using Neural Network to find the best matching of current received signal strengths (RSS) to stored sets of fingerprints (Martinez et al. 2004, Takenga & Kyamakya 2007, and Salcic & Chan 2000). Currently for fingerprinting technique, only phone assisted LDT is available, where the phone will assist in the measurements of signal levels from all BSs and then passes it on to Location Server for further calculations. For phone based LDT, special software has to be installed, but it still does not allow to capture neighboring BS’s signal levels. It only allows the measurement of one serving BS (Anon 2008e), which is as good as obtaining Cell ID with only one signal strength value. The only advantage is network interrogation is not required by RNC or BSC to get Cell ID. The phone based LDT (Cell ID) could be obtained directly via the software menu when phone is in idle or busy state.

Fingerprinting location techniques (Martinez et al. 2004) are also employed in indoor Wireless Local Area Network (WLAN). In WLAN, RSS quality is also related to distance, where location estimation could be made based on path loss analysis from wireless Access Points (AP). Currently there are high end mobile phones such as
Nokia N95 that have WLAN detection capabilities and it is hoped that WLAN AP (stations) if owned by Telcos such as Telekom Malaysia could also estimate location of those UEs within WLAN hotspots. Same concept applies, where the phone will assist in getting the measured RSS values from the various APs and sent to Telco’s location server (or UIPS) for further estimation of mobile user’s location. Telcos must have current updates of all its APs’ locations within hotspots and indoor buildings.

2.4.2 Database Correlation Method (GSM and UMTS)

Database Correlation Method (DCM) is also another type of fingerprinting technique as described earlier. It could store time delays of signal, signal strengths of BSs and power delay profiles for UMTS. Information is not dependent to LOS or none LOS, as it only requires accurate measurement of signal parameters. It is suitable in dense urban areas, unlike AOA or EOTD that could degrade in NLOS urban. Laitinen et al. (2001b) claimed that DCM heavily relies on actual measurement compared to other fingerprinting technique, and suggested that distributed processing by server is required since the data is quite large. Network planning tool and computations may be required where real measurements are not obtained. Furthermore, the signal strength could be converted to distance (between MS to BS) by using calculations from path loss models but it is not reliable for location estimation due to large errors caused by shadowing. The DCM algorithm assumes that the stored signal strength data are updated regularly and the difference between fingerprints, \( d(k) \) is represented as:

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

where, \( f_i \) is current receive signal strength fingerprint of BTS’s cell \( i \) (broadcast control channel number is used to identify each cell), \( g_i(k) \) is the stored receive signal strength \( k^{th} \) fingerprint in the database related to BTS’s cell \( i \), and summed over the available number of fingerprints corresponding to their cell numbers. The penalty term \( p \) is added for \( k^{th} \) fingerprint related to each cell. The location estimation is obtained for coordinates that minimize the difference of the above equation. For UMTS (Ahonen & Laitinen 2003), power delay profiles are stored. The stored power delay profile will be used to compare to current measured power delay profile for the
corresponding cell. The coordinate with the highest correlation point (best matching between measured and stored signals) from stored profiles will be chosen as the location estimate. Unlike GSM, software modifications are required for Node Bs.

2.4.3 Pattern Matching of Power Signatures

According to Bertoni & Suh (2005), network such as GSM, could readily hold information pertaining to sets of path gains for MS as observed from the surrounding BTSs, such as multipath interference and unique shadowing data of signals resulting from obstructions. From this unique signature, information could be stored in database tables and when used for LBS, comparisons between current measurements and stored measurements could be done to estimate the best location match for the MS. This technique does not require any extra hardware or software on the phone. It only need to construct database table with sets of path gains (in dB) to the respective (available) BSs versus location coordinate within a grid area, as similarly described in the previous section. Bertoni & Suh (2005) states that with 7 BSs, 99% of unique power signatures per stored location is achievable. The more BSs are used, uniqueness of power signatures increase, producing higher accuracy of location estimation. A set with BSs less than 5 will not meet FCC’s requirements for location accuracy.

2.4.4 Matching Technique of Network Measurement Report during Voice Call

Analyzing and storing the call signal parameters based on network measurement reports (NMR) at different components of the radio interfaces such as Abis link (link between BSC to BTSs) could also be categorized as matching technique. Firstly, the measured signal characteristics at the various interfaces will be tagged to a street location during the call. Then the set of sample information is stored. The prediction model for the street based on the signal pattern recognition and characteristics will be implemented using statistical method such as Hidden Markov Model (with training from predicted inputs). When more training of data is provided, the better the estimation accuracy becomes. For example, receive level of signal when the MS moves from the street to the end of street with certain velocity, signal quality during call, signal levels of serving cell, neighbor cells, Timing Advance (TA), and Bit Error
Rate could be obtained from the network measurement during the voice call. Laitinen et al. (2001a) presents the sample of NMR that could be captured during the call and used as training sequence for tagging the street location. Viterbi algorithm could also be used for predicting the maximum likelihood estimates (most probable) street paths taken during the actual drive by the MS (Laitinen et al. 2001a).

2.5 LDT IMPLEMENTATION AND ISSUES

2.5.1 TDOA Location Estimation and Model

As mentioned earlier, in order to estimate mobile location from TDOA measurements obtained from three hearable BSs, solving three BSs’ circles or solving two pairs of hyperbolic equations is required. Aatique (1997) and Thomas (2001) mentioned that there are few methods to solve these equations and are not straightforward. In addition, time errors due to multipath most likely exist in the environment causing the actual distance to be added with range errors. Thomas (2001) suggested using Taylor Series and Weighed Least Square Estimator, or using Chan’s Method (Chan & Ho 1994) or Cramer Rao Lower Bound Method.

Thomas (2001) uses random uniform time delay of 0 s to 0.6 μs when full obstruction occurs for TDOA model and mentioned about Geometric Dilution of Precision (GDOP) in relationship to the placement of three BSs used to obtain Time of Arrival type of measurements. GDOP is defined by Thomas (2001) as:

$$GDOP = \sqrt{\frac{\sigma_x^2 + \sigma_y^2}{\sigma_r}} = \frac{\Phi_{RMS}^0}{\sigma_r}$$

(2.10)

where, $\sigma_x$ is the square mean of $x$ distance error of estimated location, $\sigma_y$ is the square mean of the $y$ distance error of estimated location, $\sigma_r$ is the square mean of noise variance, and $\Phi_{RMS}^0$ is the Cramer Rao Lower Bound root mean square location estimator with detailed derivation presented in Thomas (2001). As was discussed in earlier sections, higher GDOP resulting from parallel placement of BSs would cause
higher inaccuracy of location estimation. The Root Mean Square (RMS) error difference, $e_{RMS}$ is also used by some references besides the E-911 standards to compare accuracy of $N$ location samples and is defined as:

$$e_{RMS} = \sqrt{\frac{1}{N} \sum_{n=1}^{N} ((\hat{x}(n) - x(n))^2 + (\hat{y}(n) - y(n))^2)}$$  \hspace{1cm} (2.11)

where, $\hat{x}$ and $\hat{y}$ are coordinate of the estimated mobile location (estimated location point) in Cartesian coordinate system, while $x$ and $y$ are the coordinate of the actual $n$-th mobile location point.

As discussed in earlier section, each $n$-th multipath signal for uTDOA measurements could be detected by specialized LMU/Node B and that each signals could be differentiated for their respective power levels $P_1,...,P_n$ corresponding to their $\tau_n$ delays as shown in Figure 2.4. For downlink TDOA (E-OTD and OTDOA), it is assumed that the mobile phone (such as Rake receiver in 3G phones) is able to detect the impulse response (each signal component’s time delay and power level), and therefore could measure the time of arrival, strongest and first arrival peak signal, and also the RMS delay spread (acceptable level of all multipath peak signals’ total delay). Porcino (2001) describes the impulse response channel model for 3G OTDOA-IPDL as below:

$$h(t, \tau) = \sum_{n=1}^{N} E_n(t) \delta(\tau - \tau_n(t))$$  \hspace{1cm} (2.12)

where, $N$ is the number of multipaths, $\tau_n(t)$ is the delay of the $n$-th multipath at time $t$, and $E_n(t)$ is the complex amplitude. According to Tranter et al. (2004), time varying-fading exists because the environment is changing due to scatterers or movement of reflectors or mobility of receivers. Porcino (2001) further elaborate each of the complex amplitude scattering:

$$E_n(t) = P_n(t) \sum_{k=0}^{K} a_{nk}(t) e^{-j(\phi_n + \frac{2\pi}{\lambda}r \cos(\alpha_n))}$$  \hspace{1cm} (2.13)
where, $P_n$ is the attenuation constant, $K$ is the maximum number of $k$-th waves (Porcino (2001) uses $K$ less than 100), $a_n$ is the amplitude, $\phi$ is the phase angle, $\lambda$ is the wavelength, $v$ is the velocity of the mobile phone, and $\alpha_i$ is the angle relative to user’s movement.

Rappaport et al. (1996) mentioned with NLOS, the accuracy of location estimation is further reduced. Thomas et al. (2001b) and Wylie & Holtzman (1996) indicated that for time difference measurement obtained from NLOS BSs, range error around 400 m greater than LOS is possible whereas in LOS, the performance is accurate.

### 2.5.2 Review on Navigation, Tracking and Road Map Matching

Several techniques for navigation and tracking services have been explored using Kalman Filter by Nypan et al. (2002) and Wann et al. (2002). For tracking, Kalman Filtering also requires the calculation or measurement of noise, state transition, and pattern of speed changes (acceleration). Thomas et al. (2001a) uses scatter information and ray tracing information to determine location estimation through AoA and TDOA, while tracking of location is improved with Kalman Filtering.

GPS receivers such as by Garmin’s Nuvi 710 Satellite Navigator (Anon 2008c) also come with navigational software to assist in reaching final destination by guiding which turn to take on the displayed road map and describing the shortest path. Forssell et al. (2002) introduces a novel vehicle navigation technique by installing sensors on wheels of cars with mapping software to determine/navigate vehicle’s location. In order to increase accuracy, integration of GPS (satellite measurements) and/or GSM (network positioning) devices are required. In Malaysia, Thong et al. (2007) uses GPS and GSM network for fleet tracking, where GSM network provides the positioning of vehicles when GPS’s inability to acquire measurements. For indoor tracking, Radio Frequency Identification (RFID) tags are used (Schiller & Voisard 2004) to track movements of objects within retail stores.
Schiller & Voisard (2004) describe a few road map matching techniques that could be used to estimate travelling paths if some of the coordinate points are known. Rigaux et al. (2002) describes the usage of Geographical Information System (GIS) database for relating objects (roads and buildings) to the acquired location coordinates, and calculating distances between road points, lines, searching paths and others. Basically, the complexity of each technique to relate GIS information or contents to estimated location should not be the major cause for slower response of the LBS information, such as searching for the nearest petrol station. Several mapping software, online maps and road direction finder are available in the market or internet, such as MapInfo (Anon 2008j), Google Earth (Anon 2008k), Google Maps (Anon 2008l) and Yahoo Maps (Anon 2008m). Digital road maps with street names and other Geographical Information System (GIS) details are also readily available for countries like USA, Canada, Europe, Japan, Hong Kong and Singapore (Schiller & Voisard 2004). JUPEM (The Department of Survey and Mapping, Malaysia) also provides area maps (Anon 2008n) for Malaysia but a more meaningful road/street map is required where data (coordinates of paths, intersections and related information) could be imported and exported easily from mapping coordinates to location estimation algorithm.

Therefore, a digital mapping tool is required for this research to work with online maps such as Google Map or downloadable mapping software such as Google Earth. Schiller & Voisard (2004) recommended a few attributes that should relate to digital road maps such as road intersection points, street names, road segments, point of interests, zip codes and others. The processing complexities or queries of the digital maps depend on the database design structure or relational tree structures used. Schiller & Voisard (2004) further suggested for navigation and route determination service based on mapping information, the shortest route avoiding areas such as traffic congestion, toll booths, and U-turns, could be presented to users.

2.5.3 Location Estimation using Received Signals of Cells

Techniques of matching received signals of BSs with captured stored signals are referred to as RF fingerprinting (Rao & Siccardo 2001), DCM (Ahonen & Laitinen
2003), RSS signature (Zhu & Durgin 2005, and Zhu 2006) or pilot correlation (Borkowski & Lempiainen 2005). When more data on signal strengths’ received levels from corresponding cells are stored, the higher the accuracy of matching becomes. Hence this will improve the accuracy of location estimation when a fingerprint stored sample pertaining to a location, consists detailed information from more neighbors to be compared to currently measured signals’ levels. For DCM in UMTS, Ahohen & Eskelinen (2003) produced simulation using algorithm (Ahonen et al. 2002) developed in Matlab for urban environment, with results of 67% location error within 25 m and 95% error within 188 m. DCM in UMTS compares receive power delay profiles to the ones stored in the database. The sample in database that has the highest correlation coefficient (closer to 1 indicates better matching) to the measured power delay profiles, is selected as the best estimation of the mobile location based on the sample’s stored location coordinate. For trials of DCM in urban GSM network, Laitinen et al. (2001b) reported 67% location error at 44 m and 90% location error at 90 m. Kemppi (2005) reported in dense Finland (Helsenki), DCM for UMTS with average of 2.2 hearable sites produced 67% location error at 96 m and 95% error at 450 m, while DCM for GSM produced 67% error at 77 m and 95% at 274 m. Weiss (2003) uses 50 m grid spacing to collect RSS measurements, and examined accuracy using Cramer-Rao bound, Circular Error Probable (CEP), concentration ellipse and other methods, but reported RSS could not meet location accuracy requirements for FCC E911. Weiss (2003) mentioned that previous literature do not provide detailed analysis on control channels and mobile to BS geometry. When there are only two BSs in GSM network available for measurements, Lin et al. (2004) uses the attenuation difference between the two BSs’ to estimate location that produced 67% error within 190 m and 95% error within 315 m in urban Taipei. However in suburban, the reported simulation results worsen when cells are larger. RSS matching is not only known in cellular but also used extensively to estimate indoor location through fingerprints of signal levels received from WLAN’s Access points (WLAN’s base stations). Martinez et al. (2004), Nerguizian et al. (2004), and Roos et al. (2002) determined indoor location using various techniques, such as using neural networks. Artificial Neural Networks’ (ANN) capabilities of performing various training methods on data sets, learning rules and prediction rules have made it popular for many types of engineering and scientific research. Salcic (2001), Salcic &
Chan (2000), Takenga & Kyamakya (2007), and Muhammad (2007) use the various neural network (NN) capabilities to assist (such as training data of RSS) in the process of location estimation of cellular users.

In the next chapter, SCM is introduced by matching GSM and UMTS RSS level of only serving cell to stored signal levels within UIPS’s database, in order to estimate mobile location.

2.6 SUMMARY AND COMPARISONS OF CURRENT LDTs

Table 2.1 presents the summary of all the currently available LDTs, their complexity to be configured in network or phone, their accuracy, their usage (emergency, navigation, LBS) and the processing time (PT) to estimate (measure and calculate) user’s location. All 3GPP listed LDTs relies on network’s control (network based positioning) except for, phone based Cell ID (stand-alone phone LDT), phone based GPS (stand-alone phone LDT), and DCM (non 3GPP LDT) that requires modifications to network and base stations. AoA is only mentioned in 3GPP and for UMTS Time Division Duplex (TDD) but no functional specification is provided yet for UMTS FDD. Even though the 3GPP standards are implemented within the network, it is up to the individual Telco to employ phone based estimation or phone assisted estimation. For phone assisted estimation, measurements done at the phone will be sent to SMLC. In Location Server, the phone measurement along with SMLC’s acquired information of the participating BSs’ coordinates, timing difference, clocking difference and other related information are used to calculate and estimate the mobile location. For phone based estimations, the network will send participating BSs’ location coordinates, timing difference, and clock synchronization information to the phone. The phone will then calculate the estimated user location from network’s information and from its own measurement. Phone based estimations require more complex computations, and require software installation. As seen in Table 2.1, Cell ID method is the simplest and the easiest to install but its accuracy is poor. Also, strongest signal does not really mean it is the nearest cell to the phone. Cell ID is only suitable for area based services or when determining proximity of user’s location. The
Table 2.1 Comparisons of current LDTs complexity, accuracy, usage and PT

<table>
<thead>
<tr>
<th>LDT</th>
<th>Complexity to Configure</th>
<th>Accuracy</th>
<th>LBS/Application</th>
<th>Processing Time (PT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell ID (GSM/UMTS) -3GPP Network Based</td>
<td>Simple- Network uses BS’s cell information to obtain proximity of mobile location, such as MS’s serving cell.</td>
<td>Low accuracy – 200m (microcell) to 10km (rural or large cell size). With RTT (3G) and TA (2G), accuracy could be improved</td>
<td>area information, area broadcast, area assistance, area group chat, area promotion, and weather services.</td>
<td>1 s to estimate mobile location</td>
</tr>
<tr>
<td>Cell ID (GSM/UMTS) -Phone Based -no network signaling involved</td>
<td>Simple- Need software to read the Cell ID of the mobile and compute against phone database or send to server that has latest stored information of Cell ID and BS coordinates. Can work in idle or busy mode.</td>
<td>Low accuracy – 200m (microcell) to 10km (rural or large cell size). -Must get latest database updates from Telcos</td>
<td>area information. CP specific information (depending on who owns the location server)</td>
<td>1 s or &lt; 3 s if need to send measurement via data bearer to server.</td>
</tr>
<tr>
<td>E-OTD (GSM) -ETSI and 3GPP</td>
<td>Medium- Telco need to implement LMU in network to synchronize clocking and timing measurements. Software at phone required.</td>
<td>Medium to High accuracy- 50m (good Los) to 300m (bad LOS). -Need at least 3 BS. -Can use TOA if BTSs transmissions are time stamped.</td>
<td>emergency, navigation, tracking, road assistance, and higher accuracy LBS services</td>
<td>&lt; 5 s</td>
</tr>
<tr>
<td>OTDOA (UMTS) or OTDOA IPDL -3GPP</td>
<td>Medium- Telco need to implement LMU in network to synchronize clocking and timing measurements. Software at phone required.</td>
<td>Medium to high accuracy- 50m to 300m. -Better accuracy in LOS or rural. -Need at least 3 BS. -OTDOA IPDL is used to increase hearability ≥ 3 BSs</td>
<td>emergency, navigation, tracking, road assistance, and higher accuracy LBS services</td>
<td>&lt; 5 s</td>
</tr>
<tr>
<td>uTDOA (UMTS) -3GPP -Could be installed for GSM also</td>
<td>Medium- Telco need to implement uTDOA LMUs in network to synchronize and measure uTDOA. Measurements are sent to Location Server. No software required for phone.</td>
<td>Medium to High accuracy- 50m to 200m -Slightly better accuracy than downlink TDOA as UE uplink TDOA is detected in BSs. -Need ≥ 3 BSs.</td>
<td>emergency, navigation, tracking, road assistance, and higher accuracy LBS services</td>
<td>&lt; 5 s</td>
</tr>
<tr>
<td>AoA (UMTS) -Not fully specified in</td>
<td>Medium – Telco need to implement smart antenna in network that</td>
<td>Medium accuracy- 100m to 2km (when LOS is bad).</td>
<td>navigation, tracking, road assistance, and medium accuracy</td>
<td>&lt; 5 s</td>
</tr>
</tbody>
</table>

Continue…
PT to calculate one estimation is less than 1 s. Cell ID stand-alone LDT and GPS phone based LDT, does not depend on Telco’s signaling and could be employed directly by CPs. TDOA (time difference of arrival) LDTs such as E-OTD, OTDOA and uTDOA are reliable but require good line of sight (LOS) and this may not always be possible in dense urban areas. Furthermore, Telcos need to invest, install, and maintain many LMUs within their network. AoA is suitable for network based LDT because the complexity of calculations could be measured in the network with receiver antenna installed at stations to measure the arrival of rays, rather than having complex measurement at the phone. Currently, A-GPS is the most accurate of all the positioning LDTs (at least 30 m of accuracy in urban). But it requires A-GPS phones to be bought by users if users want to benefit from this LDT (Kupper 2005).

Source: Zeimpekis et al. 2003, and Kupper 2005

<table>
<thead>
<tr>
<th>3GPP Based</th>
<th>measure arriving angles, timing info and related information. Phone measurement is possible but not practical.</th>
<th>LBS services</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS Phone Based LDT (regardless of cellular system)</td>
<td>Simple-Receiver built in with phone can readily estimate location</td>
<td>High accuracy 10- 150m. Urban ≥ 30 m. -Need LOS of TOA from GPS satellites -Can not work indoor or bad LOS.</td>
</tr>
<tr>
<td>A-GPS (GSM/UMTS) -3GPP</td>
<td>Medium-Telco need to install AGPS receiver units at base stations and users have to get AGPS phones</td>
<td>High accuracy-10m to 150m. -Need LOS of GPS satellites but may work indoors using network’s assistance</td>
</tr>
<tr>
<td>DCM (finger printing)</td>
<td>Medium-Require to construct database on measured points, with related cells’ signal strengths and multipath power delay profiles.</td>
<td>Medium to High accuracy-50m to 500m. -The more BSs measurements, the higher accuracy of fingerprinting LDT. -Stored data must be latest.</td>
</tr>
<tr>
<td>Non 3GPP standard (GSM/UMTS)</td>
<td>Minor software changes to Node B.</td>
<td></td>
</tr>
</tbody>
</table>

| Source: Zeimpekis et al. 2003, and Kupper 2005 |
could also work indoors with the assistance of cellular network’s LDTs such as utilizing the combination of (hybrid LDTs) Cell ID and RTT’s location estimations.

2.7 CONCLUSION

In this chapter the currently available LDTs for location estimation, implementation issues on TDOA location estimations, navigation services, tracking services, road map matching techniques and received signal LDT were presented. In addition to literature review, site survey on cell identification performed in year 2004 for Kuala Lumpur (KL), followed by pre-analysis of numerous drive test data provided by Telco in 2006 encouraged the development of various LDTs for this research. This is because in order to develop UIPS’s intelligent decision making criteria to select the best LDT pertaining to LBS or emergency service requested within an area, improved timing techniques, SCM and various predictors are required to be developed. Furthermore, Ahonen & Eskelinen (2003) reported that when multipaths are high, TDOA’s 95% location estimation could be around 467 m, which will not meet FCC’s location accuracy requirements. Therefore, timing estimation techniques need to be further improved. A new technique called SCM (using RSS of only one BS) is required to be developed to estimate location when TDOA hearability is one, and to check TDOA’s estimation when multipaths are high. Another motivation/requirement of developing SCM is due to preference by our Telco partner to use only existing signaling information of radio network (Cell ID and RSS) without requesting extra location measurements. For network based positioning (network based LDT) using SCM, no network modification and no additional location measurements are necessary: only serving cell’s information would be used. For phone assisted estimation/LDT (phone measurement) using SCM, the calculation for location estimation could be done in UIPS (or any Location Server) without interrogating Telco’s signaling.

In the next chapter, the research methodology will be described, followed by the development of timing LDTs based on geometric circles and faster computations (PT) to estimate locations in known and unknown LOS environments. Enhanced timing technique using road map matching for hearability of less than three BSs, road map suited for our research, and SCM will be also be described in details.
CHAPTER III

METHODOLOGY

3.1 INTRODUCTION

In this chapter, the data collection process within Klang Valley will be covered, where one of the selected urban-suburban areas will be used in most of the simulation cases in the next chapters. The process involved to analyze data collection, to develop LDT for time measurements, to develop LDT for signal correlation of one hearable cell, to develop UIPS LDT module simulator, and to test any further developed LDT before a new LDT is integrated as part of the UIPS LDT module, will be discussed.

Two new techniques for UIPS will be developed for location estimation based on Time of Arrival (TOA) and Time Difference of Arrival (TDOA). These two techniques which are called Close Circle Correlation 3 Circles (CCC) and Newton Raphson 3 Circles (NR3C) will be used to solve simulated TDOA (in Chapter 4) based on the collected data within Klang Valley. The simulation for TDOA (such as OTDOA) will focus on two classifications of environment models: known Line of Sight (kLOS) and unknown Line of Sight (uLOS). During the data analysis stage, certain areas time delay’s with respect to arrival of signal from surrounding BSs will be calculated, measured or surveyed. The surveyed data will be entered into a database. Data for those areas or zones with known time delay or known multipath propagation delays will be classified as kLOS and with unknown multipath time delays will be classified as uLOS. Even if the LOS between BS and MS is very good, it is still required to calculate or predict the kLOS and populate the area information accordingly, as will be discussed in the later sections of this chapter. For uLOS environment model, three averaging techniques and one comparator are further
developed from CCC and NR3C: CCC Averaging estimator, First Mean NR3C estimator, Random Search Mean NR3C estimator, and Best Comparator.

When hearability is achieved from two BSs (Base Stations of GSM or UMTS), and the target being located is on the road or walkpaths, modified CCC and modified version of NR3C will be adapted to estimate location for time measurements received from only two BSs. The assistance of maps, road networks or walkpaths will be used to further refine the prediction of the targeted UE/MS’s location. Simple Mapping Technique with Table Look Up (SMTTLU) is developed for defining Telco’s Location Services’ coverage maps rather than area maps, storing data for drive test routes and for providing Navigation Based Services (NBS). Best Route Determining Technique (BRDT) is also developed for LBS and NBS. With the meaningful and related LBS best route/road map, Minimum Best Road Comparator (MBRC) and Genetic Algorithm Comparator (GAC) could be used with modified CCC or modified NR3C to predict locations along roads when hearability is limited to two BSs.

When hearability is only limited to the serving cell (one unique BS only), time of arrival from the serving BS is used along with the road coordinates (could also use stored walkpaths information) in order to estimate the outdoor UE/MS location. The developed LDTs along with the predictions models when hearability is one, two and three, will be simulated and evaluated in Chapter 4. All simulation result’s performance will be compared with FCC E-911 location accuracy requirements: 67% location estimations’ accuracy should be within 100 m and 95% location estimations’ accuracy should be within 300 m. Processing Time (PT) to estimate mobile user’s location will also be compared between the LDTs.

A new technique called SCM is developed by matching UE/MS Received Signal Strength (RSS) level of one UMTS/GSM cell (serving cell of a BS) to stored signal levels within UIPS’s database, in order to estimate mobile location. New learning techniques called Learn Another (LEAN), Unique Sample (US), and Unique Sample Undefined Collection (USUC) are developed for different environment (urban-suburban and larger cell area). SCM with the three different learning techniques will be simulated and presented in Chapter 5. Figure 3.1 summarizes the
entire methodology of this research: process to collect, analyze data, develop simulator to test new LDT based on timing measurements of OTDOA (UMTS), E-OTD (GSM), enhanced timing technique and signal strength correlation method, test LDT’s accuracy with FCC E-911, and integrate improved LDT as part of the UIPS’s LDT module.

Figure 3.1 Entire Methodology of the research

3.2 DATA COLLECTION PROCESS USING DRIVE TEST EQUIPMENT

Since this LBS project was a collaboration work between Telco and the university, the data collection process was conducted by Telco’s personnel and our research team. The equipment used for drive test is:
1) A laptop installed with commercial software (Nemo Technologies).
2) Test receivers/scanners or test phone connected to the laptop. Two test phones (two Nokia phones) were used for the data collections. One phone to collect UMTS measurements in active mode and the other phone will simultaneously collect GSM measurements in dedicated mode for the same drive route.
3) Outdoor GPS receiver mounted on top of Telco’s car and its USB cable connected to the laptop.
4) A calibrated Map such as MapInfo (Anon 2008j) was preinstalled with the coordinates of the BSs (Node Bs for UMTS and BTSs for GSM) before beginning the drive test. The antenna directions and beamwidth was also entered in the software.

Figure 3.2 shows the drive test equipment and the laptop display during the drive test of planned routes.

**Figure 3.2 Drive test equipment used for recording measurements**

Before the test began, the map was calibrated with the GPS receiver. Other factors beyond control of drive test such as unclear sky or NLOS of satellites (under overhead bridges or in tunnels) could also affect the accuracy of GPS receiver. The
GPS will collect the coordinates (longitude, latitude and geodetic height) for every interval when measurements are made. Each measurement interval is less than 1 second for every type of measurements: such as Neighbor list (NLIST), Energy per chip divided power density in the band (ECNO), Location Update Attempt (LUA), Timing Advance (TAD), Receive Level (RXL), Enhanced Receive Level (ERXL) and others (Anon 2005b). The drive test also provide the signaling events for Layer 2 uplink and downlink, Layer 3 uplink and downlink, Radio Resource Connection Success uplink and downlink, RLC uplink and downlink, LLC uplink and downlink and MAC uplink and downlink. In scanning mode (idle), the drive test equipment is also able to scan for delay spread (DSCAN) for UMTS BS and delay (DELAY) of time between the first peak of CPICH and the last peak above PN (chips) threshold of the UMTS BS channel that is being measured. For every measurements of a new route, GPS coordinates with distance from the beginning of the measurement, number of GPS satellite visibility and type of measurements are recorded line by line as stored in the log file. Each log file could be for one route or for defined time duration. Our drive test routes were done on 20th November 2007 for GSM and UMTS according to the classifications of area (metropolitan, urban, suburban, highway, university campus, and rural areas) within Klang Valley:

1) Jalan Tun Razak, Ampang Park, Menara Maxis, Kuala Lumpur City Center (KLCC), Mandarin Oriental Hotel till Bukit Bintang (Metropolitan).
3) Plaza Phoenix, Cheras-Kajang Toll Highway, Cheras Mile 13 Sungai Sekamat, Kajang town, Jalan Reko till UKM Train Station (Suburban-Rural). Some parts of Cheras Mile 13 and Jalan Reko towards UKM are classified as rural.
4) Bangi Toll till Sungai Besi Toll Highay (Interstate North South Highway).
5) Within Universiti Kebangsaan Malaysia (UKM Campus).
6) Sg. Besi Toll, MidValley Mall to PJ (Federal and City Highway).

Extensive rural route environment was unavailable within the Telco’s vicinity to test, and therefore parts of Cheras Mile 13 Sungai Sekamat and some parts of Jalan Reko towards UKM were used for rural data case study while Kajang town center was considered as suburban. Routes metropolitan and urban-suburban were repeated three
times (start to end, end to start and finally start to end). For example route urban-
suburban, the starting point was Menara Celcom (urban) and the ending point was
Wangsa Melawati (suburban). After ending the drive at Wangsa Melawati for trial 1,
the measurements for trial 2 of a new log file started. Trial 2 was from Wangsa
Melawati to Menara Celcom and finally a new file of measurements for trial 3, from
Menara Celcom to Wangsa Melawati was created. This route is of interest since the
data obtained for measurements in July 2006, from Menara Celcom to Wangsa
Melawati for UMTS measurements, could be compared. The intention is to observe if
there is any environment or Telco’s configuration changes within the period of sixteen
months on the same route area. In general, each time stamped file will consist of one
route of a route. But in the event the active connection for GSM or UMTS drops, drive
 testers quickly have to re-establish both the calls and open a new file. If this happens,
each individual files have to be combined so that it becomes one complete file for one
route. An example of drive test raw data file for GSM is shown in Figure A.1 (refer to
Appendix A) and for UMTS is shown in Figure A.2. Figure 3.3 shows one of the
examples of the route, route urban-suburban which will be used as the main example
of urban-suburban route throughout this chapter. After all the drive test routes
(metropolitan through highways) were completed, the data files were ported to a
computer in Telco’s premises that has the commercial Radio Network Planning (RNP)
Tool. At this stage the data is ready to be analyzed.

3.3 ANALYSIS OF DRIVE TEST DATA

Some RNP allows the flexibility to choose the propagation models or combination of
propriety software’s model with well known modified models such as Hata, UMTS
vehicular or pedestrian model. For our drive tests, propagation models used by Telco
were based on the propriety’s model to predict the GSM and UMTS coverage. For
GSM as shown in Figure A.3, Received Signal Strength Indicator (RSSI) values will
be used to represent the coverage area’s signal strength: green color showing the best
coverage, yellow moderate and red being the lowest signal received. For UMTS, the
coverage prediction is shown in Figure A. 4. Receive Signal Code Power (RSCP) will
be used to represent the coverage area’s signal strength with dark green showing the
best and dark blue showing the worst signal received. According to experience, using
Figure 3.3  The yellow line indicates the urban-suburban route (from Menara Celcom to Wangsa Melawati)

Source: Kuala Lumpur Map from Mapinfo (Anon 2008j)

propagation models alone with some surrounding roads’ drive test data cannot fully suffice the requirements of representing a bigger coverage area prediction accurately. Statistical models should not be based only on empirical propagation models, BTS coordinates, antenna information, power transmits, but should also take into effect full ray tracing data as observed from each BS. Three dimensions topology area information would be helpful to understand LOS effects, reflections, scattering and other environmental factors. But for this LBS research, a more relevant propagation model will be suggested, that is also suitable to be used for distance prediction based on timing (time-distance relationship) measurements.

3.3.1 Propagation Model for Signal and Time-Distance Prediction

In general two types of environment will be used for time measurements studies. One environment will be based on known LOS (kLOS) where the averages of time delays from each BS are known and drive test have been conducted for the routes (routes mentioned earlier). The other environment conditions will be classified as unknown
LOS (uLOS) where the time delays from each BS are not measured, not calculated, or not approximated and drive test was not done specifically for some or all of those BSs. Sites with uLOS are within the coverage area of urban KL, where some or all of the BSs were not participating during the actual drive test routes. For uLOS area, we will use (to build uLOS model for simulation in Chapter 4) Typical Urban (TU) 12 rays multipath propagation model for GSM and ITU-R vehicular standards for UMTS with 12 ray multipath delays (Tranter et al. 2004). Time of Arrival will consist of real geometric time (actual distance between BS and MS), multipath delays from either of the kLOS or uLOS case, and timing error from phone measurements. Details of error and multipath delays will be discussed in the next sections. For E-OTD measurements, Green & Wang (2002) and Greenstein et al. (1997) suggest RMS time delay spread are based on lognormal MS to BS distance as represented by:

$$\tau_{\text{RMS}} = Td^\epsilon y$$  (3.1)

where,  $T$ is in sec and for Urban A and Urban B GSM, it is 0.4 $\mu$sec, $d$ is distance in km, $\epsilon$ is exponent value with 0.5 (Urban A) and 0.3 (Urban B), and $y$ is lognormal (Gaussian with 0 mean and $\sigma_y$ of 4 dB for urban environment). The basic concept of this equation will be used for building kLOS and uLOS timing measurement prediction models, in the next sections.

In UMTS, Rake receiver, built within an UE can detect multipath signals up to the resolution of one chip or 0.26 microseconds since one frame is 15 slots and equals to 10 ms for 38400 chips (Laiho et al. 2006). The purpose of Rake in UE is to combine signals from different multipath and time delays.

In general, multipath delays are caused by unwanted time delays added to the observed time measured (time from BS to UE/MS). Multipath delays occur when UE/MS is not in the line of sight of BS (BS downlink signals blocked by buildings or structures travel through different and longer paths to reach UE/MS). Figure 3.4 shows the occurrence of multipath caused by the obstruction in the environment. Even UE in LOS may have more than several copies of signals arriving toward it at
different time interval. But it is apparent that the most dominant signal is from the LOS path as compared to the reflected signal. Signals from BS not in LOS (NLOS) to UE will travel through different means to reach the UE. Fading in the environment also add uncertainty to the signal strength of the received UE. For example, fading effects in indoors might be around 12 dB and for outdoors around 5 dB (Laiho et al. 2006). Fading is one major reason why prediction of coverage by RNP tools requires model tuning and adjustment to parameter’s values corresponding to the area’s environment factors.

A propagation model prediction almost similar to Porcino (2001) for RSSI or RSCP was used for all the drive test routes. The equation for the RSSI prediction (or for path loss), \( \text{RSSI}_{\text{Pred}} \) (in dBm) versus distance is as following:

\[
\text{RSSI}_{\text{Pred}} = a \log \left( \frac{x}{1000} \right) + c
\]  

(3.2)

where, \( x \) is distance in meters, \( a \) and \( c \) are the non linear curve fitting/tuning factors that are required to predict the model for each Node B’s sector (Cell ID). Prediction is
done using Matlab’s non linear least square data fitting function that utilizes Gauss-Newton technique (Anon 2008h). Matlab, a programming language with toolbox, was used for all programming work, analysis, simulation, development of LDT prediction models, and development of LDT module for this research.

In UMTS, 3G wideband RSSI (in dBm) is also recorded during drive test in addition to RSCP. This UMTS RSSI will be the active/serving cell’s RSSI and will be used here to predict \( a \) and \( c \) tuning factors for each cell. The distance \( d \) is also known (could be calculated because the UE coordinate’s are recorded by GPS during drive test and each BS’s coordinates are stored in Telco’s database). After running the Matlab prediction program for all the cell’s that are captured during the drive test routes, each Node B’s cell (sector) produces its own propagation losses as observed by the UE/MS. Figure 3.5 shows an example of Node B cell’s prediction model with fitted \( a \) and \( c \) values \((a = -12.61, c = -92.96)\). The example of Node B with Cell ID number 1076A \((A = 1, B = 2 \text{ and } C = 3)\), is one of the active serving cells along route Menara Celcom to Wangsa Melawati, at that particular time. There were total of 34 UMTS serving cells (with different values of \( a \) and \( c \)) along this urban-suburban route.

![Figure 3.5 RSSI Prediction versus Real values for each UE distance from cell 1076A](image-url)
3.3.2 Extracting ECNO and ERXL Data from Each Drive Test Log File

The sample of each log file for one route was shown in Figure A.1 for GSM and Figure A.2 for UMTS. To study hearability effects, all ECNO measurements for UMTS will need to be extracted from the raw data log file. The same goes for ERXL or RXL for GSM, where the main interests are on the RSSI, Cell ID and other related parameters. For example, raw data file of route urban-suburban (trial 1), there are 5397 measurements made for EXRL between 3.31 pm till 4.02 pm on November 20, 2007. Since the test call was disconnected in between the route, so two files timestamped 3.31 pm and second file timestamped around 3.50 pm was combined as a single route file for the start to end point of the drive test. The data was imported to Microsoft Office Excel format and Matlab program was written to extract the values of RSSI (in dBm) and cell ID. In Figure A.5, for every ERXL measurement (Anon 2005b), coordinates are recorded in longitude, latitude and height. The distance from starting point is also recorded as in column E. The visibilities of satellites in the sky is listed in column G, the speed of the car is listed in column H, the timestamp of each measurement is in column I, and the GSM Band (1 for 900 MHz and 2 for 1800 MHz) is listed in column J. Column K provides the most important information pertaining to how many hearable cell measurements were made. For our LBS research, the number of hearable cells would only be beneficial if there are from unique coordinates or site. If it is 6 hearable cells from the same site, this will not benefit much from the fact it is actually the same BS site. As discussed in the previous chapter, triangulation technique requires at least three hearable unique sites. But knowing the information of this field would enable us to calculate how many measurements of cells (serving and neighbor cells) to expect or help to calculate the last column number for each row. The other important parameters listed and repeated for each hearable or measured cells are Absolute Radio Frequency Channel Number (ARFCN), Base Station Identity Code (BSIC), RSSI, Cell ID, Location Area Code (LAC) and Routing Area Code (RAC). For example, in row 1 and 2, column K indicates that for both rows, there will be seven cell measurements. The Matlab program will calculate the first occurrence of RSSI value and the Cell ID, the second occurrence of RSSI and Cell ID until the seventh (last occurrence) for both RSSI and Cell ID. The pattern of occurrence is predictable. The same procedures follow for rows 3 with 6 cell measurements and row
4 with only the serving cell measurement as shown in the figure. In general, fields with -1, -100 and 255 values indicate the unavailable measured data, not applicable, or the fields are not configured for the corresponding measurements.

For UMTS, as shown in Figure A.6, the pattern of occurrence is not so periodic and is made complicated with softer handovers. For UMTS, the RSSI value for each row of measurement could be obtained from column M. Column O indicates how many active cells are available, followed by the channel number of the first active cell, scrambling code of first active cell (SC A), ECNO value of first active cell (in dB), and RSCP of first active cell. This process is repeated until all the active cell(s) within the row is read. Then the next measured cells are the monitored cells. For example, row 1 through 3 has one active cell and three monitored cells. Monitored cells also have the same sequence as was discussed for active cell: channel number of first monitored cell, scrambling code of first monitored Cell (SC M), ECNO of first monitored cell (dB), and RSCP of first monitored cell (RSCP M). Again, the process is repeated until all the monitored cells within the row are read. Row 4 contains two active cells and two monitored cells measurements, and row 5 has three active cells measurements and one monitored cell measurement. In this example there are no secondary scrambling codes or detected number of cells for measurements. The total number of rows for ECNO type of measurements for UMTS is 2121 rows of file 3.31 pm till 4.02 pm on 20th November 2007. This file is also a single combined file of two different time stamps files for UMTS measurements due to lost of test call mode in the middle of the urban-suburban route during the first trial. The call was quickly redialed to continue on the journey. The second call had a different time stamp to distinguish between unique measurements caused by different time stamps of first call.

To proceed with detail analysis and programming, the information of Cell ID, BTS/Node B coordinates, BSC/RNC, antenna direction, BSIC, Broadcast Control Channel (BCCH), and Scrambling Code (SC for 3G) is required. Figure A.7 shows the sample file for GSM and UMTS which is normally maintained and updated by Telcos. To protect the confidentiality of the Telco partner’s BS, the coordinates, real cell identification and site names have been changed. Figure A.8 illustrates the data analysis and validation process for each drive test route. The analyzed data will be used as the basis for building the simulation model for kLOS: with actual cell’s
coordinates, actual UE locations (as recorded during each drive test route), and hearable cells during each of the UE sample measurements from beginning of route to end of route. The details of hearability report, hearable cell’s distribution of distance to UE along each route, and any other specific analysis for each route will be discussed in Chapter 4 (timing simulation). Another drive test tool that is also widely used by the Telco partner is TEMS or TEMS Investigations (Anon 2008f). X-TEL’s drive test tool (Anon 2008g) was also used by our team to perform measurements within UKM campus area. This usage of different drive test tools was important to observe if any measurement/experiment deviations from Nemo and for the researcher to further understand how data was being logged. Therefore, a generic program could be written for all three drive test’s data format for further processing and analysis purposes using the logged raw data files (as was done for ECNO and EXRL for this LBS studies), if the format of measurements’ field (text file’s column and rows) are known. The next section describes the process for developing the UIPS LDT simulator.

