Optimisation of Mobility Management for Mobile Satellite Systems Resources

by

Kanagasabapathy Narenthiran

Submitted for the Degree of Doctor of Philosophy from the University of Surrey

Centre for Communication System Research
School of Electronic Engineering, Information Technology and Mathematics
University of Surrey
Guildford, Surrey GU2 7XH, UK

October 2001

© K.Narenthiran 2001
Summary

The need to cope with the mobility of users is very different between mobile and fixed communication systems. Mobility management is thus a key feature in the design of mobile systems. Techniques derived for terrestrial mobile systems cannot be used for mobile satellite systems that use constellations of satellites. A major theme of this thesis is the proposal and verification of such mobility management schemes for mobile satellite systems.

Mobility management consists of location tracking, location area planning, positioning, location update method, paging method, signalling over air-interface and call set-up delay. New proposals are made for location updating, paging, positioning and database architectures for mobile satellite systems in this thesis.

A method of implementing intelligent paging in mobile satellite systems is outlined and a method of finding optimal location area considering both air-interface and fixed network resources is explained. It is also demonstrated how the new schemes save on signalling load in the air-interface and fixed network, satellite power, terminal power, and reduce the size of the terminal and call set-up delay.

As a basis for the above research work, features of different satellite constellations are explained with their ground tracking pattern and orbit type. The requirements of the constellation for communication purposes and the restrictions involved in achieving them are outlined. Comparison of different satellite constellation is also made. As the networking architecture and signalling of mobile satellite systems are based on the GSM terrestrial network, a background explanation is presented for completeness.

Key words: Mobile Satellite Communications, Constellation, Mobility Management, Location tracking, Paging, Location area, Spotbeam, Footprint.

Email: K.Narenthiran@eim.surrey.ac.uk
WWW: http://www.ee.surrey.ac.uk/Personal/K.Narenthiran
Acknowledgments

I would like to thank my supervisors Prof. R. Tafazolli and Prof. B. G. Evans for giving me the opportunity to pursue my PhD studies in CCSR and for their valuable advice and encouragement during my PhD period.

I would also like to thank Hafeez Aziz, Cyril Valadon, Payam Taaghol, Seiamak Vahid, Christopher Meenan and Tony Sammut for their help. I would like to extend my thanks to Moira, Macmillan, Stephanie Evans, Lakshmi Chennell, Emmanuelle Darut, Hannah Morris, David Brock, Adam Kirby, Chris Clark and Terry Roberts. I would like to thank all my friends in CCSR for their help and support during this period.

I would finally like to thank the Committee of Vice-Chancellors and Principals (CVCP) of the Universities United Kingdom, the University of Surrey and CCSR for their financial support to my PhD studies.
## Contents

Summary ................................................................. ii
Acknowledgments ..................................................... iii
Contents ................................................................. iv
List of Figures ........................................................... viii
List of Tables ............................................................. xiii
Glossary of Terms ..................................................... xiv

1 Introduction ........................................................... 1
   1.1 Overview of the mobile satellite systems ................. 1
   1.2 Structure of thesis ............................................. 3
   1.3 Novel work resulting from this thesis ..................... 4

2 Characteristics of Satellite Constellations ....................... 5
   2.1 Requirements of a constellation ............................ 5
   2.2 Constraints ..................................................... 8
   2.3 Type of Orbits ................................................ 10
       2.3.1 Geosynchronous orbit or resonant orbit ............... 13
       2.3.2 Sun-Synchronous Orbit ................................. 14
   2.4 Satellite Orbit Patterns .................................... 14
       2.4.1 Satellite orbit parameters ............................. 14
       2.4.2 Star pattern .............................................. 15
       2.4.3 Delta pattern ............................................. 15
   2.5 Comparison of different constellations and their design methods ........................................ 16
       2.5.1 Comparison of development cost of satellite constellations ........................................ 16
       2.5.2 Visibility and coverage ................................. 17
       2.5.3 Other factors influencing the satellite constellation selection ........................................ 19
   2.6 Summary and conclusions .................................. 20

3 PCN network architecture and signalling ....................... 21
   3.1 System architecture of GSM network and signalling ...... 23
       3.1.1 Physical entities ............................................. 24
       3.1.2 Functional entities and protocol architecture ......... 26
       3.1.3 Radio channel structure ................................ 28
       3.1.4 MM signalling in GSM network ....................... 30
   3.2 S-PCN system architecture .................................. 34
       3.2.1 Fixed Earth Stations (FES) ............................. 35
       3.2.2 Guaranteed coverage area (GCA) ..................... 36
## Table of Contents

3.3 Mobility Management ................................................................. 37  
  3.3.1 Location tracking schemes in terrestrial systems ...................... 37  
  3.3.2 Location tracking schemes in satellite systems ......................... 40  
  3.3.3 Paging in satellite systems .................................................... 43  
3.4 Comparison of different location update and paging methods ... 44  
3.5 Summary and conclusions ....................................................... 48  

4 Location area planning and positioning ........................................ 49  
  4.1 A new methodology for defining fixed location area .................. 49  
    4.1.1 Defining layout of the \textit{LatLongFLA} on the earth ............ 49  
    4.1.2 Determine the \textit{LatLongFLA} size .................................. 50  
    4.1.3 Comparison of \textit{LatLongFLA} with \textit{DLA} ......................... 52  
  4.2 Positioning ................................................................. 53  
    4.2.1 Existing positioning methods ............................................. 54  
    4.2.2 Newly proposed positioning methods ................................... 55  
    4.2.3 Comparison between the two newly proposed positioning methods 58  
    4.2.4 Evaluation of positioning method against location update and paging 59  
  4.3 Summary and conclusions ....................................................... 62  