3.4 DEVELOPMENT OF SIMULATOR TO TEST NEW LDTS

After data was collected, it was analyzed and structured in the required format before developing an LDT Simulator. The process to develop a simulator to test new LDT based on timing measurements of OTDOA (for UMTS), E-OTD (for GSM) and signal correlation was shown in Figure 3.1. Referring back to Figure 3.1, Telco data and UIPS data for signal strengths from BS, time delays pertaining to each BS, and maximum delay spread or Root Mean Square (RMS) delay spread is also obtained from databases. The completed data (from drive test survey and stored data) is simulated as a Network Measurement Report (NMR). Example of NMR for cellular network is provided by Heine (1999). For the case to calculate TDOA (OTDOA, E-OTD, uTDOA) measurements, the simulated NMR data, coordinates of the Node B (longitude and latitude or converted to x and y in meters), scrambling code, Cell ID, RNC code, and other information are passed to the new or enhanced LDT to be converted to the distance in meters from each Node B to UE, and then calculating the estimated mobile position. Noises and delay will be added accordingly as per model used (ITU-R vehicular for UMTS, Typical Urban 12 path array for GSM) (Tranter et
al. 2004). For the case to calculate signal correlation, RSCP, RSSI, LAC, RNC/BSC code, and previous stored signal strength information are passed to the algorithm to calculate the estimated location. If the Cumulative Distribution Function (CDF) of error estimation does not meet the FCC E-911 location accuracy requirements, the LDT technique is further analyzed and improved. Then the improved LDT will be simulated again with the same data measurements, same settings and same mean/variance of random timing delays/errors (time delays/errors are used for timing measurement while random signal fading/errors are used for simulation of signal correlation). Once the standard is accepted as per the 67% error and 95% error requirements of US E911 standards, the LDT technique is then integrated into UIPS LDT module.

The details of each LDT development in kLOS and uLOS, and development of prediction models (such as Minimum Best Road Comparator used for road matching when hearability is from only two cells) will be presented in the next sections. Table 3.1 summarizes the developed (new/enhanced/improved/modified) LDTs and prediction models. These LDTs and prediction models will be used to estimate the locations of mobiles when simulated in Chapter 4 (simulation of timing measurements from one, two and three hearable cells) and in Chapter 5 (simulation of signal correlation from one cell). Any improvement to the LDT algorithm will be discussed when evaluating the simulation results’ location accuracy in Chapter 4 and Chapter 5. In Chapter 6, the integrated UIPS’s LDT module’s usage and its decision criteria to choose any one of the LDT (based on hearability report, level of accuracy required, faster processing time and other factors) for LBS application and emergency location search, will be discussed.

**Table 3.1 LDTs and prediction models developed for this research**

<table>
<thead>
<tr>
<th>LDTs/Prediction Model</th>
<th>Usage</th>
<th>Hearability</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCC</td>
<td>Improved LDT (estimator) for timing measurements based on new geometrical technique</td>
<td>≥ 3</td>
</tr>
<tr>
<td>NR3C</td>
<td>Improved estimator (fastest PT) for timing measurements adapted from Newton Raphson numerical methods</td>
<td>≥ 3</td>
</tr>
</tbody>
</table>

Continue …
<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCC Averaging</td>
<td>Enhanced averaging estimator of CCC for timing measurements in uLOS environment</td>
<td>≥ 3</td>
</tr>
<tr>
<td>First Mean NR3C</td>
<td>Enhanced averaging estimator of NR3C for timing measurements in uLOS environment</td>
<td>≥ 3</td>
</tr>
<tr>
<td>Random Search Mean NR3C</td>
<td>Enhanced random averaging estimator of NR3C for timing measurements in uLOS environment</td>
<td>≥ 3</td>
</tr>
<tr>
<td>Best Comparator</td>
<td>New estimator for uLOS to compare CCC averaging’s and First Mean NR3C’s output to a reference point.</td>
<td>≥ 3</td>
</tr>
<tr>
<td>Lg (Distance checker of hearable BSs)</td>
<td>Distance comparator among three BS’s locations: to ensure optimization of CCC, NR3C and uLOS estimation methods.</td>
<td>≥ 3</td>
</tr>
<tr>
<td>L1 (BestGeo, angle checker of hearable BSs)</td>
<td>Angle comparator among three BS’s placements: to ensure optimization of CCC, NR3C and uLOS estimation methods.</td>
<td>≥ 3</td>
</tr>
<tr>
<td>Simple Mapping Technique (SMTTLU)</td>
<td>New road mapping tool and road prediction model to be used along with timing measurements when hearability &lt; 3</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>Best Route Determining Technique (BRDT)</td>
<td>Road prediction and best route proposal technique for Navigation Based Services. The predicted road path will be used as reference road when estimating location.</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>CCC2</td>
<td>Modified estimator of CCC customized for 2 hearable cells. Four estimation points will be generated.</td>
<td>2</td>
</tr>
<tr>
<td>NR2C</td>
<td>Modified estimator of NR3C adapted for 2 hearable cells.</td>
<td>2</td>
</tr>
<tr>
<td>Minimum Best Road Comparator (MBRC)</td>
<td>LDT Comparator to predict one of the four CCC2 points along the most likely travelled (predicted) road.</td>
<td>2</td>
</tr>
<tr>
<td>Genetic Algorithm Comparator (GAC)</td>
<td>LDT Comparator to predict one of the four CCC2 points along more roads within the vicinity of two hearable cells.</td>
<td>2</td>
</tr>
<tr>
<td>RLMN (basic idea adapted from 3GPP)</td>
<td>Enhanced concept (basic idea adapted from 3GPP proposal to use additional location measurement node) with our proposed implementation strategy and finally using CCC or NR3C to assist in location estimation.</td>
<td>2</td>
</tr>
<tr>
<td>OCRAA (UMTS)</td>
<td>Predictor model based on road and RTT of one UMTS cell</td>
<td>1</td>
</tr>
<tr>
<td>M-OCRAIA (GSM)</td>
<td>Predictor model based on road, ToA and previous location information</td>
<td>1</td>
</tr>
<tr>
<td>SCM (LEAN)</td>
<td>New estimator for signal correlation of only one cell with new learning technique (LEAN) for urban areas</td>
<td>1</td>
</tr>
<tr>
<td>SCM (US)</td>
<td>New estimator for signal correlation of only one cell with new learning technique (US) for urban with high fading</td>
<td>1</td>
</tr>
<tr>
<td>SCM (USUC)</td>
<td>New LBS estimator for signal correlation of one cell with new learning technique (USUC) for larger cells (suburban)</td>
<td>1</td>
</tr>
</tbody>
</table>
3.5 DEVELOPMENT OF CLOSE CIRCLE CORRELATION (CCC) TECHNIQUE

CCC is a geometric technique based on finding the best convergence or closest (minimum) point(s) between three circles: Circle 1, Circle 2 and Circle 3, such as point G as shown in Figure 3.6. The radius of each circle represents the distance, $d_i$ (distance is equivalent to time multiply with speed of light, $c$, $3 \times 10^8$ m/s) of each BS (synchronized time of arrival from LMU at Node B to UE) towards UE/MS. The center of each circle is represented by the actual coordinates of BS (x and y coordinates of $b_i$ in meters).

If location coordinates (example BSs’ coordinates) are in longitude (decimal degree) and latitude (decimal degree) conversion to x and y in meters, need to be done or vice versa. Carlson & Clay (2008) provides a detailed formula for this conversion. The scale factor, $k_s$ is used to convert decimal degree to meters (decimal degree multiplies $k_s$ to get meters or meters divide $k_s$ to obtain decimal degree) or vice versa. Based on Earth’s Equatorial radius of 6378.2 km, the scale factor could be approximated as:
Even though CCC technique looks like any geometrical circles but the benefit will be shown in its design and output of simulation result. The main purpose is to create “closeness” or estimation of convergence or approximate intersection of circles in the presence of NLOS delays or caused by multipath time delays (from one BS or all three BSs) where in real life, circles might not fully converged as per theoretical ideal expectations. As shown in the left of Figure 3.6, the objective is to find point G (within the red color region) between the intersection of circles at B, C and E. Points A, D and F are other intersection points between two circles.

Figure 3.7 illustrates the simulation process of CCC technique and how it will be used as part of Figure 3.1 in order to build UIPS simulator (develop CCC Simulator) and to calculate the estimated location based on timing measurements. As mentioned earlier, two types of environment will be used for time measurements studies: kLOS and uLOS. For kLOS, stored delay of BS (or calculated average delay of BS) will be obtained from previously stored survey data. For uLOS, TU 12 rays multipath model for GSM and ITU-R with 12 ray multipath delays (Tranter et al. 2004) will be utilized. For each cell, the Time of Arrival is simulated (Time of Arrival will consist of real geometric time, multipath delays of kLOS or uLOS and small timing error from phone measurement). In the next step of the process, predicted geometric time (approximated Time of Arrival without delays) is estimated. For kLOS, an RMS delay of the cell (BS) or average delay of an area is subtracted from the Time of Arrival. For uLOS, an estimated area delay is subtracted from the Time of Arrival. The formulation of predicted geometric time will be presented in the section that describes uLOS and kLOS environment. Once the geometric time is predicted for each cell (radius of a circle could be determined from speed of light, c multiplied by the approximated Time of Arrival without delays), a Matlab subprogram generates a circle with 360 discrete points. The resolution error between each discrete point called Geometric Error (in meters) is defined as:

\[ k_s = 1000(6378) \times \frac{2\pi}{360} \]  

(3.3)
\[ G_{\text{Error}} = \frac{2\pi(r)}{\text{Res}(360)} \]  

(3.4)

where, \( \text{Res} \), resolution constant is equivalent to 1, and \( r \) is the radius of the circle. Higher \( \text{Res} \) value would reduce \( G_{\text{Error}} \) but at the expense of more discrete points and more computing time.

Figure 3.7  CCC simulation model
Figure 3.8 shows the continuation process of CCC technique to estimate simulated location of mobile based on comparing six points on the circles as illustrated at the right side of Figure 3.6. Throughout this research, distance, $dist$.

Create comparator, C12:
1) $d_{C12} = dist[Circle 1's points, BS2's loc]$
2) $\min(d_{C12}-d2)$ **there could be several min
3) $\min(\min(d_{C12}-d2) points, BS3's loc))$
   $C12=value of this most minimum distance$

Create comparator, C13:
1) $d_{C13} = dist[Circle 1's points, BS3's loc]$
2) $\min(d_{C13}-d3)$ **there could be several min
3) $\min(\min(d_{C13}-d3) points, BS2's loc))$
   $C13=value of this most minimum distance$

Create comparator, C21:
1) $d_{C21} = dist[Circle 2's points, BS1's loc]$
2) $\min(d_{C21}-d1)$ **there could be several min
3) $\min(\min(d_{C21}-d1) points, BS3's loc))$
   $C21=value of this most minimum distance$

Create comparator, C23:
1) $d_{C23} = dist[Circle 2's points, BS3's loc]$
2) $\min(d_{C23}-d3)$ **there could be several min
3) $\min(\min(d_{C23}-d3) points, BS1's loc))$
   $C23=value of this most minimum distance$

Create comparator, C31:
1) $d_{C31} = dist[Circle 3's points, BS1's loc]$
2) $\min(d_{C31}-d1)$ **there could be several min
3) $\min(\min(d_{C31}-d1) points, BS2's loc))$
   $C31=value of this most minimum distance$

Create comparator, C32:
1) $d_{C32} = dist[Circle 3's points, BS2's loc]$
2) $\min(d_{C32}-d2)$ **there could be several min
3) $\min(\min(d_{C32}-d2) points, BS1's loc))$
   $C32=value of this most minimum distance$

Smallest value: C12, C13, C21, C23, C31 or C32?

The smallest comparator value is chosen and its corresponding location coordinate will be the final convergence point: estimated location of mobile.

End

- Circle 1 has 360 points.
- Several minimum occurs at intersection between Circle 1 and Circle 2.
- Choose one minimum point that is the closest to BS3’s location.
- Record this point as C12.
- Repeat for all comparators: C13, C21, C23, C31 and C32.
- $dist$ used here is Euclidean distance for comparison.
- $d1$ is radius Circle 1, $d2$ radius Circle 2 and $d3$ is radius of Circle 3.

Figure 3.8 CCC simulation process and technique to estimate mobile location
would be used to compare the closeness metric between two coordinate points such as point \( a \) and \( b \), and is represented as:

\[
dist = \sqrt{(a_x - b_x)^2 + (a_y - b_y)^2}
\]  

(3.5)

where, point \( a \)’s coordinate is \((a_x, a_y)\) and point \( b \)’s coordinate is \((b_x, b_y)\). To determine each comparator point, such as for \( C_{12} \), Circle 1’s 360 discrete points with respect to Circle 2, the following steps are performed:

1) Calculate the distance for each of the 360 points of Circle 1 from BS2’s coordinate point.

2) Subtract radius of Circle 2’s value from each distance values obtained from above, and then find several of the minimum values. These minimum values indicate the intersection points, but the objective is to find the common intersection point for all three circles rather than just between Circle 1 and Circle 2.

3) Therefore, compare the distances between these few minimum points to BS3’s coordinate point.

4) The smallest value (the closest to BS3) of these minimum points is designated as the comparator point, \( C_{12} \).

5) Repeat this process for \( C_{13} \) (Compare Circle 1’s 360 points with respect to Circle 3), \( C_{21} \) (Compare Circle 2’s 360 points with respect to Circle 1), \( C_{23} \) (Compare Circle 2’s 360 points with respect to Circle 3), \( C_{31} \) (Compare Circle 3’s 360 points with respect to Circle 1), and \( C_{32} \) (Compare Circle 3’s 360 points with respect to Circle 2).

6) The six comparator points’ values are finally compared, and the one with the smallest value is selected as the best (convergence point) predicted location of mobile.

A final Cumulative Distribution Function (CDF) plot should indicate the accuracy levels between estimated simulated samples’ locations versus the real mobile locations (from drive test route). CCC algorithm was also verified (checked) and tested with
zero time delays (Time of Arrival is Geometric Time) in order to obtain the optimum accuracy based on $G_{Error}$ under ideal situations.

### 3.6 DEVELOPMENT OF NEWTON RAPHSON 3 CIRCLES (NR3C)

Newton Raphson 3 Circles (NR3C) is developed as another improved LDT estimator to solve TDOA timing measurement using numerical computations. As discussed in the previous chapter, timing trilateration (time triangulation of three BSs) requires solving three BSs’ circles or solving two pairs of hyperbolic equations (Kupper 2005) that are obtained from timing measurements of three BSs.

Through experience, faster response time (feedback time of customer’s request for information) for any Telco related informational services is very important to ensure its success factor, and therefore an algorithm’s processing efficiency and processing time (PT) were considered before deciding which method could optimize and solve non-linear equations, the fastest. Agarwal & Sharir (1998) presented a few algorithms based on geometric optimization. Finally, Newton Raphson was chosen due to its efficiency in solving non-linear equations with its faster convergence characteristics (Coleman & Li 1994). Grosan & Abraham (2008) mentioned that there are a few Newton’s method and Newton Raphson converges fast but requires a good initial guessing point to ensure successful convergence. Studies of how to adapt Newton Raphson’s method to solve any time triangulation problems was carried out. And with adaptation to it function $f(x)$, it is expected to solve any non-linear triangulation problems such as E-OTD, OTDOA or uTDOA. Therefore, this timing based location estimation method is referred to as Newton Raphson 3 Circles (NR3C) when measurements are obtained from at least three BSs/LMUs. Yang et al. (2005) and Kiusalaas (2005) explain the derivation of Newton Raphson equations and provide examples of how to program (code) in Matlab. The derivations and equations (Equations B.1 through B.4) are attached in Appendix B.

For OTDOA measurements from each of the Node B’s LMU, UE can measure $OTD$ with SFN and chip information (3GPP 2007d) such as:
\[ OTD = T_{\text{RXCPICH}_j} - T_{\text{RXCPICH}_i} \]  

(3.6)

where, \( T_{\text{RXCPICH}_j} \) is the time when one primary CPICH slot arrives at UE from cell \( j \), and \( T_{\text{RXCPICH}_i} \) is the time when one Primary CPICH slot arrives at UE from cell \( i \). In idle mode, \( OTD = T_{\text{RXSFN}_j} - T_{\text{RXSFN}_i} \) is used, where \( T_{\text{RXSFN}_j} \) is the time UE received beginning of P-CCPCH (Primary Common Control Physical Channel contains broadcast information) frame from cell \( j \), and \( T_{\text{RXSFN}_i} \) is the time UE received beginning of P-CCPCH frame from cell \( i \).

Let’s say, \( T_{Ai} \) is time of arrival calculated from Node B_i (cell_i) and \( T_{Ai} = T_{Gi} + T_{Di} \) where, \( T_{Gi} \) is the geometric time (actual distance) from Node B_i, and \( T_{Di} \) is the time with delay from Node B_i. Using survey data for the estimated quadrant area, and knowing the cell ID, the stored Node B_i average time delay, \( T_{Di} \), could be subtracted from the total time of arrival, \( T_{Ai} \) (similar concept as in CCC). After this step, we can calculate the approximated (predicted) geometric distance, \( d_i \).

Now we define the 2 pairs of hyperbolic equations. The first pair is time difference observed between BS_2 to BS_1 (time difference converted to distance difference) and the second pair is the time difference between BS_3 to BS_1. Finally, the function, \( f(x,y) \) for NR3C is defined as Equations (3.7) and (3.8):

\[
\begin{align*}
  d_2 - d_1 &= \sqrt{(x - x_{b2})^2 + (y - y_{b2})^2} - \sqrt{(x - x_{b1})^2 + (y - y_{b1})^2} \quad (3.7) \\
  d_3 - d_1 &= \sqrt{(x - x_{b3})^2 + (y - y_{b3})^2} - \sqrt{(x - x_{b1})^2 + (y - y_{b1})^2} \quad (3.8)
\end{align*}
\]

where, \( x_{bi} \) is the x coordinate of BS_i in meters and \( y_{bi} \) is the y coordinate of BS_i in meters. Inserting \( x \) and \( y \) into Equation (B.4), and with 2 equations and 2 unknowns, the final estimated UE=\((x,y)\) in meters could be obtained after several iterations of substituting incremental corrections of \((x,y)\) into Equation (B.4). Figure 3.9 illustrates NR3C method. Initial point of \( x=0 \) and \( y=0 \) will be used as first guess for NR3C. The initial coordinate point of \((0,0)\) is chosen as the best guess point due to the fastest convergence (fastest PT to find each location estimate) observed after performing
Figure 3.9 NR3C estimation method

1. Develop and simulate NR3C

2. Obtain BS locations SC, Cell ID from Telco DB

3. Obtain previous stored delay averages for each BS used

4. Multipath kLoS or uLOS?

5. Generate random Multipath, (GSM TU, 3G use ITU-R)


7. From 3 BS Time Arrival?

   a. No

   b. Yes

      i. Predict Geometric Time = TOA - Delay (approx RMS delay of the cell or area delay)

      ii. Timing Error is assumed negligible

      iii. Substitute x and y into Eq B.4 and solve for Δx and Δy at every iteration

      iv. For first iteration use x = 0; y = 0

   c. New x and y for each iteration is obtained when Δx and Δy is added to current (x, y) value.

   d. The final iteration’s (x, y) output is the estimated mobile location

   e. End

Repeat to get at least 3 BSs Time of Arrival or obtain 2 pairs of hyperbolic time differences.
several experimentations on NR3C. The details and comparisons of PT for NR3C and other LDTs will be discussed in the next chapter (simulation and results for timing measurements). Maximum iteration is set at 60 (this value is sufficient based on our trial experimentations on NR3C) and tolerance is set at $2.2204 \times 10^{-12}$ (value proposed by Kiusalaas 2005). Iteration is terminated if either tolerance is reached first or maximum iteration.

Both CCC and NR3C methods will be the basis of estimating location from timing measurements for this research. But when hearability is less than three BSs, several combined LDT prediction models will be used along with the modification to these two methods and will be discussed further in the later sections of this chapter. In the next section, for uLOS environment model, three averaging techniques and one comparator estimator are further developed from CCC and NR3C.

### 3.7 AVERAGING OF CCC AND NR3C TECHNIQUES FOR ULOS

As mentioned earlier, kLOS and uLOS are two classifications of environments that will be used for simulating time measurements of three BSs. This section describes kLOS, uLOS environment and averaging techniques developed for uLOS.

#### 3.7.1 kLOS Environment

For kLOS model, when the LOS/NLOS information was observed, measured, predicted or calculated for the drive test routes, the environment is classified as known environment. The averages of delays could then be subtracted from the total time of arrival. Time of Arrival can be represented as:

$$T_A = T_G + T_D + T_E$$  \hspace{1cm} (3.9)

where, $T_A$ is the time of arrival (observed by MS/UE for downlink TDOA or observed by LMU/BS for uplink TDOA), $T_G$ is the actual geometric time-distance relationship between actual BSs and MS/UE, $T_D$ is the time delays caused by multipaths and reflections and $T_E$ is the timing error caused by inaccuracy introduced by LMUs.
related to synchronization between BSs, MS/UE’s internal clocking difference, and measurement error’s accuracy to observe SFN time difference.

If LMUs are accurate and BSs’ drift are audited and corrected regularly, $T_E$ value would be small as errors would only be contributed by the measurement’s ability to measure accurately (such as UE measurement error within UMTS chips for OTDOA). On the other hand, $T_D$ value would be larger, in the order of fractions of micro seconds. Cong & Zhuang (2005) used survey data pertaining to each area’s time of delays. Therefore, $T_G = T_A - T_D$, and when $T_D$ could be averaged (corrected and subtracted) over a particular grid area (a grid size of 100 m by 100 m), then $T_G \approx T_A$.

To elaborate this concept, we could take the example of drive testing on a given route, let say route $A$. Before starting the drive test on route $A$, the phone should be equipped with GPS or A-GPS. As soon as the drive test starts, OTDOA measurements are requested every 5 seconds and stored in the UIPS server along with the same GPS coordinate measurements captured for that time interval. Once the drive test is completed for route $A$, the OTDOA results are compared along with the GPS estimations (assuming GPS measurements provides real UE locations and OTDOA provides estimated UE locations). Time of arrival from each BSs (at least 3 BSs are required for measurement of each location estimate) at that particular locations are compared with their geometric time. Using NR3C method, we can also recalculate the real $d_1$, $d_2$ and $d_3$ for each location and could determine the approximated $T_G$ (for OTDOA measurements) assuming $T_E$ is very negligible (almost 0). But this fitting approach (determining stored previous delay values for current/future estimation) is not reliable all the time, since we do not know if future user will take the same road, or is walking “around the area” or if different sets of three BSs are hearable for the same locations. Due to all these uncertainties, the BS’s signal strengths and propagation’s distance should be tagged to the delay calculations. But again, fading causes uncertainty to the propagated received signal.

By initially offering large LBS service through A-GPS by Telco, and OTDOA measurements running in the background, wider combinations of different BSs’ timing measurements could be analyzed and stored for future OTDOA use. We could
then average out the maximum error that each BS contributed within a larger grid zone (such as 500 m by 500 m). This maximum time delay correction will be stored and used during each real OTDOA requests. Figure 3.10 illustrates stored site survey information for planning, LMU dimensioning and timing data pertaining to an area. In

![Figure 3.10 Site survey for LMU and UIPS Data module’s area information (stored data) for timing, correction and signal measurements from each BS](image)

the data acquisition stage or during continuous Operation and Maintenance (O&M) stage, UIPS Data module will store each area’s LMUs’ information, LMU addresses, time of delays from each BS (and each of its cell sector) within each grid location of size 100 m by 100 m, environment details, and the road networks starting and ending coordinate points that passes through each area. In addition to obtaining real OTDOA measurements within each grid of 100 m by 100 m, every GPS requests (samples) that go through UIPS will cumulatively assist in producing bigger sample size for reliable calculation of averaging time delays from each BS (and from each of its sectorized cell or Cell ID) covering its zone area (such as BS 7 in Figure 3.10).
In simulated environment of OTDOA time measurement (each BS equipped with LMU), multipath delay prediction error, \( \tau_D \), as in Equation (3.10) will be added to \( T_G \) to finally represent the predicted \( T_G \) or approximated \( T_A \) for kLOS environment, assuming that survey data (used for delay correction purposes) only could provide approximate (average fitting) prediction for each cell’s multipath delay in order to estimate current multipath delay from the same cell to UE. It is also assumed that using LMU at each BS, synchronization (difference in synchronization errors between BSs could be reported by LMUs) and other timing errors are taken into account and are corrected by UIPS. \( \tau_D \) is therefore represented as following:

\[
\tau_D = T_G(D_{PE})R_v
\]  

(3.10)

where, \( R_v \) is the distributed random variable from 0 to 1, \( D_{PE} \) is the delay prediction error constant, which is \( 1.8 \times 10^{-8} \) \( D_{PE} \) value is obtained based on trial experiments for different simulated kLOS areas) for dense urban and suburban, and \( 1.8 \times 10^{-9} \) for rural, and \( T_G \) is the actual geometrical time-distance between BS and UE. In a way, the intention is to simulate the effects when the BS is farther, the time to travel from BS to UE will be longer with more environment mediums. This concept is somewhat similar to Equation (3.1) as suggested by Greenstein et al. (1997). Finally, the predicted geometric time \( T_G, T_{G pred} \) or approximated \( T_A \) is represented as following:

\[
T_{G pred} = T_G(1 + D_{PE}R_v)
\]

(3.11)

where, \( T_{G pred} = T_{A approx} \) (approximate \( T_A \) without delays from BS) is then used in CCC and NR3C estimations. In Chapter 2, it was shown for a pair of hyperbolic equation, \( OTD = GTD + RTD \). When difference of synchronization errors could be reported by LMUs and taken into account by UIPS, \( RTD = 0 \), and \( GTD = OTD \). Then, similarly to Equation (3.6), \( OTD_{pair1} = T_{A approx2} - T_{A approx1} \), and \( OTD_{pair2} = T_{A approx3} - T_{A approx1} \).

For uTDOA measurements, uTDOA based LMU (uplink time of arrival at each Node B from UE), are able to distinguish time delays measurement for each Node B by comparing (matching) the reference snapshot of serving Node B (serving BS) signal’s to the observed uplink’s signal of another Node B (neighbor BS), arriving
from the same UE. Time delays could be distinguished from the first strongest received signal peak (Jativa & Vidal 2002) along with the time delays from other multipath peaks arriving at the same Node B (Ahonen & Eskelinen 2003). The RMS delay spread could be subtracted from the total observed time of arrival at that particular Node B. The corrected time (uplink time difference without delays) from all three Node Bs will then be used by CCC or NR3C to estimate the UE location.

### 3.7.2 uLOS Environment

The area selected for uLOS environment of Kuala Lumpur (KL) is nearby the test driven urban-suburban route and is shown in Figure 3.11. The urban site (north of KLCC), with few high rise buildings (banks, office buildings, apartments, hotels, etc) are located right after KLCC, Putra World Trade Center and Sogo are located on the west end of the map, and Ampang Point is located on the east end of the map. This urban area has BSs antenna with averagely good LOS towards the outdoor mobile, has NLOS towards moving subway trains, and indoor cells to cover basements and certain floors of huge buildings such as KLCC (KLCC is at the bottom tip of this map). The farther north of the area (above the dashed boundary line of suburban area as shown in the diagram) is covered by more of two storeys suburban residential, some high apartments and three to four storeys of commercial and business buildings.

For uLOS contributing BSs or all BSs within uLOS classified areas, multipath delays as in Tranter et al. (2004) for GSM and 3G, based on 12 ray multipaths with probability of detection by measurement device in between the 1st and 3rd multipath rays (time of delay between 0 and 0.3 μsec), will be randomly observed (time delays from each BS will be randomly injected during simulation of OTDOA for 3G and E-OTD for GSM), assuming the first arrival highest peak is among the desirable received signals. Tranter et al. (2004) also stated that RMS delay spread for UMTS indoor environment is typically between 30 to 300 ns. For example, 244 ns of delay would correspond to average power of -9.6 dB for indoor Case 1 (3GPP 2008) with speed of 3 km/h, -12.5 dB for pedestrian/indoor Case 2 (speed of 3 km/h) and -2.4 dB power of signal for outdoor vehicular movement Case 3 (speed of 120 km/h). For uLOS simulation, it is assumed that more pedestrian movements are on the bottom of
the map (urban zone) and average speed of 25 km/h for outdoor suburban: consisting of equal distribution between pedestrians and vehicular movements.

Since the BSs neighbors’ lists were not known and the order of each BSs’ propagation loss were also unknown (this larger area classified as “unknown”), so the simulation program calculates seven of the most nearest BSs for each UE selected within minimum and maximum boundaries of the map’s area (UE real location samples could be selected using mouse cursor during beginning of simulation). In UMTS, the nearest BS may not necessarily act as the serving BS, and therefore some randomness (6 types of random NMR cases pertaining to the BSs’ order of distances used for selecting any three BSs is presented in Chapter 4) is required in the arrangement assuming 3G network’s controller’s role, while preserving the actual locations of the BSs. This is due to the objective that the algorithm’s estimation accuracy with respect to real geometric placements/locations of BSs could be

Figure 3.11 The urban-suburban uLOS area for simulations of OTDOA and E-OTD

Source: Map from Google Earth (Anon 2008k)
simulated and evaluated for both NR3C averaging methods and CCC averaging method. Even though UE could only be selected within the area (longitude (x axis) width of 8.9 km and latitude (y axis) width of 6.68 km), but BSs from outside the area (real locations of BSs from Telco’s database) would also participate if the UE is near to the edge of the map.

uLOS represents environment that are unknown in multipath propagation which includes direct LOS BSs and NLOS (non LOS) BSs. For LOS BS, time of delay could be very negligible. For NLOS BS, time delay of 10 nanoseconds corresponds to distance error of 3 m. To mitigate the higher uncertainty of signal propagation effects within area of uLOS (unknown LOS), averaging of CCC and averaging of NR3C will be developed for improving user’s location estimation.

### 3.7.3 CCC Averaging Estimator

A CCC averaging technique, CCC Averaging estimator operates as following:

1) UIPS instructs SMLC and RNC/BSC to simultaneously transmit time measurements from three BSs (Node B or BTS). The selection criteria of BSs will be based on RSCP ECNO or receive signal level from Network Measurement Report but checked against the Telco’s BS coordinate to ensure the three BSs are of unique locations and not from the same site.

2) The instruction for transmission/downlink E-OTD/OTDOA time measurement is repeated for three consecutive times using the same three BSs used earlier. For uTDOA method, uplink time reception at three BSs is measured and also repeated for three consecutive times at the same three BSs.

3) CCC method is utilized to calculate the three times (three sets of OTDOA measurements) location estimate for the same UE/MS.

4) Averaging of the three estimated locations of the same UE/MS is finally completed by UIPS. This averaging technique is referred to as CCC Averaging estimator.

The three repetitive timing measurements could be performed within 6 s. Halonen et al. (2003) stated that it takes 1 to 2 s for their MS demonstrator to perform E-
OTD measurements for one location, and then reports the time measurements back to their SMLC demonstrator in order to estimate the location.

### 3.7.4 First Mean NR3C Estimator

An NR3C averaging technique, the First mean NR3C estimator operates as following:

1) UIPS instructs simultaneous transmission of time measurements from three BSs.
2) Time measurements are repeated for three consecutive times using the same three BSs. The process is exactly the same as in CCC Averaging Estimator for downlink (E-OTD/OTDOA) or uplink (uTDOA) measurements.
3) NR3C is used to calculate the three times location estimates for the same UE/MS.
4) Finally, UIPS calculates the mean for the three estimated locations of the same UE/MS.

### 3.7.5 Random Search NR3C Estimator

Two random search estimators are developed. The first is called Random Search Mean NR3C estimator and the second is referred to as Random BS NR3C estimator.

i) Random Search Mean NR3C Estimator

Random Search Mean NR3C estimator operates as following:

1) UIPS instructs simultaneous transmission of time measurements from three BSs.
2) Time measurements are repeated for three consecutive times using the same three BSs.
3) NR3C is used to calculate the three times location estimate for the same UE/MS. Exactly the same process as First Mean of NR3C Estimator.
4) The estimator finds the first mean and uses it as initial mean value for iteration. Iteration is set at 3000.
5) The algorithm searches within the boundary of the three estimated locations of the same UE/MS as was obtained in step 3), where the estimator randomly calculates for a new mean within the minimum and maximum boundary (square boundary is created based on the three location estimates of the same UE/MS).

6) Each iteration randomly searches for a new UE/MS mean estimate. If the average spread is too large, and calculation for UE/MS mean estimate goes very far outside from the defined boundary, warning message is sent to the UIPS Admin module, notifying the clocks are not synchronized or to check the input parameters. If the UE/MS mean estimate for the iteration is just slightly away from the boundary, random multiplier (scale factor to drive it up, down, left or right) will be applied (similar concept used for optimization by Pattern Search in Anon 2007a) to push the new mean back within the boundary.

7) At the end of the iterations, final UE mean location estimate is produced, by final averaging of all the random iteration points. The concept of Random Search Mean Estimator is to randomly guess the mean location based on the probability that the estimate will fall within the vicinity of the three location estimates. Figure A.9 illustrates the algorithm for Random Search NR3C.

ii) Random BS NR3C Estimator

The idea that random mean of the random search points should probably be within the centroid of the serving cell and the two other neighbor cells, led to the development of Random BSs of NR3C. Basically all the iterations’ estimated points from Random Search Mean of NR3C are compared:

1) to the serving cell BS1: The point that is the closest to BS1 among all iterations is the first estimation for Random BSs Mean with respect to BS1.
2) to BS2: The point that is the closest to BS2 among all iterations is the second estimation for Random BSs Mean with respect to BS2.
3) to BS3: The point that is the closest to BS3 among all iterations is the third estimation for Random BSs Mean with respect to BS3.
4) Finally all the three estimate points are averaged to produce a single location estimation called Random BSs of NR3C. In contrast, Random Search Mean of
NR3C uses all the iteration points by finally averaging them again for one location estimation.

Random Search Mean NR3C estimator is also sometimes referred to as Random Search NR3C estimator. Random BS NR3C estimator (as shown in Figure A.9) is just an extension of Random Search Mean NR3C estimator.

3.7.6 Averaging Time from Each BS and Estimating using CCC or NR3C

Another alternative approach is to average the time from each BS, and then estimate using NR3C or CCC method as following:

1) UIPS instructs simultaneous transmission of time measurements from three BSs.
2) Time measurements are repeated for three consecutive times using the same three BSs.
3) Time measurements from each of the three same set of BSs used are averaged.
4) NR3C or CCC is used to calculate the single (using average time as above) location estimate of the same UE/MS.

3.7.7 Best Comparator Estimator

Best Comparator estimator is a new hybrid comparator that uses CCC Averaging’s estimation at higher standard deviation (NR3C performs better in ideal situations and CCC is more robust in high multipath errors as will be shown in uLOS simulations in Chapter 4) and uses First Mean NR3C’s estimation for samples that is less than $\sigma$ (standard deviation of 20 m is selected based on trial experimentations related to the time delays used in simulation). The value $\sigma$ would be a deciding factor to select First Mean of NR3C’s result or CCC Averaging’s result. It basically uses CCC averaging when NR3C’s estimates are unpredictable (much deviated). The steps to determine the comparator’s output are as following:

1) In step 3) of First Mean NR3C, three location estimates of the same UE are estimated. For each location estimate, $dist$, distance is calculated from UE
estimated 1 to a reference location. The reference location’s coordinate chosen for this research is point (0,0), being the most unbiased point.

2) The step is repeated for all the other two estimated UEs (UE estimated 2 and UE estimated 3), producing three dist values.

3) These three distance values are compared in terms of standard deviation, \( \sigma \).

4) For each estimation sample, the comparator chooses First Mean of NR3C’s output if \( \sigma < 20 \) or else it chooses CCC Averaging’s location estimation.

Figure 3.12 summarizes the uLOS simulation model. In the urban/suburban environment, the objective is to obtain an estimated average from three OTDOA or
E-OTD measurements of one actual UE location. Even though three times network signaling is required for averaging (for three continuous measurements on the same UE to be located), for emergency response situation, this technique could justify its advantages. For comparison purposes, the five types of averages were used: First Mean NR3C, Random Search Mean NR3C, CCC Averaging estimator, and finally averaging time measurements from each of the three same set of BSs used and then calculating using NR3C and CCC method.

3.8 COMPARATOR TO OPTIMIZE LOCATION ESTIMATION

As summarized in Table 3.1, $L1$ and $Lg$ are two new comparators that will be used for checking the allowable distance and allowable angles between BSs, in order to ensure that the hearable BSs’ choice used for location estimation could produce optimum result. These two new comparators were discovered when performing the simulation. As mentioned in Figure 3.1, when an LDT technique suffers from inaccuracy, the development cycle will require further studies and improvement to the LDT technique.

3.8.1 Distance Comparator among Hearable Base Stations ($Lg$)

For example, at 1240th sample of ECNO’s three hearable UMTS cells for suburban-rural route, it was found that NB1 (cell 1) and NB2 (cell 2) were actually sharing the same site with a distance of 22.3 m apart from each other. This will definitely affect the performance of estimation techniques (producing high estimation errors) because the cell’s location is not unique, but are actually located in the same site. There are quite a number of samples with this type of problem. This problem arises when coordinates are recorded by GPS (GPS location estimation also produces small errors as mentioned in Chapter 2) and then entered directly by Telco in their database. But for LBS requirements (especially for trilateration techniques), it is very important to have site uniqueness, where hearability is dependent on it. Therefore, $Lg$ is added as a logical check between each BS’s distances as following:

$$Lg = \left( \text{dist}(NB1,NB2) > 30 \cap \text{dist}(NB1,NB3) > 30 \cap \text{dist}(NB2,NB3) > 30 \right)$$  \hspace{1cm} (3.12)
where, logical \textit{And} is represented as $\cap$, and Euclidean distance is represented as $\text{dist}$ (as in Equation 3.5). $L_g=1$ will allow for the execution of CCC, NR3C and uLOS averaging techniques, while $L_g=0$ will discard the unwanted sample or UIPS will use other estimation techniques (with hearability of less than 3) to estimate this timing sample. Basically the distance between Node Bs ($NB_i$) should be below 30 m.

3.8.2 Angle Comparator among Hearable Base Stations ($L_1$ or BestGeo)

Also through simulation it is learned that geometric and direction of angles between each BSs with respect to each other and finally towards the UE/MS effects location accuracy especially for numerical computations technique such as NR3C. Thomas (2001) mentioned by using the square mean of distance error of estimated location and square mean of noise variance, GDOP could be calculated. However, based on our experimentations, a new proposed algorithm for SMLC should be implemented. In UIPS this logical algorithm is added to eliminate available NMR’s choices (in our simulation ECNO takes the role of NMR) that produces hearable BSs that does not meet an acceptable geometrical requirement (bad geometry of NMR cases are eliminated). The logical Best Geometrical (BestGeo) comparator, $L_1$ is as following:

$$L_1 = (|ag_{12} - ag_{13}| > 2.5) \cap (|ag_{12} - ag_{23}| > 2.5) \cap (|ag_{13} - ag_{23}| > 2.5)$$ (3.13)

where, $ag_{12}$ is the azimuth directional angle between $BS_1$ (Base Station 1) and $BS_2$, $ag_{13}$ is the azimuth directional angle between $BS_1$ and $BS_3$ and $ag_{23}$ is the azimuth angle between $BS_2$ and $BS_3$. Matlab (Anon 2008h) mapping toolbox was used to find all directional angles. North is referred to as 0 degrees while all positive angles are in clockwise direction from 0 to 360 degrees. Equation (3.13) lists situation where two BSs’ absolute angle difference should not be smaller than 2.5 degrees. If one or all of the pairs of BSs differences are less than 2.5 degrees, $L_1=0$, the logical statement indicates situation that inaccuracy could be degraded due to at least two BSs’ placement that are not in the desired order for location estimation. This logical statement could be used to eliminate the worst error causing samples obtained from
hearability report of ECNO (UMTS) and ERXL (GSM). These discarded samples could then be estimated by some other UIPS’s technique (such as SCM).

3.9 TIMING TECHNIQUE LDT MODELS WHEN HEARABILITY IS TWO

When hearability is limited to only two hearable BSs, time trilateration (or time-distance triangulation) method could not be utilized for location estimation, as is done for timing measurements from three or more hearable BSs. BS is sometimes used instead of cell to emphasize that all hearable cells selected for timing measurements must be from a different BS.

In this research, when timing measurements are obtained from two hearable BSs, some other predictor or comparator is required to improve (optimize) the overall location estimation done by CCC or NR3C. CCC2 (modified CCC) is used when timing is received from two BSs. When the estimated mobile user is most likely (such as user is requesting for Navigation Based Services) travelling on a road, road comparators will be used to optimize CCC2’s predictions: Minimum Best Road Comparator (MBRC) or Genetic Algorithm Comparator (GAC). Reference Location Measurement Node (RLMN) could also be situated by Telcos in areas where hearability is most likely two (proposed locations of RLMNs are based on analyzing the urban-suburban drive test data). Timing measurements from RLMN and two other cells could then be utilized to estimate the locations of moving or stationary users.

In order to meet the objective of optimizing the location estimation of mobile users travelling on road, reliable, updated and extensive road data must be incorporated as part of the prediction process. The digital (discrete points) road data must also consists of local and relevant LBS information that is to be offered by the corresponding Telco. Schiller & Voisard (2004) recommended a few attributes that should relate to digital road maps such as road intersection points, street names, road segments, point of interests and zip codes. JUPEM (The Department of Survey and Mapping, Malaysia) also provides area maps (Anon 2008n) for Malaysia. However for this research, a more meaningful road/street map is required where data (coordinates of paths, intersections and related information) could be imported from
online map such as Google Earth or local database and exported easily into the developed location estimation algorithm. Simple Mapping Technique with Table Look Up (SMTTLU) is developed where drive test routes are stored to build road path information and then further utilized by Best Route Determining Technique (BRDT) in order to provide Navigation Based Services (NBS) and LBS.

3.9.1 Simple Mapping and Best Route Determining Technique

Schiller & Voissard (2004) mentioned about Nearest Neighbor Queries based on the nearest LBS point of location (Shekhar & Yoo 2003), and Map Matching of road network travel route (Bernstein & Kornhauser 1996) based on point to point, point to curve or curve to curve methods. Other methods and probabilities of choosing the correct road out of several road segments where the traveller (such as based on traveller’s GPS’s recording) is travelling, is further described by Zhao (1997), Kim et al. (2000), and Pyo et al. (2001). With map matching and proximity queries, the accuracy of outdoor location estimation when hearability is limited to two BSs, could be improved. The need to acquire a simple but efficient and less tedious digital road map for LBS and NBS becomes crucial. Figure 3.13 illustrates the process required to create a simple digital road network paths. The decision and combination of paths will lead to the best proposed route for the traveller to choose before travelling, when the starting point (Home) and the ending point (called Office) are predetermined. The same could be applied to guess the travellers’ travelling route when several points nearby the road network are matched to estimate the user’s (traveller) location, and hence the collective estimation points would determine the route being travelled. Map matching for location estimation would be discussed in the next section.