5 Mobility management signalling over the air-interface in MSS .... 64  
  5.1 Intelligent paging in MSS ..................................................... 64  
    5.1.1 Calculation of number of spotbeams for paging and paging delay 64  
    5.1.2 Implementation of intelligent paging in MSS ....................... 66  
    5.1.3 Calculation of probability of the virtual paging cells ............ 68  
  5.2 Footprint based paging method (FBP) ...................................... 68  
  5.3 Signalling cost calculations .................................................... 69  
    5.3.1 Location update rate in \textit{FLA} method .......................... 69  
    5.3.2 Location update rate in \textit{DLA} method ......................... 70  
    5.3.3 Determination of optimal location area ............................. 71  
  5.4 Performance evaluation of location tracking schemes .......... 72  
    5.4.1 Signalling load and location update rate .......................... 74  
    5.4.2 Comparison of processing time for paging ....................... 77  
    5.4.3 Comparison of satellite power consumption for paging ....... 78  
  5.5 Summary and conclusions ....................................................... 81  

6 Mobility management signalling on fixed network in MSS .... 83  
  6.1 Signalling network architecture and layout .............................. 83  
  6.2 Signalling procedures in location update ................................. 85  
  6.3 Signalling procedures in call delivery .................................... 88  
  6.4 Signalling cost calculations .................................................... 90
B.I.1. Single satellite coverage ................................................................. 141
B.I.2 Multiple satellite coverage .............................................................. 143
B.2. Spherical triangle method ..................................................................... 143
Appendix C: Coordinates calculation of MS positions on the earth surface ...... 147
Appendix D: Mobility model ........................................................................ 149
Appendix E: Selection of overlapping spotbeams or footprints with ‘LatLongFLA’ ................................................................. 150
Appendix F: Sample satellite channel data .................................................. 152
Appendix G: Satellite constellation parameters .......................................... 153
Appendix H: Signalling network parameters .............................................. 154
List of Figures