On the left side of Figure 3.13, the storing process is described where each paths could be drawn on road maps such as by using Google Earth. Each path drawn should be from road intersection to another intersection or the end of the road (where there are no intersections). It is preferred that the distance for each path be short unless it is a continuous rural or major highways where there are no other nearby roads parallel to it. For simplicity, an example of twelve paths is drawn for the urban-suburban route out of more than few hundreds of paths within the area. Figure 3.14
Figure 3.13  Process for storing paths and to determine the best route to travel illustrates the 12 paths data drawn for this area, with Home (starting) at Menara Celcom and Office (ending) at Wangsa Melawati. The Home which is located to the nearest three intersection paths (5, 8, 11) might have 2 possible starting paths to reach Office. Office also is located near to the ending of intersection between path 1 and path 6. The stored neighboring information in table format for 10 paths (Paths.xls) is shown as snapshot in Figure A.10. There are 12 paths but for this example only 10 paths are entered into table while the other 2 paths (path 11 and path 12) will be considered as learning paths.

In Figure A.10 (snapshot of table sample) of Paths.xls, for Home point nearest to path 5 and Office point nearest to path 1 and path 6, will have the following routes: [5 4 3 7 1] (with [4 3 7] being the neighbors) and [5 4 3 2 6] (with [4 3 2] being the neighbors). Similarly with Home point nearest to path 8 and Office point nearest to path 1 and path 6 will have the following routes: [8 9 10 3 7 1] (at this table column
there also exist another optional route which is [8 5 4 3 7 1] and [8 9 10 3 7 1 6]. For Home path starting closer to path 8 and ending at path 1, there exist two optional routes. The optional route’s selection criteria could be determined based on another look up table related to weather report, traffic jam report such as from DBKL (Anon 2008o), road diversion, road construction, avoidable roads or busy hour report. By default (when selection criteria is not set), if there are more choices of routes, the best route to be proposed to the traveller before the journey is taken is based on the shortest distance. As in Figure 3.13, after the neighboring paths’ data is stored as in Paths.xls file, new paths could still be added and updated when drive tests are done. It is preferred that everytime a new drive test route is performed, the paths are updated in Paths.xls. But for convenience, learning paths could also be inputed directly into the stored paths database without updating the Paths.xls. For example route 11 and 12 were not entered in the Paths.xls list but paths’ information (keyhole markup language (.kml) format files) is available in the database. In the main program this path could be referred to as learning path with information of [11 5] and [12 4] which means path 11 is neighboring with path 5 and path 12 is neighboring with path 4. This saves time for entering information into the Paths.xls, when all the basic paths are already in
existence. If a user at KLCC (near path 11) would like to travel to Wangsa Melawati, travelling information from path 5 to path 1 or path 5 to path 6 could be combined with this starting path (path 11). To read all the path files in the database, which are in kml format, conversion to Matlab is required (to convert all path information to discrete geographical coordinates such as longitude and latitude) and is available from Farris (2006). To find the best route, for the urban-suburban example, the Home point was closest to path 8, while the office point was closest to path 6. Nevertheless, Best Route Determining Technique (BRDT) still checks for the other nearer paths to Home (second nearer path is path 5) and Office (second nearer path is path 1). So a choice of four routes is checked by the main program and the route with the shortest distance will be selected. The first route plot is shown in Figure A.11 with travelling paths of [8 9 10 3 7 1 6], the second route is shown in Figure A.12 with travelling paths of [8 9 10 3 7 1], the third route is shown in Figure A.13 with travelling paths of [5 4 3 2 6], and the fourth route is shown in Figure A.14 with travelling paths of [5 4 3 7 1]. Recalling from the urban-suburban route map that was shown in Figure 3.3, the fourth route is the same drive test route. The fourth route is the proposed best route since it is the shortest with minimum distance (travel distance and not LOS distance) of 9.888 km compared to the rest of the routes. For this example, default option (shortest distance between routes) was used when more routes are compared.

Satellite navigator software such as for NUVi710 (Anon 2008c) also proposes similar function of directing road directions on road maps. Its interactive use of GPS receiver and voice based directions could guide the user to get back on track if wrong turning points are selected. The complexity of their propriety algorithm is unknown and the accuracy of tracking depends on the GPS’s accuracy. In this research a simple Mapping Tool was presented for developing road paths (through maps or actual drive test coordinates), and BRDT was developed as part of UIPS capabilities to track vehicular movements or pedestrian movements on walkpaths when hearability is limited to one or two BSs. Similar concept for pedestrian walkpaths could also be drawn on city maps covering the points along a building or blocks. Only important and main walkpaths should be saved in database because too detailed digitized points (with longitudes and latitudes) would not increase the accuracy of tracking user any further since GPS’s error is also within several meters to 30 m, and at times GPS is
unable to function where the receiver is constantly being blocked by huge buildings. Data collected via drive test does not need to be converted to .kml format. The drive test’s coordinate (longitude and latitude in decimal degrees) could be taken as it is. The usage of Google Earth is beneficial where certain paths are not stored using drive test data.

Before proceeding with the road matching comparators, the best proposed or travelled route or road networks must have sufficient number of points for comparison. This led to the process of digitizing the paths and routes that are stored earlier in the database. Figure A.15 shows the algorithm of digitizing a route called BestRoad which initially has 33 points (road coordinate points excluding Home and Office points). This is the Best route chosen from Figure 3.14 with paths 5, 4, 3, 7, 1, and shown in Figure A.14. The purpose is to add more resolution points in between each point such as 20 meters apart from each other, in order to increase accuracy when used for location estimation. The final number of points for the route after digitization is 497 coordinate points.

3.9.2 Close Circle Correlation for 2 Circles (CCC2)

When hearability is only from two BSs, where MS/UE can receive time measurements from only the serving cell and another neighboring BS’s cell, some adoptions have to be made to CCC estimation method. The new adaption technique for CCC when only two unique BSs’ time measurements are achievable (hearable or complete decoding of the full sets of available measurement parameters from the GSM ERXL or NMR report) is referred to as Close Circle Correlation for 2 Circles (CCC2). The purpose is to obtain the intersection points between the two circles (two hearable BSs). Each Node B is represented by a circle as shown in Figure 3.15. For example the serving cell of Node B1, is represented by Circle 1 with radius $d_1$ and is centered at the location of Node B1’s coordinates, and the neighboring cell at Node B2 is represented by Circle 2 with radius $d_2$, centered at location of Node B2. The radii $d_1$ and $d_2$ can be estimated using the time of arrival from LMU (3GPP 2007a) of Node B1 and LMU of Node B2 towards the UE (the predicted geometric time-distance were discussed earlier). When Circle 1 and Circle 2 intersect, two intersection points are produced.
The exact mobile location could be in the proximity of the two intersection points. Hence, to improve uncertainty of prediction, a third circle is required for triangulation or trilateration. Predicting a mobile user’s vehicular movement on a road network or routes, could further increase the accuracy of estimating mobile user’s location between the intersection of the two circles and the nearest matched road points. Therefore the CCC2 algorithm will output four initial prediction points, $A_1$, $A_2$, $B_1$ and $B_2$. Point $A_1$ is generated on Circle 1, which is due to the first intersection between circles 1 and 2. Point $A_2$ is generated on Circle 2 due to the first intersection between circles 1 and 2. Point $B_1$ is generated on Circle 1, which is due to the second intersection between circles 1 and 2. Point $B_2$ is generated on Circle 2 due to the second intersection between circles 1 and 2. The road networks’ digitized points such as Road 1, Road 2 and Road 3 that is passing through the coverage area of the two cells will then be used as part of the road matching points, to assist in the final selection of the estimated location. This technique will be described in the later section. The first road matching technique, called Minimum Best Road Comparator (MBRC) will be used when there is only one major route (when probability of target vehicle is high on the highway and main roads), such as only Road 1 in the vicinity of the two circles (or the probability of user on Road 1 is definitely higher than any other
roads based on prior knowledge). By comparing the nearest Road 1 points to the four CCC2 output points, the nearest of the four CCC points (A1 or A2 or B1 or B2) will be the final best predicted location point. In actuality, the best estimated point should be on the road (such as Road 1), but the reason will be made clear when demonstrated through simulations, that the deviations of meters between the actual travelled paths versus GPS coordinate measurements differs in the order of several 10’s of meters when several repetitions of drive on the same routes or path were done. It will also be hard to distinguish which lane of a three lane highways a user is travelling due to the slight inaccuracy of GPS. In this example the nearest road point NRP, which is on Road 1 is the nearest to point A1, and point A1 will be the estimated location of mobile. Therefore, the suitability of selecting the CCC2 output points as the estimated location become more meaningful when the user is travelling on a road or walkpaths. But as in Figure 3.15, when there are three roads (Road 1, Road 2 and Road 3) within the vicinity instead of just one road (Road 1), Genetic Algorithm Comparator (GAC) will be used to select the best of the CCC2 points when compared to about 30 digitized points of the road network (30 initial nearest points to A1, A2, B1 and B2 are selected from the three roads’ points passing through the intersection of the two circles’ cell coverage). One of the four CCC2’s points that is the fittest (with minimum fitness function value) when compared to the 30 closest road network points will be selected as the estimated location. Using GAC, point A1 will be the estimated location, the nearest to point NRP of Road 1 when compared to the rest of the three roads’ points.

3.9.3 Newton Raphson 2 Circles (NR2C)

Adaption to NR3C should be made when hearability is limited to only two BSs (Node Bs/BTSs). The function, \( f_i(x) \) for Newton Raphson 2 Circles (NR2C) is modified as following:

\[
d_1 = \sqrt{(x-x_{b1})^2 + (y-y_{b1})^2}
\]  \hspace{1cm} (3.14)

\[
d_2 = \sqrt{(x-x_{b2})^2 + (y-y_{b2})^2}
\]  \hspace{1cm} (3.15)
where, $x_{bi}$ is the x coordinate of BS$ i$ in meters, $y_{bi}$ is the y coordinate of BS$ i$ in meters, $d_i$ is the distance between BS$ i$ (LMU) to UE/MS. Inserting $x$ and $y$ into (B.4) (similar process as described for NR3C), and with 2 equations and 2 unknowns, the final estimated UE=$(x,y)$ in meters could be obtained after several iterations of substituting incremental corrections of $(x, y)$ into (B.4). Initial points of $x=0$ and $y=0$ will be used as first guess for NR2C (or could also use CCC2’s estimated point as initial guess point), maximum iteration is set at 80 (this value is found suitable based on our trials) and tolerance is set at $2.2204 \times 10^{-7}$ (value for tolerance is slightly modified from NR3C as found through experimentation in order to accept solution with less precision due to limited hearability). Iteration is terminated if either tolerance is reached first or maximum iteration is completed.

### 3.9.4 Minimum Best Road Comparator (MBRC)

When the best route has been proposed to the user as in example of Figure A.14 for the urban suburban direction, any other location or navigation queries by the same user will be directed to MBRC algorithm when hearability is limited to only two hearable BSs. For three hearable BSs, road matching is not required to be performed because the estimation is within the location accuracy requirements. For two hearable BSs, MBRC will compare the four best CCC2’s points ($A1$, $A2$, $B1$, $B2$) and select the point that is the closest (minimum Euclidean distance) to the best (or main road such as Road 1 in Figure 3.15) road points around the vicinity (within the cell coverage) of the two circles. The 497 digitized points of the best route (BestRoad) will be used to compare the four CCC2 points produced during hearability of two along the urban-suburban route (Menara Celcom to Wangsa Melawati). The performance of the simulation will be shown in the next chapter. Figure A.16 shows the algorithm for MBRC.

### 3.9.5 Genetic Algorithm Comparator (GAC)

As in Figure 3.15, when there are more roads (Road 1, Road 2, and Road 3) passing through the two circle’s area, and when further direction (or final destination) of the
UE or MS is not certain, then some kind of random selection is required to search for global minimum or one of the several minimum road points. As in Figure 3.15, Road 1 is definitely closer to Point A1 when compared to Road 2 and Road 3. But if the roads are almost running closer to each other, with respect to all four points A1, A2, B1 and B2, and with slight GPS’s measurement error (during site survey) or inaccurate mapping error, and time delay errors during timing measurements, then any one of the road could be the best travelled path to either of the CCC2’s points. Therefore, Genetic Algorithm Comparator (GAC) would be used to compare at least 30 closest distances between all three roads or more roads’ closest points. The comparison of the 30 closest road network’s points with respect to each CCC2’s points will produce one final fitness value. Any of the four CCC2’s point with the smallest of this fitness value will be chosen as the estimated mobile location. Fitness function at each iteration or generation corresponding to each CCC2’s point is defined as:

\[
F = \sum_{i=1}^{i=\text{pop}} \left[ \text{dist}(p_{i1}, p_{j31}) + \sum_{j=2}^{j=31} \text{dist}(p_{ij}, p_{j-1}) \right]
\]

Equation (3.16)

where, \( \text{pop} \) is the population size, \( p_{ij} \) corresponds to one of the 31 points (30 closest points to one of the CCC2’s point being evaluated plus the CCC2’s point itself makes a total of 31 points). Equation (3.5) is used to determine the Euclidean distance, \( \text{dist} \) between each pair of points (for 30 closest road networks’ points within the vicinity of two circles and one of the CCC2’s points). The order of which distance points’ pair comes first will be determined by \( i \) population random order depending on genetic functions of random permutations, mutations and crossover. The process flow of Genetic Algorithm Comparator (GAC) is shown in Figure 3.16. Matlab toolbox (Anon 2007a) is used for this coding purpose with derivation of fitness function and genetic functions (random permutations, mutations and crossover algorithm) from travelling salesman’s example provided by Mathworks (Anon 2007b).

The concept in travelling salesman has motivated the development of this comparator, where in the example of travelling salesman, the salesman is required to
Figure 3.16 GAC selects one of CCC2’s point as the estimated mobile location.

fly to all the cities in the USA by following the optimized route order because the objective is to travel between all the cities with the lowest cost or shortest travelled distance. The example uses maximum generations \((Gen)\) of 500 and \(pop\) of 60. Similarly in GAC case, the final fitness function value between one CCC2’s point and at least 30 nearest road points (30 points are sufficient to be compared if there are
three to six roads, such as five to ten nearest points from each road), relates to the final distance value travelled between all the 31 points based on the best optimized travelled order. This final fitness value provides an indication of how close the user is travelling to that corresponding CCC2 point. One of the four CCC2 point with the lowest final fitness function value will be the estimated location of the user.

Firstly GAC algorithm retrieves from database, the discrete points of road data (road data and walk-paths that are digitized based on our earlier drive test routes or the kml files developed through Google Earth) that passes through the vicinity of the two circles’ area. As discussed earlier, the objective is to compare which of the CCC2’s points \((A1, A2, B1 \text{ or } B2)\) has the smallest (optimized) fitness value (final iterations or generations value of \(F\) pertaining to the CCC2 point being evaluated) to the road networks. The smallest fitness value is selected as the winner or the final estimated location. Fitness function as in Equation (3.16) is implemented so that the distance of each CCC2 points could be compared to the proximity points of the road networks within the coverage of the two circles. Population size \((pop)\) of 32 (chosen based on 31 compared coordinates) is assigned to the selection of searching one final fitness value for one CCC2 point. The maximum numbers of generations \((Gen)\) is set to 250 (different \(Gen\) will be compared during simulation because too small of value may not optimize the final result or too large of value may be very time consuming to process). In each generation, random permutations of the 31 points’ (30 road network’s closest points and one CCC2 point) order of arrangement as population takes effect, where Crossover Permutation Function will select parents from population to produce crossover children and Mutation Function will produce mutated children (such as mutating the order of road points selections). Each generation (iteration) produces new children and the process is repeated until maximum number of generations is achieved or when there is no changes to the Fitness’s score. The optimized Fitness score (value) is finally produced for point \(A1\), and the same entire process of finding Fitness values for \(A2, B1\) and \(B2\) is repeated, so a total of four corresponding CCC2’s points’ final fitness values could be compared. CCC2’s point with the lowest Fitness value will be selected. For example in Figure 3.15, point \(A1\) has the smallest Fitness value and is also the closest to Road 1, and therefore is the UE or MS’s estimated location.
3.9.6 Reference Location Measurement Node (RLMN)

As per data collection done on UMTS for three repetitions (three files were created) of drive test, from Menara Celcom to Wangsa Melawati, it was found that the hearability of two was almost dominant around the proximity of five highlighted areas of the urban-suburban route as shown in Figure A.17. For these areas, it is proposed to be installed with Reference Location Measurement Node (RLMN) that could be mounted to tall structures with good LOS towards UEs in outdoor settings. Since it may not be a good investment for Telcos to build new stations for LBS purposes, it is hoped that RLMN could be placed with Local Authority’s approval on higher structures and able to communicate with neighboring Node Bs and RNCs using available or modified 3GPP interfaces and protocols such as being used by standalone LMUs. Similarly, in 3GPP specification (3GPP 2001b), OTDOA Positioning Element (PE), is proposed where PE(s) are placed in building or near Node B to assist in OTDOA measurements. RNC uses RRC protocols to communicate with PE and PE does not need extra LMU for synchronization as it is synchronized with a Node B. The document (3GPP 2001b) shows example of four PEs being used within a Node B’s cell for positioning. PE specified by 3GPP could be the size of handheld phone, where measurements could be observed by UE even in soft handovers state. In the example of urban-suburban route, three RLMN with directional/sectorization capabilities are proposed to cover the five prominent areas as shown in Figure A.17. It is hoped that with dedicated RLMNs, hearability of three could be achieved most of the time for the five coverage spots from the proposed installed sites. This is due to the concept that RLMN will always be on standby waiting for SMLC/RNC’s instructions to perform timing measurements. When only two hearable BSs are available within the vicinity, RLMN will be instructed as the third hearable site. Figure A.18 illustrates proposed RLMN implementation along the same route for GSM. For GSM, more thorough studies are required in terms of hearability because the areas where hearability of 2, are almost covering the whole urban-suburban route. For GSM, the major reason that three hearable sites was not easily achievable was due to the fact of incomplete measurement data to decode from the network parameters and therefore causing difficulty to frequently obtain three complete unique BSs’ measurements. This is due
to network’s parameters intermittently not being reported on measurement device when recordings were done in shorter time intervals for GSM compared to 3G.

Finally NR3C or CCC will be used to estimate the simulated stationary or vehicular mobile location when hearability has been increased to three (for GSM and UMTS) by using RLMN along the urban-suburban route.

### 3.10 TIMING TECHNIQUE LDT MODELS WHEN HEARABILITY IS ONE

In the case where hearability is limited to only one BS, the serving cell’s time of arrival from the BS to UE or MS will be used (time of arrival with same delay conditions as mentioned earlier will be used for simulation in the next chapter) along with the road data in order to estimate mobile’s location. Cell ID would provide the initial proximity of the mobile location and would determine the nearest road network points to be utilized for comparison. The cell’s antenna beam direction (from Telco’s database) would also provide rough estimation of the beam’s angle towards UEs or MSs but the exact beamwidth’s information from Telco’s database is not known, and a program has been written to determine each cell’s beamwidth angle along any drive test route’s or an average beamwidth ($Abwt$) if all the cell along a drive test route has almost the same configurations (such as site with three sector cells).

#### 3.10.1 One Cell Road Angle Algorithm (OCRAA)

If the antenna beamwidth information is used to improve the prediction accuracy, then the tested average antenna beamwidth, $Abwt$ should be used. The algorithm in Figure A.19 called One Cell Road Angle Algorithm (OCRAA) is used to find $Abwt$ when first run with serving BSs of 3 sector cells assuming each cell is covering at least 60 degrees. The maximum error position is recorded and its angle difference would be used as the new $Abwt$ (to get the $Abwt$ for this maximum error, running of algorithm at 360 degrees is performed). In the example for OCRAA, the $Abwt$ tested suitable for UMTS along the urban-suburban route was between 71 degrees to 90 degrees. This $Abwt$ is tested for the entire three cell sectors site covering this route (Menara Celcom to Wangsa Melawati). However, this same $Abwt$ should not be applied to 6 sectors or
omni cell, where they have to be tested separately by the OCRAA. After the test is completed, $Abwt$ should be entered into UIPS database for each serving cell based on its site sectorization: omni cell, three cell sites, and any specific sites with different configuration of cell sectorization along a route or within an area that were tested. However, it is necessary to ensure (Telco’s data) that the directional antenna data is latest because at times antenna orientation and optimization work has been performed by Telco but information is not yet updated in the database.

The next step of OCRAA’s algorithm is to ensure that the nearest matching road point is also the point that fall within the serving cell’s beam coverage. The beam coverage is determined by RTT (RTT divide by 2 is the time of arrival), knowledge of the serving cell’s directional antenna, and $Abwt$. If the nearest matching road point is outside the beamwidth, another new point is searched for the estimated UE location.

Figure A.20 shows another algorithm called One Cell Road Angle Iteration Algorithm (OCRAIA), which will create a circle around the time of arrival of the serving Node B. In this algorithm, an iteration of 1 to 360 degrees is performed to find the closest $x$ and $y$ coordinates that are on the circle to the nearest road points. The estimated UE location will be on the circle rather than on the road points. In OCRAIA, checking for serving cell’s directional angle is not done, but could also be incorporated as was done for OCRAA.

### 3.10.2 Modified One Cell Road Angle Iteration Algorithm (M-OCRAIA)

For GSM, a different approach is found suitable to estimate location, where time of arrival with the previous known location of user would be used along with modification to OCRAIA’s algorithm. The chance of estimating current location with more accuracy is high if the previous location was not determined too long ago. For example, one minute earlier’s location of a vehicle travelling at 70 km/h would mean that the previous distance was 1.17 km away. Not knowing the speed of the vehicle, some guidelines must be set for the algorithm. For urban area, a previous location of 10 seconds is acceptable because the farthest a vehicle could go is only by 195 m (at maximum speed of 70km/h). The modified algorithm for OCRAIA, M-OCRAIA
(with known previous location) is shown in Figure A.21. Basically the previous location is used as a guideline to find the closest current position with respect to the time of arrival not far from the previous location’s angle.

3.11 SIGNAL CORRELATION METHOD WHEN HEARABILITY IS ONE

SCM’s algorithm is developed based on Artificial Neural Network (ANN) for RSS measurement of only one serving cell. SCM with a new learning technique, LEAN is developed for the urban and dense suburban areas to estimate mobile locations. The simulation results will be based on signal strength data collected for the three repetitive trials of urban-suburban KL route (Menara Celcom to/from Wangsa Melawati). In areas where fading is high, SCM with Unique Sample (US) is introduced. For less populated suburban or rural, where cells are larger, training and learning of Unique Sample and Undefined Collection (USUC) algorithm is proposed, where experiments on another Telco’s (no collaboration with this Telco) 3G internet and GPRS data services will be evaluated in a small township, called Bandar Sungai Long, between Cheras and Kajang (in the state of Selangor): a town with golf course, apartments, houses, shops and a college. Results of populated urban-suburban for voice measurements and less populated suburban for phone assisted location estimation of data services using only one cell’s measurement will be discussed in terms of location accuracy in Chapter 5.

3.11.1 Requirements to Develop SCM Based on One Cell

Even though as mentioned in literature review that it is very challenging to perform fingerprinting or pattern matching on only few levels of signals such as from less than three cells in order to estimate location accurately, but the motivation to still develop SCM is as following:

1) Within UIPS to complement and/or verify timing methods’ estimation especially in dense urban where due to multipath delays, location estimation of timing methods may be inaccurate
2) To complement or substitute time measurements when hearability of timing measurements are from less than three BSs for all environment area (urban, suburban or rural)

3) As phone assisted positioning (phone takes full measurement without network’s instructions but assisted by UIPS/server for location estimation), to support huge (mass) LBS requests especially in NBS, or where continuous queries are required.

Continuous LBS and Navigation Based Services (NBS) requests by many users could burden/congest Telco’s voice and data signaling networks. Instead of acquiring signal level from the UTRAN or BSS network, LBS client could be installed on the phones that could interrogate over the air parameters for signal level of UMTS/GSM serving cell and then pass this measured information directly to UIPS server via GPRS/3G data without going through Telco’s measurement requests. NBS and the nearest point of interest (such as restaurants) are a few examples that UIPS could feedback to the user’s client via the same data bearer such as GPRS, 3G, and High Speed Downlink Packet Access (HSDPA). LBS client to measure signal of serving cell could be developed using Application Programming Interface (API) available from phone manufacturers. At present phone manufacturers only allow one cell’s measurement to be retrieved (Anon 2008e).

For SCM based on one cell measurement, the signal strength information in dBm is required along with the Cell ID of the BS. The measurement of RSSI or sometimes referred to Signal Strength (SS) is generally provided by the test tool in dBm unit, and therefore throughout this research, dBm will be used to express RSSI or SS value’s unit when measurements are obtained from those drive test tool or test phone. In urban, cell sizes are small and there are more BSs (such as above 30 unique serving cells along the urban-suburban route). In very less populated rural, a cell size could be up to 15 km, and if the cell in rural is omni, SCM will face even more challenges to estimate location accurately. Unlike fingerprinting technique that has the luxury to predict information based on more signal levels pertaining to the serving and neighboring cells, SCM would have to rely on using ANN with specialized training and learning sequences of one cell’s signal in order to estimate user’s location within
accuracy better than Cell ID’s method (Cell ID only provide estimation based on proximity of cell size or proximity of its sectorized cell area).

3.11.2 Development of Signal Correlation Method (SCM)

In application requiring pattern recognition, Neural Networks are used to train data, learn and predict the occurrence of pattern (Fausett 1994). There are many types of neural networks, for example Muhammad (2007) compares back propagation Multi Layered Preceptron (MLP) with Generalized Regression Neural Network (GRNN), when signal strengths are received from two or three GSM Base Stations. GRNN and Probabilistic Neural Network (PNN) belong to the family of Radial Basis Networks (Demuth et al. 2007, and Wasserman 1993). In Matlab’s user guide (Demuth et al. 2007), the transfer function for radial basis neuron is described, where the input to the function is defined as \( \text{dist}(P, W)b \): the Euclidean distance between the input \( P \) vector and the weightage \( W \) vector, while \( b \) is the bias multiplier.

SCM would be designed using GRNN with suitable spreading value in order to provide approximation of target location’s coordinate based on received input that is compared to stored samples’ data. One stored sample data is represented by one signal value and one Cell ID (in decimal) for a given location coordinate measured via GPS during drive test (data collection). The intention is to approximate location based on limited information of one signal and one cell value. SCM is built in Matlab using GRNN two layers network for function approximation. The first layer consists of Radial Basis neurons with inputs and weights calculated using Euclidean distance, while the second layer consists of Purelin Neurons. The sample’s location vector, \( SL(i) \) of SCM is determined as:

\[
SL(i) = [\text{Longitude}_{ijk}, \text{Latitude}_{ijk}]
\]

where, \( i \) is one SCM sample located in a grid of 100 m by 100 m in urban (based on mean distance of 0.5 km between serving BSs along route to mobile or serving BSs to mobile within the grid), 200 m by 200 m in suburban (mean distance of 1 km or more between serving BSs and mobile) and 400 m by 400 m in rural (mean distance of 3
km or more between serving BSs and mobile), $j$ are all the BSs’ Cell ID that are capable of serving the grid’s $SL(i)$, and finally $k$ are the list of signal strengths pertaining to each BS’s Cell ID that are capable to serve the $i^{th}$ sample location. The first GRNN layer’s bias, $b$ is configured to 0.8326/spreading, where larger value of spreading enables the curve fitting to be smoother. The varying effect of this spreading constant will be discussed in the simulation performance. The first layer weights are the transpose of input vector $[P(i)]^T$ while the second layer weights are set to $[SL(i)]$. The input vector, $P(i)$ is defined as:

$$P(i) = [Cell ID_j, SS_k]$$

(3.18)

Figure 3.17 illustrates the relationship between grids, sample location and inputs from serving cells. In example of Figure 3.17, when the data collection process is done in urban, one area block could contain 5 by 5 grids (25 grids) which mean 500 m by 500 m per area (since one grid size is 100 m by 100 m). Several hundreds of the area blocks would represent a big city. The data collection work could then be segregated among the regional staff of Telco. From experiments, GRNN requires a lot of memory for processing and careful planning is required in order to determine the size of an area because loading a GRNN with too big of irrelevant coverage area could slower the PT and sometimes the processors may not be able to compute due to insufficient memory. Consideration of large LBS requests, number of processors to be used, memory capacity and handling, number of sub GRNN networks to be trained and loaded as “standby” for selected areas, and number of GRNN networks to process
only upon requests should be analyzed in order to get the maximum efficiency of LBS services offered.

Figure 3.17 Data collection, processing and storing for SCM samples

In Ahonen & Eskelinen (2003), a receiving grid size of 12.5 meter was used for DCM. In SCM, a smaller grid size will cause dilemma for the algorithm to predict location within certain accuracy, for example if a new input is received from a mobile user with Cell ID 5001 and Signal Strength (SS) of -90 dBm, referring to the stored values in Figure 3.17, there will be two competing samples: SL(1) and SL(2) located within Grid (5,5) of Area n. In this case, if either one of the SL is selected within this grid, the accuracy is still within 100 meters. However for adjacent grids, both input values (exact Cell ID with same SS) is recommended not to be the same in order to avoid conflict of prediction. However, closer SS value for the same Cell ID could enable SCM to select or calculate a location between the two neighboring grid’s locations. Statistical tools (Martinez & Martinez 2002) such as using Gaussian distribution, probability distribution function or by using Cumulative Distribution Function (CDF) to calculate the mean and standard deviation of all the available SS
for one cell collected over 12 hours in one location grid (such as in SL(1), Grid (5,4) of Area n), would provide the most likely SS range (from determining mean $\mu$ value and standard deviation $\sigma$ value) to be stored for the Cell ID within the SL of the corresponding area. The data collection process and proposed grid sizes for urban, suburban and rural has been based on our analysis of different area of drive tests, and stationary samples collected. The state of phone in idle mode or voice call or data call during data collection must be noted as this same state of storage data should only be matched to the real state of measured data. The process of selecting and optimizing data sets for storage, learning/training process of the data sets and processing the data could influence the location estimation accuracy of SCM, and therefore several learning techniques are introduced.

SCM-LEAN, SCM-US and SCM-USUC are introduced in the following subsections, where all these three new learning techniques are to be used in different area settings: SCM-LEAN used in populated urban and suburban, SCM-US used in populated urban and suburban with high fadings, and SCM-USUC used in larger cell suburbs.

### 3.11.3 Data collection process and development for SCM-LEAN

The same data collection process that was discussed in the beginning of Chapter 3 was used here. Using Telco’s drive test equipment installed on a laptop, connected to mountable outdoor GPS unit, one Nokia phone for GSM measurements and one UMTS phone for 3G measurements, the drive test route was performed. Figure 3.3 shows the urban-suburban drive test route (Menara Celcom to Wangsa Melawati). For SCM, both the phones were set on active voice call mode in order to collect active serving cells along the route. The vehicle speed was maintained as slow as possible (but not too slow to disrupt other traffic). For SCM corresponding to urban-suburban route, three repetitions (three trials on the same route) were conducted on the same day. The first trial (started at about 3.31 pm) was from Menara Celcom to Wangsa Melawati. The second trial (started at 4.02 pm) was from Wangsa Melawati back to Menara Celcom, and the third trial (started at 4.21 pm) was again from Menara Celcom to Wangsa Melawati, with slower speed and stopping over in the middle of
the route. The purpose of the three repetitive trials, slower speed, opposite directions and stationary position is to grab as much unique serving cells’ information (Cell ID with measured signal levels) as possible by covering the different direction of handovers, and dominant cells (where handovers are less for stationary point) within the covered route in a given day. The drive test device is capable to collect one SS for the serving Cell (Cell ID) pertaining to one SL (sample location coordinate) within one second for UMTS network. For GSM, two or three samples (one sample contains one SS value, one Cell ID and one SL coordinate) measurements are possible within a second. Figure 3.18 illustrates the process of collecting samples for SCM-LEAN. Let say the collection of samples for trial 1 of the urban-suburban route is represented by matrix $R_{i1}$, for trial 2 represented by matrix $R_{i2}$, and for trial 3 represented by matrix $R_{i3}$, where $i$ corresponds to one collected sample: one SS value in dBm, one serving Cell ID in decimal, and one GPS coordinate of longitude and latitude. Once the data collection process for the three trials of the same route (such as urban-suburban route) is completed, data analysis and development of an LDT (for this case is SCM-LEAN)

![Diagram](image-url)

Figure 3.18 SCM data collection process requires at least three trials of same route
to meet accuracy requirements follows as methodology described in Figure 3.1. The developed SCM-LEAN algorithm to select relevant datasets, training and learning process is shown in Figure 3.19.

The concept here is to use unique data or highly diverse data for processing the new location estimation because too much of unnecessary data could slower the ANN process (slower PT) and utilize large memory allocations. Also unprocessed data with

![Figure 3.19 SCM with processed optimized Learn-Another (LEAN) data ready for actual location estimation](image-url)
conflicting (same Cell ID and same SS but farther locations) measurements could increase inaccuracy of GRNN’s estimation. Because SCM is based on correlating (finding the nearest match) the current signal value to stored signal value and the current cell value to stored cell value in order to predict the best approximated coordinate of location. So the acquisition of highly diverse data is crucial for SCM’s location accuracy. The first step as in Figure 3.19 is to select only 12% unique data (samples) of Trial 1. Then with this small sample size of Trial 1, location would be estimated using GRNN network based on simulated input of Cell ID and SS of all Trial 2’s samples. The estimated trial 2’s mobile locations are compared to the actual trial 2’s mobile locations. The higher 5% (or 5% worst performing samples with higher location error differences) of total trial 2’s samples is then injected (combined) into the initial 12% trial 1’s samples. This is where SCM learns another (related to human behavior where one is learning from another’s weakness in order not to totally repeat the same mistake again). Learn-another (LEAN) process will optimize the acquisition of more diversified samples, and maintaining a small storage (processed data) sample size for the drive test route. After trial 2’s worst data has been combined with unique trial 1’s 12% data, simulation for trial 3 begins, where all trial’s 3 data are compared (matched) with the combined stored samples of unique trial 1 and LEAN of trial 2. Similarly, the higher 5% location error difference samples of trial 3 are taken as LEAN in order to be combined to the earlier unique samples of trial 1 and LEAN samples of trial 2. Finally, the LEAN process is repeated by simulating all trial 1’s samples in order to find samples in trial 1 that causes higher location error results. The 5% samples of trial 1 are then injected to the earlier combined unique trial 1, LEAN trial 2 and LEAN trial 3 samples. The final processed SCM-LEAN will store unique trial 1 samples, LEAN trial 1, LEAN trial 2 and LEAN trial 3 samples and contain around 25% to 35% of route 1’s total sample size, representing all the unique Cell ID within the drive test route. The SCM-LEAN is now ready (standby) to simulate any new inputs (such as one measured SS level corresponding to the Cell ID) and will output the corresponding Estimated Location=[Longitude, Latitude]. In general, SCM-LEAN should be used in densely populated areas but when SS variations are high for a grid or fixed position (such as indoors Laiho et al. (2006) use slow fading constant of 12 dB and outdoor fading constant of 7 dB for calculating allowable UMTS propagation loss), another method called SCM-USS will be used.
3.11.4 Development for SCM-US (high variations of SS)

After the raw data collection of Figure 3.18 is completed for the three trials of drive test, the mean and variance of SS for each cell could be obtained using statistical tools. If more than 70% of grids covered by the three trials or stationary area’s grids have SS variance (variations or range difference) greater than 6 dB, then SCM-US is used. The recommended SS variance for SCM is the difference between SS at 5% of CDF and SS at 95% of CDF, received from within the grid (when doing drive test trials) or from the same cell at a fixed location (when stationary indoor or outdoor is measured) monitored over a period of 6 to 12 hours.

The process for SCM-US is shown in Figure 3.20. Firstly all the trials for a drive test route (or data collected within an area of grids) are combined together as a single matrix, called RC. Then, unique samples are selected based on the range of SS for each serving cells within the grid area (for all the three trials or over several hours of data collection in stationary indoor/outdoor grid areas). For example, during trial 3 of route urban-suburban, the vehicle detoured about 100 m from the main road and stopped for 16 minutes at coordinate 101.7026, 3.188345 while recording UMTS stationary samples’ number 726 to 1668 (total sample recorded for trial 3 is 2540). Trial 3 was the only trial where this grid (with the above stationary coordinate) was being measured. So the total observation (from all the trials) at this particular grid produced SS mean of -90.8 dBm, SS minimum at -94 dBm, SS median at -91 dBm, SS maximum at -88 dBm, SS 5% CDF at -92 dBm, SS 95% CDF at -89 dBm, and standard deviation of 0.923, where 92% of these stationary samples were covered by one serving cell (11203) while 4 other serving cells covered the rest 8% of the samples during this stationary position. The dominant cell (11203) also produced SS minimum at -94 dBm, SS maximum at -88 dBm, SS 5% CDF at -92 dBm, SS 95% CDF at -89 dBm and mean of -90.79 dBm. The SCM variation is therefore 3 dB for this grid on cell 11203, and 3 dB for all the other cells too. Only SS value range of -89 till -92 dBm (SS values between CDF 5% till 95 %) will be stored for all the 5 Cell IDs corresponding to this grid’s sample’s location. If more than 70% of the route/area’s grid has SCM SS variations of more than 6 dB, then SCM-US is used,
otherwise SCM-LEAN is preferred because of its smaller sample collection and faster PT. When SCM-US is used, cumulative unique samples of all the trials should not exceed 2500 stored samples or else GRNN will run out of memory. If unique samples are more than 2500, every third or fourth alternate sample in the order from beginning to end of the route are processed and stored.

Figure 3.20  SCM with Unique Sample (US) data ready for location estimation
After processing, SCM-US is ready for actual usage. For SCM to be used in larger cellular coverage areas, SCM-USUC is developed.

3.11.5 Data collection process and development for SCM-USUC (large cell size)

In less dense suburbs and rural areas, cell size are large and SCM technique would need to be modified if certain range of accuracy is required or better than Cell ID’s location estimation. To test this technique, data collection is done in suburban Bandar Sungai Long (between Cheras and Kajang) where the objective is to collect SS (RSSI) and Cell ID of 3G/UMTS/GPRS data services from Telco B’s network. It is also hoped with this study, UIPS client that is to be installed on Symbian/Window CE phones would be able to support phone based measurements, also known as phone assisted location estimation since all calculation done at UIPS server side, when LBS queries are made through data bearer during 3G data active mode. Performing drive test for data mode is more complicated than voice mode, because in suburbs when HSDPA or 3G services are unavailable, the phone will be handed over to GPRS data services. GPRS data services are more prominent in the areas where drive test was performed. Figure 3.21 illustrates the data collection routes on vehicle collected at

![Figure 3.21 Data collection for 3 routes and one stationary point in suburban Cheras](source: Map from Google Earth (Anon 2008k))
late night of 28th June 2008, along with a stationary test point’s location used for data collection. Route 1 (red color is 6.152 km in distance) was repeated for 4 trials in clockwise direction, Route 2 (green color is 1.29 km in distance) was done once because it is a very short route, and Route 3 (blue color is 4.63 km in distance) was repeated 3 trials in anticlockwise direction. The fourth trial of Route 1 will be used for evaluation of SCM’s location estimation algorithm. For stationary point, data was collected for 10 hours starting at 1343 on 28th June 2008 till midnight in an indoor two storey house. Stationary data measured on 29th June 2008 at the same indoor location will be used for SCM’s location evaluation by matching with SCM’s previously stored data (drive test collection and USUC stationary data of 28th June 2008). It was assumed that Telco B did not do any GPRS or 3G network optimization on the time of data collection. The equipment used for data collection is one Nokia N95 phone (equipped with internal GPS) and CellTrack91 software downloaded from website (Fischer 2008) running on Symbian OS (Anon 2008p). Our version of UIPS’s data logger for drive test and stationary data collection was not fully usable at the time of experiment and therefore had to use CellTrack91 for both data collection and real data measurements of RSSI and Cell ID. The phone was on active 3G/GPRS data service mode, with activity of browsing internet and reading webpages. After the data was collected for the routes and stationary point, it was analyzed as described in Figure 3.1 and SCM-USUC was developed for this category of suburban area.

Figure 3.22 illustrates the process for SCM-USUC. Since LBS requests will be low for suburbs such as Bandar Sungai Long, the Area n (as in Figure 3.17) could be larger in order to cover all the 3 routes along with the one stationary test point. The combined matrix, RC will consists of all routes trial’s samples (3 trials of route 1, 1 trial of route 2, 3 trials of route 3). The same process as SCM-US follows in order to only select unique samples, where one cell’s SS range will be between 5% to 95% of the CDF collected for SS within single grid on a road (grid size for suburban is 200 m by 200 m). The one stationary test point’s samples collected over several hours (28th June 2008) will be matched and correlated against all the stored drive test routes’ samples during GRNN simulation in order to estimate mobile location. A very low spreading value of 0.1 is used in order to evaluate SCM’s failure rate and to test the robustness of the unique drive test’s stored data in covering the surrounding stationary
grids and housing areas. The samples collected over the housing area (one single stationary test point) will have the lists of SS (non unique) for each Cell IDs (serving cells) and when run against the stored data, GRNN will try to match and predict the best estimated location. If the test point’s inputs (one SS and one Cell ID) are badly correlated with stored drive test samples, then GRNN will not produce any result for the given inputs. This undefined result would be reported from the stationary samples’

Figure 3.22 SCM Unique Sample Undefined Collection (USUC) data ready for actual location estimation
index of the corresponding SS and Cell ID, and later would be programmaticalrexinserted into the previously stored drive test data. In some trials of experimentation
to test SCM-USUC, only a few undefined samples (1% collected and corrected samples from the total samples run for a stationary test point) are required to be inserted into the database, for example Cell 100 with SS range of -90 dBm to -93 dBm and Cell 200 with SS range of -81 dBm to -82 dBm, that would be able to solve all the undefined estimated locations pertaining to the test point. In this case, the test point’s location is known. But when there are more test locations for the suburbs, GPS coordinates should be sent along through the test phones or data collecting equipment during this initial surveying and data collection phase. Once stored data has been inserted/corrected in the collection phase for all the grids of stationary test locations within the suburb area, the GRNN would be run again with the regular spreading value of 0.5. Finally SCM-USUC is ready for actual usage of correlating one SS of one Cell ID to stored values in order to produce an estimated location.

3.12 CONCLUSION

In this chapter, the entire research methodology was described and summarized in Figure 3.1. The process of data collection, data analysis, development of simulator for timing measurements and RSS measurements were presented. Table 3.1 summarizes each LDTs and prediction models that were developed for this research and would be used for location estimation. All LDTs and prediction models developed for UIPS goes through continuous improvement process until certain level of accuracy is met, before each estimation technique is integrated into UIPS LDT module. For emergency services, the accuracy standard should comply with US FCC E-911 location accuracy requirements, where 67% of location estimations should be below 100 m and 95% of location estimations should be below 300 m.

The simulated performance of these LDTs and prediction models developed for timing measurements of one, two and three hearable cells will be presented in Chapter 4, while the LDTs developed for Signal Correlation Method of one cell will be evaluated in Chapter 5.
CHAPTER IV

PERFORMANCE OF TIMING TECHNIQUES

4.1 INTRODUCTION

In this chapter, the simulation and performance of CCC and NR3C techniques will be presented for kLOS UMTS (using OTDOA) and GSM (using E-OTD) environment based on the drive test data collected along urban-suburban, metropolitan, suburban-rural, and highway routes. For uLOS UMTS and GSM environment, an urban-suburban area will be simulated to evaluate the performance of CCC averaging and NR3C averaging techniques. Simulations of urban-suburban drive test route for kLOS will also be evaluated when hearability of BSs is two and then evaluated when hearability is limited to one, using LDTs and prediction models (developed in Chapter 3) to estimate GSM and UMTS user’s location. Finally the results on simulated timing measurements will be presented and discussed in the final section of this chapter.

4.2 SIMULATION AND PERFORMANCE OF CCC AND NR3C TECHNIQUES FOR UMTS DRIVE TEST ROUTES (KLOS)

For simulation, each route is played back with the same order of ECNO RSCP values and same arrangements of active and monitored hearable base stations as collected from beginning to end of route. By using ECNO measurements for each route, UIPS will programmatically arrange at least three BS (Node Bs) before simulating TDOA (OTDOA) measurements. The step of utilizing ECNO (NMR measurements) will provide the hearability report of BSs and hence update UIPS of which technique to use (timing, enhance timing or signal correlation). In this case of simulation, where ECNO has indicated at least three unique BSs presence (one serving and two other neighbors), OTDOA measurements are then simulated with random timing delays as
described in Chapter 3. CCC and NR3C estimation techniques will be utilized to estimate the location of UE along each route. Performance of the estimated UE versus actual UE samples collected will be compared and presented for each LDT technique.

4.2.1 UMTS Urban-Suburban Route: Menara Celcom to Wangsa Melawati (3.31 PM, 20/11/2007)

Figure 4.1 illustrates the route of the drive test. Some gaps between the route indicated the unavailability to obtain measurements and due to dropped voice call (network disconnection). When the test call is disconnected, every effort to quickly stop the vehicle and reconnect was done for measurements to have the continuation effect. Through data validation, the gaps were small compared to the total trip distance, and will not influence the order of simulation. Furthermore, this route was repeated three times during measurements because this area was the main focus of the urban-suburban study for timing technique and signal correlation technique.

Figure 4.1 Route Menara Celcom to Wangsa Melawati at 3.31 pm, 20/11/2007
Menara Celcom, located in urban Kuala Lumpur (KL) was chosen as the starting point as it is one of the tallest structures within this urban-suburban route, followed by a few other landmarks. This route (average travel distance of 9.7 km) then continues to cover three storey shophouses, commercial shopping areas and more suburban residential areas (Wangsa Maju) towards the end of the route, before ending at Wangsa Melawati shops (opposite Taman Melawati commercial area). For UMTS this route was also recorded in July 2006. Table 4.1 shows the hearability (N) for this urban-suburban route.

Table 4.1  \( N \) for route Menara Celcom to Wangsa Melawati (3.31 pm) with average velocity (\( \nu \))= 19 km/h (max= 70 km/h), dist= 9.7 km and trip time= 31 min

<table>
<thead>
<tr>
<th>Measurement</th>
<th>( N=1 )</th>
<th>( N=2 )</th>
<th>( N=3 )</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>194</td>
<td>199</td>
<td>1728</td>
<td>2121</td>
</tr>
<tr>
<td>% of samples</td>
<td>9.1</td>
<td>9.4</td>
<td>81.5</td>
<td>100 ( (N=\text{all}) )</td>
</tr>
</tbody>
</table>

CCC and NR3C methods will be utilized for UE location estimation when hearability of three BSs (\( N=3 \) for 1728 samples) or more are observed. For \( N \) less than 3, enhanced techniques using LDT prediction models will be evaluated in the later sections. The distribution of Node Bs’ distance to UE (during each sample all the three Node Bs’ distances are measured with respect to UE) is shown in Figure 4.2.

First of all, to check the algorithm’s performance (such as to verify \( G_{Error} \)) in an ideal scenario, CCC is simulated through this route without any time delays (only Geometric Time, where \( T_A=T_G \)). The CDF plot (vertical axis’s 100% normalized to 1) for error distance in meters (using Equation 3.5) for UE estimated versus actual UE along route Menara Celcom to Wangsa Melawati is shown in Figure C.1 (Appendix C) for CCC method, and is shown in Figure C.2 for NR3C method. It can be observed that NR3C produced below 7 nanometers of location errors while CCC produced 95% (Probability, \( P \leq 0.95 \)) of errors less than 3.2 m and maximum error of less than 18 m.

Figure 4.3 shows the CDF result for OTDOA timing simulation (using random delays for kLOS model described in Chapter 3) on urban-suburban route using CCC method to estimate 1728 (hearability of three BSs) UE locations.
Figure 4.2 Actual UE distances to three Node Bs (1728 samples) for above route.

Figure 4.4 shows the CDF result using NR3C method to estimate UE locations (actual UE locations are known from drive test coordinates) along the same route.

Figure 4.3 CDF Results for CCC method to estimate UE locations (1728 samples) along Menara Celcom to Wangsa Melawati (3.31 pm)
Figure 4.4 CDF Results for NR3C method to estimate UE locations (1728 samples) along Menara Celcom to Wangsa Melawati (3.31 pm)

Figure C.3 shows the geometrical placement of three BSs with respect to the actual UE, at maximum and minimum error locations of estimated UE obtained through CCC. Figure C.4 shows the placement of three BSs at maximum and minimum error locations of estimated UE obtained through NR3C methods. At maximum error of estimated location, it is found that three hearable BSs are placed in a row. As a note, best geometry algorithm ($L_1$) and distance check algorithm ($L_g$) were not applied for some of the kLOS route, unless stated. The reason is to study the actual BSs’ placement’s effect towards the location estimations’ technique. However $L_g$ will be used when more samples are affected as in the next subsections.

4.2.2 UMTS Suburban-Urban Route: Wangsa Melawati to Menara Celcom (4.02 PM, 20/11/2007)

This is the opposite direction of the same route described earlier. The same process of simulation is also applied here. The hearability for this route is as listed as in Table 4.2. Table 4.3 shows the CDF distribution of three BSs’ distance to UE for 910
samples when hearability is three \((N=3)\), CCC results for location estimation of UE and NR3C results for location estimation of UE.

Table 4.2 \(N\) for route Wangsa Melawati to Menara Celcom (4.02 pm) with avg \(v=30.3\) km/h (max \(v=66\) km/h), dist= 9.6 km and trip time= 19 min

<table>
<thead>
<tr>
<th>Measurement</th>
<th>(N=1)</th>
<th>(N=2)</th>
<th>(N=3)</th>
<th>Total Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>10</td>
<td>207</td>
<td>910</td>
<td>1127</td>
</tr>
<tr>
<td>% of samples</td>
<td>0.887</td>
<td>18.4</td>
<td>80.74</td>
<td>100 ((N=all))</td>
</tr>
</tbody>
</table>

Table 4.3 CDF of BSs’ distances to UE and CDF for UE estimated using CCC and NR3C for route Wangsa Melawati to Menara Celcom (4.02 pm)

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% of CDF (m)</th>
<th>67% of CDF (m)</th>
<th>95% of CDF (m)</th>
<th>Max Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB1</td>
<td>465.4</td>
<td>653</td>
<td>1242</td>
<td>1699</td>
</tr>
<tr>
<td>NB2</td>
<td>804.3</td>
<td>940.9</td>
<td>1305</td>
<td>2461</td>
</tr>
<tr>
<td>NB3</td>
<td>1011</td>
<td>1246</td>
<td>1994</td>
<td>3190</td>
</tr>
<tr>
<td>CCC Results</td>
<td>4.56</td>
<td>6.6</td>
<td>17.94</td>
<td>160.2</td>
</tr>
<tr>
<td>NR3C Results</td>
<td>3.8</td>
<td>5.85</td>
<td>27.6</td>
<td>421.2</td>
</tr>
</tbody>
</table>

4.2.3 UMTS Urban-Suburban Route: Menara Celcom to Wangsa Melawati (4.21 PM, 20/11/2007)

This is the same urban route repeated again for Menara Celcom to Wangsa Melawati, as was shown in Figure 4.1. The hearability for the route is as listed in Table 4.4.

Table 4.4 \(N\) for route Menara Celcom to Wangsa Melawati (4.21 pm) with avg \(v=13.4\) km/h (16 min stationary), max= 57 km/h, trip= 9.6 km within 43 min

<table>
<thead>
<tr>
<th>Measurement</th>
<th>(N=1)</th>
<th>(N=2)</th>
<th>(N=3)</th>
<th>Total Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>64</td>
<td>248</td>
<td>2228</td>
<td>2540</td>
</tr>
<tr>
<td>% of samples</td>
<td>2.52</td>
<td>9.76</td>
<td>87.7</td>
<td>100 ((N=all))</td>
</tr>
</tbody>
</table>
Table 4.5 shows the CDF distribution of three BSs’ distance to UE for 2228 samples when hearability is three \((N=3)\), CCC results for location estimation of UE and NR3C results for location estimation of UE. In the middle of the route, there was some stopover (16 minutes) while the phone was in active voice call. It can be observed for 3G system, serving cell or NB1 is not always the nearest cell to the mobile (UE) if compared to neighbor cells (NB2 distances to UE are closer than NB1).

Table 4.5  CDF of BSs’ distances to UE and CDF for UE estimated using CCC and NR3C for route Wangsa Melawati to Menara Celcom (4.21 pm)

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% of CDF</th>
<th>67% of CDF</th>
<th>95% of CDF</th>
<th>Max Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB1</td>
<td>726.1</td>
<td>1796</td>
<td>1796</td>
<td>2551</td>
</tr>
<tr>
<td>NB2</td>
<td>612.3</td>
<td>824.4</td>
<td>1684</td>
<td>2525</td>
</tr>
<tr>
<td>NB3</td>
<td>849.1</td>
<td>849.1</td>
<td>1831</td>
<td>4246</td>
</tr>
<tr>
<td>CCC Results</td>
<td>7.55</td>
<td>13.8</td>
<td>42.76</td>
<td>46.96</td>
</tr>
<tr>
<td>NR3C Results</td>
<td>6.932</td>
<td>16.67</td>
<td>40.21</td>
<td>417.3</td>
</tr>
</tbody>
</table>

Maximum Error of NR3C is higher due to 3 BSs placement in straight line (almost vertically placed) for the simulated UE sample.

4.2.4 UMTS Urban-Suburban Route: Menara Celcom to Wangsa Melawati (1.10 PM, 27/07/2006)

This route’s data was first collected in year 2006. Since then the ECNO field has been slightly updated by Telco to include an extra “reserved” field for each active channel measured. The hearability for the route is as listed in Table 4.6.

Table 4.6  \(N\) for route Menara Celcom to Wangsa Melawati (July 2006), with avg \(v=45\) km/h (max= 87km/h), trip dist= 9.7 km and trip time= 13 min

<table>
<thead>
<tr>
<th>Measurement</th>
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<th>(N=2)</th>
<th>(N=3)</th>
<th>Total Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>24</td>
<td>31</td>
<td>596</td>
<td>651</td>
</tr>
<tr>
<td>% of samples</td>
<td>3.69</td>
<td>4.762</td>
<td>91.55</td>
<td>100 ((N=\text{all}))</td>
</tr>
</tbody>
</table>
Table 4.7 shows the CDF distribution of three BSs distance to UE for 596 samples when hearability is three ($N=3$), CCC results for location estimation of UE and NR3C results for location estimation of UE. Sample size was lesser than the same routes of year 2007 because faster movement of vehicle to cover measurements. There were only twenty three unique serving Node Bs along this route. The 95% error of NR3C is higher than similar routes because higher-error (error $\geq 95\%$) samples occurred even though with smaller total sample size. If the sample size was bigger, the higher errors could be averaged out with smaller errors. The maximum error for CCC is also higher than similar routes because the UE sample measured took the farthest NB1 as the serving cell, followed by NB3 as second farther and, NB2 as the closest. As was discussed earlier, the farther the Node Bs to UE, the higher delays are added (proportional relationship) to the actual distance.

Table 4.7 CDF of BSs’ distances to UE and CDF performance for UE estimated locations using CCC and NR3C for route Menara Celcom to Wangsa Melawati (July 2006)

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% of CDF (m)</th>
<th>67% of CDF (m)</th>
<th>95% of CDF (m)</th>
<th>Max Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB1</td>
<td>500</td>
<td>707.4</td>
<td>1640</td>
<td>3503</td>
</tr>
<tr>
<td>NB2</td>
<td>928.1</td>
<td>1030</td>
<td>2226</td>
<td>3572</td>
</tr>
<tr>
<td>NB3</td>
<td>1257</td>
<td>1702</td>
<td>3024</td>
<td>3558</td>
</tr>
<tr>
<td>CCC Results</td>
<td>6.112</td>
<td>8.90</td>
<td>56.14</td>
<td>314.9</td>
</tr>
<tr>
<td>NR3C Results</td>
<td>5.345</td>
<td>8.545</td>
<td>117.4</td>
<td>244.8</td>
</tr>
</tbody>
</table>

4.2.5 UMTS Metropolitan Route: Jalan Tun Razak-Ampang-KLCC-Bukit Bintang (2.31 PM, 20/11/2007)

This is a metropolitan route starting from Jalan Tun Razak (after Menara Celcom), towards Jalan Ampang (Nikko Hotel), Menara Maxis, Kuala Lumpur City Center (KLCC), Mandarin Oriental Hotel, Jalan Pinang (high rise office buildings), Jalan Bukit Bintang (passing high rise hotels) and finally towards Bukit Bintang shopping complex. This route was chosen as metropolitan route as it is one of the busiest with the biggest concentration of high rise buildings (KLCC is one of the world’s tallest office building located along this route). Unlike Manhattan environment, that is
normally used as reference for dense urban propagation studies, KL urban is quite unique with its distribution of smaller areas of high rises and wider areas of 3 to 4 storeys of commercial shoplot buildings. Therefore this route was chosen as it covers almost all the major high rises in KL’s dense urban settings. Figure 4.5 illustrates the route, while Table 4.8 illustrates the hearability along this route. Figure 4.6 shows the three BSs’ distances (serving Node B and two neighbors Node Bs) to UE while on the route. It can be observed that the maximum distances between all serving and neighbor Node Bs to UE are less than 1230 meters. With the same delay equation as applied to the urban-suburban route (as in the previous section), the results for CCC and NR3C location estimation of UE for \( N=3 \) is shown as CDF plot in Figure 4.7.

![Figure 4.5 Metropolitan KL route at 2.31 pm on 20/11/2007](image)

**Table 4.8**  Hearability for metropolitan route (2.31 pm, 20/11/2007) with avg \( v=8.4 \) km/h (heavy traffic jam, max \( v=62 \) km/h), distance= 4.2 km and trip time= 30 min

<table>
<thead>
<tr>
<th>Measurement</th>
<th>( N=1 )</th>
<th>( N=2 )</th>
<th>( N=3 )</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>27</td>
<td>177</td>
<td>1545-uncorrected</td>
<td>1749</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1528-corrected (87%)</td>
<td></td>
</tr>
</tbody>
</table>


Figure 4.6 UE distances to three Node Bs while travelling on the metro route

Figure 4.7 CCC and NR3C performances to estimate UE locations for metro route

It is worth a note that during simulation of NR3C, only 1528 samples out of 1545 ($N=3$) of UE locations were successfully computed. This is due to the reason that the 17 samples even though were with unique identification but were sharing the same site locations (some of the Node B coordinates are the same) and hence there were more unknown and less equations to solve for the hyperbolic equations. In CCC case,
this was not a problem as CCC is not purely based on mathematical computations but rely on geometrical proximity. CCC produces an error within 132.5 meters for all the 17 samples which was still accepted for E-911 accuracy requirements. However, the CDF plot for both CCC and NR3C in Figure 4.7 was based on \( N=3 \) of 1528 corrected samples. The sample size still represented 87% of the entire ECNO measurements for \( N=3 \). The accuracy in metropolitan route is better than urban-suburban because all the three Node Bs/microcells placements were quite distributed and close to the road (UE) during measurement.

### 4.2.6 UMTS Metropolitan Return Route: Bukit Bintang-KLCC-Jalan Tun Razak (3.01 PM, 20/11/2007)

This is the metropolitan route from Bukit Bintang complex towards Jalan Imbi (Berjaya Times Square), Jalan Raja Chulan, KLCC, Menara Maxis, Ampang Park, towards Jalan Tun Razak (near Menara Celcom shoplots). This route is almost the return trip as above’s route but had to deviate slightly near Jalan Raja Chulan as to follow one way street direction. Figure 4.8 shows the direction of the route, while Table 4.9 lists the hearability along this return metropolitan route. Table 4.10 lists the distribution between the distances of three BSs to UE, CCC results and NR3C results.

![Figure 4.8 Metropolitan KL return route at 3.01 pm on 20/11/2007](image)
Table 4.9  \( N \) for metropolitan return route (3.01 pm, 20/11/2007) with avg \( v\) = 10.3 km/h (heavy traffic, max \( v\) = 68 km/h), distance= 5 km and time= 29 min

<table>
<thead>
<tr>
<th>Measurement</th>
<th>( N=1 )</th>
<th>( N=2 )</th>
<th>( N=3 )</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>10</td>
<td>334</td>
<td>1435-uncorrected</td>
<td>1779</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1369-corrected (76.9%)</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.10 CDF of BSs’ distances to UE and CDF for UE estimated locations using CCC and NR3C for metropolitan return route (3.01 pm, 20/11/2007)

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% of CDF</th>
<th>67% of CDF</th>
<th>95% of CDF</th>
<th>Max Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB1</td>
<td>189.7 (m)</td>
<td>297 (m)</td>
<td>501.3 (m)</td>
<td>947.9 (m)</td>
</tr>
<tr>
<td>NB2</td>
<td>418.8 (m)</td>
<td>458.7 (m)</td>
<td>691.9 (m)</td>
<td>1297 (m)</td>
</tr>
<tr>
<td>NB3</td>
<td>497.1 (m)</td>
<td>577.4 (m)</td>
<td>764.3 (m)</td>
<td>1524 (m)</td>
</tr>
<tr>
<td>CCC Results</td>
<td>1.976</td>
<td>2.93</td>
<td>7.953</td>
<td>73.3</td>
</tr>
<tr>
<td>NR3C Results</td>
<td>2.135</td>
<td>3.097</td>
<td>14.74</td>
<td>172.7</td>
</tr>
</tbody>
</table>

NRC3 has a maximum error which is large because of the BSs’ placements. During this event NB2 was so close to the UE, while NB1 (serving) is quite far and NB3 is the farthest. NB1 and NB3 are aligned vertically with same longitude coordinate. This demonstrates NR3C’s sensitivity to BSs’ GDOP problems.

4.2.7 UMTS Suburban-Rural Route: Plaza Phoenix Cheras-UKM Train Station (5.41 PM, 20/11/2007)

This route starts near Plaza Phoenix of Cheras Kajang toll highway, passing through both toll booths and moving towards Cheras old road, Cheras Batu 13, Sungai Sekamat (semi rural village), passing through Kajang town, Jalan Reko (old road to UKM campus in Bangi) and ending near UKM train station. The route is illustrated as in Figure 4.9. Table 4.11 illustrates the hearability of BSs’ along this route. Table 4.12 illustrates the three BSs’ distances to UE during the route, CDF for CCC location estimations and CDF for NR3C location estimations. Each hearable Node B as observed by UE also reaches maximum distances (about 6000 meters) to UE when approaching towards the end of the rural route.
Figure 4.9  Suburban to rural route started at 5.41 pm on 20/11/2007

Table 4.11  \( N \) for route Cheras Kajang highway to UKM Bangi (5.41 pm) with avg \( v= 48 \text{ km/h} \) (max \( v= 81 \text{ km/h} \)), distance= 18.4 km and trip time= 23 min

<table>
<thead>
<tr>
<th>Measurement</th>
<th>( N=1 )</th>
<th>( N=2 )</th>
<th>( N=3 )</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>42</td>
<td>217</td>
<td>&lt;1241 (uncorrected)</td>
<td>1500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1236 (corrected)</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.12  CDF of BSs’ distances to UE and CDF performances for UE estimated using CCC and NR3C for suburban-rural route (5.41 pm, 20/11/2007)

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% of CDF (m)</th>
<th>67% of CDF (m)</th>
<th>95% of CDF (m)</th>
<th>Max Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB1</td>
<td>805</td>
<td>1262</td>
<td>2849</td>
<td>6213</td>
</tr>
<tr>
<td>NB2</td>
<td>1495</td>
<td>1830</td>
<td>3601</td>
<td>6266</td>
</tr>
<tr>
<td>NB3</td>
<td>1576</td>
<td>1955</td>
<td>3928</td>
<td>6383</td>
</tr>
<tr>
<td>CCC Results</td>
<td>9.136</td>
<td>13.44</td>
<td>52.05</td>
<td>2981</td>
</tr>
<tr>
<td>CCC Results (Lg)</td>
<td>9.096</td>
<td>13.38</td>
<td>51.11</td>
<td>1552</td>
</tr>
<tr>
<td>NR3C Results</td>
<td>8.788</td>
<td>16.91</td>
<td>242.6</td>
<td>10620</td>
</tr>
<tr>
<td>NR3C Results (Lg)</td>
<td>8.739</td>
<td>16.68</td>
<td>221.7</td>
<td>1092</td>
</tr>
<tr>
<td>NR3C Results (Lg)</td>
<td>2.1</td>
<td>3.68</td>
<td>56.86</td>
<td>151.1</td>
</tr>
</tbody>
</table>

\( D_{PE} = 1.8 \times 10^{-9} \)
It is analyzed that almost at the end of the simulated 1240th sample, CCC has the highest error distance of 2981 meters. This is caused by NB1 and NB2 were actually sharing the same site with a distance of 22.3 m apart from each other. NR3C method also suffered from this non-unique site’s data causing 5 samples’ measurements at the end of the route to suffer from maximum erroneous estimations. As was discussed in Figure 3.1, when an LDT technique suffers from inaccuracy problems, the software development cycle will require further improvement to the LDT technique. Here the cause was realized and the logical statement \( Lg \) (distance check) was added to check and discard ECNO measurements that are caused by non-unique site’s data. In this example, 5 measurements were identified to have BSs differences (distances among each BS) to be below 30 meters. The new hearability for \( N=3 \) after \( Lg \) is applied is 1236, and the process of estimation by NR3C and CCC is repeated. For the corrected unique site data, CCC’s result for 95% and below is about the same (estimated location accuracy within 55 m) but the maximum error has reduced to 1552 m. These high estimated maximum errors are of small numbers (small samples with error \( \geq 95\% \)) and are caused by high unresolved erroneous time delay prediction, in addition to further distances of BSs to UE in rural settings. In addition, the maximum error sample also suffered from three BSs alignment in vertical order (latitude about the same but with distant longitudes) over the actual measured UE. NR3C’s maximum error has dropped significantly when \( Lg \) is applied, but the new maximum error is still due to GDOP when 3 BSs latitude is almost parallelly aligned. The 95% estimated errors are rather high, with 221.7 m of errors. As distances of BSs to UE increases when travelling from suburban to rural areas, time delays travelling through longer mediums are increased, making it tough for certain samples to be estimated accurately by NR3C in the presence of larger noisy delays and high GDOP (due to BSs placements). But if the BSs’ antenna is placed in higher tower with good LOS, \( D_{PE} \) constant could be modified to \( 1.8e^{-9} \) for rural to compensate for rural distance losses, and the 95% error of NR3C is further reduced significantly even in the presence of high GDOP. In general, the performance of rural sites should be better than dense urban which suffers from various types of structural obstructions (such as reflections). But in our case, the BSs in rural area suffer from high GDOP (such as when three BSs’ pair angle difference is less than 10°).
Table 4.13 proves that with already predefined NMR or ECNO report based on drive test of suburban-rural route for UMTS kLOS (results were shown in Table 4.12), Best Geo ($L1$) could filter out the samples or resort the order of hearability before UIPS or SMLC initiates any TDOA based location estimation for that particular UE target. In this way UIPS could decide earlier if alternate estimation techniques should be used for the discarded samples, such as signal correlation method. From the results, CCC’s minimum error could achieve 0.05 meters and the maximum error was at 255 meters. As for CCC, it can be seen its maximum and high percentage errors had been reduced by using Best Geo, but the 67% or less errors are not reduced. The maximum is caused by two UE samples along the route where CCC was sensitive to the placement of BSs. The angles between BSs: $ag_{12}$ was 0, $ag_{13}$ was 90 degrees and $ag_{23}$ was 178.8 degrees. With Best Geo (using $L1$ angle checker), and using $D_{PE} = 1.8e^{-9}$ for suburban-rural route, the maximum error for NR3C was at 27.44 meters and its other percentage errors of CDF were also the lowest when compared to CCC with Best Geo. Basically the hearability of three BSs has been reduced to 1085 samples along this route from the previous 1241 because the rest of the samples were affecting NR3C’s optimum performances. Finally, NR3C or numerical method improves more when using Best Geo, especially in lower delays or rural environment than applying Best Geo for CCC.

Table 4.13   Improved CDF of UE estimated using CCC and NR3C, with Best Geo for $N=3$ (1241 reduced to 1085) on suburban-rural route (5.41 pm, 20/11/2007)

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% (m)</th>
<th>67% (m)</th>
<th>95% (m)</th>
<th>Max Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCC (without) $D_{PE} = 1.8e^{-8}$</td>
<td>9.096</td>
<td>13.38</td>
<td>51.11</td>
<td>1552</td>
</tr>
<tr>
<td>NR3C (without) $D_{PE} = 1.8e^{-8}$</td>
<td>8.739</td>
<td>16.68</td>
<td>221.7</td>
<td>1092</td>
</tr>
<tr>
<td>NR3C (Best Geo), $D_{PE} = 1.8e^{-8}$</td>
<td>7.338</td>
<td>11.52</td>
<td>48.03</td>
<td>357.1</td>
</tr>
<tr>
<td>CCC (without) $D_{PE} = 1.8e^{-9}$</td>
<td>2.78</td>
<td>4.605</td>
<td>22.43</td>
<td>1800</td>
</tr>
<tr>
<td>CCC (Best Geo), $D_{PE} = 1.8e^{-9}$</td>
<td>3.042</td>
<td>4.893</td>
<td>17.72</td>
<td>255</td>
</tr>
<tr>
<td>NR3C (without) $D_{PE} = 1.8e^{-9}$</td>
<td>2.1</td>
<td>3.68</td>
<td>56.86</td>
<td>151.1</td>
</tr>
<tr>
<td>NR3C (Best Geo), $D_{PE} = 1.8e^{-9}$</td>
<td>0.756</td>
<td>1.22</td>
<td>4.585</td>
<td>27.44</td>
</tr>
</tbody>
</table>
4.2.8 UMTS Campus Route: UKM Stadium Gate-UKM Main Gate (6.02 PM, 20/11/2007)

This is the campus route for Universiti Kebangsaan Malaysia (UKM), entering from the stadium (golf range) gate, passing through the stadium, library, faculties, hostels, medical center and finally exiting via the main gate. The hearability is listed in Table 4.14. The route is very short with only 377 samples covered by three hearable unique sites. Table 4.15 shows the three BSs’ distances to UE during the measurements and the simulated results for location estimations using CCC method and NR3C method. The $D_{PE}$ constant used here is still $1.8e^{-8}$ even though the BSs are further from the UE. Although this route is very near to the previous suburban-rural route with maximum BSs’ distances to UE reaching 7000 m, but both the NR3C and CCC performances are more consistent with a good curve of CDF plot even though the $D_{PE}$ used here was meant for urban-suburban route. NR3C also performs as good as CCC when the geometric BSs placements are transmitting measurements within different angles (good GDOP). Both techniques were able to efficiently estimate location errors within 125 m of accuracy.

Table 4.14 Hearability for UKM campus route (6.02 pm) with avg $v= 25.5$ km/h (max $v= 44$km/h), distance=3.4 km and trip time=8 min

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$N=1$</th>
<th>$N=2$</th>
<th>$N=3$ (81.6%)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>46</td>
<td>39</td>
<td>377</td>
<td>462</td>
</tr>
</tbody>
</table>

Table 4.15 CDF of BSs’ distances to UE and CDF performances for UE estimated using CCC and NR3C for campus route (6.02 pm, 20/11/2007)

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% of CDF (m)</th>
<th>67% of CDF (m)</th>
<th>95% of CDF (m)</th>
<th>Max Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB1</td>
<td>653.1</td>
<td>2283</td>
<td>6730</td>
<td>7263</td>
</tr>
<tr>
<td>NB2</td>
<td>2991</td>
<td>3676</td>
<td>7025</td>
<td>7361</td>
</tr>
<tr>
<td>NB3</td>
<td>2934</td>
<td>3179</td>
<td>7242</td>
<td>7600</td>
</tr>
<tr>
<td>CCC Results</td>
<td>17.34</td>
<td>22.04</td>
<td>65.76</td>
<td>109</td>
</tr>
<tr>
<td>NR3C Results</td>
<td>16.38</td>
<td>26.88</td>
<td>60.92</td>
<td>124.4</td>
</tr>
</tbody>
</table>
4.2.9 UMTS North South Highway Route: Bangi Toll-Sungai Besi Toll (6.16 PM, 20/11/2007)

This is the North South Highway route which starts after the Bangi toll and passes through Kajang, UPM toll and finally reaches Sungai Besi toll (near Serdang and Mines area). Table 4.16 lists the hearability of this route and auto corrections using $Lg$, distance checker. Table 4.17 shows the BSs’ distances to UE while on this route and the CDF of location estimations obtained using CCC and NR3C techniques.

Table 4.16 Hearability for North South Highway route (6.16 pm) with avg $v = 59.15$ km/h (max $v = 77$km/h), trip distance= 13.8 km and trip time =14 min

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$N=1$</th>
<th>$N=2$</th>
<th>$N=3$ Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>3</td>
<td>27</td>
<td>818 (uncorrected) 816-corrected (96.23%)</td>
</tr>
</tbody>
</table>

Table 4.17 CDF of BSs’ distances to UE and CDF performances for UE estimated using CCC and NR3C for Highway route (6.16 pm, 20/11/2007)

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% of CDF (m)</th>
<th>67% of CDF (m)</th>
<th>95% of CDF (m)</th>
<th>Max Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB1</td>
<td>606.7</td>
<td>922.3</td>
<td>1810</td>
<td>2585</td>
</tr>
<tr>
<td>NB2</td>
<td>1310</td>
<td>1689</td>
<td>2572</td>
<td>6065</td>
</tr>
<tr>
<td>NB3</td>
<td>1542</td>
<td>1950</td>
<td>3873</td>
<td>6082</td>
</tr>
<tr>
<td>CCC Results</td>
<td>6.854</td>
<td>11</td>
<td>35.68</td>
<td>557</td>
</tr>
<tr>
<td>NR3C Results</td>
<td>6.372</td>
<td>9.555</td>
<td>79.69</td>
<td>991.5</td>
</tr>
</tbody>
</table>

Figure 4.10 shows the highway route, the maximum estimated locations obtained using CCC and NR3C, along with the BSs placements, and the original UE location. Both maximum values for CCC and NR3C occurred at 605th simulated sample (in general for all simulations, measurement samples start-end order and simulated samples’ order are the same). It can be observed that both techniques suffer from bad geometric placements of BSs along the highway. NR3C maximum distance error is 991.5 m, and is higher than CCC maximum distance error, which is 557 m. Figure 4.11 shows the placements of BSs’ when UE estimated is minimum for both CCC and NR3C techniques.
Figure 4.10 Highway route with maximum error estimation (6.16 pm, 20/11/2007)

Figure 4.11 Highway route with minimum error estimation (6.16 pm, 20/11/2007)
4.2.10 UMTS City and Federal Highway: Sungai Besi Toll-Federal Highway PJ (6.31 PM, 20/11/2007)

This route starts after the Sungai Besi toll and makes a turn into Waterpark highway (just before the old airport) and goes towards MidValley Mega Mall, adjoining to Federal Highway, entering Petaling Jaya (PJ) and turning to Jalan University (University Malaya) and ends near Jalan Kemajuan, PJ. Table 4.18 shows the hearability along this route. Table 4.19 shows the CDF of three BSs’ distances to UE, CCC estimated locations error and NR3C estimated locations error along this route.

Table 4.18 Hearability for city highway route (6.31 pm) with avg \( \nu = 30.4 \) km/h (max=72km/h), trip distance=14.2 km and trip time=28 min

<table>
<thead>
<tr>
<th>Measurement</th>
<th>( N=1 )</th>
<th>( N=2 )</th>
<th>( N=3 )</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>24</td>
<td>107</td>
<td>1564 (uncorrected)</td>
<td>1695</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1546-corrected (91.21%)</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.19 CDF of BSs’ distances to UE and CDF performances for UE estimated using CCC and NR3C for city highway route (6.31 pm, 20/11/2007)

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% of CDF (m)</th>
<th>67% of CDF (m)</th>
<th>95% of CDF (m)</th>
<th>Max Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB1</td>
<td>468.4</td>
<td>732.9</td>
<td>2043</td>
<td>3062</td>
</tr>
<tr>
<td>NB2</td>
<td>930.4</td>
<td>1139</td>
<td>2218</td>
<td>3489</td>
</tr>
<tr>
<td>NB3</td>
<td>1104</td>
<td>1393</td>
<td>2947</td>
<td>3790</td>
</tr>
<tr>
<td>CCC Results</td>
<td>4.719</td>
<td>7.137</td>
<td>23.53</td>
<td>250.7</td>
</tr>
<tr>
<td>NR3C Results</td>
<td>6.821</td>
<td>11.01</td>
<td>48.65</td>
<td>878.2</td>
</tr>
</tbody>
</table>

Figure 4.12 shows the route and NR3C’s maximum estimated error location. Again the placement of BSs (the spread between the three BSs’ angles are less for this case) influences the accuracy for NR3C but with lesser impact to CCC estimation (maximum error of only 250.7 m for CCC with the same BSs placements). It is worth a note that when the route moves from Seremban highway to densely populated PJ city, the higher location estimation errors reduces to below 100 m as shown in Figure C.5.
4.3 SIMULATION AND PERFORMANCE OF CCC AND NR3C TECHNIQUES FOR GSM DRIVE TEST ROUTES (KLOS)

The approach to simulate time measurements is similar to UMTS. In Green & Wang (2002), to study E-OTD location accuracy, $\tau_{\text{RMS}}$ median for delay spread (RMS) was chosen as 0.4 $\mu$s for urban, 0.3 $\mu$s for suburban and 0.1 $\mu$s for rural. The delay spread will increase when distance becomes farther as shown in Equation (3.1). For delay prediction, $\tau_D$ represents the best fitted correction based on the uncertainty of survey data between each cell and MS, which was similarly done for RSSI or RSCP prediction using Equation (3.2). Therefore, Equation (3.10) will be used to determine the delay prediction error, $\tau_{D}$, with $D_{PE}$ value $1.8e^{-8}$ for urban and suburban, and $1.8e^{-9}$ for rural (or distant cells) settings. Each ERXL file (as shown in Figure A.5) that was obtained from the drive test routes will be used as the NMR hearability report during simulations, assuming the same playback order of the route’s measurement samples are simulated, with the same placement of BSs, same receive signal levels, same actual MS coordinates, same order of distances to three BSs, same BSC ID, same Cell ID and others. For GSM, the same processes described for kLOS model in Chapter 3
will be utilized to simulate E-OTD time measurements (with random value of delays) in order to evaluate the performance of CCC and NR3C estimation techniques.

### 4.3.1 GSM Urban-Suburban Route: Menara Celcom to Wangsa Melawati (3.31 PM, 20/11/2007)

This is the same route as in Figure 4.1. Table 4.20 lists the hearability along the route. Table 4.21 illustrates the three hearable sets of BSs’ distances from the MS during the route, results for location estimations using CCC and estimations using NR3C.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>N=1</th>
<th>N=2</th>
<th>N=3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>2607 (48.3%)</td>
<td>1805 (33.5%)</td>
<td>983 (18.2%)</td>
<td>5395</td>
</tr>
</tbody>
</table>

Table 4.21 CDF of BSs’ distances to MS and CDF performances for MS estimated using CCC and NR3C for urban-suburban route (3.31 pm, 20/11/2007)

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% of CDF (m)</th>
<th>67% of CDF (m)</th>
<th>95% of CDF (m)</th>
<th>Max Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTS1</td>
<td>206.3</td>
<td>239.3</td>
<td>453.3</td>
<td>710.9</td>
</tr>
<tr>
<td>BTS2</td>
<td>357.4</td>
<td>412</td>
<td>1495</td>
<td>1659</td>
</tr>
<tr>
<td>BTS3</td>
<td>517.7</td>
<td>656.6</td>
<td>1596</td>
<td>2285</td>
</tr>
<tr>
<td>CCC Results</td>
<td>2.64</td>
<td>4.754</td>
<td>15.63</td>
<td>322.2</td>
</tr>
<tr>
<td>NR3C Results</td>
<td>2.815</td>
<td>4.3</td>
<td>20.52</td>
<td>145.4</td>
</tr>
</tbody>
</table>

Hearability of three unique BSs in GSM is only 18.2% for this route, which is smaller than 3G (UMTS). In GSM, NMR or signal strength reports could be obtained every 480 ms from serving cell and 6 other strongest neighbors’ cells when the MS is in active voice call (Halonen et al. 2003). Using Enhanced Receive level (ERXL), MS could measure up to nine cells but sometimes some cells’ are from the same site. In our location estimation using E-OTD for GSM, CCC produces 3 samples with higher error values close to 322.2 m. This maximum value is higher than NR3C because BTS1 and BTS2 is so close and BTS3 is very far, thus larger (from random delay error generator) prediction time error could cause inability to estimate (to find the best
convergences between two small circles and one big circle) accurately. In general all CCC and NR3C errors are very small, and location accuracy is within E-911 location accuracy requirements. Halonen et al. (2003) stated that it takes 1 to 2 s for their MS demonstrator to perform E-OTD measurements for one location and then report the time measurements back to SMLC demonstrator. Their SMLC will then perform the calculation for location estimation. Halonen et al. (2003) stated that for E-OTD field test done with 150 measurement samples in suburban area with 2 storey buildings and the MS was moving in a vehicular speed of less than 50 km/h, 67% location error was at 42 m and 90% error was at 85 m. When MS was stationary, 45 measurements were made in a single location, where 67% error was at 30 m while 90% error was at 33 m.

4.3.2 GSM Suburban-Urban Route: Wangsa Melawati to Menara Celcom (4.02 PM, 20/11/2007)

This is the same urban-suburban route but on the return trip from Wangsa Melawati to Menara Celcom. The hearability during this route is as listed in Table 4.22. Table 4.23 lists the three hearable sets of BSs’ distances from the MS during the route, location estimations using CCC and estimations using NR3C.

Table 4.22 Hearability (N) for GSM suburban-urban route (4.02 pm)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>N=1</th>
<th>N=2</th>
<th>N=3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>1431 (44%)</td>
<td>1287 (39.6%)</td>
<td>533 (16.4%)</td>
<td>3251</td>
</tr>
<tr>
<td></td>
<td>315-corrected (9.7%)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.23 CDF of BSs’ distances to MS and CDF for MS estimated locations using CCC and NR3C for suburban-urban route (4.02 pm, 20/11/2007)

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% of CDF (m)</th>
<th>67% of CDF (m)</th>
<th>95% of CDF (m)</th>
<th>Max Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTS1</td>
<td>418.5</td>
<td>570.8</td>
<td>732.5</td>
<td>799.4</td>
</tr>
<tr>
<td>BTS2</td>
<td>802.1</td>
<td>933.8</td>
<td>4186</td>
<td>4198</td>
</tr>
<tr>
<td>BTS3</td>
<td>917</td>
<td>1459</td>
<td>2669</td>
<td>4162</td>
</tr>
<tr>
<td>CCC Results</td>
<td>4.158</td>
<td>6.06</td>
<td>21.4</td>
<td>41.57</td>
</tr>
<tr>
<td>NR3C Results</td>
<td>5.51</td>
<td>10.04</td>
<td>41.67</td>
<td>138.3</td>
</tr>
</tbody>
</table>
Preventing unique BSs to be less than 30 m apart, using \( L_g \) has corrected the hearability of three BSs to 315 measurements, otherwise causing CCC’s 95% errors to be within 128 m and NR3C’s 95% error to be within 111.1 m (not shown in table). In real UIPS implementation, when NMR provides a report before executing E-OTD measurement, hearability would be checked. If hearability of less than three BSs is attained, other techniques will be utilized to estimate the mobile locations.

### 4.3.3 GSM Urban-Suburban Route: Menara Celcom to Wangsa Melawati (4.21 PM, 20/11/2007)

Same repeated route from Menara Celcom to Wangsa Melawati with corrected hearability listed in Table 4.24. Hearability data was corrected using \( L_g \) for this route. This is a mix setting (moving at slightly slower speed) of the similar route where the vehicle was stopped in the middle of the journey to capture stationary measurements for about 16 minutes. Table 4.25 illustrates the three hearable sets of BSs’ distances from the MS during the route, location estimations using CCC and estimations using NR3C.