Figure 1-1: Comparison of different communication systems ................................................................. 2
Figure 1-2: Outline of the research work .................................................................................................. 3
Figure 2-1: Path loss variation with satellite altitude .................................................................................. 6
Figure 2-2: Antenna size variation with satellite altitude ............................................................................. 6
Figure 2-3: Propagation delay variation with satellite altitude ................................................................. 7
Figure 2-4: Effect on orbit due to precession .............................................................................................. 8
Figure 2-5: Radiation pattern above the earth [24] .................................................................................... 9
Figure 2-6: Type of orbits .......................................................................................................................... 10
Figure 2-7: Variation of cost, launch cost and total cost with altitude per satellite [20] ............................... 11
Figure 2-8: Visibility time versus orbit altitudes ....................................................................................... 11
Figure 2-9: Delay variation with time for LEO-66 at L-band .................................................................... 12
Figure 2-10: Doppler variation with time for LEO-66 at L-band .............................................................. 12
Figure 2-11: Delay variation with time for MEO-10 at L-band .................................................................. 13
Figure 2-12: Doppler variation with time for MEO-10 at L-band ............................................................. 13
Figure 2-13: Definition of satellite orbit parameters .................................................................................. 14
Figure 2-14: Earth tracking pattern of polar and inclined orbits on the reference plane .............................. 16
Figure 2-15: Minimum number of satellites versus altitude for global coverage ..................................... 16
Figure 2-16: Constellation cost versus satellite altitude .......................................................................... 16
Figure 2-17: Visibility statistics of LEO-66 ............................................................................................... 17
Figure 2-18: Visibility statistics of LEO-48 .............................................................................................. 17
Figure 2-19: Visibility statistics of MEO-10 ............................................................................................. 17
Figure 2-20: Polyhedron orbits ................................................................................................................ 18
Figure 2-21: Comparison of design methods from [32] based on single global coverage ....................... 18
Figure 3-1: GSM system architecture ...................................................................................................... 23
Figure 3-2: GSM service area partitioning .................................................................................................. 23
Figure 3-3: GSM signalling protocol architecture ...................................................................................... 27
Figure 3-4: Registration procedure in GSM ................................................................................................ 31
Figure 3-5: Location update procedure in GSM (LA change within the same VLR) ................................. 31
Figure 3-6: Location update procedure in GSM (LA change with two different VLRs) ............................ 32
Figure 3-7: MS terminated call set-up ...................................................................................................... 33
Figure 3-8: International connection to called mobile ............................................................................... 33
Figure 3-9: MS originated call set-up ...................................................................................................... 34
Figure 3-10: Model of S-PCN architecture ............................................................................................... 34
Figure 3-11: Similar functional elements in terrestrial and satellite systems ......................... 35
Figure 3-12: Guaranteed coverage area layout for LEO-48 .................................................. 37
Figure 3-13: Location area and paging area arrangement in terrestrial system .................. 38
Figure 3-14: Location update points of FLA and DLA methods for the same movement MS .. 39
Figure 3-15: Selective or intelligent paging strategy .............................................................. 40
Figure 3-16: FLA using location area identity (LAI) ................................................................. 41
Figure 3-17: Variation of paging area radius with time ........................................................... 42
Figure 3-18: Location updating using dynamic location area .................................................. 43
Figure 3-19: Redundant spotbeam paging ............................................................................. 43
Figure 3-20: Redundant Satellite Paging .................................................................................. 44
Figure 4-1: LatLongFLA layout in MSS ................................................................................. 48
Figure 4-2: Geometry of the LatLongFLA on the earth surface .............................................. 50
Figure 4-3: Strip width versus LAR for defining LatLongFLA in MSS .................................... 50
Figure 4-4: Number of spotbeams for paging versus LAR ...................................................... 52
Figure 4-5: Existing positioning methods ................................................................................ 53
Figure 4-6: Averaging phenomena ......................................................................................... 54
Figure 4-7: Flow chart for satellite selection in position determination procedures ............... 54
Figure 4-8: Position Error versus averaging duration in different altitudes ......................... 55
Figure 4-9: Way of storing the spotbeam position data ............................................................ 56
Figure 4-10: Spotbeam boundary crossing phenomena ............................................................ 56
Figure 4-11: Position error with latitude for spotbeam boundary crossing method .................. 57
Figure 4-12: Position error variation with time for LEO-66 and LEO-48 ............................. 57
Figure 4-13: Positioning error statistics for LEO-66 and LEO-48 ............................................ 58
Figure 4-14: Paging areas representing different paging scenarios used for the simulation ...... 59
Figure 4-15: Relative positions of location update, call arrival and paging failure for LEO-48 ... 59
Figure 4-16: Probability of paging failure versus call arrival rate for MS speed of 50km/h .... 60
Figure 4-17: Probability of paging failure versus call arrival rate for MS speed of 250km/h ... 60
Figure 4-18: Probability of paging failure versus call arrival rate for MS speed of 800km/h ... 61
Figure 4-19: Probability of paging failure versus call arrival rate for MS speed of 2200km/h .. 61
Figure 5-1: Location area, paging area and spotbeam overlap arrangement in MSS ............ 64
Figure 5-2: Virtual paging cell arrangement .......................................................................... 66
Figure 5-3: Layout of footprints, spotbeams and VPCs on top of the LA .............................. 66
Figure 5-4: Mapping of PDF of MS speed onto LA for VPC probability calculation ............. 67
Figure 5-5: Paging and paging response in FBP ................................................................... 67
Figure 5-6: LA layout in DLA method .................................................................................... 69
Figure 5-7: Time diagram for call arrival pattern .................................................................... 69
Figure 5-8: Time diagram for Location Update ...................................................................... 69
Figure 5-9: Number of spotbeams versus location area radius .......................................................... 71
Figure 5-10: Method of finding optimum location area size ............................................................. 71
Figure 5-11: Optimal LAR and number of spotbeams versus MS speed ........................................... 71
Figure 5-12: Number of spotbeams or footprints versus LAR for LEO-48 ........................................ 72
Figure 5-13: Number of spotbeams or footprints versus LAR for LEO-66 ....................................... 72
Figure 5-14: Number of spotbeams or footprints versus LAR for MEO-10 .................................... 73
Figure 5-15: Optimal location area versus MS speed ..................................................................... 73
Figure 5-16: Signalling load versus MS speed for case P1 and P6 .................................................... 73
Figure 5-17: Signalling load versus MS speed for case P3 and P7 .................................................... 73
Figure 5-18: Signalling load versus MS speed for case P4 and P8 .................................................... 74
Figure 5-19: LUR versus speed of MS for case P1 and P6 ................................................................. 74
Figure 5-20: LUR versus speed of MS for case P3 and P7 ................................................................. 74
Figure 5-21: LUR with versus of MS for case P4 and P8 ................................................................. 74
Figure 5-22: Overall average of signalling load and location update rate per user .............................. 76
Figure 5-23: Processing time for intelligent paging ....................................................................... 77
Figure 5-24: Power ratio between FBP & SBP versus LAR ............................................................. 79
Figure 5-25: Power ratio between FBP & SBP versus speed ............................................................. 79
Figure 5-26: Power ratio between SBP & FBP versus call arrival rate ............................................ 80
Figure 6-1: MSS signalling network architecture ............................................................................. 82
Figure 6-2: Layout of the signalling network for MSS ..................................................................... 83
Figure 6-3: Signalling flow for cases LU1 & LU5 ............................................................................. 85
Figure 6-4: Signalling flow for cases LU2, LU3, LU6, & LU7 ............................................................. 85
Figure 6-5: Signalling flow for cases LU4 ......................................................................................... 86
Figure 6-6: Signalling flow for cases LU8 ......................................................................................... 87
Figure 6-7: Signalling flow for cases LU9 ......................................................................................... 87
Figure 6-8: Signalling in call delivery for the case of calling MS inside the called MS's H-HLR ........ 88
Figure 6-9: Signalling in call delivery for the case of calling MS outside the called MS's H-HLR .... 89
Figure 6-10: Signalling cost versus LAR for u=100km/h ................................................................. 90
Figure 6-11: Signalling cost versus LAR for u=800km/h ................................................................. 91
Figure 6-12: Call set-up procedures between HLR and VLR in GSM .............................................. 91
Figure 6-13: Location update procedures between HLR and VLR in GSM ....................................... 91
Figure 6-14: Queuing network for call set-up delay calculations ...................................................... 92
Figure 6-15: Call set-up delay with simple queuing model ............................................................... 93
Figure 6-16: Link between calling and called terminals ................................................................. 94
Figure 6-17: Position of MS and satellite with respect to Earth for delay calculation ...................... 94
Figure 6-18: Virtual strip layout for propagation delay distribution calculation within LA .............. 94
Figure 6-19: Propagation delay distribution in air interface .......................................................... 95
Figure 6-20: Queuing model for S-PCN network ......................................................................... 96
Figure 6-21: Call set-up delay versus call arrival rate for different location tracking scenarios ... 97
Figure A-1: Propagation environment for land mobile satellite system ....................................... 115
Figure A-2: Basic elements of a satellite link ............................................................................. 115
Figure A-3: Channel model development process ....................................................................... 116
Figure A-4: Concept of Doppler shift ....................................................................................... 117
Figure A-5: Multipath propagation in satellite systems ............................................................. 119
Figure A-6: Two ray model for multipath signal construction ................................................... 119
Figure A-7: Impact of multipath propagation on wideband and narrowband signal ............... 119
Figure A-8: Power delay profile in L-band at 45° elevation angle ............................................. 120
Figure A-9: Tap delay line structure for multipath modelling ................................................... 120
Figure A-10: Normalised autocovariance, for wooded and suburban environment at L-band with
elevation angles, a) 60°, b) 80° ............................................................................................... 122
Figure A-11: Model for generating correlated shadowing process ............................................. 122
Figure A-12: Fish-eye picture of urban environment, London .................................................... 123
Figure A-13: Variation of azimuth correlation coefficient ......................................................... 123
Figure A-14: Comparison of measured channel data for urban from CCSR and DLR ............... 124
Figure A-15: Comparison of measured channel data of highway, suburban and urban from CCSR
............................................................................................................................................... 125
Figure A-16: Sample received signal envelope in Land Mobile Satellite environment ............... 126
Figure A-17: Two state Markov model for one mobile satellite channel .................................... 127
Figure A-18: Four state Markov model for a mobile satellite channels with two satellites ....... 128
Figure A-19: Narrow band channel model for mobile satellite communication systems ........... 128
Figure A-20: Wide band channel model for mobile satellite communications systems .......... 129
Figure A-21: Sources of interference ....................................................................................... 129
Figure A-22: Channel condition with the signal and interferences ............................................. 130
Figure A-23: Interference simulation model .............................................................................. 131
Figure A-24: Carrier to interference ratio .................................................................................. 131
Figure A-25: HPA Characteristics ......................................................................................... 132
Figure A-26: Satellite repeater architecture .............................................................................. 132
Figure A-27: Payload non-linearity simulation model ............................................................... 133
Figure A-28: Non-linearity performance of QPSK ................................................................. 133
Figure A-29: Additional noise factor for non-linearity .............................................................. 133
Figure A-30: SLE arrangement ............................................................................................... 134
Figure A-31: Emulation of radio channel characteristics .......................................................... 134
Figure A-32: Emulation of interference and payload non-linearity .......................................... 135
List of Figures