**Table 4.24** Hearability after corrections for GSM urban-suburban route (4.21 pm)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>( N=1 )</th>
<th>( N=2 )</th>
<th>( N=3 )</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>2322</td>
<td>413</td>
<td>3843</td>
<td>7165</td>
</tr>
<tr>
<td>(35.3% of corrected)</td>
<td></td>
<td>(6.3% of corrected)</td>
<td>(58.4% of corrected) 587 samples discarded</td>
<td>6578 (corrected)</td>
</tr>
</tbody>
</table>

**Table 4.25** CDF of BSs’ distances to MS and CDF for MS estimated locations using CCC and NR3C for urban-suburban route (4.21 pm, 20/11/2007)

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% of CDF (m)</th>
<th>67% of CDF (m)</th>
<th>95% of CDF (m)</th>
<th>Max Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTS1</td>
<td>101.9</td>
<td>118</td>
<td>305</td>
<td>601.1</td>
</tr>
<tr>
<td>BTS2</td>
<td>524.5</td>
<td>524.5</td>
<td>748.1</td>
<td>4210</td>
</tr>
<tr>
<td>BTS3</td>
<td>694.6</td>
<td>701.8</td>
<td>1482</td>
<td>4162</td>
</tr>
<tr>
<td>CCC Results</td>
<td>1.9</td>
<td>2.61</td>
<td>73.66</td>
<td>263.3</td>
</tr>
<tr>
<td>NR3C Results</td>
<td>2.75</td>
<td>3.6</td>
<td>84.71</td>
<td>729.1</td>
</tr>
</tbody>
</table>
NR3C. NR3C maximum error was high due to all three BSs and MS were almost aligned together. CCC’s maximum error occurred when 3 BSs are aligned among each other, causing less difference of angles between each of them (for example, BTS3’s directional angle is the same towards BTS2 and BTS1). It is observed that for half of the $N=3$ sample size, the serving BTS1’s distance to UE was very close (101.9 m as shown in table) because during the stationary period the BSs signal level was quite stable (with some fading fluctuations) and therefore Telco’s network didn’t require handing over to another further BTS.

4.3.4 GSM Metropolitan Route: Jalan Tun Razak-Ampang-KLCC-Bukit Bintang (2.31 PM, 20/11/2007)

This route was shown in Figure 4.5 with hearability listed in Table 4.26. Table 4.27 illustrates the three hearable BSs’ distances from the MS during the route, the results for location estimations using CCC and estimations using NR3C.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$N=1$</th>
<th>$N=2$</th>
<th>$N=3$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>2489 (57.83%)</td>
<td>872 (20.26%)</td>
<td>943 (21.91%)</td>
<td>4304</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% of CDF (m)</th>
<th>67% of CDF (m)</th>
<th>95% of CDF (m)</th>
<th>Max Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTS1</td>
<td>171.5</td>
<td>200</td>
<td>436.4</td>
<td>678.9</td>
</tr>
<tr>
<td>BTS2</td>
<td>983.2</td>
<td>1921</td>
<td>3876</td>
<td>3959</td>
</tr>
<tr>
<td>BTS3</td>
<td>911.1</td>
<td>1015</td>
<td>1829</td>
<td>3686</td>
</tr>
<tr>
<td>CCC Results</td>
<td>3.543</td>
<td>5.943</td>
<td>17.04</td>
<td>55.83</td>
</tr>
<tr>
<td>NR3C Results</td>
<td>4.027</td>
<td>6.245</td>
<td>18.93</td>
<td>25.87</td>
</tr>
</tbody>
</table>
4.3.5 GSM Metropolitan Return Route: Bukit Bintang-KLCC-Jalan Tun Razak (3.01 PM, 20/11/2007)

The route was shown in Figure 4.8 with hearability listed in Table 4.28. Table 4.29 illustrates the three hearable BSs’ distances from the MS during the route, the results for location estimations using CCC and estimations using NR3C.

Table 4.28 Hearability for GSM metropolitan return route (3.01 pm)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>N=1</th>
<th>N=2</th>
<th>N=3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>758 (19.4%)</td>
<td>2500 (63.99%)</td>
<td>649 (16.61%)</td>
<td>3907</td>
</tr>
</tbody>
</table>

Table 4.29 CDF of BSs’ distances to MS and CDF for MS estimated locations using CCC and NR3C for metropolitan return route (3.01 pm, 20/11/2007)

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% of CDF (m)</th>
<th>67% of CDF (m)</th>
<th>95% of CDF (m)</th>
<th>Max Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTS1</td>
<td>289.3</td>
<td>486.9</td>
<td>507.6</td>
<td>677.6</td>
</tr>
<tr>
<td>BTS2</td>
<td>518</td>
<td>746.1</td>
<td>1022</td>
<td>1674</td>
</tr>
<tr>
<td>BTS3</td>
<td>521.3</td>
<td>585.6</td>
<td>1367</td>
<td>1674</td>
</tr>
<tr>
<td>CCC Results</td>
<td>2.572</td>
<td>3.95</td>
<td>10.57</td>
<td>26.41</td>
</tr>
<tr>
<td>NR3C Results</td>
<td>1.752</td>
<td>2.84</td>
<td>7.89</td>
<td>12.02</td>
</tr>
</tbody>
</table>

In this route where GDOP is low (good) and microcells placement are good (larger angle spread of BSs’ directions towards UE), NR3C’s accuracy is better in estimating mobile location.

4.3.6 GSM Suburban-Rural Route: Plaza Phoenix Cheras-UKM Train Station (5.41 PM, 20/11/2007)

The route was shown in Figure 4.9. Table 4.30 shows the hearability of BSs. Simulations could not be done for this route since hearability of three BSs were not achievable. This may not be an objective indication to rule out that there were not any unique three BSs sites but rather the inability to process complete report from three BSs sites would best described this situation. This is because some neighbors’ Cell IDs and Location Area Code (LAC) were not able to be reported either by BSC (or
network) or MS even though their signal strength values were reported. Upon further investigation, the idea of using BSIC, BSC code with BCCH or ARFCN (Absolute Radio Frequency Channel Number) may be able to solve this problem: linking the missing Cell IDs and LAC to these codes. But for certain measurement samples, even the BSIC number was missing. Therefore too much of guessing was involved to figure which missing cell from Telco’s database was used along this route. For this record file (GSM suburban-rural route), we were unable to decode those missing/corrupted values and therefore have less hearable sites.

Table 4.30  Hearability for GSM suburban-rural route (5.41 pm)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>N=1</th>
<th>N=2</th>
<th>N=3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>4202 (96%)</td>
<td>173 (4%)</td>
<td>0</td>
<td>4375</td>
</tr>
</tbody>
</table>

4.3.7  GSM Campus Route: UKM Stadium Gate-UKM Main Gate (6.02 PM, 20/11/2007)

The route was the same short campus route that was described for 3G, with hearability of BSs shown in Table 4.31. Simulations could not be done for this route also because hearability of three BSs were not achievable due to incomplete measurement parameters (similar situation with GSM drive test data for suburban-rural route).

Table 4.31  Hearability for GSM campus route (6.02 pm)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>N=1</th>
<th>N=2</th>
<th>N=3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>1316 (100%)</td>
<td>0</td>
<td>0</td>
<td>1316</td>
</tr>
</tbody>
</table>

4.3.8  GSM North South Highway Route: Bangi Toll-Sungai Besi Toll (6.16 PM, 20/11/2007)

The same North-South Highway route was shown in Figure 4.10. Table 4.32 shows the hearability along this route for GSM network. Table 4.33 shows the BSs’ distances to MS during the data collection route (and the same for simulated route), location estimations result for CCC and location estimations result for NR3C.
Table 4.32  Hearability for GSM North South highway route (6.16 pm)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>N=1</th>
<th>N=2</th>
<th>N=3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>1568 (65.33%)</td>
<td>512 (21.33%)</td>
<td>320 (13.33%)</td>
<td>2400</td>
</tr>
</tbody>
</table>

Table 4.33  CDF of BSs’ distances to MS and CDF for MS estimated using CCC and NR3C for North South highway route (6.16 pm, 20/11/2007)

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% of CDF (m)</th>
<th>67% of CDF (m)</th>
<th>95% of CDF (m)</th>
<th>Max Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTS1</td>
<td>1079</td>
<td>1315</td>
<td>1600</td>
<td>1724</td>
</tr>
<tr>
<td>BTS2</td>
<td>1668</td>
<td>1844</td>
<td>3282</td>
<td>3601</td>
</tr>
<tr>
<td>BTS3</td>
<td>1710</td>
<td>1959</td>
<td>2719</td>
<td>3508</td>
</tr>
<tr>
<td>CCC Results</td>
<td>8.642</td>
<td>11.43</td>
<td>22.36</td>
<td>35.21</td>
</tr>
<tr>
<td>NR3C Results</td>
<td>5.255</td>
<td>7.228</td>
<td>15.17</td>
<td>24.05</td>
</tr>
</tbody>
</table>

4.3.9  GSM City And Federal Highway: Sungai Besi Toll To Federal Highway PJ (6.31 PM, 20/11/2007)

The same route was shown in Figure 4.12. Table 4.34 lists the hearability along this route. Table 4.35 shows the BSs’ distances to MS during the route, location estimations result for CCC and location estimations result for NR3C.

Table 4.34  Hearability for GSM city highway route (6.31 pm)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>N=1</th>
<th>N=2</th>
<th>N=3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>2906 (58.34%)</td>
<td>507 (10.18%)</td>
<td>1568 (31.48%)</td>
<td>4981</td>
</tr>
</tbody>
</table>

Again with all GSM files the inability to decode full rows of measurements for Cell ID and LAC made the samples with lesser N=3 sites. Furthermore some of the neighbor sites that were able to be decoded are far (up to 15 km) because only the few last columns (farthest BSs sites) were readable (with complete sets of Cell IDs and LAC) in order to make up for at least three hearable sites per measurement. Hence
with farther hearable sites, $D_{PE} 1.8e^{-9}$ was used. Farther BTSs also caused some of the maximum error for location estimation by CCC and NR3C to be up to 228 meters.

Table 4.35 CDF of BSs’ distances to MS and CDF for MS estimated using CCC and NR3C for city highway route (6.31 pm, 20/11/2007), $D_{PE}= 1.8e^{-9}$

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% of CDF (m)</th>
<th>67% of CDF (m)</th>
<th>95% of CDF (m)</th>
<th>Max Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTS1</td>
<td>394.9</td>
<td>939.3</td>
<td>2252</td>
<td>2595</td>
</tr>
<tr>
<td>BTS2</td>
<td>1245</td>
<td>2246</td>
<td>14080</td>
<td>15470</td>
</tr>
<tr>
<td>BTS3</td>
<td>1700</td>
<td>2411</td>
<td>4793</td>
<td>15570</td>
</tr>
<tr>
<td>CCC Results</td>
<td>1.93</td>
<td>3.855</td>
<td>16.72</td>
<td>227.1</td>
</tr>
<tr>
<td>NR3C Results</td>
<td>2.556</td>
<td>6.149</td>
<td>59.3</td>
<td>195.5</td>
</tr>
</tbody>
</table>

Finally, it is important to check at every step for actual UIPS implementation (programmatically check thresholds and send alert to UIPS Admin module), the accuracy of the measurement data when referring to lookup tables or Telco’s information that could have caused erroneous impact to the simulation results for location estimation, prediction of RSSI, prediction of time delays and other timing errors.

4.4 SIMULATION AND PERFORMANCE OF ENHANCED CCC AND NR3C TECHNIQUES FOR UMTS AND GSM IN URBAN-SUBURBAN (ULOS)

The simulation process for uLOS environment was described in Figure 3.12. Table 4.36 shows the simulation parameters for uLOS pertaining to the uLOS simulated area in KL, as shown in Figure 3.11. For the simulation of OTDOA (UMTS) and E-OTD (GSM), random time delays between 0 and $\tau_{ray}$ will be added to the geometrical time in order to incorporate the effect of multipath from this urban-suburban area.

4.4.1 Results for UMTS uLOS

Figure 4.13 shows that time averaging of CCC is not really the same as estimating three CCC estimates and then averaging the estimates (CCC averaging estimator). But for NR3C, time averaging and NR3C averages (First Mean NR3C estimator) are
Table 4.36 Simulation parameters for uLOS urban-suburban (8.9 km by 6.68 km)

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMR BSs’ random case to select 3 hearable BSs based on shortest distance order from BSs to UE/MS</td>
<td>Case 1=[1, 2, 3], Case 2=[1 ,3, 4], Case 3=[1 ,3,5], Case 4=[1, 4, 6], Case 5=[2, 1, 5], Case 6=[2, 1,4]</td>
</tr>
<tr>
<td>GSM TDOA:</td>
<td>E-OTD 3GPP/ETSI</td>
</tr>
<tr>
<td>UMTS (3G) TDOA:</td>
<td>OTDOA 3GPP</td>
</tr>
<tr>
<td>Propagation Model for UMTS and GSM Urban:</td>
<td>Averagely good LOS outdoor and some NLOS subways, $\tau_{ray} = 0.25 \mu$s between 1st and 3rd of 12 ray model (Tranter et. al 2004) and propagation prediction as per Eq (3.2)</td>
</tr>
<tr>
<td>Propagation Model for UMTS and GSM Suburban:</td>
<td>Moderately good LOS outdoor with mainly 3-4 storeys structures, $\tau_{ray}=0.21 \mu$s and propagation prediction as per Eq (3.2)</td>
</tr>
<tr>
<td>Number of UE samples randomly selected:</td>
<td>100 (52 samples in urban zone and 48 in suburban zone)</td>
</tr>
<tr>
<td>Number of average per sample:</td>
<td>3 consecutive OTDOA/EOTD measurements</td>
</tr>
<tr>
<td>Location estimation techniques:</td>
<td>Three timing measurement averages for CCC and NR3C, CCC averaging estimator, First Mean NR3C estimator, Random Search NR3C estimator, and Best Comp.</td>
</tr>
<tr>
<td>$\sigma$ for comparing deviation of NR3C</td>
<td>20 meters</td>
</tr>
<tr>
<td>Optional feature: $L_g$ and $L_1$</td>
<td>$L_g$ applied to check distances between each BS and $L_1$ for Best Geometric.</td>
</tr>
</tbody>
</table>

almost identical. Table 4.37 lists the CDF results for all the 5 estimation techniques and the Best Comparator technique. From the result it is obvious that CCC averaging and time averaging CCC (averaging time measurements for each BS and then calculate the three BSs’ UE estimate using CCC) are the most desirable to use as compared to NR3C averages. At UE 5th sample location where maximum error occurs for mostly all estimates, the angles between BSs was inline, where angle12 (angle between BS1 and BS2) was 336 degrees, angle 13 (angle between BS1 and BS3) was 154 degrees and angle 23 (angle between BS2 and BS3) was 155 degrees. Also at UE 75th, angle12 was 336, angle13 was 335 and angle23 was 334 degrees. Figure 4.14 shows UE estimates obtained using First Mean NR3C, CCC averaging and Best Comparator for the 100 UE samples. Even though urban has higher
Figure 4.13 Location estimation in uLOS (UMTS) without using Best Geo

Table 4.37 CDF for location estimation on uLOS using timing averages of NR3C, CCC, First Mean NR3C, Random Mean NR3C, CCC averaging and Best Comparator

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% (m)</th>
<th>67% (m)</th>
<th>95% (m)</th>
<th>Max Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timing Avg NR3C</td>
<td>39.53</td>
<td>54.02</td>
<td>447.1</td>
<td>1237 (UE 5th)</td>
</tr>
<tr>
<td>Timing Avg CCC</td>
<td>48.29</td>
<td>59.06</td>
<td>133.1</td>
<td>801 (UE 5th)</td>
</tr>
<tr>
<td>First Mean NR3C</td>
<td>39.56</td>
<td>53.97</td>
<td>449.4</td>
<td>1242 (UE 5th)</td>
</tr>
<tr>
<td>Random NR3C</td>
<td>38.75</td>
<td>55.22</td>
<td>515.8</td>
<td>1161 (UE 75th)</td>
</tr>
<tr>
<td>CCC Averaging</td>
<td>49.39</td>
<td>58.25</td>
<td>147.5</td>
<td>798.5 (UE 5th)</td>
</tr>
<tr>
<td>Best Comparator</td>
<td>45.87</td>
<td>55.05</td>
<td>147.5</td>
<td>798.5 (UE 5th)</td>
</tr>
</tbody>
</table>

multipath, higher delay of rays compared to suburban, it is surprising that the 5th and 75th UE samples for maximum error occurred in the suburban area. On the other hand, minimum error for time average NR3C and First Mean NR3C occurred at urban, while for time average CCC, minimum error of 19.58 meters occurred at suburban and for CCC averaging, minimum error of 6.35 meters occurred at urban. Since time average for NR3C and First Mean NR3C are identical, time average will be used as it is faster to process one UE estimate rather than three UE estimates. For
CCC, CCC averaging could still be used as it has smaller minimum and smaller maximum compared to time averaging of CCC. A difference of 20 milliseconds of processing time (PT) would be sacrificed for each estimate done through CCC averaging compared to time averaging of CCC method. It is apparent that for E-911 accuracy requirements, all the 6 techniques meet the requirement only at 67 percent of the CDF (should be below 100 meters), while all three NR3C techniques failed at 95 percent of the CDF (should be below 300 meters). Therefore averaging of CCC (time or CCC averaging) is the first choice when First Mean NR3C’s comparison between its three UE estimates is high. In earlier section of this chapter it was shown that without the presence of delays (in ideal mathematical situation), NR3C which is a numerical technique provide better accuracy than CCC. But in real situations, when delays are high, CCC proofed to be more reliable as it is less sensitive to BSs’ geometric and directional problems. Standard deviation of less than 20 (this value is related to the surrounding and time delays used) would be a deciding factor by Best Comparator to select First Mean of NR3C’s estimate or CCC averaging’s estimate. It basically uses CCC averaging when NR3C’s estimates are unpredictable (much deviated). This way the new hybrid will produce less errors compared to CCC averaging at 67% and below (because NR3C averaging performs better at 67% and
below compared to CCC averaging) and maintain the same CCC averaging error for higher percentage of CDF (for error $\geq 95\%$ and maximum error, CCC averaging is better than NR3C averaging). The slight improvement of Best Comparator could be seen in Figure 4.14.

Also in this simulation it is learnt that geometric and direction of angles between each BS with respect to each other and finally towards the UE/MS effects location accuracy (especially for numerical computations technique such as NR3C) even more than higher delays caused by errors in urban area. Therefore $L1$ should be implemented, where in UIPS this logical algorithm is added to eliminate available NMR’s choices (checks the six cases of NMR) that does not meet an acceptable geometrical requirement (bad geometry of NMR cases are eliminated). The improvement could be proven as shown in Figure 4.15 and Figure 4.16 when the simulations are run again for the same area and conditions with using Best Geo ($L1$ algorithm). Best Geo will check all the 6 cases of NMR and indicate which cases should be eliminated. Only cases where $L1$ is true would be used. This logical

Figure 4.15  CDF for time averages of NR3C, CCC and Best Comparator using Best Geo for uLOS UMTS environment
statement will eliminate the worst error causing BSs’ combinations from the available hearability of three BSs as obtained from NMR (ECNO or ERXL) report. Using Best Geo, with 100 UE samples, the estimation results shown in both figures for all 6 methods are within E-911 accuracy requirements for 67% and 95% errors.

4.4.2 Results for GSM uLOS

Table 4.38 shows the CDF results for CCC averaging estimator, First Mean NR3C and Random Search Mean NR3C. For this case, $L_g$ (30 m distance apart from each BS) and $L_1$ (Best Geo) are not used. NMR for this simulation is assumed to provide the best signal to the nearest BSs with arrangement of Case 1 (1, 2, 3) only: BS1 is the nearest, BS2 is the second nearest and finally BS3 is the third nearest to MS. In general throughout this thesis, BS1 for both UMTS and GSM is designated as the serving cell. From the result (table), it can be seen that CCC averaging provides the best result even though the same Geometric Dilution had badly affected both NRC3 averaging methods’ results. Both (95% and above of CDF) NR3C averaging
techniques failed for 95% of E-911 accuracy requirements. Figure 4.17 shows CDF plot of CCC averaging estimator along with the first CCC estimate, second CCC estimate and third CCC estimate. It is clear that without averaging, the first CCC and second CCC estimate had 95% errors that do not meet E-911 accuracy requirements. Only the third CCC estimate met the requirement and therefore it was important to use averaging techniques such as using CCC averaging location estimator when ULOS is not known in order to finally achieve a desirable result. Table 4.39 shows the summary of CDF performance for location estimation using First Mean NR3C, Random Search Mean NR3C, Random BSs NR3C, CCC Averaging and Best Comparator, when Best Geo is used as part of the NMR with 6 cases on GSM uLOS.

Table 4.38 CDF for estimation on GSM uLOS (NMR Case 1, without Lg and L1), using First Mean NR3C, Random Mean NR3C and CCC averaging

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% (m)</th>
<th>67% (m)</th>
<th>95% (m)</th>
<th>Max Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Mean NR3C</td>
<td>36.17</td>
<td>55.16</td>
<td>2338</td>
<td>8467 (suburban)</td>
</tr>
<tr>
<td>Random NR3C</td>
<td>38.17</td>
<td>59.02</td>
<td>2309</td>
<td>8476 (suburban)</td>
</tr>
<tr>
<td>CCC Averaging</td>
<td>52.47</td>
<td>63.81</td>
<td>250.8</td>
<td>447.3 (urban)</td>
</tr>
</tbody>
</table>

Figure 4.17 CDF for CCC averaging and each CCC estimates in uLOS
Table 4.39 CDF for estimation on GSM uLOS (with $L_g$ and $L_I$), using First Mean NR3C, Random Search NR3C, CCC averaging and Best Comparator

<table>
<thead>
<tr>
<th></th>
<th>50% (m)</th>
<th>67% (m)</th>
<th>95% (m)</th>
<th>Max (m)</th>
<th>PT (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Mean NR3C</td>
<td>39.71</td>
<td>48.43</td>
<td>219.5</td>
<td>472.7 (urb)</td>
<td>0.0285</td>
</tr>
<tr>
<td>Random BSs NR3C</td>
<td>31.24</td>
<td>43.97</td>
<td>140.3</td>
<td>268.7 (sub)</td>
<td>0.90</td>
</tr>
<tr>
<td>Random Mean NR3C</td>
<td>36.88</td>
<td>52</td>
<td>208.6</td>
<td>426.7 (sub)</td>
<td>0.90</td>
</tr>
<tr>
<td>CCC Averaging</td>
<td>46.9</td>
<td>56.26</td>
<td>137.5</td>
<td>303.6 (sub)</td>
<td>0.0564</td>
</tr>
<tr>
<td>Best Comparator $\sigma=60$</td>
<td>38.78</td>
<td>47.76</td>
<td>167.5</td>
<td>303.6 (sub)</td>
<td>0.103</td>
</tr>
<tr>
<td>Best Comparator $\sigma=20$</td>
<td>41.05</td>
<td>51.3</td>
<td>137.5</td>
<td>303.6 (sub)</td>
<td>0.103</td>
</tr>
</tbody>
</table>

The processing time (PT) to find each UE average estimate corresponding to the technique used is also shown in the table. The processor was running on Intel Core 2 CPU with 1.73GHz, 2038 MB RAM, and 32 bit operating system of Windows Vista 2006. First Mean NR3C processes the fastest UE estimate for uLOS, followed by CCC averaging, Best Comparator and finally Random Search techniques. When Best Geo is used, all the techniques for urban and suburban area are able to meet FCC E-911 requirements. As was seen earlier, NR3C and its enhanced techniques work well to predict the target location when delay errors are small. CCC on the other hand can still perform well when delay errors are average or large and it is not as sensitive as NR3C to geometrical problems. Even without using Best Geo, CCC could meet E-911 standards for 67% and 95% errors. Best Comparator is therefore designed to accommodate the best of smaller errors (error $\leq 67\%$) from NR3C’s First Mean estimates and inherits the higher errors (error $\geq 95\%$) of CCC averaging. If standard deviation between three of NR3C’s estimates are high (above 20), CCC averaging’s estimate would be used as Best Comparator’s estimate. If the threshold $\sigma$ chosen to be 60, more of First Mean of NR3C’s estimates are selected by Best Comparator than CCC averaging’s estimates, which will also affect the cumulative errors of the 100 UE samples as shown in Table 4.39. So using $\sigma$ of 20 for Best Comparator is reasonable, where CCC’s averaging estimate below 95% are improved (due to selecting First Mean NR3C estimates corresponding to samples where NR3C’s estimates for $\sigma \leq 20$)
and maintaining the same CCC averaging estimates for higher delay deviations ($\sigma > 20$) for this urban-suburban area evaluated for location prediction.

In Le et al. (2003), Kalman filter is used for smoothing and mitigating NLOS of BSs conditions for time of arrival type of location estimation. A hypothesis tester is used to differentiate between LOS and NLOS of BSs even though false alarms could occur. Higher standard deviation notifies the existence of NLOS compared to smaller standard deviation (Wylie & Holtzman 1996). Le et al. (2003) uses unbiased Kalman filter to mitigate the NLOS biased error. And with Gaussian noise $\sigma$ of 150 m (Wylie & Holtzman 1996), the CDF result from simulations produced 67% error at 96.7 meters while 95% error at 248.5 meters, when NLOS smoothing is applied in the LOS/NLOS changed environment conditions. BS could change from LOS to NLOS when mobile moves especially in vehicular velocities. Cong & Zhuang (2005) proposes NLOS detection and correction technique, and by using database, good location estimation could be obtained in severe NLOS conditions. However, in our uLOS environment, it was assumed that the mobile environment is unknown (LOS or NLOS or both) and therefore with Best Geo algorithm, it has been shown that CCC averaging and all NR3C averaging techniques could be utilized for UMTS and GSM uLOS, with good accuracy (also meeting FCC location standards) in comparison to other NLOS detection techniques.

4.5 SIMULATION AND PERFORMANCE OF TIMING TECHNIQUE IN UMTS NETWORK WHEN HEARABILITY IS TWO

In this section, CCC2 will be used when user is on a road or walkpaths and hearability of time measurements are from two Node Bs. One of the four CCC2’s outputs will be chosen using MBRC when one major road is within the vicinity of the two circles, or using GAC to choose CCC2’s point when more roads are within the vicinity of the two circles. If the mobile user is on road or off road when the initial hearability is two, using additional RLMNs installed as in Figure A.17, the simulation of the kLOS urban-suburban UMTS route would be estimated using CCC and NR3C. The simulation parameters for all the above techniques are listed in Table 4.40.
Table 4.40 Simulation parameters for UMTS location estimation techniques using OTDOA measurements from two hearable Node Bs

<table>
<thead>
<tr>
<th>Descriptions</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total query of (N=2) location during trip:</td>
<td>199 samples (location of real UE with (N=2) is shown in Figure A.17, file1531year 2007)</td>
</tr>
<tr>
<td>Distance of trip:</td>
<td>Real drive test urban-suburban route: 9.7 km (from Menara Celcom to Wangsa Melawati)</td>
</tr>
<tr>
<td>Type of location search:</td>
<td>Vehicular Navigation/Tracking</td>
</tr>
<tr>
<td>Avg vehicular speed:</td>
<td>19 km/h (maximum speed 70km/h)</td>
</tr>
<tr>
<td>Terrain Environment:</td>
<td>known Line of Sight (kLOS), propagation prediction as per Eq (3.2), (D_{PE} = 1.8e^{-8})</td>
</tr>
<tr>
<td>Node Bs distances to UE along route:</td>
<td>UMTS drive test with time stamped 3.31pm, 2007. Node Bs average antenna height 35 m</td>
</tr>
<tr>
<td>Total navigation time:</td>
<td>31 minutes (start to end of trip)</td>
</tr>
<tr>
<td>GA Parameters:</td>
<td>(Gen=250) and others, (pop=32) and others, probability crossover=0.8, prob mutation=0.01</td>
</tr>
<tr>
<td>NR2C Parameters:</td>
<td>Max iterations =80, tolerance =2.2204x10^-7</td>
</tr>
<tr>
<td>CCC2:</td>
<td>Four points output: (A1, A2, B1) and (B2)</td>
</tr>
<tr>
<td>NR3C (used when (N=3))</td>
<td>Max iterations =60, tolerance =2.2204x10^-12</td>
</tr>
<tr>
<td>CCC (used when (N=3))</td>
<td>Only one convergence point</td>
</tr>
<tr>
<td>MBRC:</td>
<td>Best Route (Figure A.14 urban-suburban route is 9.89km*) with more resolution points (497).</td>
</tr>
<tr>
<td>GAC:</td>
<td>Best Route (497 points) as main road along with two other dummy roads nearby the urban suburban route (as shown in Figure 3.15).</td>
</tr>
<tr>
<td>RLMN (concept as in Figure A.17):</td>
<td>Three dummy RLMN sites along this route. Each RLMN near 2 hearable sites produces (N= 3). CCC and NR3C would be used, (D_{PE} = 1.8e^{-8})</td>
</tr>
</tbody>
</table>

*Difference in trip distance between map and real drive test route is due to inaccuracy in drawing the paths on the software map versus the actual GPS measured drive test routes. GPS also introduces some of its prediction errors as mentioned in Chapter 2.

4.5.1 CCC2 and MBRC (or NR2C) on urban-suburban kLOS route

Firstly CCC2’s points will be estimated along the urban-suburban route. Figure C.6 through Figure C.9 shows the distance error (location error) for \(A1, A2, B1\) and \(B2\) estimated points versus the actual UE locations along the urban-suburban route. Then MBRC will be used to determine which CCC2’s point will be the estimated mobile location. Figure C.10 shows the MBRC’s estimated locations’ error that are based on
choosing the best CCC2’s point, and the best CCC2’s point referring to estimated location on the nearest road point (estimated location is not the CCC2’s point but the nearest road point to the chosen CCC2 point). As shown in Figure C.10, the 80th sample (example) is chosen from $B_2$, which is also the nearest to the road point. If CCC2’s point with reference to the nearest estimated road point is chosen for the 80th sample, the error distance is 22.9 meters, which is higher than 5.243 meters (when estimated location is the CCC2 point itself). Figure C.11 proofs that when the map is corrected, by adding the first route point with actual travelled UE’s first sample point, the error distance for earlier samples are improved for both the MBRC CCC2 point (with or without the nearest road reference). However, this method is not practical because GPS could also introduces its own estimated errors and sometimes cars are not in the same lane of main roads or cars could be entering or exiting main roads, thus moving away from the main road data points to a smaller road, where smaller road data (such as new housing area) are not yet entered into maps or stored in databases from drive test collection. However, the approach of calibration is suitable to test MBRC’s algorithm’s robustness. For example, when Best route (Figure A.14 was produced from map) was totally replaced with the actual UE’s travelled points, and time of arrival is the actual geometric time (ideal situation where there is no delay errors), the estimated locations’ error is totally 0 meters for CDF performances at all percentages. So this is important to check and validate before the road comparator algorithm is simulated with the map’s road points and with time delays caused by NLOS/multipaths. The reason why the map’s coordinate for Best route is used instead of the real drive test route is because in actual implementation of UIPS, GPS’s will also have its own estimation errors, thus vehicle travelling along the same road will still have some coordinate differences. In the map’s case, the beginning coordinates of the route was much deviated from the actual travelled path during the drive test. This is the reason the best CCC2 point is preferred as the estimated location rather than referring to the road point itself.

Figure C.12 shows the usage of NR2C without MBRC in order to predict $N=2$ locations irrespective of vehicular or stationary UE positions. The errors are rather high at certain samples as NR2C by itself could only guess (with initial guess at 0,0) to find one final estimation point for each location request. Figure 4.18, shows the
CDF performances for location estimation using CCC2-MBRC, CCC2-MBRC with reference road points, and using NR2C with CCC2-MBRC’s estimated point (estimated point of CCC2-MBRC is used as NR2C’s initial guess point). Using NR2C with CCC2-MBRC, does not improve the performance for this case. Using CCC2-MBRC alone does meet the FCC E-911 location accuracy requirements, and is within 81.63 meters of accuracy at all times. Out of the 199 samples, A1 was selected 24 times, A2 was selected 63 times, B1 was selected 72 times and B2 was selected 40 times. Basically CCC2’s more than 2 points per intersection does help in the selection process to find the best estimated position even though A1 and A2 might be close to each other (such as 8 meters) as B1 and B2. The CDF for the four CCC2’s points produced on the urban-suburban route are shown in Figure C.13. At 67% both B1 and B2 are within 78 meters but A1 and A2 are at 219 meters. At 95%, all points are within 546 meters. So CCC2’s points without MBRC would not be able to meet FCC’s location accuracy requirements.

![Empirical CDF for CCC2-MBRC, CCC2-MBRC (reference road) and CCC2-MBRC-NR2C](image)

**Figure 4.18** CDF location error between UE estimated and UE real for 199 samples with N=2. All techniques is within FCC location accuracy requirements

### 4.5.2 CCC2 and GAC (or NR2C) on urban-suburban kLOS route

The best one of the four CCC2’s points (A1, A2, B1 or B2) is chosen as the estimated location using Genetic Algorithm Comparator (GAC). GAC will compare the 30
nearest road(s)' points along with every CCC2 point to determine the optimized fitness value. The lowest among the four CCC2 points’ optimized fitness value will be the estimated location. Table 4.41 summarizes the final CDF results for location estimation using CCC-GAC (Gen=250, pop=32), NR2C, CCC-GAC-NR2C and CCC-GAC (various Gen, various pop).

Table 4.41 CDF for location estimation using CCC2-GAC, NR2C, and CCC2-GAC-NR2C on urban-suburban route with hearability of two Node Bs

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% (m)</th>
<th>67% (m)</th>
<th>95% (m)</th>
<th>Max Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCC2-GAC (Gen=250, pop=32)</td>
<td>7.055</td>
<td>10.81</td>
<td>92.58</td>
<td>293.6 (UE 58th)</td>
</tr>
<tr>
<td>NR2C (without GAC) PT=4.47 ms/estimate</td>
<td>7.642</td>
<td>24.77</td>
<td>414.2</td>
<td>491.5 (UE 76th)</td>
</tr>
<tr>
<td>CCC2-GAC-NR2C</td>
<td>6.443</td>
<td>9.725</td>
<td>92.58</td>
<td>296.6 (UE 58th)</td>
</tr>
<tr>
<td>CCC2-GAC* (Gen=500, pop=32)</td>
<td>7.468</td>
<td>36.39</td>
<td>227.9</td>
<td>325.9 (UE 60th)</td>
</tr>
<tr>
<td>CCC2-GAC* (Gen=500, pop=64)</td>
<td>7.39</td>
<td>55.64</td>
<td>281.8</td>
<td>380.4 (UE 65th)</td>
</tr>
<tr>
<td>CCC2-GAC* (Gen=100, pop=16)</td>
<td>6.38</td>
<td>9.64</td>
<td>260</td>
<td>470 (UE 75th)</td>
</tr>
<tr>
<td>CCC2-GAC* (Gen=100, pop=26)</td>
<td>6.721</td>
<td>9.88</td>
<td>182</td>
<td>472.9 (UE 75th)</td>
</tr>
<tr>
<td>CCC2-GAC* (Gen=100, pop=32)</td>
<td>6.4</td>
<td>9.764</td>
<td>149.6</td>
<td>470 (UE 75th)</td>
</tr>
<tr>
<td>CCC2-GAC* (Gen=250, pop=32)</td>
<td>6.848</td>
<td>10.93</td>
<td>101.4</td>
<td>217.1 (UE 50th)</td>
</tr>
<tr>
<td>PT=1.83 sec/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCC2-GAC* (Gen=150, pop=32)</td>
<td>6.306</td>
<td>9.59</td>
<td>91.8</td>
<td>293.2 (UE 57th)</td>
</tr>
<tr>
<td>PT=1.27 sec/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCC2-GAC* (Gen=150, pop=31)</td>
<td>6.51</td>
<td>9.718</td>
<td>76</td>
<td>380.4 (UE 65th)</td>
</tr>
</tbody>
</table>

*running with the same time arrival & delays but with only GAC parameters changed

It is observed from the table that CCC2-GAC with Gen=150 and population of 32 (2^5) could optimally meet the best requirements (even though Gen=150, pop=31 performance is also better but maximum error is high) with processing time of 1.27 s per UE estimate (using the same Dell PC as before). This has been run over several times even with different time delays as shown in Figure 4.19, and therefore this CDF value for Gen=150 and pop=32 is quite satisfactory. The slight difference of result in Figure 4.19 (such as 76.03 m at 95%) to the one in Table 4.41 (CCC2-GAC* (Gen=150, pop=32)) is due to time of arrivals had different random delays in different runs of the simulation.
Other higher iteration (generation) and higher population does not help in improving the prediction of road networks because higher population tend to rearrange more of the order of the number of variables used (for \( \text{pop}=64 \)). The idea is to keep the minimum fitness but with balanced randomness when predictions are hard to make, especially at several road intersections (such as when Road 1 and Road 2 intersects). It is also very time consuming to use higher populations size and higher generations (PT is 3 to 5 seconds per estimate), where the results are not any better than using \( \text{Gen}=150 \) and population size of moderately enough. The desired population size (\( \text{pop}=32 \)) is therefore close to 31 (number of road points and one CCC2 point used in the Fitness Function). Running GAC with lesser than 31 populations and less than 100 generation per each CCC2’s fitness is also not sufficient because more of GAC’s randomness should not be the determining comparator’s role. The purpose of using GAC is to calculate minimum distances of CCC2’s points to the road points and at intersections where the prediction errors are probably high, GA randomness should take effect, where at most times it predicts the movement correctly, and at certain times (CDF > 95%) it does not. Unlike MBRC’s prediction,
which is always based on most likelihood probability that the vehicle is travelling on the one main road or major road, GAC will use randomness when predictions are hard to make but within acceptable tolerance.

### 4.5.3 RLMN on urban-suburban kLOS route

Three dummy RLMN sites are located as shown in Figure A.17. The location of each RLMN was planned according to their coverage towards two hearable spots (method described in Chapter 3) based on analysis of drive test data. The closest of the RLMNs to the serving cell and the neighbor cell will be instructed by SMLC to perform timing measurements. This will produce three timing measurements or two pair of hyperbolic equations from three hearable sites (serving cell, neighbor cell and RLMN). Since RLMN’s location is known and also the assumption that each RLMN’s directional antenna and coverage towards the UE with multipath delays are known, CCC or NR3C will then be used for location estimations. Figure 4.20 illustrates the CDF performance for CCC and NR3C along the urban-suburban route, which meets FCC’s location accuracy requirements.

![Figure 4.20 CDF results using CCC and NR3C with RLMN for 199 samples (N=2)](image)
4.6 SIMULATION AND PERFORMANCE OF TIMING TECHNIQUE IN GSM NETWORK WHEN HEARABILITY IS TWO

Table 4.42 shows the simulation parameters used for GSM location estimation techniques using E-OTD (downlink time difference) measurements from two hearable BTSs. Table 4.43 summarizes the CDF performances for location estimation using CCC2-MBRC (the best CCC2 point and the best CCC2 point nearest to road reference

Table 4.42 Simulation parameters for GSM location estimation techniques using E-OTD measurements from two hearable BTSs.

<table>
<thead>
<tr>
<th>Descriptions</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total query of $N=2$ location during trip:</td>
<td>1805 samples (location of real MS with $N=2$ shown in Figure A.18 with red points for file1531)</td>
</tr>
<tr>
<td>Distance of trip:</td>
<td>Drive test: 9.7 km (from Menara Celcom to Wangsa Melawati), same as UMTS drive.</td>
</tr>
<tr>
<td>Type of location search:</td>
<td>Vehicular Navigation/Tracking</td>
</tr>
<tr>
<td>Average vehicular speed</td>
<td>19 km/h (maximum speed 70km/h)</td>
</tr>
<tr>
<td>Terrain Environment:</td>
<td>known Line of Sight (kLOS), propagation prediction as per Equation (3.2), $D_{PE}=1.8e^{-8}$</td>
</tr>
<tr>
<td>BTSs distances to MS along route:</td>
<td>GSM drive test with time stamped 3.31pm, 2007 with BTSs’ average antenna height 35 m.</td>
</tr>
<tr>
<td>Total navigation time:</td>
<td>31 minutes (start to end of trip)</td>
</tr>
<tr>
<td>GA Parameters:</td>
<td>$Gen=250$ and others, $pop=32$ and others, probability crossover=0.8, prob mutation=0.01</td>
</tr>
<tr>
<td>NR2C:</td>
<td>Max iterations =80, tolerance=$2.2204x10^{-7}$</td>
</tr>
<tr>
<td>CCC2:</td>
<td>Four points output: $A1$, $A2$, $B1$ and $B2$</td>
</tr>
<tr>
<td>NR3C (used when $N=3$):</td>
<td>Max iterations =60, tolerance=$2.2204x10^{-12}$</td>
</tr>
<tr>
<td>CCC (used when $N=3$):</td>
<td>Only one convergence point.</td>
</tr>
<tr>
<td>MBRC:</td>
<td>Best Route (Figure A.14 urban-suburban route is 9.89km*) with more resolution points (497).</td>
</tr>
<tr>
<td>GAC:</td>
<td>Best Route (497 points) as main road along with two other dummy roads nearby the urban suburban route (as shown in Figure 3.15).</td>
</tr>
<tr>
<td>RLMN (as in Figure A.18 for GSM):</td>
<td>Four dummy RLMN sites along this route. Each dummy RLMN near 2 hearable sites produces $N=3$. CCC and NR3C would be used, $D_{PE}=1.8e^{-8}$</td>
</tr>
</tbody>
</table>

*Difference in trip distance between map and real drive test route is due to inaccuracy in drawing the paths on the software map versus the actual GPS measured drive test route. GPS also introduces some of its prediction errors as mentioned in Chapter 2.
point), CCC2-GA, NR2C (without MBRC or GAC), and finally CCC/NR3C with the assistance of RLMN on two hearable BTSs. The estimated MS sample number with maximum error is also listed in the right most column of Table 4.43.