Figure A-33: A typical handover scenario ................................................................. 138
Figure A-34: Satellite channel emulator arrangement and interfaces ......................... 139
Figure B-1: Spacing arrangement between co-rotating and counter rotating orbits .... 141
Figure B-2: Number of satellites versus altitude for street of coverage method .......... 142
Figure B-3: Street of coverage overlap and footprint overlap for polar orbits ............. 143
Figure B-4: Spherical triangle arrangement and farthest point from the satellites ......... 146
Figure C-1: Coordinates calculations on the earth surface ....................................... 147
Figure D-1: Movement of the terminal on earth ....................................................... 149
Figure E-1: Overlap layout of LatLongFLA with footprints/spotbeams ....................... 150
List of Tables

Table 2-1: Characteristics of satellite orbits ................................................................................... 10
Table 3-1: Comparison of different location update methods .......................................................... 45
Table 3-2: Comparison of different paging methods ..................................................................... 46
Table 4-1: Comparison of new LatLongFLA against DLA ............................................................ 51
Table 6-1: Notations for database access cost and link cost .......................................................... 84
Table 6-2: Notations for signalling message arrival rates ............................................................... 92
Table 6-3: Possible number of steps for step paging in SBP and FBP .............................................. 97
Table A-1: Hughes 261-H tube model ............................................................................................. 132
Table D-1: Mobile population distribution with speed ................................................................. 149
Table F-1: Urban direct path parameters ....................................................................................... 152
Table F-2: Urban environment near echo parameters .................................................................... 152
Table G-1: Satellite constellation parameters .............................................................................. 153
Table H-1: Link, database access and switching cost ................................................................. 154
Table H-2: Processing time of network entities ............................................................................. 154
### Glossary of Terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1G</td>
<td>First generation mobile systems</td>
</tr>
<tr>
<td>2G</td>
<td>Second generation mobile systems</td>
</tr>
<tr>
<td>3G</td>
<td>Third generation mobile systems</td>
</tr>
<tr>
<td>3GPP</td>
<td>3rd Generation Partnership Project</td>
</tr>
<tr>
<td>ACM</td>
<td>Address complete message (ISDN message)</td>
</tr>
<tr>
<td>AGCH</td>
<td>Access Grant Channel</td>
</tr>
<tr>
<td>AMPS</td>
<td>Advanced mobile phone system</td>
</tr>
<tr>
<td>AM</td>
<td>Amplitude modulation</td>
</tr>
<tr>
<td>AN</td>
<td>Access network</td>
</tr>
<tr>
<td>ANS</td>
<td>Answer message (ISDN message)</td>
</tr>
<tr>
<td>ATM</td>
<td>Asynchronous transfer mode</td>
</tr>
<tr>
<td>AuC</td>
<td>Authentication Centre</td>
</tr>
<tr>
<td>BCCH</td>
<td>Broadcast Control Channel</td>
</tr>
<tr>
<td>FCCH</td>
<td>Frequency Correction Channel</td>
</tr>
<tr>
<td>BCH</td>
<td>Broadcast Channels</td>
</tr>
<tr>
<td>BER</td>
<td>Bit error rate</td>
</tr>
<tr>
<td>BS</td>
<td>Base stations</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 subsystems</td>
</tr>
<tr>
<td>BSSAP</td>
<td>BS subsystem application part</td>
</tr>
<tr>
<td>BSSMAP</td>
<td>BSS management application-process</td>
</tr>
<tr>
<td>BTS</td>
<td>Base station transceiver station</td>
</tr>
<tr>
<td>C/N</td>
<td>Carrier to noise ratio</td>
</tr>
<tr>
<td>CAR</td>
<td>Call arrival rate</td>
</tr>
<tr>
<td>CC</td>
<td>Call control</td>
</tr>
<tr>
<td>CCCH</td>
<td>Common control channel</td>
</tr>
<tr>
<td>CCH</td>
<td>Control channel</td>
</tr>
<tr>
<td>CCITT</td>
<td>International Telegraph and-Telephone Consultative Committee</td>
</tr>
<tr>
<td>CCSR</td>
<td>Centre for Communication System</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code division multiple access</td>
</tr>
<tr>
<td>CM</td>
<td>Communication management</td>
</tr>
<tr>
<td>CN</td>
<td>Core network</td>
</tr>
<tr>
<td>DCCH</td>
<td>Dedicated control channel</td>
</tr>
<tr>
<td>DLA</td>
<td>Dynamic location area</td>
</tr>
<tr>
<td>DLL</td>
<td>Data link layer/Dynamic link-library</td>
</tr>
<tr>
<td>DLR</td>
<td>German Aerospace Centre</td>
</tr>
<tr>
<td>DSSI</td>
<td>Digital subscriber signalling-system No.1</td>
</tr>
<tr>
<td>DTAP</td>
<td>Direct transfer application part</td>
</tr>
<tr>
<td>EC</td>
<td>Echo Canceller</td>
</tr>
<tr>
<td>EIR</td>
<td>Equipment Identity Register</td>
</tr>
<tr>
<td>EIRP</td>
<td>Equivalent isotropic radiated-power</td>
</tr>
<tr>
<td>ESA</td>
<td>European space agency</td>
</tr>
<tr>
<td>FACCH</td>
<td>Fast associated control channel</td>
</tr>
<tr>
<td>FBP</td>
<td>Footprint based paging</td>
</tr>
<tr>
<td>FDMA</td>
<td>Frequency division multiple access</td>
</tr>
<tr>
<td>FES</td>
<td>Fixed earth station</td>
</tr>
<tr>
<td>FLA</td>
<td>Fixed location area</td>
</tr>
<tr>
<td>FM</td>
<td>Frequency modulation</td>
</tr>
<tr>
<td>FN</td>
<td>Frame number</td>
</tr>
<tr>
<td>GCA</td>
<td>Guaranteed coverage area</td>
</tr>
<tr>
<td>GEO</td>
<td>Geostationary orbit</td>
</tr>
<tr>
<td>GMSC</td>
<td>Gateway mobile switching centre</td>
</tr>
<tr>
<td>GPS</td>
<td>Global positioning system</td>
</tr>
<tr>
<td>GSM</td>
<td>Global system for mobile</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphic user interface</td>
</tr>
<tr>
<td>HAPS</td>
<td>High altitude platform</td>
</tr>
<tr>
<td>HCF</td>
<td>Highest common factor</td>
</tr>
<tr>
<td>HDLC</td>
<td>High-level data link control.</td>
</tr>
<tr>
<td>HEO</td>
<td>Highly elliptical orbit</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td><strong>HLR</strong></td>
<td>Home Location Register</td>
</tr>
<tr>
<td><strong>HPA</strong></td>
<td>High power amplifier</td>
</tr>
<tr>
<td><strong>IAM</strong></td>
<td>Initial address message (ISDN message)</td>
</tr>
<tr>
<td><strong>IBO</strong></td>
<td>Input backoff</td>
</tr>
<tr>
<td><strong>ICO</strong></td>
<td>Intermediate circular orbit</td>
</tr>
<tr>
<td><strong>ID</strong></td>
<td>Identity</td>
</tr>
<tr>
<td><strong>IMSI</strong></td>
<td>International Mobile Station-Identity</td>
</tr>
<tr>
<td><strong>IMT200</strong></td>
<td>International mobile-telecommunication 2000</td>
</tr>
<tr>
<td><strong>IN</strong></td>