Table 4.43  CDF for CCC2-MBRC, NR2C, CCC2-GAC, RLMN with CCC and NR3C on urban-suburban route with hearability of two BTSs

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% (m)</th>
<th>67% (m)</th>
<th>95% (m)</th>
<th>Max Error (m) &amp; sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCC2-MBRC (CCC2 point)</td>
<td>7.08</td>
<td>7.7</td>
<td>41.94</td>
<td>282.6 (M1782)</td>
</tr>
<tr>
<td>PT=0.34 sec/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCC2-MBRC (Road point)</td>
<td>19.35</td>
<td>28.13</td>
<td>48.11</td>
<td>165.6 (M914)</td>
</tr>
<tr>
<td>PT=0.34 sec/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NR2C (without MBRC or GAC)</td>
<td>368</td>
<td>425.6</td>
<td>656.1</td>
<td>1162 (M1596)</td>
</tr>
<tr>
<td>PT=4.47 ms/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCC2-GAC* (Gen=250, pop=32)</td>
<td>6.436</td>
<td>7.658</td>
<td>56.67</td>
<td>461.4 (M890)</td>
</tr>
<tr>
<td>PT=1.83 sec/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCC2-GAC-NR2C</td>
<td>6.436</td>
<td>7.658</td>
<td>56.67</td>
<td>461.4 (M890)</td>
</tr>
<tr>
<td>CCC2-GAC* (Gen=500, pop=64)</td>
<td>6.454</td>
<td>7.646</td>
<td>65.31</td>
<td>552.1 (M889)</td>
</tr>
<tr>
<td>PT=5.41 sec/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCC2-GAC* (Gen=150, pop=32)</td>
<td>6.44</td>
<td>7.664</td>
<td>66.06</td>
<td>461.6 (M891)</td>
</tr>
<tr>
<td>PT=1.27 sec/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCC2-GAC* (Gen=250, pop=32)</td>
<td>6.44</td>
<td>7.662</td>
<td>57.54</td>
<td>478.9 (M891)</td>
</tr>
<tr>
<td>PT=1.25 sec/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCC2-GAC* (Gen=150, pop=31)</td>
<td>6.434</td>
<td>7.662</td>
<td>59.64</td>
<td>448.7 (M895)</td>
</tr>
<tr>
<td>PT=1.25 sec/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCC (RLMN)</td>
<td>5.621</td>
<td>7.673</td>
<td>33.35</td>
<td>140.6 (M1519)</td>
</tr>
<tr>
<td>NR3C (RLMN)</td>
<td>7.783</td>
<td>14.42</td>
<td>56.12</td>
<td>117.3 (M1564)</td>
</tr>
</tbody>
</table>

*indicates different runs of simulation for GAC

Figure C.14 shows that without CCC2-MBRC, the CCC2 points by itself do not meet FCC E-911 location accuracy requirements. NR2C (in Table 4.43) also does not meet location accuracy requirements. Figure C.15 shows the distribution of selection between CCC2’s points along the urban-suburban route when N=2 (hearability of two BTSs). Figure C.16 illustrates the MS estimated versus the actual MS locations along the urban-suburban route (using CCC2-MBRC based on the best
CCC2 point). The maximum error occurred where all four CCC2’s points are far from the road and choosing any one of them does not help much. This is due to higher multipath errors and delays causing the real geometrical distance’s prediction around this area to be highly erroneous. Also some mapping and GPS’s measurement errors could also have contributed to the accuracy of road calibration and the overall prediction, such as shown in the beginning of the MS sample where error was high.

Figure C.17 illustrates the CDF performance for location estimation using CCC2-GAC with Gen=250 and pop=32. From Table 4.43, it is apparent that with GAC comparing a set of 31 variable points (each CCC2’s points with 30 closest road network points), a population size of 31 or 32 ($2^5$) could optimize the prediction. This is the same findings for UMTS’s case also. When generations are 250, the results are desirable but the processing time is slightly longer than when the generations are 150 (Gen=150, pop=32), which also produce satisfactory results except its 95% percentage’s error is by 10 meters less accurate than by running the GAC’s generations by 250. The response time to customer’s LBS request is very important, so GAC with Gen=150 or 250 could be used along with population size of 31 or 32. The best population size could be determined as the number of variables used or the closest power of 2 which is greater or equals to the number of variables used. It can be observed from Table 4.43 that running GAC with Gen=500 and pop=64 is of no additional use, as it will repeat the variables order unnecessarily and causing longer processing time (PT of 5.41 s). CDF (for GSM 1805 samples used compared to 199 samples for UMTS) for GACs’ usage between the various populations and generations for GSM samples almost produce close results for 67% and 95% (between different combinations of Gen and pop) because the overall number of samples are large, and therefore averages out GACs’ optimum performance for the urban-suburban route with maximum possibilities of various occurances (road intersections, geometrical problems, random time delays). In short, when there are more samples to be simulated, more possible occurances could be observed by the algorithm where the smaller high-errors (>95%) and larger low-errors would be averaged out, and the estimator’s characteristic could be unbiasedly analyzed. Figure C.18 illustrates these location errors for CCC2-GAC (Gen=250, pop=32) along the urban-suburban drive test route ($N=2$). Similarly, as was mentioned in UMTS’ case, the main characteristic
of GAC is to predict with some tolerance of randomness the best minimum point when occurrence of various minimum points could exist(such as near road intersections). In most cases of location samples estimated as shown in Figure C.18, the optimum fitness function meets the objective and in few cases (few high-error locations such as error ≥ 95%) it does not.

Figure C.19 illustrates the location error using RLMN with CCC, and RLMN with NR3C along the urban-suburban drive test route. The CDF results show that the FCC E-911 location requirement is met even though few high-errors exist (above 100 m) that could be caused by the geometric placements of the new RLMN, where each RLMN covers a bigger sector size of more \( N=2 \) (for GSM samples) on the route.

4.7 SIMULATION AND PERFORMANCE OF ROUND TRIP TIME (RTT) FROM UMTS SERVING CELL WITH ROAD MATCHING TECHNIQUE

Similar multipath delay conditions for one hearable UMTS serving site along kLOS urban-suburban route (same route of 3.31 pm, 2007) with \( D_{PE} \) for time of arrival (half of the Round Trip Time) as in Table 4.40, will be utilized for this simulation. The location estimation technique used will be OCRAA/OCRAIA and the number of samples to be simulated are 194 for \( N=1 \) on this route.

Table 4.44 summarizes the CDF results for OCRAA and OCRAIA location estimation techniques when UE is on a roadpath with \( N=1 \) (194 samples of estimated locations). Before the simulation was performed, for calibration and verification purposes, time of arrival without error delays (real geometric time) and the actual UE travelled points were run to estimate location using OCRAA. Of course, the result should be 0 in ideal situation for all CDF percentages. It is clear that OCRAA could produce the best result. Its results are generally consistent for most of the simulation because it is based on the road’s proximity point that is the closest to the time of arrival/delay’s calculations of the serving Node B. Its accuracy is also dependent on the road map’s accuracy versus the real travelled position by mobile user.
Putting angle control, \( Abwt \), which limits the beamwidth of estimated search area to be within \( Abwt \)'s value, also helps prediction for both OCRAA and OCRAIA algorithm’s estimation to meet FCC location standards. As mentioned in Chapter 3, the main purpose of introducing \( Abwt \) is because the actual Telco’s antenna beamwidth is not known (only planned beamwidth is known), and therefore \( Abwt \) calculates the average beamwidth prediction for each serving cell along all the routes that were driven based on the drive test data, and then the angle control is used during the road matching prediction in order to estimate the mobile location. Without angle control, OCRAIA failed to meet FCC location accuracy requirements. OCRAIA with angle control will still have a few high errors (error > 95%) because it may search for the Node B’s coverage angle that produces the closest distance to the roads (within \( Abwt \) limit) and this prediction may not always be true. OCRAA on the other hand, provides freedom of angle search (matching) within tolerance of \( Abwt \), as its main priority is to find the closest road to the Node B (with respect to the time of arrival).

Table 4.44  CDF for UMTS location estimation using OCRAA and OCRAIA

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% (m)</th>
<th>67% (m)</th>
<th>95% (m)</th>
<th>Max Error (m) and sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCRAA (( Abwt=60 ))</td>
<td>13.75</td>
<td>38.21</td>
<td>561</td>
<td>656 (UE 83th, 7.1 degrees diff)</td>
</tr>
<tr>
<td>PT=0.38 sec/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OCRAA (( Abwt=71 ))</td>
<td>12.9</td>
<td>17.77</td>
<td>65.43</td>
<td>124.3 (UE 83th, 71 degrees diff)</td>
</tr>
<tr>
<td>PT=0.38 sec/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OCRAA (( Abwt=85 ))</td>
<td>8.335</td>
<td>10.78</td>
<td>65.43</td>
<td>224.2 (UE 192nd, 74.2 deg diff)</td>
</tr>
<tr>
<td>PT=0.38 sec/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OCRAA (( Abwt=90 ))</td>
<td>8.335</td>
<td>10.96</td>
<td>65.43</td>
<td>224.2 (UE 192nd, 74.2 deg diff)</td>
</tr>
<tr>
<td>PT=0.38 sec/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OCRAA (( Abwt=100 ))</td>
<td>8.335</td>
<td>10.76</td>
<td>65.43</td>
<td>224.2 (UE 192nd, 74.2 deg diff)</td>
</tr>
<tr>
<td>PT=0.38 sec/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OCRAA (( Abwt=105 ))</td>
<td>8.4</td>
<td>11.08</td>
<td>124.3</td>
<td>259.9 (UE 12th, 104.9 deg diff)</td>
</tr>
<tr>
<td>PT=0.38 sec/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OCRAA (( Abwt=120 ))</td>
<td>8.6</td>
<td>11.29</td>
<td>349</td>
<td>515.1 (UE 70th, 106 deg diff)</td>
</tr>
<tr>
<td>PT=0.38 sec/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OCRAIA (with ( Abwt=71 ))</td>
<td>11.2</td>
<td>12.68</td>
<td>77.7</td>
<td>654.2 (UE 83th, 7 degrees diff)</td>
</tr>
<tr>
<td>PT= 0.49 sec/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OCRAIA (no angle control)</td>
<td>77.96</td>
<td>126</td>
<td>384.9</td>
<td>508.9 (UE 71st, 106 degrees diff)</td>
</tr>
<tr>
<td>PT= 0.114 sec/estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.21 illustrates the location error between UE estimated and the actual UE. For comparison purposes, the serving Node B’s distances to UE are also shown along the route when \( N=1 \). Figure 4.22 illustrates the azimuth direction between the corresponding Node B to UE estimated while on the route, azimuth direction between the corresponding Node B to actual UE, and the corresponding Node B’s directional antenna beam (as obtained from Telco’s database). Figure 4.22 also shows that the maximum beamwidth of 71 degrees of difference is observed (when angle control of \( Abwt \) is 71), from sample number 73 to sample number 83, where the Node B’s directional angle was at 240 degrees and its direction towards UE estimated for sample 73 through 83 is about 311 degrees (311-240=71° also shown in the right most column of Table 4.44 where maximum error for \( Abwt=71 \) occurs at sample 83). If \( Abwt \) is reduced to 60 degrees of freedom, the UE estimated angles are also controlled to be below 60 (such as 7.1 degrees of directional difference between Node B to UE estimated with maximum error for \( Abwt=60 \) as shown in Table 4.44) causing the location estimation accuracy to reduce. This is due to more bad estimations that are also closer to the road are accepted by OCRAA within 60 degrees range. The actual UE at 83th sample is at 324.6 degrees from Node B, which means Telco has provided

![Location errors between UE estimated and UE real when N=1](image)

**Figure 4.21** Location errors for OCRAA along the urban-suburban drive test route \((Abwt=71, \text{ with } 194 \text{ samples where } N=1)\)
Azimuth direction to UE estimated (Abwt=71) from Node B, azimuth direction to UE real from Node B and Telco’s Node B antenna direction 84.6 degrees of beamwidth (324.6°-240°=84.6°) towards the UE. Running Abwt with 85 degrees will not help on reducing the maximum error compared to Abwt=71. In fact a higher maximum error emerges by increasing the freedom of angle. However OCRAA with Abwt=85 definately reduces the 50% and 67% errors. Therefore the suitable and safer choices of Abwt, average beamwidth that could be used is from 71 till 105 degrees as shown in Table 4.44 for similar configuration of three sector sites (with assumption at least 60 degrees antenna beamwidth is assigned/planned per sector by the Telco) along the urban-suburban route.

4.8 SIMULATION AND PERFORMANCE OF TIME OF ARRIVAL FROM GSM SERVING CELL WITH ROAD MATCHING TECHNIQUE

Similar multipath delay conditions for one hearable GSM serving site along urban-suburban route (same route of 3.31 pm, 2007) with prediction error for time of arrival as in Table 4.42, is utilized for this simulation of 2607 samples (where N=1). Table 4.45 summarizes the CDF results for OCRAA and OCRAIA estimation techniques when MS is on a roadpath of urban-suburban route using road mapping of Best route (as shown in Figure A.14). Angle control of Abwt does not perform well for GSM. For
example at certain samples, beamwidth of 143 degrees were observed for three sector sites. Also along this route, certain BTS or vendor specific radio stations is equipped with directional antenna capable of covering 210 degrees of beamwidth. Simulating $Abwt$ from 60 till 120 (as done for UMTS) did not meet location accuracy requirements for the Telco’s GSM network. Determining $Abwt$ for each GSM sample by sequential programming (trial and error) in real live scenario is not practical because each travelled route could also deviate slightly from the drive tests’ routes. Furthermore, Telco may perform changes to antenna orientation from time to time during their optimization process. It is proposed that in addition to other information pertaining to each cell, Telco’s record should also indicate maximum allowable beamwidth for each cell. All records should be updated after optimization or

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% (m)</th>
<th>67% (m)</th>
<th>95% (m)</th>
<th>Max Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCRAA ($Abwt=360$) PT= 0.38sec</td>
<td>123</td>
<td>223</td>
<td>747.6</td>
<td>1166</td>
</tr>
<tr>
<td>OCRAA ($Abwt=71$) PT= 0.38sec</td>
<td>82.74</td>
<td>161.4</td>
<td>719.6</td>
<td>1007</td>
</tr>
<tr>
<td>OCRAA ($Abwt=90$) PT= 0.38sec</td>
<td>62.82</td>
<td>151.7</td>
<td>721.3</td>
<td>1112</td>
</tr>
<tr>
<td>OCRAA ($Abwt=100$) PT= 0.38sec</td>
<td>55.37</td>
<td>152.7</td>
<td>721.3</td>
<td>1112</td>
</tr>
<tr>
<td>OCRAIA (without angle control) PT=0.1137 sec/estimate</td>
<td>115</td>
<td>215.8</td>
<td>766.2</td>
<td>1167</td>
</tr>
<tr>
<td>Serving BTS distance to actual MS</td>
<td>286.1</td>
<td>376.1</td>
<td>763.9</td>
<td>1123</td>
</tr>
<tr>
<td>M-OCRAIA (with known previous MS positions of 1 sec), PT=5 ms, where previous N=1 (when no initial position, MS pos= BTS1)</td>
<td>33.55</td>
<td>62.14</td>
<td>206</td>
<td>795.7</td>
</tr>
<tr>
<td>M-OCRAIA (with known previous MS positions of 1 sec), PT=5 ms, where previous N=1,2,3</td>
<td>32.23</td>
<td>52.57</td>
<td>197.4</td>
<td>249.6</td>
</tr>
</tbody>
</table>

Table 4.45 CDF for location estimation using OCRAA, OCRAIA and M-OCRAIA
upgrading process. For cells with omni directional, the usage of angle control is useless because Abwt of 360 means (total freedom) the MS could be anywhere within the cell.

To solve tracking problems when $N=1$ for GSM, some prior knowledge of the most recent (MS’s previous) location is required. Figure 4.23 shows the hearability occurrence for drive test route of 3.31pm, 2007. Along this urban-suburban route, when $N=3$, NR3C or CCC could be used to estimate the mobile locations, and when $N=2$, RLMN could be used to assist NR3C or CCC to perform location estimations. When $N=1$, as seen in Table 4.45, OCRAA and OCRAIA failed to meet location accuracy requirements. Both methods perform slightly better (for CDF error $\leq 67\%$) than Cell ID (serving BTS’s distance to MS).

![GSM hearability along urban-suburban route](image)

**Figure 4.23** Samples’ location and actual MS hearability along the urban-suburban drive test route (2607 out of total 5395 samples where $N=1$)

From Table 4.45, when the previous locations are measured within 1 seconds apart (for GSM as observed from the drive test data logs, the drive test equipment is capable to generate 3 ERXL measurements for the same MS within 1 seconds), the CDF results at 67% and 95% for both cases of Modified OCRAIA (when previous locations are just $N=1$ and when previous locations are based on the sample’s order of
hearability $N=1, 2, 3$ as shown in Figure 4.23) meet FCC’s location accuracy requirements. Modified OCRAIA (M-OCRAIA) also has faster processing time (PT) than OCRAA or the ordinary OCRAIA.

### 4.9 PERFORMANCE OF COMBINED TIMING TECHNIQUE

Figure 4.24 shows the GSM location error along the urban-suburban route using combined UIPS timing technique (M-OCRAIA for $N=1$, NR3C with RLMN for $N=2$, and NR3C for $N=3$) to estimate location when $N=1, 2$ and 3. The CDF result for combined UIPS timing technique for GSM and UMTS are listed in Table 4.46. For UMTS, using OCRAA (when $N=1$), NR3C with RLMN (when $N=2$), and NR3C (when $N=3$) produced maximum error of 817.2 m at sample number 26 along the urban-suburban route. PT for OCRAA is high (0.38 seconds) but since $N=1$ is less than 200 samples (total 2121 samples for all $N$), so the total PT is not so burdening.

![Figure 4.24 Location errors along the GSM urban-suburban drive test route (using M-OCRAIA for $N=1$, NR3C with RLMN for $N=2$, and NR3C for $N=3$)](image)

It is worth a note for tracking users, the transition of serving cells should be stored for GSM and UMTS, and could be used (compared current to stored Cell IDs)
Table 4.46  CDF for location estimation using UIPS combined technique (N=1,2,3)

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% (m)</th>
<th>67% (m)</th>
<th>95% (m)</th>
<th>Max Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSM combined timing technique Average PT = 2.4 ms/estimate</td>
<td>14.96</td>
<td>27.63</td>
<td>155.2</td>
<td>249.6</td>
</tr>
<tr>
<td>UMTS combined timing technique Average PT = 37 ms/estimate</td>
<td>3.98</td>
<td>8.02</td>
<td>47.82</td>
<td>817.2</td>
</tr>
</tbody>
</table>

when UIPS is required to estimate the percentage of dominant cells for an unknown travelled route (in order to predict the most likely travelled road). Moler (2004) suggests that for web pages and search engines, Markov Chain could be utilized. Similarly, if the transition probability for each state (in and out or handover from previous to current state) at samples’ location are calculated and stored for each route, it is possible to also trace the route because Cell IDs could be readily captured from the NMRs while the user is inquiring NBS through active data mode. Figure C.20 illustrates the transitions of Cell ID (Cell numbers are converted to smaller decimal for illustration purposes) from each sample location, where each sample’s location is stored as decimal degrees or as degree minutes seconds (DMS) or as Universal Transverse Mercator (UTM) earth coordinates. There are 34 serving cells along this route. For NBS, it is also possible for UIPS to propose best alternate routes because UIPS could query if the best route has congestion (such as too many voice calls than the average hourly voice calls hooked to the list of Telco’s cells along the proposed best route may indicate extensive amount of road users or big event in the area) and alert the user about the probable cause.

4.10 DISCUSSION

In this chapter, drive tests data performance was evaluated for urban-suburban route, metropolitan route, suburban-rural route, university campus route (within suburban/rural area) and highway routes (north south and city highway). Table 4.47 summarizes the results for all the location estimation techniques when \( N=3 \) (hearability of three BSs) in kLOS and uLOS. It was found that when multipath delays are known for the routes (kLOS), even in high multipath surroundings especially such as metro and urban, the location estimation errors for UMTS and GSM were small. As
shown in Table 4.47 (based on averages of trials’ results at 67% and 95% on the same route), 67% error is within 10 m and 95% error is within 60 m for urban-suburban route. When BSs distances becomes farther from the UE, the prediction based on known multipath delays becomes inaccurate and a different $D_{PE}$ constant is recommended ($D_{PE} = 1.8e^{-9}$ is used instead of $1.8e^{-8}$ when BS to UE distances are very far). Prediction of multipath delays from each BS is as tricky as coverage prediction of propagation signal from the same BS, due to the characteristics of medium between BS and UE, environment factors, signal fading and new construction on structures especially in developing cities like Kuala Lumpur. Analyzing data of three trials of urban-suburban and two trials of metro route, indicated that typical signal measurements deviate from 2 dB to 6 dB due to fading. This would be discussed further in Chapter 5 when stored signal data collection is used for location estimation.

<table>
<thead>
<tr>
<th>CDF for Techniques</th>
<th>GSM 67% (m)</th>
<th>GSM 95% (m)</th>
<th>GSM N=3 (%)</th>
<th>3G 67% (m)</th>
<th>3G 95% (m)</th>
<th>3G N=3 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban-Sub CCC</td>
<td>4.473</td>
<td>36.90</td>
<td>28.77</td>
<td>8.92</td>
<td>33.21</td>
<td>85.42</td>
</tr>
<tr>
<td>Urban-Sub NR3C</td>
<td>5.98</td>
<td>49</td>
<td>28.77</td>
<td>9.4</td>
<td>59.22</td>
<td>85.42</td>
</tr>
<tr>
<td>Metro CCC</td>
<td>4.95</td>
<td>13.8</td>
<td>19.3</td>
<td>3.37</td>
<td>9.5</td>
<td>82</td>
</tr>
<tr>
<td>Metro NR3C</td>
<td>4.54</td>
<td>13.41</td>
<td>19.3</td>
<td>3.35</td>
<td>13.87</td>
<td>82</td>
</tr>
<tr>
<td>Sub-Rural CCC</td>
<td>NA</td>
<td>NA</td>
<td>0</td>
<td>4.6*</td>
<td>22.43*</td>
<td>82.4</td>
</tr>
<tr>
<td>Sub-Rural NR3C</td>
<td>NA</td>
<td>NA</td>
<td>0</td>
<td>3.68*</td>
<td>56.86*</td>
<td>82.4</td>
</tr>
<tr>
<td>Campus CCC</td>
<td>NA</td>
<td>NA</td>
<td>0</td>
<td>22.04</td>
<td>65.76</td>
<td>81.6</td>
</tr>
<tr>
<td>Campus NR3C</td>
<td>NA</td>
<td>NA</td>
<td>0</td>
<td>26.88</td>
<td>60.92</td>
<td>81.6</td>
</tr>
<tr>
<td>Highway CCC</td>
<td>11.43</td>
<td>22.36</td>
<td>13.3</td>
<td>11</td>
<td>35.68</td>
<td>96.23</td>
</tr>
<tr>
<td>Highway NR3C</td>
<td>7.3</td>
<td>15.17</td>
<td>13.3</td>
<td>9.55</td>
<td>76.69</td>
<td>96.23</td>
</tr>
<tr>
<td>City Highway CCC</td>
<td>3.855*</td>
<td>16.72*</td>
<td>31.48</td>
<td>7.137</td>
<td>23.53</td>
<td>91.2</td>
</tr>
<tr>
<td>City Highway NR3C</td>
<td>6.149*</td>
<td>59.3*</td>
<td>31.48</td>
<td>11.01</td>
<td>48.65</td>
<td>91.2</td>
</tr>
<tr>
<td>uLOS First Mean</td>
<td>48.43</td>
<td>219.5</td>
<td>100</td>
<td>53.58</td>
<td>223.9</td>
<td>100</td>
</tr>
<tr>
<td>uLOS Random Search</td>
<td>52</td>
<td>208.6</td>
<td>100</td>
<td>51.71</td>
<td>191.1</td>
<td>100</td>
</tr>
<tr>
<td>uLOS CCC</td>
<td>56.26</td>
<td>137.5</td>
<td>100</td>
<td>58.93</td>
<td>130.4</td>
<td>100</td>
</tr>
<tr>
<td>uLOS BestComp σ 20</td>
<td>51.3</td>
<td>137.5</td>
<td>100</td>
<td>57.63</td>
<td>199.5</td>
<td>100</td>
</tr>
</tbody>
</table>

NA indicates Not Available, and * denotes the usage of $D_{PE} = 1.8e^{-9}$
For example, when a new building is constructed, signals could be reflected and bounced with even more delays than the error predicted earlier. A more suitable delay error constant would be required for the following grid area and BSs that are affected by the new building. Collecting and constructing database from signal characteristics (signal strength, signal propagation travelled paths, ray tracing, actual time of arrival to the UE from the known BS coordinates) could only help to model the delay prediction error as in Equation (3.10). More averages of data collection samples could help to further reduce the delay prediction error for a given route as was done for metro kLOS routes. Also for signal loss prediction, Equation (3.2) is identical to Free Space propagation model but predicting the accurate $a$ and $c$ constants would assist in identifying the optimized standard deviation of fading for a given route or predicting each BSs’ propagation within an area. Studies on propagation models related to time delays and location estimation were also performed by Chu et al. (2004). Kurner et al. (1994) presented some prediction models for received impulse response delays and also measurements using Impulse Response Analyzer for GSM urban and forest environment. McGuire et al. (2003) presented a model with signal diffracted paths for Manhattan type of cities where mobile locations could be estimated from path loss of survey data.

In uLOS urban-suburban case, it has been shown from Figure 4.17, that without averaging of CCC (or NR3C), most of CCC’s 95% error were not acceptable for E-911 location requirements. With averaging of CCC and several types of NR3C averages, UE/MSs’ estimation accuracy have been improved. From Table 4.47, CCC averaging provided 67% estimation errors within 60 m and 95% estimation errors within 140 m for both GSM and UMTS. Best Comparator works well for GSM but did not help for UMTS as CCC averaging’s performances compared to First Mean of NR3C was better and therefore the comparator could not produce good comparison, where it had selected more estimates of First Mean of NR3C than CCC averaging estimates, causing a reduction of its performance for CDF $\geq$ 95% compared to CCC averaging’s $\geq$ 95% estimates. This is due to $\sigma$ selected for UMTS as compared to GSM should be lower than 20 due to different UMTS BS’s placements effect and different time delay effects towards the simulated UE. On the other hand for GSM, Best Comparator has inherited the same 95% error of CCC’s averaging and also
improved the 67% error of CCC’s averaging. When comparing uLOS results to other trials, such as to E-OTD that was tested in field by Cambridge Positioning Systems (CPS) with software modification on the phone, as reported by Laitinen et al. (2001a), the trial could not meet 67% requirement in dense urban Hong Kong, with 125 m of error estimation. But CPS was successful in suburban of Cambridge, where 67% of the estimations tested, error was within 50 m. The response time was a few seconds for each estimate. Table D.1 summarizes CDF performances of related studies based on simulation and field tests by Halonen et al. (2003). The parameters used are different and therefore each researcher’s performances are different. Bertoni & Suh (2005) used six BTSs and therefore the accuracy for urban’s 67% is below 40 m. But its higher error at 95% is worse than CCC averaging for urban-suburban. CCC averaging’s 95% errors also perform better than high floors of apartments in suburban trials by Halonen et al. (2003). But in good suburban, CCC averaging in urban-suburban cannot match results by Halonen et al. (2003) for GSM and Porcino (2004) for UMTS OTDOA-IPDL. Furthermore, CCC averaging was not tested purely on low rise suburban, because 52% of the UE samples were tested in dense urban of KL area and 48% was tested for suburban KL. However, pure CCC’s timing technique performance in kLOS urban-suburban (Table 4.47) is better than Halonen et al. (2003) for GSM and Porcino (2001) for UMTS. With averaging and Best Geo (eliminate selection of BSs that causes geometrical problems and chooses only BSs that are acceptable from the NMR or ECNO/ERXL records), 95% of all NR3C and CCC averaging techniques’ estimations are below 230 m for urban-suburban area and 67% are below 60 m. Finally for uLOS, CCC averaging works well when environment conditions are not known and error delays are high. And cumulatively, when location search is required from a wider coverage of urban/suburban region, CCC averaging could produce 95% errors below 140 m and 67% errors below 60 m for both GSM and UMTS, with PT of 0.0564 s for one estimate (from Table 4.39).

In OTDOA, CPICH (Common Pilot Channel) takes 5 to 20 percent of downlink power for UE to perform measurements and by cross correlating CPICHs’ measurements from two Node Bs, where from the peak of the cross correlator, the time difference between the pair of Node Bs could be determined (Yap et al. 2002). CPICH ECNO (3GPP 2007d) and CPICH RSCP are easily measured by the UE and
must be done a few steps earlier to find out the hearability status before UIPS initiate instructions for time difference measurements from the UE. After the time difference measurements are sent to UIPS or SMLC, the estimation process starts. Table 4.48 shows the processing time (PT) for each estimate by CCC, NR3C and Fsolve. Matlab toolbox’s function Fsolve (Anon 2008i) was used and structured the same way as NR3C’s flow for location estimation. Fsolve is a built-in function for solving non linear equations based on numerical methods (Powell 1970). It is obvious that NR3C produces the fastest and the most accurate location estimation when no environmental conditions are applied. NR3C’s best initial guessing point (for ideal and non ideal environment) is always found to be at coordinate (0,0). CCC is the second fastest but produces maximum error of 17.93 m in ideal environment due to its already assumed geometric error characteristics and its processing resolutions. Fsolve is based on numeric methods but it is not as fast as NR3C or CCC. It is able to produce errors below 0.016 m. Other Matlab built-in functions tested are Genetic Algorithm (GA) and Pattern Search. Both methods took several seconds to process an estimate and furthermore the estimates were not as accurate. However GA’s usage in the next paragraph will be discussed when time measurements are hearable from less than three BSs ($N<3$).

Table 4.48 Performance and PT for each UE estimate using CCC, NR3C and Fsolve on UMTS urban-suburban route (3.31pm) with no delay errors

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% (m)</th>
<th>67% (m)</th>
<th>95% (m)</th>
<th>Max (m)</th>
<th>PT (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCC (Ideal)</td>
<td>1.062</td>
<td>2.09</td>
<td>3.2</td>
<td>17.93</td>
<td>9.7 milli</td>
</tr>
<tr>
<td>NR3C (Ideal)</td>
<td>0</td>
<td>0</td>
<td>1.70 nano</td>
<td>6.74 nano</td>
<td>0.85 milli</td>
</tr>
<tr>
<td>Fsolve (Ideal)</td>
<td>0.6791 μ</td>
<td>0.6791 μ</td>
<td>3.46 μ</td>
<td>0.0162</td>
<td>23.5 milli</td>
</tr>
</tbody>
</table>

For less than three hearability conditions, Simple Mapping Technique with Table Look Up (SMTTLU) was introduced to meet the requirement of this LBS project even though other extensive (Schiller & Voisard 2004) database techniques and tree structures of road networks exists in order to perform road matching or acquire road information from databases. In this research, SMTTLU is relevant and easy to use by Telcos where data can be imported immediately after drive test routes.
are completed (manual import of raw data or programmatically grabbing the files from predefined servers). Furthermore, SMTTLU has a faster PT due to its inextensive processing technique. When drive test data does not exist, mapping software (such as Google Earth) could be used to draw each paths and saving the files as .kml files. All saved paths with neighboring nodes information and alternate neighboring nodes are then entered into the Table Lookup. Alternate routes should also be entered, if it is known that some routes are closed on certain days or construction works are going on for certain time period. The criteria for selecting main versus alternate routes should be referred to another table (such as live feed traffic report from trusted source, flag from Markov transition of Node B’s along the route or other logical/decision format). Best Route Determining Technique (BRDT) was developed to propose the best route or alternate route from SMTTLU. It is also used within road prediction model.

Utilizing high resolution of digitized road maps, mobile user’s position (location) on a road network or walk paths could be estimated within acceptable accuracy even if the hearability of BSs is less than three. CCC2 method is developed to produce four points (2 points close to the first intersection and 2 points close to the second intersection of the two circles). For two hearable UMTS site, when user travels on one main road, CCC2-MBRC location estimation’s CDF produces 67% error within 10 m and 95% error at 66 m. For GSM, the 67% error are also within 10 m while 95% error at 41.94 m. The PT for each CCC2-MBRC estimate is 0.34 s. When there are more roads around the vicinity of the two UMTS circles, CCC2-GAC (Gen=150 or 250, pop=31 or 32) is utilized, where the CDF produces 67% error within 11 m while 95% error within 102 m. The PT for Gen of 250 (pop=32) is 1.83 sec/estimate, the PT for Gen of 150 (pop=32) is 1.27 sec/estimate while the PT for Gen of 150 (pop=31) is 1.25 sec/estimate. Any of the three genetic configurations could be chosen to be used for UMTS but preferably the one with the lowest PT. After many runs, CCC2-GAC with Gen of 150 (pop=32) is found suitable for UMTS. For GSM, CCC2-GAC (Gen=150 or 250, pop=31 or 32) produces 67% error within 8 m while 95% error within 67 m for the same urban-suburban route. Since in GSM there are more N=2 samples, CCC2-GAC with Gen of 150 (pop=31) is suitable due to the lowest PT compared to the other two configurations. NR2C method is unable to provide more points, whereby it only solves the best intersection point as per the
tolerance value provided. NR2C by itself and CCC2 points by itself could not meet FCC E-911 location accuracy requirements for the kLOS urban-suburban route.

RLMN are proposed to be located within $N=2$ coverage zones along a surveyed GSM or UMTS network. However RLMN should not be confused with radio repeaters. Radio repeaters would add additional multipath delays as specified by 3GPP (2004b). For example, if the repeater is placed at 1 km away from the main BS, then additional multipath delay of 3.33 $\mu$s would be added as one of the possible paths arriving at the UE. Surveying RLMN sites is crucial if it is to be classified as kLOS because only a few RLMNs placed in strategic higher locations are required for covering the areas (as per example of urban-suburban route) along a drive test route. These new RLMN would act as the third BS as in NR3C’s location estimation (where at least three BSs are required by NR3C’s technique). The dimensioning and justification to plan RLMN should be done similar to capacity planning, where for LBS, the number of location request per area and averaged hearability report for the area should be analyzed together. RLMN should also be placed even if hearability is three, in addition to some cells that are totally in NLOS towards UE/MS. In this case UIPS should discard those cells and instruct the nearby RLMN to make the measurements instead. In the UMTS kLOS urban-suburban simulation, using RLMN when hearability of two for stationary (on road/off road) or vehicular movement, 67% location error for both CCC and NR3C estimation is within 7 m while the 95% error is within 61 m. For GSM, the location error of 67% is within 15 m and location error of 95% is within 57 m, for both methods. PT for RLMN technique is the fastest (as per PT of CCC/NR3C in ms) compared to road matching techniques.

When hearability is only limited to the serving cell ($N=1$), for UMTS, RTT would be used along with road matching to determine the closest interception point of the serving’s cells angular approximations towards the road. Using OCRAAA with PT of 0.38 s, and with average beamwidth, $Abwt$ between 71 to 100 degrees for angle control, produces 67% location error within 18 m and 95% location error within 66 m. The beam direction records should be updated by Telcos for OCRAAA to work correctly. For GSM OCRAAA and OCRAIA does not meet FCC E-911 requirements. Therefore M-OCRAIA was utilized with PT of 5 ms and produces 67% error within
53 m while 95% error within 198 m. The errors are high because in GSM, serving cell’s time of arrival are matched with previous known location in order to determine the closest road point with respect to the previous location’s angular approximation.

In Thomas (2001), location estimation model and receiver architecture was presented. Thomas (2001) proposes three algorithms for Multipath Rejection which are: highest peak of impulse response as per an acceptable threshold, first arrival as per acceptable threshold or first peak as per acceptable threshold. Thomas (2001) uses Kalman Filtering for preprocessing/detecting NLOS and then uses Weighted Least Square with Chan’s Method to estimate location. As shown in Table D.2, Thomas (2001) produced (for hearability above three) 67% error within 10 m and 95% error within 20 m for rural vehicular navigation, 67% error within 20 m and 95% error within 40 m for suburban vehicular navigation, and 67% within 45 m and 95% within 75 m for urban vehicular speed. Knowledge of speed is required to determine which receiver to switch. When hearability of only two BSs, Thomas (2001) produced 67% error within 20 m and 95% error within 40 m for rural vehicular, 67% error within 30 m and 95% error within 80 m for suburban vehicular navigation, and 67% error within 90 m and 95% error within 110 m for urban vehicular speed. In our timing technique based on two hearable BSs, we were able to achieve results within 15 m at 67% error for GSM and UMTS, within 67 m at 95% error for GSM, and within 102 m at 95% error for UMTS on the urban-suburban route, when CCC2-MBRC or CCC2-GAC or RLMN were used. However, in actual situations, not knowing UMTS chip uncertainty, UE/MS detection capabilities and misleading or uncomprehensive kLOS information could lead the CDF error at 67% to be in the range of higher errors such as close to 60 m as produced for uLOS environment (as in Table 4.47). Therefore simulation results of timing measurement for kLOS case should not be taken for granted that the performances were good. In this research the scope is not to design the receiver part or not to change the existing OTDOA/E-OTD measurement processes by UE or MS as specified by 3GPP/ETSI. However, the main objective of this research is to make good use of various measurement information (such as avoid bad geometry BSs, use ECNO or ERXL information), develop prediction models for various possible situations (kLOS, road matching, GAC, MBRC, RLMN, averaging techniques) and find ways to maximize the prediction method through estimation.
techniques such as CCC or NR3C. Therefore for further studies, it is important to evaluate TDOA hardware (LMU and SMLC) and design a receiver/simulator based on actual TDOA supported by vendor’s trials. It is hoped with actual tests, better improvement could be done on CCC/NR3C and the other proposed timing techniques based on real network integration effects and end to end environment effects.

4.11 CONCLUSION

The research on three circles has evolved into a robust geometric algorithm called CCC that is able to cater high delay errors and predict location of mobile user. A faster numerical computing algorithm was adopted for location estimation, and called NR3C. The averaging of CCC and NR3C also assisted in improving location estimation accuracy in uLOS areas. For kLOS, drive test had to be done and survey data was used to study ECNO/ERXL hearability for timing measurements. The measurement of ECNO and ERXL is proposed to be done earlier before deciding which location techniques to be used based on hearability status (such as use CCC when hearability is three). For Klang Valley (KL, PJ and Bangi), the findings on hearability studies for GSM and UMTS was done. Probability of at least 81% of UMTS measurements will have three hearable BSs and the probability is less than 32% for GSM. The absence of LAC, Cell ID, BCCH made some of the route’s measurements’ sample incomplete to qualify for GSM’s hearability of at least three BSs. For UMTS, the hearability is good for Klang Valley. Nevertheless, Telcos have to ensure SC, Cell ID, BSs’ coordinates, LAC, BCCH and other information effecting location estimation are well updated in their databases. Survey, drive tests, LMUs’ data and BSs’ clock drifts also have to be audited and updated quarterly. Prediction for multipath and propagation loss was also made for the different routes within Klang Valley. When multipath delays are able to be predicted within certain accuracy, location estimation errors are small. Combination of area such as urban-suburban and suburban-rural are used because in real environment, UIPS need to distinguish the search from the whole area (such as from entire Klang Valley), where LAC and Cell ID are used to first narrow the search into smaller area in order to use the desired propagation model, multipath model and $D_{PE}$ constant. On the other hand, when an area’s environment condition is not known (uLOS), CCC averaging, First Mean of
NR3C, Random Search Mean of NR3C and Best Comparator are used. These uLOS estimation techniques produce accuracy within acceptable FCC E-911 location requirements, when used with Best Geo algorithm. Best Geo could be used to detect BSs that would lead to degradation of estimation caused by unsuitable BSs placement, where bad placements were one of the largest error contributors for NR3C estimation.

Timing LDT and prediction models with road data such as CCC2, MBRC, GAC, OCRAA, M-OCRAIA and RLMN provide the solution for navigation, tracking and determining location when hearability is less than three. The techniques proposed for tracking do not require any acceleration or velocity knowledge of the moving vehicle. Even though all the timing LDT and prediction models developed as in Table 3.1 (except NR2C and CCC2) meet FCC’s location accuracy requirements, timing techniques especially in urban or metropolitan may suffer more multipath effects than what is represented as kLOS. Averaging a few readings from different paths for each BS cannot guarantee that all delay paths are fully recorded. Especially when new neighboring buildings are constructed, more new paths could emerge. Therefore, UIPS cannot depend on timing measurements alone especially when multipaths are really high in cities/urbans, and may need to invoke another LDT for confidence check when a higher Quality of Positioning (QoP) is demanded by users. This motivates the development of Signal Correlation Method (SCM) by using only one BS (serving cell) in the strictest real environment conditions (Cell ID and signal strengths are taken from real network measurements) to estimate location. Performance of SCM will be discussed in the next chapter. Processing Time (PT) was also evaluated for CCC, NR3C and all timing techniques. For actual location search, UIPS will then decide which LDT and prediction model should be used based on QoP, PT, kLOS or uLOS area, hearability, bearer used (SMS/GPRS/3G/HSDPA), type of service requested (emergency, LBS, NBS), and other factors, which will be discussed in Chapter 6.
CHAPTER V

PERFORMANCE OF SIGNAL CORRELATION METHOD

5.1 INTRODUCTION

The performance of SCM-LEAN, SCM-US and SCM-USUC will be evaluated, where for each measurement sample obtained through drive test data collection (LEAN and US), the input SS value will be added (or subtracted) with a random fading value. SCM algorithm will then compare the faded SS of the sample’s serving cell to all the stored SS of cells in order to determine the estimated mobile location. For SCM-USUC, new input samples (SS of serving cell) will be obtained, and then compared to the stored SS of cells for location estimation.

5.2 PERFORMANCE OF SCM ON URBAN-SUBURBAN UMTS ROUTE

The CDF distances of BSs or serving cells towards the measured UE for each drive test trial of urban-suburban route (Menara Celcom to/from Wangsa Melawati) is shown in Table 5.1. SCM-LEAN and SCM-US will be utilized for this 3G route with simulation parameters as listed in Table 5.1 in order to estimate the locations of all Trial 1’s samples (2121 samples). The real data set of Trial 1 with 2121 samples (from Menara Celcom to Wangsa Melawati) will be used to evaluate the performance of SCM-LEAN (SS with and without fading value) and SCM-US (higher fading value).

The CDF plot of SCM-LEAN (SS simulated with and without random fading) is illustrated in Figure 5.1. Using maximum fading magnitude of 6 dB, -3 dB below the original SS value or +3 dB above the original SS value, the CDF result shows that SCM-LEAN barely meets FCC’s location accuracy requirements for both 67% and
95% location estimation. Any higher fading/noise value added to the SS at each corresponding Trial 1’s simulated sample, would cause inaccuracy of more than 100 m for 67% estimated locations and more than 300 m for 95% estimated locations. The entire PT (same Dell PC was used) for LEAN (trials 1 through 3) took 7.5 s to complete, running learning process once for the route, with final 705 stored LEAN samples (33.2% of sample size compared to Trial 1 and 12.2% sample size compared to combined total of Trial 1, Trial 2 and Trial 3 samples). The PT for one location estimation of SCM-LEAN (SS with or without fading) is 0.42 ms.