<td>Intelligent network</td>
</tr>
<tr>
<td><strong>IP</strong></td>
<td>Internet protocol</td>
</tr>
<tr>
<td><strong>IS-95</strong></td>
<td>Interim standard-95</td>
</tr>
<tr>
<td><strong>ISC</strong></td>
<td>International switching centre</td>
</tr>
<tr>
<td><strong>ISDN</strong></td>
<td>Integrated services digital network</td>
</tr>
<tr>
<td><strong>ITU-T</strong></td>
<td>International Telecommunication-Union-Telecommunication-Standardization Bureau-</td>
</tr>
<tr>
<td><strong>IWF</strong></td>
<td>Interworking function</td>
</tr>
<tr>
<td><strong>IWTF</strong></td>
<td>Internet wireless task force</td>
</tr>
<tr>
<td><strong>LA</strong></td>
<td>Location area</td>
</tr>
<tr>
<td><strong>LAC</strong></td>
<td>Location area code</td>
</tr>
<tr>
<td><strong>LAI</strong></td>
<td>Location area identity</td>
</tr>
<tr>
<td><strong>LAPD</strong></td>
<td>Link access protocol for D-channel of DSS1</td>
</tr>
<tr>
<td><strong>LAPDm</strong></td>
<td>Modified version of the LAPD</td>
</tr>
<tr>
<td><strong>LAR</strong></td>
<td>Location area radius</td>
</tr>
<tr>
<td><strong>LEO</strong></td>
<td>Low earth orbit</td>
</tr>
<tr>
<td><strong>LOS</strong></td>
<td>Line of sight</td>
</tr>
<tr>
<td><strong>LSTP</strong></td>
<td>Local signalling transfer point</td>
</tr>
<tr>
<td><strong>LUR</strong></td>
<td>Location update rate</td>
</tr>
<tr>
<td><strong>MCC</strong></td>
<td>Mobile country code</td>
</tr>
<tr>
<td><strong>MEO</strong></td>
<td>Medium earth orbit</td>
</tr>
<tr>
<td><strong>MM</strong></td>
<td>Mobility management</td>
</tr>
<tr>
<td><strong>MNC</strong></td>
<td>Mobile network code</td>
</tr>
<tr>
<td><strong>MS</strong></td>
<td>Mobile station</td>
</tr>
<tr>
<td><strong>MSC</strong></td>
<td>Mobile switching centre</td>
</tr>
<tr>
<td><strong>MSISDN</strong></td>
<td>Mobile station ISDN number</td>
</tr>
<tr>
<td><strong>MSRN</strong></td>
<td>Mobile Station Roaming Number</td>
</tr>
<tr>
<td><strong>MSS</strong></td>
<td>Mobile satellite system</td>
</tr>
<tr>
<td><strong>MSSC</strong></td>
<td>Mobile satellite switching centre</td>
</tr>
<tr>
<td><strong>MT</strong></td>
<td>Mobile terminal</td>
</tr>
<tr>
<td><strong>MTP2</strong></td>
<td>Message transfer part level 2</td>
</tr>
<tr>
<td><strong>NASA</strong></td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td><strong>NCC</strong></td>
<td>Network control centre</td>
</tr>
<tr>
<td><strong>N-CDMA</strong></td>
<td>Narrowband CDMA</td>
</tr>
<tr>
<td><strong>NLOS</strong></td>
<td>Non line of sight</td>
</tr>
<tr>
<td><strong>NMS</strong></td>
<td>Network management subsystem</td>
</tr>
<tr>
<td><strong>NMT</strong></td>
<td>Nordic mobile telephone</td>
</tr>
<tr>
<td><strong>NSS</strong></td>
<td>Network subsystem</td>
</tr>
<tr>
<td><strong>OAM</strong></td>
<td>Operation, Administration and Maintenance</td>
</tr>
<tr>
<td><strong>OMC</strong></td>
<td>Operation and maintenance centre</td>
</tr>
<tr>
<td><strong>OSI</strong></td>
<td>Open Systems Interconnection</td>
</tr>
<tr>
<td><strong>PA</strong></td>
<td>Paging area</td>
</tr>
<tr>
<td><strong>PAGCH</strong></td>
<td>Paging and Access Grant Channel</td>
</tr>
<tr>
<td><strong>PCH</strong></td>
<td>Paging Channel</td>
</tr>
<tr>
<td><strong>PCN</strong></td>
<td>Personal communication network</td>
</tr>
<tr>
<td><strong>PDC</strong></td>
<td>Personal digital cellular</td>
</tr>
<tr>
<td><strong>PDF</strong></td>
<td>Probability density function</td>
</tr>
<tr>
<td><strong>PES</strong></td>
<td>Primary Earth Stations</td>
</tr>
<tr>
<td><strong>PLMN</strong></td>
<td>Public land mobile network</td>
</tr>
<tr>
<td><strong>PM</strong></td>
<td>Phase modulation</td>
</tr>
<tr>
<td><strong>PRI</strong></td>
<td>Pattern repetitive interval</td>
</tr>
<tr>
<td><strong>PRM</strong></td>
<td>Protocol reference model</td>
</tr>
<tr>
<td><strong>PSTN</strong></td>
<td>Public switched telephone network</td>
</tr>
<tr>
<td><strong>PU</strong></td>
<td>Pattern unit</td>
</tr>
<tr>
<td><strong>QoS</strong></td>
<td>Quality of service</td>
</tr>
<tr>
<td><strong>QPSK</strong></td>
<td>Quadrature phase shift key</td>
</tr>
<tr>
<td><strong>RAAN</strong></td>
<td>Right Angle of Ascending Node</td>
</tr>
<tr>
<td><strong>RACH</strong></td>
<td>Random access channel</td>
</tr>
<tr>
<td><strong>RMSC</strong></td>
<td>Remote mobile switching centre</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>RF</td>
<td>Radio frequency</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>RR</td>
<td>Radio resource management</td>
</tr>
<tr>
<td>RSTP</td>
<td>Regional signalling transfer point</td>
</tr>
<tr>
<td>RVC</td>
<td>Reverse virtual call</td>
</tr>
<tr>
<td>S/N</td>
<td>Signal to noise ration</td>
</tr>
<tr>
<td>SACCH</td>
<td>Slow associated control channel</td>
</tr>
<tr>
<td>SAR</td>
<td>Specific absorption rate</td>
</tr>
<tr>
<td>SBP</td>
<td>Spotbeam based paging</td>
</tr>
<tr>
<td>SCC</td>
<td>Satellite control centre</td>
</tr>
<tr>
<td>SCCP</td>
<td>Signalling connection control part</td>
</tr>
<tr>
<td>SCH</td>
<td>Synchronisation Channel</td>
</tr>
<tr>
<td>SCP</td>
<td>Service control points</td>
</tr>
<tr>
<td>SDCCH</td>
<td>Stand alone dedicated channel</td>
</tr>
<tr>
<td>SIM</td>
<td>Subscriber identity module</td>
</tr>
<tr>
<td>SINUS</td>
<td>Satellite Integration into Networks for UMTS</td>
</tr>
<tr>
<td>TES</td>
<td>Traffic Earth Stations</td>
</tr>
<tr>
<td>TLDN</td>
<td>Temporary local directory numbers</td>
</tr>
<tr>
<td>TMSI</td>
<td>Temporary mobile station identity</td>
</tr>
<tr>
<td>T-PCN</td>
<td>Terrestrial personal communication network</td>
</tr>
<tr>
<td>TRAU</td>
<td>Transcoder/rate adaptor unit</td>
</tr>
<tr>
<td>TS</td>
<td>Terrestrial system</td>
</tr>
<tr>
<td>TT&amp;C</td>
<td>Telecontrol, tracking and command</td>
</tr>
<tr>
<td>T-UMTS</td>
<td>Terrestrial universal mobile telecommunication system</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal mobile telecommunication system</td>
</tr>
<tr>
<td>UniS</td>
<td>University of Surrey (UK)</td>
</tr>
<tr>
<td>VLR</td>
<td>Visitor Location Register</td>
</tr>
<tr>
<td>VPC</td>
<td>Virtual paging cell</td>
</tr>
<tr>
<td>S-PCN</td>
<td>Satellite personal communication network</td>
</tr>
<tr>
<td>SPOC</td>
<td>Simulation package of orbit constellation</td>
</tr>
<tr>
<td>SS</td>
<td>Supplemental services</td>
</tr>
<tr>
<td>SS7</td>
<td>Signalling system No.7</td>
</tr>
<tr>
<td>SUMO</td>
<td>Satellite-UMTS Multimedia Service Trials Over Integrated-Testbeds</td>
</tr>
<tr>
<td>S-UMTS</td>
<td>Satellite universal mobile telecommunication system</td>
</tr>
<tr>
<td>TACS</td>
<td>Total access communication system</td>
</tr>
<tr>
<td>TC</td>
<td>Transcoder</td>
</tr>
<tr>
<td>TCH</td>
<td>Traffic channel</td>
</tr>
<tr>
<td>TDM</td>
<td>Time division multiplexing</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time division multiple access</td>
</tr>
</tbody>
</table>