Table 5.1 Simulation parameters for SCM-LEAN and SCM-US (UMTS)

<table>
<thead>
<tr>
<th>Descriptions</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement samples for Trial 1:</td>
<td>2121 samples</td>
</tr>
<tr>
<td>Measurement samples for Trial 2:</td>
<td>1127 samples</td>
</tr>
<tr>
<td>Measurement samples for Trial 3:</td>
<td>2540 samples</td>
</tr>
<tr>
<td>Serving BSs (34 cells) distances to UE for Trial 1:</td>
<td>50% at 288 m, 67% at 360 m and 95% at 767 m</td>
</tr>
<tr>
<td>Serving BSs (34 cells) distances to UE for Trial 2:</td>
<td>50% at 420 m, 67% at 553 m and 95% at 1238 m</td>
</tr>
<tr>
<td>Serving BSs (40 cells) distances to UE for Trial 3:</td>
<td>50% at 564 m, 67% at 1796 m and 95% at 1796 m</td>
</tr>
<tr>
<td>Type of location search:</td>
<td>Navigation/Tracking/Single Point Search</td>
</tr>
<tr>
<td>Simulation using SCM-LEAN technique:</td>
<td>All Trial 1’s 2121 samples will be simulated against SCM-LEAN (optimized learn-another diversified samples from Trials 1, 2, 3). Random variation/fading between -3dB to +3dB value will be added to original SS value of Trial 1 (for all 2121 samples). Spreading value=0.5 used for all GRNN LEAN and current simulation.</td>
</tr>
<tr>
<td>Simulation using SCM-US technique:</td>
<td>All Trial 1’s 2121 samples will be simulated against SCM-US (combined unique Trial 1, 2, 3) samples. Higher (than LEAN) random fading value between -4.67dB to +5dB will be added to original SS values of Trial 1. Spreading=0.35 used for GRNN learning and current simulation.</td>
</tr>
</tbody>
</table>

Figure 5.2 illustrates the speed and stationary positions of vehicle for each trial. Figure 5.3 shows that when LEAN was not used, simulating all Trial 3’s 2540
samples (Trial 3’s measurement performed with longer stationary time, longer overall time, and with 40 unique serving cells along the urban-suburban route) against Trial 1’s data, produced higher inaccuracy (errors), especially on stationary samples.

Figure 5.1  CDF for location estimation using SCM-LEAN

Figure 5.2  Vehicle speed at collected sample for each trial
Figure 5.4 illustrates that when SCM-LEAN is used, location errors are reduced for all samples of Trial 3 to below 719 m, and this maximum error occurred at sample number 2533. For example at 1000\textsuperscript{th} sample, before LEAN was used, the location error was 2096 m (as in Figure 5.3) and when LEAN was used, the 1000\textsuperscript{th} sample of Trial 3’s estimated location error as in Figure 5.4 has been reduced.
significantly to almost zero. Before LEAN was used, Trial 1 stored data (12% Trial 1 data was used as stored data for matching with incoming simulated inputs) only had 34 unique serving cell’s information. LEAN helped in the acquisition of unlisted cells especially pertaining to Trial 3’s stationary samples (such as Cell ID number 11203). In other words, SCM has learnt the bad behavior from another source (from high distance error between UE estimated and UE real of Trial 3) and acquired the skill as part of its diversified knowledge (stored sample) in order to further improve accuracy for current or future location estimations. Referring to serving cell size (Table 5.1), during Trial 1 through Trial 3, the 95% CDF for serving BSs distance to UE was the highest for Trial 3 at 1796 m and the lowest for Trial 1 at 767 m. Even then, using LEAN (of Trial 1 through Trial 3), SCM was able to estimate 95% simulated locations within 297.8 m, when maximum fading and noise of 6 dB was applied to Trial 1’s samples, and estimate 95% of original Trial 1’s samples’ locations within 291.5 m of accuracy. SCM-LEAN not only provides better estimation than Cell ID (size of cell) but also meets FCC’s location accuracy requirements. Figure 5.5 shows the 2121 samples of estimated location when fading and noise is applied to the original SS of Trial 1.

Figure 5.5 SCM-LEAN simulated location estimations on urban-suburban route

When fading and noise or variations are higher, SCM-US will be utilized by combining unique samples from Trial 1 through Trial 3. The CDF plot for simulated
results performed on all Trial 1’s 2121 samples with SS (RSSI) added with normal distributed random number between -4.67 dB to +5 dB is shown in Figure 5.6. The overall PT for learning process took 8.83 seconds (learning or training process for SCM is only performed once as described in Chapter 3), which produced 3983 unique samples for final storage (68.8% of total sum of Trial 1, Trial 2 and Trial 3 sample size). The PT for one estimated location is 1.1 ms which is more than twice the PT of SCM-LEAN. But location estimations is still within FCC’s location requirements when maximum fading magnitude of 9.6 dB (-4.67 dB below the original value and +5 dB above the original value) is applied. SCM-US is more robust to higher fading and even without fading, it performs better than SCM-LEAN (CDF as in Figure 5.1) but at the expense of PT, utilizing more memory (more processor resource for correlating all location possibilities within a selected area) and storing bigger sample sizes compared to SMC-LEAN. In certain runs of the simulation, 3983 unique samples were able to be processed by SCM-US even though this is above the recommended threshold for SCM-US based on our tests. However in real implementation, only SCM-US stored samples pertaining to smaller selected area of LAC (serving cell and few surrounding cells) will be loaded for correlation purposes.

Figure 5.6 CDF for location estimation error using SCM-US
5.3 PERFORMANCE OF SCM ON URBAN-SUBURBAN GSM ROUTE

Table 5.2 shows the simulation parameters for SCM-LEAN and SCM-US in GSM network. The velocity, directions and duration of each trial are similar to UMTS as both network files were collected simultaneously by using two separate phones (however the starting time or termination time of call recording for GSM phone and 3G phone may slightly varied when call drops). The only difference is, measurement for UMTS are captured at the rate of 1 sample per seconds, while measurement for GSM are captured at few samples per seconds as shown in the table below for the same trials of the drive test route. From data analysis of drive tests, higher fading was found for GSM’s SS compared to UMTS, and therefore higher fading values are simulated for GSM to study the effects in terms of meeting FCC E-911 standard.

Table 5.2 Simulation parameters for SCM-LEAN and SCM-US (GSM)

<table>
<thead>
<tr>
<th>Descriptions</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement samples for Trial 1:</td>
<td>5395 samples</td>
</tr>
<tr>
<td>Measurement samples for Trial 2:</td>
<td>3251 samples</td>
</tr>
<tr>
<td>Measurement samples for Trial 3:</td>
<td>7165 samples</td>
</tr>
<tr>
<td>Serving BSs (39 cells) distances to MS for Trial 1:</td>
<td>50% at 281.3 m, 67% at 301.2 m, 95% at 637.6 m and maximum at 1123 m</td>
</tr>
<tr>
<td>Serving BSs (28 cells) distances to MS for Trial 2:</td>
<td>50% at 337.5 m, 67% at 476.6 m, 95% at 894.2 m and maximum at 1053 m</td>
</tr>
<tr>
<td>Serving BSs (28 cells) distances to MS for Trial 3:</td>
<td>50% at 175.9 m, 67% at 242 m, 95% at 601.1 m and maximum at 1091 m</td>
</tr>
<tr>
<td>Type of location search:</td>
<td>Navigation/Tracking/One Point Search</td>
</tr>
<tr>
<td>Simulation using SCM-LEAN technique:</td>
<td>All Trial 1’s 5395 samples is simulated against SCM-LEAN (optimized learn-another diversified samples from Trials 1, 2, 3). Higher (than 3G) random fading between -7.1 dB to +7.4 dB value will be added to original SS value of Trial 1 (for all 5395 samples). Spreading=0.5 used for GRNN LEAN simulation.</td>
</tr>
<tr>
<td>Simulation using SCM-US technique:</td>
<td>All Trial 1’s 5395 samples is simulated against SCM-US (combined unique Trial 1, 2, 3) samples. Higher (than 3G) random fading value between -10.7 dB to +10.8 dB will be added to original SS values of Trial 1. Spreading=0.35 for GRNN learning &amp; current simulation.</td>
</tr>
</tbody>
</table>
The cumulative of all samples’ estimated location for Trial 1 produced location accuracy that meets FCC’s requirements even though each input SS was added with higher random fading value (maximum fading magnitude of 14.5 dB) compared to fading value for UMTS’s SCM-LEAN. Figure 5.7 illustrates the CDF for location accuracy using SCM-LEAN for GSM network (SS with and without fading). The PT for total learning (training process) took 24.15 s, storing 993 unique LEAN samples (18.4% of Trial 1’s sample size and 6.3% of total sum of Trial 1, Trial 2 and Trial 3 samples). The PT for each location estimate is 0.45 ms.

Trial 3’s samples were simulated against 12% unique Trial 1 stored samples (before LEAN) and the location estimation accuracy compared to Trial 3’s samples simulated with LEAN. The difference of location error is small on stationary Trial 3’s samples before LEAN or after LEAN, and is shown in Figure 5.8. However, applying LEAN on all Trial 3’s samples for location estimation did reduce the overall errors and reduce the maximum error to 645 m. During drive test of Trial 1, the MS was connected to 39 unique serving cells, while for Trial 3 only 28 unique cells were connected to the MS along the route. Serving Cell ID 1114 captured during Trial 1.
Figure 5.8 Evaluating SCM (with and without LEAN) on all trial 3’s samples

also covered all of Trial 3’s stationary samples (sample number 2197 through sample number 4572 of Trial 3 was covered by Cell ID 1114 for about 16 minutes). During stationary of Trial 3, Cell ID 1114’s SS at 5% CDF is at -70 dBm and SS at 95% CDF is at -64 dBm, SS mean is -67 dBm, SS minimum is -79 dBm and SS maximum is -62 dBm. The SS variance, as defined in Chapter 3, is calculated as 6 dB (between 5% and 95% CDF of SS range for Cell 1114). This SS variance is higher in GSM compared to UMTS at the same stationary position. The MS to serving cell distance during this stationary period is 101.9 meters while the maximum distance from serving cell to MS along the route of Trial 3 is 1091 m. Upon analyzing data collected for Trial 1 on cell 1114, it was found that signal levels from -45 dBm till -88 dBm was captured for cell 1114 even though Trial 1 remained on the main road and did not enter the small detour (about 100 m to 200 m from main road) as was done on Trial 3. The data captured in the earlier Trial 1 was able to produce estimations for Trial 3’s stationary point and after applying LEAN could not help much to improve the same stationary point of Trial 3 except at few samples (such as sample 3972 location error is reduced from 148 m to 12.41 m) as shown in Figure 5.8.
Another important aspect to counter check SCM is by using the RSSI prediction model described in Equation (3.2). For example data collected during drive test for all SS pertaining to Cell ID 1114, after curve fitting could be used to predict the distance between MS to the serving cell (BS) as shown in Figure 5.9. From the graph, it is shown that with -67.7 dBm of SS, the distance to MS from Cell ID 1114 is 101.9 meters. This tallies to our actual distance of the stationary samples’ coordinate to the actual BS, which is also 101.9 m. The mean of SS for Cell ID 1114 is -67 dBm at this stationary location, which is also close to -67.7 dBm of predicted RSSI value with the same distance. Therefore SCM-LEAN also confirms our model of RSSI prediction versus distances between BS and MS (or Node B to UE).

![Figure 5.9 Predicting RSSI versus distances for Cell ID 1114](image)

Lastly, SCM-US is simulated for all of Trial 1’s samples in order to evaluate accuracy for location estimation. The CDF produced more accurate results even at higher fading magnitude of 21.5 dB, when using unique combined samples of more than 2500 (exceeding tested memory capacity for GRNN on SCM-US). The result is shown in Figure 5.10. The total learning process for SCM-US took 24.77 s (using same Dell PC the clock timer records PT from start of process till end of process),
storing 3117 unique samples (57.8% sample size of Trial 1, 19.7% sample size of total sum for Trial 1, Trial 2 and Trial 3 samples). The PT for each SCM-US location estimate is 1.2 ms. Figure 5.11 shows that when unique samples (taking only every third samples’ interval out of all the unique samples in order not to exceed GRNN memory limits) are reduced to only 2078 stored samples, FCC requirements are barely met with maximum fading magnitude of 17.5 dB. PT for each estimate is 0.79 ms, which is faster when smaller stored sample size is used.

![Figure 5.10 CDF for location estimation on Trial 1 using SCM-US (3117 samples)](image)

Figure 5.10 CDF for location estimation on Trial 1 using SCM-US (3117 samples)

In general, the more unique samples that are stored by SCM-US for GSM, the better its prediction in the event of high fading and noise. But due to memory limitations for GRNN, some reduction in sample size is required (the trade off process was described in Chapter 3). Even then, the performance (as shown in Figure 5.11) is still robust at maximum fading magnitude of 17.5 dB, which is able to withstand higher fading compared to SCM-US (UMTS) and SCM-LEAN for UMTS. SCM-LEAN for GSM with maximum fading magnitude of 14.5 dB also performed much better (better here refers to higher fading magnitude where FCC’s 67/95 limit could still be met) than the maximum 6 dB fading limit of SCM-LEAN (UMTS), and also
Figure 5.11 CDF for location estimation on Trial 1 using SCM-US (2078 samples)

performed better than 9.7 dB maximum fading magnitude of SCM-US (UMTS). The lower location estimation error for GSM SCM compared to UMTS SCM is because the average distances of cells along the route towards the mobile for GSM are smaller compared to UMTS. Finally, the mean location error for SCM-LEAN using signal strength of one serving cell in GSM network without fading in order to estimate location is 33.9 m. Muhammad (2007) was able to estimate mobile location using signal strengths of two base stations (GSM) with mean location error of 44.4 m by using MLP, and mean estimated location error of 43.6 m by using GRNN.

5.4 PERFORMANCE OF SCM-USUC ON SUBURBAN 3G/GPRS ROUTES

From the collected data as shown in Figure 3.21 for suburban Bandar Sungai Long (suburban of Cheras/Kajang is not as populated as suburban of Kuala Lumpur), the following parameters as listed in Table 5.3 are applied during simulation in order to evaluate the estimation of location using SCM-USUC (and SCM-US). Table 5.4 shows the CDF for location errors when Trial 4 of Route 1 is correlated (using SCM-US) against the stored unique values from Trial 1, Trial 2 and Trial 3 of the same
route. For Trial 4, almost 80% of the route was covered by 3G data service while others were covered by GPRS/GSM Cell IDs. Both 67% and 95% of the CDF result failed to meet FCC’s location accuracy requirements for SCM-US. This is due to GRNN was unable to match closely UMTS’s Cell and SS from only the small pool of

Table 5.3 Simulation parameters for SCM-USUC (3G/GPRS)

<table>
<thead>
<tr>
<th>Descriptions</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average serving cell size</td>
<td>Exact coordinates not known</td>
</tr>
<tr>
<td>Type of location search:</td>
<td>Navigation/Tracking/Point Search</td>
</tr>
<tr>
<td>Unique Samples stored for Route 1 (red), 2 (green), 3 (blue) and one trial of</td>
<td>427 samples (11.42pm 28th June till 1.47am 29th June) will be used as</td>
</tr>
<tr>
<td>small route within (pink) housing area (between stationary test point to</td>
<td>original unique stored drive test</td>
</tr>
<tr>
<td>beginning of Route1).</td>
<td>samples for the entire Sungai Long area.</td>
</tr>
<tr>
<td>Route 1’s samples to be used for comparison: 4th trial compared to Route 1’s</td>
<td>250 samples of Route 1’s Trial 1 through 3 used as stored SCM samples,</td>
</tr>
<tr>
<td>Trials 1, 2, 3</td>
<td>while 50 samples of Trial 4 is used as actual simulated inputs.</td>
</tr>
<tr>
<td>Indoor stationary test point data collection samples to be used to built</td>
<td>177 unique samples stored (measurements from 1.43 pm 28th June till</td>
</tr>
<tr>
<td>SCM-USUC</td>
<td>2.28 am 29th June.</td>
</tr>
<tr>
<td>New indoor stationary test point input samples to be used to evaluate SCM-USUC</td>
<td>793 measured samples taken between 6.12 am till 2.23 pm 29th June will be</td>
</tr>
<tr>
<td>location estimation.</td>
<td>compared with previously stored SCM-USUC samples.</td>
</tr>
<tr>
<td>Simulation using SCM-US technique:</td>
<td>All Trial 4’s 50 samples will be</td>
</tr>
<tr>
<td>-using Route 1’s Trial 1, Trial 2, Trial 3 as stored unique data. Location</td>
<td>simulated against SCM-US (250 unique samples from Trials 1, 2, 3).</td>
</tr>
<tr>
<td>will be estimated for Trial 4’s samples of Route 1.</td>
<td>Spreading 0.5 for GRNN simulation.</td>
</tr>
<tr>
<td>Simulation using SCM-USUC technique:</td>
<td>New indoor stationary test point</td>
</tr>
<tr>
<td>-Firstly, using all the Sungai Long’s uniquely stored routes’ 427 samples,</td>
<td>New indoor stationary test point</td>
</tr>
<tr>
<td>indoor stationary point data collection samples (177 samples) will be</td>
<td>input samples (793 input samples) collected from morning till</td>
</tr>
<tr>
<td>simulated with low spreading=0.1.</td>
<td>afternoon of 29th June will be used to</td>
</tr>
<tr>
<td>-Then missing undefined data will be added to the original 427 samples of</td>
<td>evaluate SCM-USUC for Sungai Long. Spreading value=0.5 for</td>
</tr>
<tr>
<td>Sungai Long and reprocessed with GRNN spreading of 0.5, and ready for actual new simulation.</td>
<td>GRNN input simulation.</td>
</tr>
</tbody>
</table>
Table 5.4  CDF of Trial 4 (Route 1) using SS of data services to estimate locations

<table>
<thead>
<tr>
<th>CDF</th>
<th>50% (m)</th>
<th>67% (m)</th>
<th>95% (m)</th>
<th>Max Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCM-US (250 stored samples), training time=2.52 s, PT each estimate=0.3ms</td>
<td>128.9</td>
<td>167.6</td>
<td>460</td>
<td>881</td>
</tr>
</tbody>
</table>

(58% storage data contains UMTS/WCDMA while the rest contains GPRS Cell IDs) uniquely stored data captured using CellTrack91 running on Nokia N95 phone. Also the coverage sizes for suburbs’ cell are quite large and therefore SCM was not able to perform within acceptable accuracy range due to the fact that the SS of the same cell ID could practically be located in even more points of the cell’s larger coverage area, thus degrading the prediction accuracy. The feedback improvement loop (process for developing and improving LDT) as outlined in Figure 3.1, was continuously attempted until six months, it was accepted that SCM-US could not meet FCC’s requirements in larger cells, especially for data services where only fewer cells have higher data rate from 3G/3.5G data services while more cells are covered by lower data rate from GPRS services. Further studies should also be performed on data services’ handover effect from HSDPA, WCDMA, and GPRS on LBS and compared to studies for voice calls in the same suburban area. Nevertheless, with extreme condition of only choosing data services for our experiment within a newly developing township of Bandar Sungai Long, it was observed that with SCM-US, 67% of the accuracy was within 168 m and 95% of the accuracy was within 460 m, while maximum accuracy could be maintained within 881 m. This is still better than Cell ID services and as good as Lin et al. (2004), using two BSs to predict location in urban with 67% error within 190 m. Further studies of SCM using other signal parameters’ measurements in addition to SS of the serving cell in suburbs and rural should be carried out in order to improve accuracy.

In order to begin the actual evaluation process for SCM-USUC, where the accuracy for location estimation on a stationary test point in Bandar Sungai Long area would be evaluated based on new 793 indoor test point samples collected on 29th June 2008, the Undefined Collection phase (surveying phase or collection phase for GRNN) for designated grid points (200 m by 200 m) should be trained first (processed with USUC learning technique as described in Chapter 3). The earlier 177 samples
that were collected on the same indoor stationary test point (from 1.43 pm of 28th June till 2.28 am of 29th June) would be used as training samples, and were run against the 427 stored drive test unique samples (drive test collection from Route 1, 2, 3 and a few initial drive test samples within the housing area near the stationary test point) using GRNN with low spreading of 0.1 (higher correlation accuracy is required from GRNN when spreading is low) in order to evaluate if the original drive test samples need to recollect some additional samples pertaining to the housing area represented by the test point. This algorithm of Undefined Collection (UC) is important to cover for grid areas such as houses, that are slightly away from the main roads, where drive test data collection could not fully cover the entire town in few drive test trials, and hence some undefined SS or Cell IDs are not fully stored within the database.

Figure 5.12 illustrates the location estimation errors using SCM-US with low spreading value on the initial test point’s 177 training samples. The CDF is shown in Figure 5.13 on the same 177 training samples before UC (Undefined Collection) was applied and after UC had been applied. The improvement is apparent on the 67% of

![Figure 5.12 Location errors on trained samples of indoor test point (SCM-US)](image-url)
Figure 5.13 CDF for location estimation on the training samples (SCM-USUC)

the CDF where the location errors reduced from 226.3 m to 121.6 m. For 95% and above, the location errors were unable to be reduced. 16 samples of the training data sets were unable to be estimated (undefined). Due to the low spreading value used as intended by SCM-US, limitations to match by the GRNN should produce undefined outputs. The samples’ input SS and Cell ID that caused the undefined location estimations were collected programmatically by the algorithm from the 177 samples of training data. For example, 3 samples’ information (SS -99 dBm for Cell ID 8862, SS -95 dBm for Cell ID 8871 and SS -95 dBm for Cell ID 8857) were identified as Undefined Collection (UC) samples that had caused 16 samples of training data to be undefined, and the three UC samples will be inserted into the original drive test stored data to improve future estimation pertaining to the grid of housing area being surveyed. The three UC samples was then added programmatically to the existing 427 drive test samples, making a final total of 430 hybrid stored drive test (drive test and additional surveyed samples) samples. These hybrid drive test samples would be processed (trained) with spreading of 0.5 and will be ready (standby) to estimate any new real measurement’s inputs. To evaluate the usage of SCM-USUC, 793 new samples were collected for a period of few hours using CellTrack91 on 29th June in order to be used as inputs to the SCM-USUC. The estimated output will be compared
to the actual stationary test point’s location coordinate as shown in Figure 5.14. The CDF results (with or without SCM-USUC) show that location accuracy is significantly improved at 67% and below percentage after SCM-USUC is used. Only one sample (out of 793 samples) was undefined for both SCM-US (spreading 0.5) and SCM-USUC because the input of the sample had a positive SS of 99 dBm at Cell ID 8856. Due to the unusual input of SS value (which is caused by unavailability to collect SS measurement by device during manual request at that time), GRNN was unable to match (correlate within acceptable spreading range) this value to any other value in the stored samples. The total training time (similar to other SCM process, training is done only once) for USUC took 2.8 s, with 430 stored hybrid samples, while the PT for each estimate is 0.25 ms. During the few hours of data services at this stationary location, out of 793 measured samples, 9 samples were connected to Cell ID 8856 (SS range of 12 dB calculated from SS between 5% to 95% of CDF pertaining to the cell), 18 samples were connected to Cell ID 8862 (SS range of 4 dB), 664 samples were connected to Cell ID 8871 (SS range of 10 dB) and 102 samples were connected to Cell ID 37303 (SS range of 12 dB). The maximum fading deviation

![Figure 5.14 CDF for location estimation to evaluate SCM-USUC on 793 samples](image)
for indoor received signal based on SCM’s SS range (variance) is 12 dB for this GPRS/GSM network.

Finally, in suburbs, even though SCM cannot meet FCC’s location accuracy requirements but the accuracy of using only one serving cell’s SS is still better than Cell ID and could support various other navigational and LBS services, with 67% accuracy within 107.4 m and 95% accuracy within 379 m. Figure 5.15 shows the estimated points (792 estimated points as 1 point unestimated from simulation of 793 input samples) pertaining to the actual stationary test point using SCM-USUC, with maximum distance error of 597 m. The CDF error was shown in Figure 5.14. The one undefined sample was due to the test phone’s inability to obtain SS measurement for an instantaneous moment, and therefore had erroneously given the maximum positive SS value, which then caused GRNN not to produce any correlation based on required spreading/tolerance value.

Similar process for training UC samples should be followed for other housing areas within Bandar Sungai Long. As described earlier for suburb example, adding only 3 UC samples’ information to the drive test stored samples, the 67% estimation accuracy (as in Figure 5.14) for the stationary point improved significantly from 379 m to 107.4 m (slightly above the 100 m requirement of FCC’s 67% accuracy). The whole idea is to collect the least number of additional samples (UC) which are capable to optimize the location accuracy for the entire area. Acquiring too much of irrelevant information may cause competition among stored samples that could affect GRNN’s weightages and final estimation. Therefore, it is necessary to define the suitable number of grids and test points pertaining to each housing area, and also the number of quality samples (SS range stored for each cell) to represent each test point for SCM-USUC.

5.5 DISCUSSION

In this chapter, SCM was introduced by correlating one cell’s SS with stored SSs values in order to estimate mobile location. GRNN neural network was used for SCM. Even though there are a lot of training schemes available for neural network,
Figure 5.15 Estimated locations of the stationary point using SCM-USUC on data services for suburban Bandar Sungai Long
the difficulty faced of comparing only one measured SS value to stored SS value, calls for the development of a new training and learning scheme referred to as LEAN. This training scheme may not be as accurate (DCM for GSM produce 67% error at 44 m for urban) as fingerprinting technique that measures several SSs values and match to the stored sets of SSs values. But in urban or populated suburban, SCM-LEAN with only one cell’s SS can meet FCC’s E911 location accuracy requirement. SCM LEAN is more robust for GSM than 3G network since 3G can only accept about 6 dB of fading to meet FCC’s requirements in the event of higher fading (SS deviation) on the original stored sample’s SS values. In indoor, when fading is high, SCM-US is suggested for location estimation. SCM-US also performs better in GSM network with higher fading tolerance compared to in 3G environment. In suburbs, SCM-USUC is used. Even though USUC was unable to meet FCC’s requirements but the experimented samples could provide accuracy within 107.4 m for 67% of the time and 379 m for 95% of the time, which is still good for many categories of LBS. However, extra care need to be taken in the event Telco changes the network settings when network optimization is performed. Collaboration with the Telco ensures new samples and information are shared or else frequent automated monitoring is required from the test points sending regular feedback of each grid’s measurements to UIPS for checking. If for example, the 95% error of 379 m has suddenly increased to more than 600 m, an alert should be sent out to the operator. The acquisition of all SS training samples should be done as thoroughly as coverage prediction is done from signal strengths (Manoj 1999). In general, SCM’s PT for location estimation is very fast, within ms, where SCM could be used in parallel to complement or cross check other LDTs that are being used, so that in worse case 95% location errors are within 300 meters for urban, and are within 400 m for suburbs.

For actual implementation of SCM, the process of data collection and training samples using the mentioned learning techniques (as in Chapter 3) for each category of route or each classification of area should be done once, right after the drive test and test point collections are obtained. Then for actual location search, UIPS will check the LAC and Cell ID of the current measurements before deciding whether to use LEAN, US or USUC depending on the categorization of area stored in its
database. If the area’s data (SS and Cell ID) has not been stored for which location estimation is requested, then other LDT methods are used for location estimation.

5.6 CONCLUSION

SCM has proofed its usefulness when only one cell’s SS is measured and compared to stored values; location estimation could be made within acceptable accuracy meeting FCC’s location standards in urban and densely populated suburban. However SCM is sensitive to network changes and require to be audited when optimization is performed by Telco. Further studies are required in suburbs to compare voice services and data services’ handover effects to SCM’s performance. The accuracy of CellTrack91 (or other manufacturer’s API for SS measurement) with commercially available drive test equipments should be compared. However, it is more important for phone based measurement that the accuracy of measurement during data collection using vendor’s API (such as developed for UIPS’s client or similar to CellTrack91), should also provide the same accuracy/reliability for future real measurements when location (or LBS) is requested. The difference between different models and brands of phones pertaining to software client’s measurement accuracy should be analyzed. All major issues related to the implementation of SCM LDT were covered: planning for data collection, route or area classification, process to train samples, suggested grid size, location estimation for voice or data service, phone based measurement/terminal assisted estimation, PT, trade off between memory limits and loaded area’s sample size, operational issues and future audits. In the next chapter, UIPS’ LDT module consisting of timing techniques and SCM, along with examples of location application will be presented as the final discussion of the entire research.
CHAPTER VI

IMPLEMENTATION OF UIPS’S LDT MODULE

6.1 INTRODUCTION

There are many types of LBS applications such as information related (searching for the nearest restaurant, petrol stations, point of interest, emergency assistant, car breakdown assistance), navigation related (route finder, step by step directions guide), area related (shopping promotions, road closures, traffic jam, area chats), tracking related (friend finder, child tracking) and games related (treasure hunting). In Malaysia, Maxis was among the first local Telco to implement Friend Finder services in 2004 (Anon 2004a). Unlike infotainment services like SMS downloads, ringtone downloads and SMS quizzes, LBS did not move much after Friend Finder due to several reasons, such as inability to provide desired range of location accuracy pertaining to type of location services offered, unattractive location applications and privacy issues faced by Telcos. LBS applications are generally initiated by the user. Location search is initiated from the network for emergency request like user calls to emergency number and network searches user’s location, or for network request such as alert Telco’s system when user enters certain cell area or identify user’s location for troubleshooting purposes when user complaints to Telco’s call center. Kupper (2005) mentioned that certain LDT can deliver the location information in terms of floor number, room number, Cell ID, WGS84 or UTM coordinate system. In this chapter, an example of LBS application will be presented after user’s position has been determined or estimated by UIPS. The application assists users to plan their tasks according to the available location content and information. Location contents are either stored in local database within UIPS system, intranet or through external third party content providers (CP). LDT module consisting of timing techniques, SCM and other prediction techniques that were developed for this research will be further
discussed in this chapter. The process flow of user’s LBS request, network or emergency location request will be presented along with the decision criteria of UIPS’ LDT module.

6.2 LOCATION BASED TASK PLANNER (LBTP)

As mentioned earlier, there are many categories of LBS content and applications (Das 2008) but there should be a few “killer” applications that could promote the active usage of LBS by bringing benefits to consumers (immediate assistance to provide location effective decision) and by increasing revenue to both Telcos and CPs (content providers). An application that could help an individual to make immediate decision (or select choices) or assist in tasks planning could be helpful because with too much content around, sometimes it is hard to make a simple decision like, “Where should I go for dinner today?” A system knowing the proximity of the user could provide effective response and when integrated with some other Artificial Intelligence (AI) program, could interactively ask user for more inputs like, “What type of food do you like and what is your budget limit?” in order for the integrated application to produce optimum response.

Location Based Task Planner (LBTP) is therefore introduced as a simple example to assist mobile user to make decision on where to complete his or her list of tasks based on user’s current estimated location. The user also has an option to select final destination on the map (installed as client program in UE or MS). The tasks to be completed such as eating dinner in a restaurant, buying flowers, buying grocery and shopping for clothes will be planned sequentially in between the journey (between currently estimated location and final destination). If final destination is unknown or not defined, then all tasks will be planned within the closest distance to the estimated location. Another goal of LBTP is also to provide convenience to the user: all tasks could be done in one building, or nearby buildings. The key success factors for this type of service are contents must be latest (updated) and heavily populated for all categories of tasks such as shopping, restaurants, sale promotions, airline ticketing, groceries, pay bills and post office. It will discourage user for future use if contents are not latest, contents’ locations are far away, frequent system’s response of search
not found, and inconvenience for user to reach the locations (such as traffic jam, one way street, road blocks). This type of LBS application when integrated or combined with the best route application (that was introduced in Chapter 3), could further propose to the mobile user the best route to take for each tasks in terms of avoiding road congestion, by checking data feed of traffic reports and checking other factors, or by default, providing the shortest unobstructed road distance.

Figure 6.1 shows an example of the output for LBTP display menu (the client output with graphical map) after the final destination was selected by clicking on the map (in the client) and the to-do lists categories were selected in the menu: restaurant, flower shop, grocery shop and shopping center. LBTP algorithm will then check for the nearest restaurant, flower shop, grocery store and shopping center within estimated location and final destination. For this example, two categories of tasks, restaurant and flower shop are found in one area, while two other categories of tasks, grocery store and shopping center are found in another area, within the same building. If one or all of the task categories are not found till the end of the final destination or within 1 km of the final destination, the output will also display the unfound task category, for example, “Sorry post office is not found within this search towards your final nearest

Figure 6.1 An example of urban-suburban route with 4 categories of tasks searched by LBTP between the simulated (estimated) location and the final destination
destination, please go to the search menu to perform individual search for post office”. If final destination is not provided, then the system will search for all tasks within 2 km of radius from the estimated user’s location. With graphical interface, the LBS application becomes more interactive. For example, user can further click on the task points to read extra directions on how to reach each tasks points, and read the name and address of restaurant, flower shop, grocery store and shopping center. Information exchange between UE/MS (client) and UIPS server is shown in Figure 6.2.

Figure 6.2 LBTP process involves user’s request for task planner, location estimation by UIPS, and UIPS’s content response to the user
In Figure 6.2, after the user presses send button, the request will be sent via data bearer (GPRS/3G/3.5G) to UIPS. UIPS then requests the network to find the serving RNC for the corresponding mobile number and further interrogates RNC to check the ECNO/RXL/NMR measurements. UIPS receives feedback that LMUs are available within the reach of the mobile with hearability of three or more. The QoP (Quality of Positioning) level pertaining to the service offered indicates what level of accuracy UIPS should provide. For this example, the QoP set for this service is level 1, the highest positioning level, with predefined (advertised) price tag to be charged to the user. UIPS decides (referring to QoP/LDT database table) to use NR3C and instructs RNC to perform OTDOA measurements. Upon receiving the timing measurements, UIPS estimates the location of the user. Then UIPS checks the database on where the content is located (placed) pertaining to this service. In this example, the content is not located internally and is being contracted to third party CP. UIPS communicates with 3rd party CP through agreed API format and VPN connections. CP’s server submits the required information to UIPS (such as coordinates of tasks between estimated location and final location). Information is finally responded by UIPS to client, and client displays the information as in Figure 6.1. From experience, the response time for SMS mobile originating (MO) request is acceptable if the responding SMS’s (such as ringtone download message) message arrives within 50 s. For data service or requesting from HTTP page, this end to end response time (time user’s first request till the time of arrival of the response information) should not be more than 10 s. The 10 s time is based on worst case: using uLOS averaging technique, an estimate should not take more than 6 s plus 4 s of acquiring LBS information from external servers. If it is more than 10 s, an SMS message terminating (MT) (Henry-Labordere & Jonack 2004) should be sent to the user where the user could click on the URL link and be redirected to an HTTP site in order to view the output map. Upon successful delivery of response information (error messages or error codes should not be charged), UIPS will send billing flag to Telco’s billing mediation in order to bill the user’s phone number. Transaction Identification number, time stamps and phone number are three important keys that are being tracked from the client towards server and finally back to the client as part of the complete successful transaction.
Please note, the simulation was done on a single server and real time PT information was not available for end to end response time. The database is also not populated (currently only about 14 entries for each category from KLCC towards Wangsa Melawati), where restaurants’ names and other categories’ name in our database are all dummy names. The objective is only to illustrate an LBS application with interactivity to UIPS that could benefit users, Telcos and CPs. In the next section, the process between user’s phone and LBS application residing in CP’s server will be presented.

6.3 LBS OFFERED BY THIRD PARTY CP

Referring to Figure 1.2, all communications and signaling protocols between UIPS and mobile network (2G or 3G), enter and exit through UIPS’s Routing module, which will then communicate with UIPS’s LDT module for further instructions. LDT module, as shown in Figure 6.3 is the central processor where all other modules report to it after processing their tasks. LDT module decides which LDT to use by checking DB (database), performs location estimations, provides information and bills users.

![Figure 6.3 CP requests UIPS for location estimate of UE](image)
CPs could offer their LBS through HTTP site (or CP’s URL address), where UE/MS having connectivity to data services could access those sites and be charged upon successful LBS content received (charging via IP address billing). In this way variety of LBS applications/contents could be offered by numerous CPs partnering with Telco, where UIPS is located. For regular users visiting their favourite CPs, CPs’ customized clients could also be downloaded to UE or MS and used frequently.

Figure 6.4 illustrates the process flow of LBS offered by CPs. After user selects the type of LBS required, the request is sent via data services (3G/GPRS) to the CP’s URL site. CP’s server will then communicate with UIPS to request for location estimation of user pertaining to the service being offered. UIPS checks its table for reference on QoP, pricing, preinput lists of LDT for each service, other criteria, and finds out from RNC, ECNO or NMR hearability status. Upon reply from RNC, UIPS decides if the first choice of LDT is usable for the type of service by checking cell’s area classification if categorized as kLOS or uLOS, or to use another choice of LDT such as SCM or road matching. Then UIPS instructs RNC to proceed with the type of measurements. Upon reply from RNC, UIPS estimate the location coordinates and sends the response to CP. Since CP’s application has been waiting for the reply, a timer will check if the response message to user should be in the same medium of HTTP page or via SMS gateway connection (CP could utilize Telco’s SMS gateway in order to send messages to mobile users). If user gets SMS service message from CP (via the Telco’s gateway), by clicking on the SMS message (redirecting to CP’s URL), the LBS information would be displayed at CP’s HTTP site. After CP has responded the LBS information/content to user, CP will then send successful response to UIPS to charge the user’s phone number.

In both LBTP and LBS by CP, it is assumed that the location measurements would be performed when the phone is on active data call (3G or GPRS), and the cumulative PT for a user’s request (end to end response time) includes PT of location measurements, location estimation and retrieving the content response from internal source or from CP’s server. In the next section, location search initiated by network or emergency services will be presented.
6.4 LOCATION SEARCH BY NETWORK OR EMERGENCY SERVICES

When mobile user calls an emergency number such as 112, 999 or 911, the Emergency Gateway would immediately prompt the core network and UIPS to trace the location of the phone number. Figure 6.5 shows the process for location search (LS) initiated by network or emergency services. The highest level of QoP is required for emergency service. For network search, Telco will define the level of QoP. When location request is initiated by network, UIPS checks the lists of LDT and request network to search for serving RNC with report of latest NMR or ECNO or ERXL.
pertaining to user’s voice call. Then UIPS decides to use the best LDT that meets FCC’s location accuracy requirement for the area, such as OTDOA for uLOS or kLOS area. From the NMR report of latest SS with its Cell ID, UIPS could already estimate location using SCM, while RNC instructs three BSs’ OTDOA measurements. UE sends this time difference measurements to RNC via signaling (details of OTDOA measurements can be found in 3GPP 2007a) and RNC further redirects the results to UIPS via its Iupc interface. Upon receiving the timing measurements of OTDOA results, UIPS performs location estimation and reports the estimated location to Emergency Gateway, Network, requesting server or Operations and Maintenance Center (OMC) via UIPS’ modules and interfaces. The alternative solution of estimated location coordinates by SCM is also provided to Telcos and Emergency personnel, for comparison purposes. In the next section, LDT module’s selection criteria based on service requested, area category, hearability status, and other relevant information, will be discussed.

Figure 6.5 Process flow for location search by network or emergency services
6.5 LDT MODULE’S SELECTION CRITERIA

In the previous sections (process for location services), UIPS’s usage of LDT module (that comprises of developed location estimation techniques) to select type of location measurements based on service offered, to instruct RNC/UE (BSC/MS) to perform measurements and finally to estimate mobile location were described. In this section, LDT module’s selection criteria of choosing the best LDT to be utilized will be focused. Even though initial lists of the best LDTs pertaining to each QoP level are already categorized in UIPS database table, the selection criteria could overwrite the initial selection if certain evaluations are not met. For example, if the area to be evaluated is considered as kLOS, but has data dated 2 months ago and new configuration updates took place a week ago, with addition of a new cell, then the choice of using NR3C kLOS is now changed to either CCC averaging estimator or First Mean NR3C estimator for uLOS environment. However if the type of service is suddenly promoted to the mass market and incoming LBS requests for that service is huge, the final decision would be to use First Mean of NR3C due to faster PT to estimate mobile’s location. An instruction will be sent three times (more than three times measurement averages for uLOS LDT will burden network’s signaling resources) by UIPS to RNC/UE to perform OTDOA measurements on the same mobile. SCM could be used as a secondary LDT for this case if the stored data has been updated after optimization. If SCM’s data is also not latest, then Cell ID should be used as proximity check.

Using road or walkpath networks with prior knowledge such as if the user is on a vehicle or as a pedestrian, previous known location, last intended destination, intention or type of location search, using subscribed service as used by trucking companies to find the best route of the day, continuous tracking of vehicular movement through previously attached serving cells and other historical information, would be helpful to further improve the LDT selection criteria by UIPS, and hence improve the location estimation. For example, using a client customized for UIPS that is installed on the subscribers’ mobile phone, upon receiving the request of service that is chosen, UIPS will be able to determine the type of techniques to be utilized when user is asking the best route to go for the nearest shopping center from the
current location. And during the drive, if the user wants to request for additional information, UIPS knows that the previous request was made, and the user’s last intention was known and the last final destination is also known. When no possible information is available, then UIPS will determine the serving cell and the best neighbors’ cell to look up from table information if the area has been classified as highway roads, city roads, metropolitan walkpaths, multiple road networks or rural area. When there are too many combinations, the probability of uncertainty increases. Also, when there is no specific information, the probability of uncertainty increases. When confidence level or probability of uncertainty increases, the type of location technique is changed accordingly to signal based rather than time based.

Figure 6.6 summarizes the selection criteria of UIPS’s LDT module. With more LDT and enhanced techniques developed, more criterias have to be evaluated before the final LDT is chosen. The ultimate goal is to use the best LDT customized for the area’s requirement. Even though scripts could be run to update UIPS database when optimization drive test files had been updated, but checks and measure must be taken to audit script tasks. Running periodic audits to check clocks of network and measurement elements, checking last optimized site, new installed site, latest drive test files and comparing with the last date and file size updated in UIPS, would really help to prevent human or system errors. An alarm from this routine programming script could be sent out to the UIPS’s Administrator module and redirected to Telco’s Network Monitoring Center. Upon receipt of alarm notifications, action could be taken to calibrate measurement devices or update reports. Routine programs with dummy parameters should also be run on hourly basis to check if billing mediation is being charged successfully. QoP, new services, price lists could be added manually by Telco’s administrator when new services are launched.