---

**Glossary of Terms**

**TES** - Traffic Earth Stations
**TLDN** - Temporary local directory numbers
**TMSI** - Temporary mobile station identity
**T-PCN** - Terrestrial personal communication network
**TRAU** - Transcoder/rate adaptor unit
**TS** - Terrestrial system
**TT&C** - Telecontrol, tracking and command
**T-UMTS** - Terrestrial universal mobile telecommunication system
**UMTS** - Universal mobile telecommunication system
**UniS** - University of Surrey (UK)
**VLR** - Visitor Location Register
**VPC** - Virtual paging cell

---

**S-PCN** - Satellite personal communication network
**SPOC** - Simulation package of orbit constellation
**SS** - Supplemental services
**SS7** - Signalling system No.7
**SUMO** - Satellite-UMTS Multimedia Service Trials Over Integrated-Testbeds
**S-UMTS** - Satellite universal mobile telecommunication system
**TACS** - Total access communication system
**TC** - Transcoder
**TCH** - Traffic channel
**TDM** - Time division multiplexing
**TDMA** - Time division multiple access
Chapter 1

1 Introduction

1.1 Overview of the mobile satellite systems

The growth of telecommunications in the last decade has been explosive and is expected to take on a new dimension in the beginning of 21st century as complete global communication with the integration of satellite, high-altitude platforms (HAPS), optical fibres and terrestrial wireless technologies [1]. Such a global system will provide access to a wide variety of services from high quality voice to high definition videos anywhere anytime in the world [2]. Therefore satellite communication continues to play its role in personal communications with major advantages for wider area coverage [3]. Satellites were used in the past for fixed communication and then extended to mobile communications by ships, aircraft and land vehicles. Now in the age of personal communications, satellites are present via Iridium and Globalstar. Iridium is an extraordinary achievement from a technology standpoint, even though it was unable to grab the consumer market and failed due to the poor market prediction and the use of complex and expensive technology without flexibility. The experience of Iridium indicates that cheap and flexible mobile satellite technology is needed to fit with the rest of the telecommunication industry. Mobile satellite systems (MSS) [4][5] are nowadays considered to be complementary to terrestrial systems (TS or T-UMTS). The satellite component of the universal mobile telecommunication system (S-UMTS) [6][7] rather than being considered as a stand alone global communication system is considered as a complementary part of an integrated system due to the resources effectiveness and market prospective [7].

In this conjecture, it is better to figure out the similarities and dissimilarities among fixed telecommunication systems, terrestrial mobile communication systems, high altitude platform systems [8] and mobile satellite communication systems. The major difference between fixed telecommunication systems and mobile communication systems is the user movement from place to place and hence the dynamically changing wireless link between the network and the end user. These factors are similar to those with the high altitude platforms, but they can be more significant in mobile satellite systems due to the movement of the satellites (LEO/MEO) [9] as well as the terminal movement. Satellite systems can be both power and bandwidth limited. The
power limitation comes from heat dissipation constraints on the spacecraft, solar panel power generation constraints especially at the end of satellite life time, antenna size hence gain and thus EIRP. The bandwidth limitation comes from restricted allocation on the mobile and feeder links. Satellite systems can provide very wide area coverage, but with low capacity per unit area. On the other hand, terrestrial cellular stations provide high capacity per unit area, but each station has limited area coverage. Consequently, providing wide area coverage with terrestrial systems requires many stations with attendant real estate and landline costs. The ability of satellites to provide small cells of higher traffic density is fundamentally limited by the antenna aperture. So the advantage of each of the different systems can be exploited to realise an integrated effective and efficient global communication. The comparison between different systems is shown in Figure 1-1.

As shown in Figure 1-1, the prominent feature of the MSS is the movement of the satellites (LEO/MEO). This feature creates the dynamic network topology, which eventually leads to more complicated mobility management functionalities and the vulnerable nature of the radio link through satellite between mobile station (MS) and fixed earth station (FES).

Mobility management (MM) functionality in mobile network takes care of the location of the MS when it communicates with other MS or a fixed terminal in the PSTN or ISDN network (active mode) or in silent mode (idle mode) for maintaining the continuity of the call and routing the call effectively when the MS receives a call. The MM process in active mode and idle mode are called...
handover and location tracking respectively. In mobile satellite systems MM should also take care of the movement of the satellite and therefore it is different from MM in terrestrial mobile systems. Hence there is a need for a new or modified MM protocol for MSS. Only location tracking aspects are investigated in this thesis.

1.2 Structure of thesis

Based on the discussion so far, main research area selected for investigation in this thesis is the development of a location tracking scheme by optimising air-interface traffic, fixed network traffic, frequency of accessing databases, satellite power and terminal power with the constraint call set-up delay. The outline of the research work is shown in Figure 1-2. This thesis is divided into seven chapters. The next two chapters give the foundation for the research work, which is explained in chapter 4 to 6.

Chapter 2 gives details of satellite constellation characteristics and design techniques. Requirements of the satellite constellations for communication purposes and constraints involved in achieving the requirements are identified. The categorisation of different types of satellite orbits and patterns are addressed. Methods of selecting satellite constellations for specific scenarios are investigated with comparison.
Chapter 3 reviews the 1G, 2G and 3G cellular systems and explains fundamentals of the GSM network architecture and signalling with different physical and functional entities. The mobile satellite system network architecture with additional functionalities is also introduced. The mobility management techniques used in terrestrial systems are presented and the difficulties in using these techniques in MSS are identified. Existing mobility management techniques for MSS are also described as background.

Chapter 4 describes the existing methodologies for defining location area and positioning methods. New methods for defining location area and finding terminal positions are proposed and their effective implementation is evaluated.