As an example for LBTP service, if QoP is assigned as high level and the pricing per each response received by user is for example RM0.50, the initial LDT choices that are tied to high QoP are NR3C, CCC and averaging estimators. But if this service was requested from a user in metropolitan area (an area could be categorized from its serving and neighboring Cell IDs’ locations) with 2 months old
Figure 6.6 Summary of LDT module’s selection criteria for the best LDT to be used to estimate location
kLOS data, due to heavy multipaths in metropolitan, this data could be outdated and therefore CCC averaging estimator should be used to estimate the location. But when the service becomes heavily utilized by mass users, then only SCM should be used because SCM has faster PT per estimate than CCC averaging. If SCM is also not available, then only CCC or NR3C is utilized as last resort, with the 2 months old kLOS information. By using angle checks of serving sectorized cell (serving BS) and neighboring BSs, an LDT’s estimation could be confirmed if it is within the right direction. But when, this check fails, alternative LDT should be used to verify (even though alternative LDT has slower PT) or to re-estimate the final location. But again the reliability of the cell’s angle is also questionable if data is not updated correctly by Telco after antenna orientation has been changed. When all levels of verification checks fail, the default initial LDT listed in the database is used as the best LDT. To avoid UIPS’s failure of not being able to choose appropriate LDT or failure to confirm primary LDTs’ proximity from secondary LDT’s estimation, regular audits as mentioned above should be done through programming scripts in order to check if cells’ directional antenna and drive test lists are latest, and compared to Telco’s last updated lists. LMU and clock drifts should also be checked at least quarterly.

6.6 DISCUSSION

In Chapter 4, timing technique’s performance in kLOS and uLOS (Table 4.47) were compared to other related TDOA studies (Table D.1). As shown earlier, the 67% and 95% errors for location estimation using CCC and NR3C in all kLOS drive test areas were below 77 m. CCC averaging in uLOS urban/suburban region could produce 67% error below 60 m and 95% errors below 140 m for both GSM and UMTS. When hearability is limited to two BSs, CCC2-MBRC or CCC2-GAC or RLMN could produce 67% error within 15 m for both GSM and UMTS, 95% error within 67 m for GSM, and 95% error within 102 m for UMTS. The timing result for location search or navigation using two hearable BSs performed better than other studies done for vehicular navigation in urban when N=2 (Table D.2). In Chapter 5, the performance of SCM LEAN using one GSM BTS cell (50% error within 33.9 m, 67% error within 68.7 m, and 95% error within 250 m) compared with other RSS studies as listed in Table D.3, performed better than Kempi (2005), Lin et al. (2004) and Muhammad
(2007). SCM-LEAN using only one UMTS cell also performed better than Kempi (2005) with average of 2.2 UMTS cells. As mentioned in earlier chapters, when more cells are used to estimate location, the location estimation accuracy improves. Therefore, when more cells’ information is used for DCM in urban, DCM (Laitinen et al. 2001b) performed better than SCM.

All LDT and prediction models that met FCC’s standard (except SCM-USUC in suburbs) as developed in Table 3.1 would be utilized by LDT module for location estimation. Even though SCM-USUC failed to meet FCC E-911 location accuracy requirements, the technique could still be used for LBS when lower QoP is required. NR2C and CCC2 are not meant to be used alone for location prediction, but would be used along with GAC or MBRC comparators (road prediction models). In Chapter 5, it was also discussed in addition to location accuracy and PT, processor resources should also be dimensioned according to sample sizes designated for an area, where only certain percentage of samples are required to be loaded from UIPS’s storage in order to be compared to the current SS. For example, an area of 4 km by 4 km represented by 1600 SCM-US samples, with mass LBS request should always have a standby trained processed GRNN data loaded so that SCM can immediately estimate location without utilizing additional UIPS’s processing resources.

6.7 CONCLUSION

This chapter summarizes UIPS’s LDT module consisting of timing estimation techniques, enhanced timing prediction techniques, and SCM. It describes the flow and communication between LDT module, network, measurement devices and other servers when mobile user, network and emergency gateway request for location services. Finally, LDT module’s selection criterion for a service pertaining to an area where certain level of accuracy is required was described. Even though the best LDT could be selected based on fulfilling the current requirements, but checks should still be performed by the system to verify if estimation falls within the cell’s coverage or within its antenna’s beam or if the estimated location’s distance from serving cell is within allowable difference compared to predicted RSSI model’s distance (comparing measured SS value with predicted SS value of the serving cell) from serving cell.
When all checks fail, then a secondary LDT must be used. Routine scripts should also be run by UIPS to verify if billing and log tables are updated correctly.

Moving towards 4G, Wimax (Anon 2008q) and other IP wireless networks (Hossain & Leung 2007) are being planned to be integrated with current mobile’s 2G and 3G network. With more Access Points (stations) available in future, it is hoped that LMUs could be integrated as part of the new stations. The principle introduced in this research of checking for Best Geo in terms of allowable geometric positions between BSs and checking of allowable distance between each trilateral stations, could still be applied to check the geometry of new 4G base stations before using timing measurements. It is hoped that when one network does not have the required location measurement equipment or cannot provide the desired accuracy level, UIPS could request Telco’s network to perform network change such as hard handover from 2G to 4G, in order to utilize LMU which is available only from the nearest or co-located 4G stations.
CHAPTER VII

CONCLUSION

7.1 INTRODUCTION

This chapter concludes the entire research and development of LDTs or enhanced location estimation techniques based on time measurements in various hearable situations and signal strength measurement of GSM, GPRS and WCDMA (3G) cellular networks. The problem statement, hypothesis and objectives defined for this research in Chapter 1 will be revisited, and discussed in terms of achievements, failures and limitations. Certain findings from numerous experiments that have led to the discovery of improved algorithms will be highlighted along with the contributions of the entire research work. Suggestions for further studies will be provided in the final section of the chapter.

7.2 RESEARCH CONCLUSION AND FINDINGS

The main goal is to build an LBS engine/server called UIPS, that is located in Telco’s premises, capable of providing various types of LBS, navigation services and the most important of all, to estimate user’s and emergency caller’s location. Even though the focus of this research is to study location estimation using timing and signal strength measurements in order to introduce new location estimation algorithm or enhanced location estimation techniques, other aspects were required to be incorporated in order to provide an end to end testing (simulation) effect. With end to end testing environment (by using an LBS application, matching road maps, predicting SS value from propagation loss model, and checking actual antenna’s directional information), especially on a real Telco’s drive test samples, the effects of current Telco’s
configurations, hearability problems, the inability of phone (or network) to provide cells’ measurements at certain time for GSM network, and physical settings of base stations were analyzed on each LDT being studied. For example, the geometrical position of BSs’ does influence the accuracy of numerical method’s (such as NR3C) estimations. Processing Time (PT) is also one important evaluation criteria used to measure the performance of an LDT’s efficiency in terms of response time to estimate location. The knowledge of PT is useful for location planning of LBS traffic before being deployed in the real servers.

When hearability is from three BSs in GSM and UMTS networks, 67% and 95% location estimation of CCC and NR3C for all kLOS drive test areas are below 77 m, meeting FCC E-911 requirements. CCC shows better performance to NR3C at 95% location estimation in worst multipath conditions, especially in urban Kuala Lumpur. The PT for each location estimate by CCC is 9.7 ms while an estimate by NR3C is 0.85 ms. Nevertheless, for mass LBS requests, the usage of NR3C would be preferred due to its faster PT. In uLOS environment, CCC averaging estimator performs well at 95% of location estimation for GSM and UMTS, and is within 140 m of accuracy for urban-suburban KL. First Mean of NR3C and Random Search of NR3C produce 67% location estimates slightly better than CCC averaging, which produces 67% estimations within 60 m of accuracy for both GSM and UMTS in the same urban-suburban simulated area. When stored information is out dated or when multipath delays are severe and uncertain as in dense urban areas, CCC averaging or First Mean of NR3C averaging in uLOS could be safely used instead of CCC or NR3C in kLOS. It was also shown without averaging estimators in uLOS urban, FCC’s E-911 requirements could not be fully satisfied. With averaging estimators such as First Mean NR3C, Random Search NR3C and CCC averaging, location estimations could meet FCC’s location accuracy requirements in urban-suburban KL for GSM and UMTS. For all averaging estimators, Best Geo (geometrical angle check) and allowable distance check algorithms between BSs were developed to improve estimations, where choices between the allowable hearable neighbors are selected by UIPS (based on NMR or ECNO or ERXL) before requesting radio network to perform timing measurements of at least three hearable BSs. Best Geo and distance check algorithms were discovered after analyzing the performance of
NR3C/CCC estimations in various geometrical locations, various distances of BSs from each other, and the distances between BSs as observed by the mobile.

A simple mapping technique (SMTTLU) was introduced for Telco’s staff to update routes on map after their drive test data collections. The updated map would be used as reference for location search of mobile users on the road or recorded walkpaths. Best Route Determining Technique (BRDT) was also developed for proposing to the user the best choice of roads based on the shortest distance or none obstructed roads (based on traffic feed reports). CCC2 proved to be useful when used as first stage estimator to predict four estimated points from only two hearable BSs. These four points would be shortlisted by Minimum Best Road Comparator (MBRC) algorithm when there is only one major road passing through the coverage area of the two hearable cells. CCC2-MBRC (PT 0.34 s) provides 67% accuracy within 10 m, while 95% accuracy within 66 m for UMTS and GSM users. When there are more road possibilities within the intersection of the two cells’ coverage area, Genetic Algorithm Comparator (GAC) is used to shortlist CCC2’s points. CCC2-GAC (Gen=150, pop=31 or 32, PT=1.27 s) produces 67% accuracy within 10 m and 95% accuracy within 92 m for GSM and UMTS networks. NR2C by itself cannot meet FCC’s location accuracy requirements because it only outputs one estimated point from the intersections of two BSs (cells). Reference Location Measurement Node (RLMN) was proposed to be installed on the surveyed urban-suburban route. Using RLMN, hearability of existing two BSs is increased to three, and location estimation could then be performed using CCC or NR3C. RLMN could be located at strategic locations as described in Chapter 3 in order to estimate on road or off road user’s location. Simulation of RLMN on both UMTS and GSM networks produced 67% accuracy within 15 m and 95% accuracy within 61 m. PT used for RLMN (PT for NR3C or CCC) is many times faster than CCC2-GAC or CCC2-MBRC techniques. When hearability is limited to one Node B (for UMTS), and it is assumed that the user is travelling on a road (such as user request for NBS), RTT is used along with road matching algorithm called OCRAA (PT=0.38 s). Location estimation using RTT of the serving cell and OCRAA’s Abwt (serving cell’s average beamwidth of 71 to 100 degrees) produced 67% accuracy within 18 m and 95% accuracy within 66 m. For GSM, time of arrival was used along with M-OCRAIA algorithm. M-OCRAIA (PT 5
ms) would match the time of arrival from serving cell to the previous known location (an earlier estimate is required for M-OCRAIA) in order to estimate the best point of the road. Simulation produced 67% location accuracy within 53 m while 95% location accuracy within 198 m. When hearability is less than three, CCC2-MBRC, CCC2-GAC, RLMN, OCRAA and M-OCRAIA meet FCC E-911 requirements.

Performance of SCM-LEAN for urban-suburban KL produces 67% accuracy within 85 m and 95% location accuracy within 292 m for both 2G and 3G networks, meeting FCC’s E-911 requirements. SCM-US (storing only unique drive tests samples) produces much higher accuracy than SCM-LEAN and its estimation is still better in higher fadings but at the expense of longer PT (between 2 to 3 times slower than LEAN), utilizing more memory of Neural Network and uses more storage capacity. In less populated suburbs coverage of cells are larger than urban-suburban of KL. Therefore, SCM LEAN and SCM-US cannot work accurately because when cell is large, the same SS could practically be scattered anywhere within the cell’s coverage. For this situation, the grid test points have to be distanced away from each other. Using training scheme called USUC (unique sample undefined collection), a few undefined samples that do not exist from the drive test of a larger surrounding town area could be filled with the test point’s (grid’s location) latest SS and Cell ID information. Performance for suburb using SCM-USUC produced 67% accuracy within 107.4 m and 95% accuracy within 379 m. Even though SCM-USUC failed for FCC’s requirement in suburbs, but it is still suitable for other types of LBS and NBS.

Location Based Task Planner (LBTP) was introduced as an LBS application that may assist users in planning where to perform their tasks. Various other types of LBS applications hosted by third party CP could utilize UIPS to promote LBS growth. The process for emergency services and network requested location service was described in Chapter 6 along with the most suitable LDT to be utilized based on the required accuracy level pertaining to the service requested within a classified area. It should be anticipated by LBS planners that with location services offered, location estimation introduces location errors while unpopulated content or irrelevant content’s location or distant content’s location would also add up more distance errors for LBS services. The aim of LBS services is also to supply location information convenient
for users to access and easily navigated to reach their destinations. The incorporation of BRDT algorithm into LBS could assist mobile users by proposing them several choices of routes to take and the best route for reaching their destinations. Routine audits should be done on LMU, network clocks, log files, and other communication elements.

7.3 ACHIEVEMENT OF OBJECTIVES AND HYPOTHESIS

The problem statement was solved and all the objectives defined in Chapter 1 were met for this research, except CCC2, NR2C, and SCM in large cell areas such as suburbs or rural, could not meet FCC E-911 location requirements. CCC2 or NR2C could not be used alone when hearability is two, and should be used with road comparators such as CCC2-MBRC or CCC2-GAC or CCC2-GAC-NR2C to meet FCC’s requirement. SCM failed in larger cells because measured SS of serving cell could practically be scattered in many locations when compared to stored SSs’ of suburbs or rural areas. However, using learning technique of USUC in suburbs, 67% location accuracy had significantly improved from 379 m to 107.4 m. Therefore, SCM-USUC could be used for LBS applications that demand low accuracy level. In the same suburb, phone based measurement (without network) was used to collect SS of GPRS and 3G data services, and the same phone was used to measure new SS samples in order to evaluate SCM-USUC. In urban, SCM with new learning techniques of LEAN and US were able to meet FCC’s E-911 location requirement.

All new LDTs and prediction models that were developed as in Table 3.1 for this research would be formed into a complete UIPS’s LDT module. In Chapter 4, the performance of all timing techniques were compared to other studies, where CCC and CCC averaging estimator improves estimation accuracy even in unknown LOS of three BSs in dense urban. In Chapter 5, SCM’s performance by utilizing only one cell’s measurement in urban is better than studies done using two BS’s signal measurements. In dense urban Finland, DCM using average 2.2 hearable UMTS cells could not meet 95% of FCC’s location accuracy requirement. Therefore, the hypothesis to develop UIPS’s LDT module with various timing and signal correlation LDTs in order to provide QoP and QoS for location search was successful.
However some limitation does exist in SCM when using US technique to train unique samples, which is due to signal fading where in different trials of the same route, the same SS of serving cell could also be present in different grid locations. Statistical tool was used to calculate the frequent occurrence when these same SS samples (of same Cell ID) repeatedly exist in order to determine which grid location the SS should best be stored in. But when there are less samples of this repeated occurrence of the same SS, US technique must randomly choose either one of the grid location to store the SS’s coordinate or choose a grid location in between the same SS collected. Therefore, an efficient training process for storing the learning technique’s samples is a prerequisite if accuracy is required in any urban areas, because during estimation the correlator will only pick up the best match as sequenced in the storage.

7.4 MAIN CONTRIBUTIONS OF RESEARCH WORK

The ultimate objective of developing timing and SCM location determination techniques to be utilized by UIPS was met and with the following contributions:

1) Algorithm such as CCC was developed for timing estimation to improve accuracy in TOA and TDOA timing methods.

2) NR3C was adapted for TDOA timing estimation from Newton Raphson’s method, to provide the fastest PT per estimate.

3) Averaging techniques such as First Mean NR3C estimator, Random Search NR3C estimator, and CCC Averaging estimator were developed for timing techniques in uLOS to meet FCC E-911 requirements.

4) Detection of hearability algorithm using ECNO or EXRL before timing measurements are requested was incorporated to UIPS’s LDT module’s selection criteria.

5) Best Geometrical check and allowable distance check of BSs before selecting allowable BS neighbors from neighbor’s list for timing measurements, were developed to improve location accuracy for uLOS sites.

6) Simple mapping technique was introduced for LBS map building, to be used for road matching and NBS.
7) CCC2-MBRC and CCC2-GAC were developed to estimate user’s location on road when hearability is two.

8) OCRAA and M-OCRAIA were developed to estimate user’s location on a road when hearability is one. Angle control of OCRAA could also be used to verify Telco’s actual antenna’s information (direction and beamwidth).

9) The usage of RLMN and important issues regarding reference stations were addressed in this work.

10) SCM was developed for only one cell (GSM, GPRS, UMTS, HSDPA) with new training/learning schemes called LEAN and US for urban, and USUC for suburbs. SCM could also be used as phone based measurement in LBS, reducing Telco’s signaling communications for location measurements.

11) Sample of LBS called LBTP was developed. Interactions among network/servers with UIPS, and UIPS’s LDT module were described for different examples of location search.

12) PT for each estimation technique was also studied and improved. Accuracy level of each LDT, PT of each LDT, available area information, type of service requested, stored data’s last update date, and other relevant information are used as LDT module’s decision criteria for selecting suitable LDT.

13) RSSI prediction model was also proposed to be used to verify LDT’s distance (estimated distance) to serving cell.

Appendix E lists published journals and papers contributed for this research. In addition, this research also covers data collection process, planning considerations, deployment issues, hearability issues, operations matters, maintenance issues, audits, and running of new location services by UIPS, CP, Telco or Emergency Gateway. Findings that are uniquely based on drive test data of Telco in Malaysia could also be applied and improved elsewhere if the parameters, processes, assumptions and consideration issues are taken into account.

7.5 SUGGESTION FOR FUTURE STUDIES

It is suggested that an end to end pilot testing for timing method such as TDOA (OTDOA/uTDOA) be studied on 3G and upcoming 4G stations, where time
difference from three BSs (installed with LMU) in the actual testing environment could be observed by an UE. The performance of different models of UE should also be analyzed if detection software is installed for obtaining TDOA measurements, and evaluated if different models may perform differently. The end to end time should be studied (time requested by users, time taken for OTDOA measurements, and time network responds to user) and the multipath delays should be observed for five classifications of area: metropolitan, urban, less populated suburb, rural and highways. It is hoped that with real environment measurement and network integration (or testbed), some new findings could be analyzed and further improvement could be made to CCC, NR3C, UIPS’s LDT module, and other UIPS’s on-going development.

The database of SMTTLU should be further populated with smaller roads and paths (residential roads). The processing performance and matching decision by a combined MBRC and GAC should be further studied. This hybrid comparator should reduce the PT of GAC.

For SCM phone based measurement or phone assisted estimation, different phone models’ measurement performance should be studied even though the software (API) is the same. Different performances of phones could impact on SCM’s matching capabilities. SCM should also be studied to include more measurement parameters from the serving cell if possible, besides using only SS of serving cell. Even though performing hard handovers by network in order to measure SS of one UMTS cell and also SS of one GSM cell is not an efficient method for LBS, but could assist in increasing the accuracy level for emergency location estimation. This effect should be simulated or studied in a pilot environment. In suburbs/rural, fingerprinting technique such as DCM should be studied by comparing signals and power delay profiles from more cells, where USUC could be used as a hybrid learning scheme.

Finally, LDT module’s decision criteria (intelligent) should be continuously improved when newer LDTs are developed such as studying reliability checks for primary LDT’s location estimation with comparison to secondary LDT’s estimations.
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APPENDIX A

ATTACHMENT OF FIGURES FROM CHAPTER 3

Figure A.1  Sample log file of raw data collected for 2G metropolitan route

Figure A.2  Sample log file of raw data collected for 3G metropolitan route
Figure A.3  GSM coverage predictions for metro, urban and within Klang Valley

Figure A.4  3G RSCP level coverage prediction for route metro, suburban and others
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**Cell ID | LAC | RAC | ARFCN BSC | BSIC | RSSI |**

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- Tracking of Row 1 and 2 for RSSI cells
- Tracking of Row 1 and 2 for Cell ID cells
- Highlight of RSSI or Cell ID values for Row 1 and 2.
- In general, values with -100, 255 or -1 indicate values are not configured for measurements or not available for measurements.
- GSM Band:
  1 is for 900MHz
  2 is for 1800 MHz
- Total 5397 rows for this entire ERXL file of urban-suburban route
- For this example only first 4 rows of Enhance RXL was shown for Route urban-suburban
- RSSI value in dBm

Figure A.5  GSM ERXL data file for route Menara Celcom to Wangsa Melawati (Trial 1), 3.31 pm, 20 November 2007
Figure A.6 UMTS ECNO data file for route Menara Celcom to Wangsa Melawati (route trial 1), 3.31 pm, 20 November 2007
CI and Cell is the Cell ID number of each cell, and the cells are under the control of BSC.

CID is the Cell ID number for UMTS, and the cells are under the control of RNC. For example, a three-sector cell at the same BS: 11001, 11002 and 11003 with the last digit indicating the sector number.

SAC-Service Area Code,
URA-UTRAN Registration Area,
LAI-Location Area Identity,
UARFCN-UTRA Absolute Radio Frequency Channel Number

Figure A.7  GSM and UMTS Cell Site Information (sample tables that are maintained by Telcos)
Figure A.8  Data analysis and validation process of each drive test route
Program to estimate location: Random Search Mean NR3C & Random Search BS NR3C function

function [All_dist,All_UE,Me]=corr_NLOS3(UE_estimated4_init,BTS1,BTS2,BTS3,UE,iteration,mfac,dfac)

% use the initial 3 estimations of UE_estimated4 from First Mean NR3C, BTS coordinates, real UE location for comparison later, number of iteration, random search constants are mfac=100 and dfac=20, which assists the searching factor horizontally or vertically.
scale=1000*6378*2*pi/360;
sg=size(UE_estimated4_init);
ninput=sg(1,1);
UE_estimated4=UE_estimated4_init;

x_init=UE_estimated4(:,1);
y_init=UE_estimated4(:,2);

% Calculate the first mean
x10=mean(x_init);
y10=mean(y_init);

% Calculate the max and min boundaries
xmin=min(x_init);
xmax=max(x_init);
ymin=min(y_init);
ymax=max(y_init);

% Alert operator if deviation is huge in both the x and y direction
% It could be caused by system or clocking problems

diffxc=xmax-xmin;
if diffxc>=0.02&&diffxc<0.06
    ax=0.5;
    Message='Clocking Error'
    Me=1;
elseif diffxc>=0.06
    ax=0.05;
    Message='Clocking Error'
    Me=1;
else
    ax=1;
    Me=0;
end

diffyc=ymax-ymin;
if diffyc>=0.02&&diffyc<0.06
    ay=0.5;
    Message='Clocking Error'
    Me=1;
elseif diffyc>=0.06
    ay=0.05;
    Message='Clocking Error'
    Me=1;
else
    ay=1;
    Me=0;
end

% start the iteration process of random search
for k=1:iteration

x1=UE_estimated4(:,1);
y1=UE_estimated4(:,2);

xt=mean(x1);
yt=mean(y1);
for i=1:sg(1,1);
    Errorx(i)=(x1(i)-xt)^2;
    Errory(i)=(y1(i)-yt)^2;
end
MSEx(k)=(sum(Errorx))/ninput;
MSEy(k)=(sum(Errory))/ninput;

% the random cases for x direction: use multiplying and
% division factor mfac and dfac for movement in x direction
hw=randperm(4);
s=randperm(2);
if xt>=xmin&xt<=xmax
    if s(1)==1;
        fx=ax*mfac*hw(1)/dfac;
    else
        fx=ax*(-mfac)*hw(1)/dfac;
    end
elseif xt<xmin
    fx=ax*mfac*hw(1)/dfac;
else
    fx=ax*(-mfac)*hw(1)/dfac;
end

% random case for y direction
if yt>=ymin&yt<=ymax
    if s(1)==1;
        fy=ay*mfac*hw(1)/dfac;
    else
        fy=ay*(-mfac)*hw(1)/dfac;
    end
elseif yt<ymin
    fy=ay*mfac*hw(1)/dfac;
else
    fy=ay*(-mfac)*hw(1)/dfac;
end

% The estimated target (before searching process) in the iteration process
UE_target(k,:)=[xt yt];

…………………………………… ……..Page 2……………………Continue

Continue...
%Compare this target with all the three BTS locations
dist_target_Meters_BTS1(k)=sqrt((scale*BTS1(1,1)-
scale*UE_target(k,1))^2+(scale*BTS1(1,2)-scale*UE_target(k,2))^2);
dist_target_Meters_BTS2(k)=sqrt((scale*BTS2(1,1)-
scale*UE_target(k,1))^2+(scale*BTS2(1,2)-scale*UE_target(k,2))^2);
dist_target_Meters_BTS3(k)=sqrt((scale*BTS3(1,1)-
scale*UE_target(k,1))^2+(scale*BTS3(1,2)-scale*UE_target(k,2))^2);
%increment or decrement the movement of x and y and repeat this
%process for the next estimated target of the iteration
UE_estimated4=[x1+(fx*x1*MSEx(k)) y1+(fy*y1*MSEy(k))];
%%%%end of iteration
end

%Random Search Mean NR3C
UE_t=[mean(UE_target(:,1)) mean(UE_target(:,2))];
% Compare with real UE's distance
dist_target_avg=sqrt((scale*UE(1,1)-scale*UE_t(1,1))^2+(scale*UE(1,2)-
scale*UE_t(1,2))^2);

%proceed to calculate for Random BS NR3C
%find min location from the above iteration
[aBTS1,bBTS1]=min(dist_target_Meters_BTS1);
[aBTS2,bBTS2]=min(dist_target_Meters_BTS2);
[aBTS3,bBTS3]=min(dist_target_Meters_BTS3);
UE_target1=UE_target(bBTS1,:);
UE_target2=UE_target(bBTS2,:);
UE_target3=UE_target(bBTS3,:);

%Random BS NR3C
UEFFT=((UE_target1(1,1)+UE_target2(1,1)+UE_target3(1,1))/3
(UE_target1(1,2)+UE_target2(1,2)+UE_target3(1,2))/3);
%Compare with real UE's distance
Fdistavg=sqrt((scale*UEFFT(1,1)-scale*UE(1,1))^2+(scale*UEFFT(1,2)-
scale*UE(1,2))^2);

…………………………………… ……..Page 3……………………End of Program
Example: Pathh 5 (Home) and Patho 1 (Office) with neighbors [4,3,7]

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<td>10</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>4.3</td>
<td>1</td>
<td>0</td>
<td>9</td>
<td>10,3</td>
<td>10,3</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>(7,10,9)/(7,3,4,5)</td>
<td>(3,10,9)/(3,4,5)</td>
<td>10.9</td>
<td>(10,9)/(5,0)</td>
<td>(10,9)/(10,9)</td>
<td>1.7</td>
<td>3.10</td>
<td>9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td>7.3</td>
<td>10</td>
<td>3.10</td>
<td>10</td>
<td>4.10</td>
<td>1.7</td>
<td>3.10</td>
<td>9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>10</td>
<td>7.3</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>1.7</td>
<td>3.10</td>
<td>9</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure A.10  Database table format for neighbors’ path(s) between home’s path to office’s path (or vice versa). The numbers of parenthesis indicates the number of alternative routes.
Figure A.11  Route 1 when Home at path 8 and Office at path 6

Route 1, Home (at path 8) has 2 possible intersection paths and Office (at path 6) also has 2 possible intersection paths. In this example, Home is the nearest to path 8 and second nearest to path 5. Office is the nearest to path 6 and second nearest to path 1.

Figure A.12  Route 2 when Home at path 8 and Office at path 1

Route 2 of the same example when Home (at path 8) and Office (at path 1). Route 2 is slightly shorter than route 1.
Figure A.13  Route 3 when Home at path 5 and Office at path 6

Figure A.14  Route 4 when Home at path 5 and Office at path 1

This is the shortest and the best route among the proposed routes.
%Purpose is to digitize roads with at least 20 meters of resolution points between them
sr=size(BestRoad(:,1));
scale=1000*6378*2*pi/360;% convert decimal degrees to meters or vice versa
for i=1:sz(1,1)-1;
    DistPoint_m(i)=sqrt((scale*BestRoad(i+1,1)-
    scale*BestRoad(i,1))^2+(scale*BestRoad(i+1,2)-scale*BestRoad(i,2))^2);
end
[fa,fb]=find(DistPoint_m~=0);
fb=[fb sz(1,1)];
nBestRoad=BestRoad(fb,:);
%%%%%Corrected Best Road with no repeated points and divide resolution to 20 meters
nsr=size(nBestRoad(:,1));
xprev=[ ];%Empty matrix for initialization
yprev=[ ];%Empty matrix for initialization
for i=1:nsr(1,1)-1
    DistPointn=sqrt((scale*nBestRoad(i+1,1)-
    scale*nBestRoad(i,1))^2+(scale*nBestRoad(i+1,2)-scale*nBestRoad(i,2))^2);
    DistPointn_m(i)=DistPointn;
    if DistPointn>0&&DistPointn<40
        num(i)=2;
    elseif DistPointn>=40
        num(i)=int8(DistPointn/20);
    else
        num(i)=0;
    end
    x=linspace(nBestRoad(i,1),nBestRoad(i+1,1),double(num(i)));
p=polyfit(nBestRoad(i:i+1,1),nBestRoad(i:i+1,2),1); polynomial fitting to increase points
y=p(1,1)*x+p(1,2); find the coefficients
xnew=[xprev;x'];
xprev=xnew;
ynew=[yprev;y'];
yprev=ynew;
end;
rroad=[xnew ynew];figure; plot(xnew,ynew,'rd'),hold on;.................End of Program

Figure A.15  Algorithm for increasing road resolutions
Figure A.16 Algorithm for MBRC

%%Algorithm for Minimum Best Road Comparator to choose which of the four CCC2’s
points is the closest to the travelled road. The four stored CCC2’s point in \textit{parr} matrix.
BestRoad=rroad% use the digitized road points or best route within this coverage area

\texttt{sparr}=\texttt{size(parr)}
\texttt{for } i=1:\texttt{sparr(1,1)}
\texttt{for } m=1:\texttt{sparr(1,2)/2}
\texttt{for } n=1:\texttt{length(BestRoad(:,1))}
\texttt{Dp(n)=sqrt((parr(i,m)-BestRoad(n,1))^2+(parr(i,m+4)-BestRoad(n,2))^2)};
\texttt{end}
\texttt{[abbt,bbt]=sort(Dp)};
\texttt{cm(i,m)=abbt(1)};
\texttt{bm(i,m)=bbt(1)};
\texttt{end}
\texttt{end}
\texttt{[oo,kk]=sort(cm,2)};

\texttt{kkk=kk(:,1)};
\texttt{for } i=1:\texttt{sparr(1,1)}
\texttt{Uest(i,:)=[parr(i,kkk(i)) parr(i,kkk(i)+4)]; The final selection of CCC2 point}
\texttt{Uest1(i,:)=[BestRoad(bm(i,kkk(i)),1) BestRoad(bm(i,kkk(i)),2)]; The final selection of the}
\texttt{%CCC2 point but in reference to the nearest road coordinate}
\texttt{end}
toc
\texttt{UE_true=UE(t2,:);% obtain UE real values when hearability of two on area simulated}
\texttt{DcheckCCC2=distancecalc_func1(UE_true,Uest);check and do CDF plot all the estimated}
\texttt{%UE values vs. the real UE values}
\texttt{DcheckRoad=distancecalc_func1(UE_true,Uest1);}
\texttt{figure, hist(kkk);}......................End of Program
Figure A.17  Proposed installation of RLMN for three sites along the studied urban-suburban route to improve hearability from two to three UMTS BSs.

Figure A.18  Example of four GSM RLMN sites along the urban-suburban route.
Figure A.19 One Cell Road Angle Algorithm (OCRAA) to find the nearest road point within the coverage range of serving cell
%One Cell Road Angle Iteration Algorithm
sroad=size(road);% load the road points
for kj=1:sroad(1,1)
    ffg=1;
    for theta=1:360;% start the iteration with theta 1 to 360 or multiple if ffg is more than 1.
        xc(theta)=BTS1(i,1) + D*cos((90-(theta/ffg))*pi/180);
        yc(theta)=BTS1(i,2) + D*sin((90-(theta/ffg))*pi/180);
        distheta(theta)=sqrt((xc(theta)-road(kj,1))^2+(yc(theta)-road(kj,2))^2);
    end
    [da,db]=min(distheta);
    dta1(kj)=da;
    dtb1(kj)=db;
end
[mint,post]=min(dta1); thetamin=dtb1(post);
xc1=BTS1(i,1) + D*cos((90-(thetamin/ffg))*pi/180);
yc1=BTS1(i,2) + D*sin((90-(thetamin/ffg))*pi/180);
UE4=[xc1 yc1];% the value on the circle of radius D, the time of arrival with delay and the
            center of circle at BS’s coordinates.
UE_estimated4(i,:)=[UE4]; figure, hist(kkk);………………End of Program

Figure A.20 Algorithm for OCRAIA
%Modified One Cell Road Angle Iteration Algorithm (with previous known location)
clear dta1;clear db1; sroadd=size(rroad);%load the Best route points for this route
for kj=1:sroadd(1,1)
    if i==1
        ame=1;
    else
        ame=i-1;
    end
    disr(kj)=sqrt((UE_estimated4(ame,1)-rroad(kj,1))^2+(UE_estimated4(ame,2)-
        rroad(kj,2))^2);%compare distances of previous location estimations and road points
end
[adr,bdr]=min(disr);
%start for UE_estimated4(i-1) closest to Road, and compare towards road index to end,
%where the while loop will break if distance theta is more than previous distance of theta,
%all the theta circle's minimum distance compared to the point after (i-1)
ffg=1;% initially compare for all theta with one circle resolution of 0 to 360 degrees
for theta=1:360*ffg; % D(1) is the time of arrival with delay and BTS coordinates are used
    xc(theta)=BTS1(i,1) + D(1)*cos((90-(theta/ffg))*pi/180);
    yc(theta)=BTS1(i,2) + D(1)*sin((90-(theta/ffg))*pi/180);
    distheta(theta)=sqrt((xc(theta)-rroad(bdr,1))^2+(yc(theta)-rroad(bdr,2))^2);
end
[da,db]=sort(distheta);
bdr1=bdr; n=1; m=1; dta1(n)=da(1); dtb1(n)=db(1);
while m<2,%%%%%%%%%%%%%begin while loop comparison and increment
    n=n+1;
    if bdr1~=sroadd(1,1)% check if end of road map points
        bdr1=bdr1+1;
    else
        bdr1=bdr1;
    end
    for theta=1:360*ffg;% to increase resolution, increase ffg.
        xc(theta)=BTS1(i,1) + D(1)*cos((90-(theta/ffg))*pi/180);
        yc(theta)=BTS1(i,2) + D(1)*sin((90-(theta/ffg))*pi/180);
        distheta(theta)=sqrt((xc(theta)-rroad(bdr1,1))^2+(yc(theta)-rroad(bdr1,2))^2);
    end
    [dta,dtb]=min(distheta);
    dta1(n)=dta;
    dtb1(n)=dtb;
end;%%%%%%%%%%%%%%%%%end of while loop and write result for N=1 portion
UE4=[xc1 yc1];UE_estimated4(i,:)=UE4;..……………End of Program

Figure A.21  Algorithm for Modified OCRAIA (previous known location)
APPENDIX B

DERIVATION OF NEWTON RAPHSON’S METHOD

According to Kiusalaas (2005) and Yang et al. (2005), Taylor series expansion of \( f_i(x) \) near \( x \), is represented as:

\[
f_i(x + \Delta x) = f_i(x) + \sum_{j=1}^{n} \frac{\partial f_i}{\partial x_j} \Delta x_j + O(\Delta x^2)
\]  

(B.1)

If the right term of higher order \( \Delta x^2 \) is eliminated, then Equation (B.1) becomes:

\[
f_i(x + \Delta x) = f_i(x) + J(x)\Delta x_j
\]

(B.2)

where, \( J(x) \) is the Jacobian Matrix and equivalent to:

\[
J(x) = \frac{\partial f_i}{\partial x_j}
\]

(B.3)

It was mentioned above that the intention is to approximate for \( x \) or near \( x \). Then letting the left term of Equation (B.2) be equivalent to zero, the new equation becomes:

\[
f_i(x) = -J(x)\Delta x
\]

(B.4)

An initial value of \( x \) would be used as guess point to start the process. After solving the non linear simultaneous equations for \( \Delta x \) as in Equation (B.4), we can again substitute \( x \) of Equation (B.4) with \( (x + \Delta x) \) and recalculate Equation (B.4). In the second iteration, the guess point will be added with the incremental point \( \Delta x \) in order to solve for a new \( \Delta x \). The iteration process is repeated until \( \Delta x \) reaches a small number or tolerance value of less than \( 2.2204 \times 10^{-12} \), where the iteration would be terminated. Newton Raphson’s method above requires guessing an initial point for it to converge fast.
APPENDIX C

ATTACHMENT OF FIGURES FROM CHAPTER 4

Figure C.1  Ideal result performance for CCC method to estimate UE locations (67% is at 0.67 of CDF’s probability (P) and 95% is at 0.95 of CDF’s P)

Figure C.2  Ideal result performance for NR3C method to estimate UE locations with error near zero (in nanometers)
Figure C.3 BSs placements for UE maximum and UE minimum error estimation using CCC method

Figure C.4 BSs placements for UE maximum and UE minimum error estimation using NR3C method
Figure C.5 Location error estimations at each simulated sample

Figure C.6 CCC2’s first point, A1 for all the 199 samples with N=2 (example at 80th sample the distance error to actual UE is 512.6 meters)
Figure C.7 CCC2’s second point, $A_2$ for all the 199 samples with $N=2$ (example at 80th sample the distance error to actual UE is 517.2 meters)

Figure C.8 CCC2’s third point, $B_1$ for all the 199 samples with $N=2$ (example at 80th sample the distance error to actual UE is 5.376 meters)
Figure C.9 CCC2’s fourth point, B2 for all the 199 samples with $N=2$ (example at 80th sample the distance error to actual UE is 5.243 meters)

Figure C.10 Distance error between UE estimated location and UE actual for 199 samples with $N=2$ (example at 80th sample the distance error is 5.243 m)
Figure C.11 Distance error between UE estimated location of corrected map and UE real for 199 samples with $N=2$ (80th sample the distance error is still 5.243 m)

Figure C.12 Location error between UE estimated (only using NR2C) and UE actual for 199 samples with $N=2$ (not using MBRC or GAC). With CDF of 67% at 25.44 m, 95% at 414.1 m and max error at 492.8 meters
Figure C.13 CDF location error for $A_1$, $A_2$, $B_1$ and $B_2$ for 199 samples with $N=2$. Only $B_1$ and $B_2$ partially meet location accuracy requirements at 67%.

Figure C.14 CDF results for CCC2-MBRC and the comparison between $A_1$, $A_2$, $B_1$ and $B_2$ (for $N=2$ along urban-suburban route)
Figure C.15 The selection of $A1$, $A2$, $B1$ and $B2$ along urban-suburban route

Figure C.16 MS estimated along the urban-suburban route for 1805 samples where $N=2$, and the maximum error location where it occurs
Figure C.17 CDF result for MS estimated along the urban-suburban route using CCC2-GAC ($Gen=250$, $pop=32$) with 95% errors at 56.67 m.

Figure C.18 Location errors for MS estimated along the urban-suburban route using CCC2-GAC ($Gen=250$, $pop=32$).
Figure C.19  Location errors for CCC and NR3C along the urban-suburban drive test route (with $N=2$ using RLMN)

Figure C.20  Transition of UMTS serving cells along route
APPENDIX D

PERFORMANCE OF OTHER RESEARCH WORK

Table D.1  CDF error for other related TDOA studies in urban/suburban

<table>
<thead>
<tr>
<th>CDF</th>
<th>67% (m)</th>
<th>95% (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDOA GSM urban Munich, 6BTS,10ns, (Bertoni &amp; Suh 2005)</td>
<td>31</td>
<td>262</td>
</tr>
<tr>
<td>EOTD 2 storey suburban, speed below 50km/h (Halonen et al. 2003)</td>
<td>42</td>
<td>85 (90%)</td>
</tr>
<tr>
<td>EOTD high floors suburban, speed &lt; 50km/h (Halonen et al. 2003)</td>
<td>120</td>
<td>240 (90%)</td>
</tr>
<tr>
<td>OTDOA-IPDL UMTS Bad Urban (Porcino 2001)</td>
<td>113</td>
<td>224</td>
</tr>
<tr>
<td>OTDOA-IPDL UMTS Urban dense (Porcino 2001)</td>
<td>68</td>
<td>156</td>
</tr>
<tr>
<td>OTDOA-IPDL UMTS Suburban (Porcino 2001)</td>
<td>18</td>
<td>36</td>
</tr>
<tr>
<td>OTDOA UMTS urban, delay 0.5-1 μs (Ahonen &amp; Eskelinen 2003)</td>
<td>215</td>
<td>467</td>
</tr>
</tbody>
</table>

Table D.2  CDF error for vehicular navigation with different hearability

<table>
<thead>
<tr>
<th>CDF for Thomas (2001)</th>
<th>Hearability (N)</th>
<th>67% (m)</th>
<th>95% (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural</td>
<td>&gt; 3</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Suburban</td>
<td>&gt; 3</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Urban</td>
<td>&gt; 3</td>
<td>45</td>
<td>75</td>
</tr>
<tr>
<td>Rural</td>
<td>2</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Suburban</td>
<td>2</td>
<td>30</td>
<td>80</td>
</tr>
<tr>
<td>Urban</td>
<td>2</td>
<td>90</td>
<td>110</td>
</tr>
</tbody>
</table>

Table D.3  CDF error for RSS technique

<table>
<thead>
<tr>
<th>CDF</th>
<th>67% (m)</th>
<th>95% (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCM in UMTS simulation, Ahonen &amp; Eskelinen (2003)</td>
<td>25</td>
<td>188</td>
</tr>
<tr>
<td>Trials of DCM in urban GSM, Laitinen et al. (2001b)</td>
<td>44</td>
<td>90 (90%)</td>
</tr>
<tr>
<td>Dense Finland (Helsinki), DCM for UMTS with average of 2.2 hearable sites, Kemppi (2005)</td>
<td>96</td>
<td>450</td>
</tr>
<tr>
<td>Dense Finland (Helsinki), DCM GSM, Kemppi (2005)</td>
<td>77</td>
<td>274</td>
</tr>
<tr>
<td>Attenuation difference between two BTS for GSM to estimate location in urban Taipei, Lin et al. (2004)</td>
<td>190</td>
<td>315</td>
</tr>
<tr>
<td>Two GSM BTS with MLP NN, Muhammad (2007)</td>
<td>44.4 (50%)</td>
<td>NA</td>
</tr>
<tr>
<td>Two GSM BTS with GRNN NN, Muhammad (2007)</td>
<td>43.6 (50%)</td>
<td>NA</td>
</tr>
</tbody>
</table>
APPENDIX E

LIST OF PUBLICATIONS

**Journals**


**Proceeding Papers**