Chapter 5 investigates MM signalling over the air-interface due to location tracking. The concept of intelligent paging is explained with an implementation method for MSS. Disadvantages of intelligent paging are identified and a new paging method is proposed as an improvement. Performance of different combinations of location update methods and paging methods are evaluated and a suitable combination is then proposed.

Chapter 6 deals with MM signalling in the fixed network. Signalling network architecture for MSS and a method of distributing the physical entities of the network architecture all over the globe are outlined. Using this network architecture layout, performance of different location tracking mechanisms on the fixed network are investigated to identify an optimised scheme based on the call set-up delay.

In chapter 7, conclusions are drawn and the future work is outlined.

1.3 Novel work resulting from this thesis

1. A new methodology for defining a fixed location area on the earth is proposed.
2. Two simple positioning methods for location tracking are proposed.
3. A method of implementing the virtual paging cell method is given.
4. A new paging method using footprint size beam is proposed to overcome the problems in implementing the intelligent paging scheme.
5. A full database architecture and layout for MSS are introduced.
6. A method of calculating optimal location area considering both air-interface signalling and fixed network signalling is introduced.
7. A simulation platform is developed to investigate different location tracking schemes in MSS.
Chapter 2

2 Characteristics of Satellite Constellations

Satellite constellations [10] are the backbone of mobile satellite communication systems that attempt to provide good global coverage for personal communications [11]. The characteristics of the constellation have enormous influence on most of the functionalities of the MSS. Location tracking, handover [12][13], power control [14][15][16], modulation & coding [17], frequency reuse, Doppler tracking and delay tracking are some examples. Further there are new communication technologies such as Internet Protocol (IP) [18] and asynchronous transfer mode (ATM) [19] that have also targeted the satellite links to realize global and cost effective multimedia communication. Therefore the next generation satellite constellations should have the capability to handle all types of service with minimum cost. This section identifies the requirements of different types of services and the constraints in achieving them. Different types of orbits and their characteristics are explained. Methods of selecting the satellite constellation considering all different aspects are discussed.

2.1 Requirements of a constellation

- Path loss

The size and the power consumption of a ground terminal and satellite depend on the path loss between a satellite and a ground terminal. For example, the antenna should be large to receive weak signals at the ground terminal or the satellite according to the equation (2-1) or the received signal should be made strong enough to detect by the ground terminal or satellite by increasing the transmit power of the satellite or terminal respectively. Otherwise path loss should be reduced so as to have a stronger signal at the terminal or satellite receivers by selecting lower altitude orbits. The path loss and antenna size variation with satellite altitude are shown in Figure 2-1 and Figure 2-2 respectively.

\[ G = \eta (\pi D/\lambda)^2 \]  

(2-1)

Where \( \lambda \) is the wavelength, \( \eta \) is the efficiency and \( D \) is the diameter of the antenna.
Figure 2-1: Path loss variation with satellite altitude

Figure 2-2: Antenna size variation with satellite altitude

- Propagation delay

Significant propagation delay affect multi-access communication, network synchronisation and protocols for handling time critical data. According to ITU-T recommendation for any voice communication, delay more than 150ms requires the use of echo cancellors. CCITT has

Chapter 2. Characteristic of Satellite Constellations

Proposition 1: Consider the following optimization problem:

\[
\min_{x \in \mathbb{R}^n} f(x) \quad \text{subject to} \quad Ax = b, \quad x \geq 0,
\]

where \( f: \mathbb{R}^n \rightarrow \mathbb{R} \) is a convex function, \( A \in \mathbb{R}^{m \times n} \) is a matrix, and \( b \in \mathbb{R}^m \) is a vector. Let \( x^* \) be the optimal solution to this problem. Then, for any \( x \in \mathbb{R}^n \):

\[
 f(x) \geq f(x^*) + \nabla f(x^*)^T (x - x^*) + \frac{1}{2} (x - x^*)^T \nabla^2 f(x^*) (x - x^*).
\]

Proposition 2: Consider the following convex optimization problem:

\[
\min_{x \in \mathbb{R}^n} f(x) + h(x) \quad \text{subject to} \quad g(x) \leq 0,
\]

where \( f: \mathbb{R}^n \rightarrow \mathbb{R} \) is a convex function, \( h: \mathbb{R}^n \rightarrow \mathbb{R} \) is a convex function, and \( g: \mathbb{R}^n \rightarrow \mathbb{R} \) is a convex function. Let \( x^* \) be the optimal solution to this problem. Then, for any \( x \in \mathbb{R}^n \):

\[
 f(x) + h(x) \geq f(x^*) + h(x^*) + \nabla f(x^*)^T (x - x^*) + \frac{1}{2} (x - x^*)^T \nabla^2 f(x^*) (x - x^*) + \nabla h(x^*)^T (x - x^*) + \frac{1}{2} (x - x^*)^T \nabla^2 h(x^*) (x - x^*).
\]

Proposition 3: Consider the following convex optimization problem:

\[
\min_{x \in \mathbb{R}^n} f(x) \quad \text{subject to} \quad g_i(x) \leq 0, \quad i = 1, \ldots, m,
\]

where \( f: \mathbb{R}^n \rightarrow \mathbb{R} \) is a convex function, and \( g_i: \mathbb{R}^n \rightarrow \mathbb{R} \) are convex functions. Let \( x^* \) be the optimal solution to this problem. Then, for any \( x \in \mathbb{R}^n \):

\[
 f(x) \geq f(x^*) + \sum_{i=1}^m \nabla f(x^*)^T g_i(x) + \frac{1}{2} \sum_{i=1}^m (g_i(x) - g_i(x^*))^T \nabla^2 f(x^*) g_i(x) - g_i(x^*) \nabla^2 f(x^*) g_i(x^*)^T (g_i(x) - g_i(x^*)) + \sum_{i=1}^m \frac{1}{2} (g_i(x) - g_i(x^*))^T \nabla^2 g_i(x^*) (g_i(x) - g_i(x^*)).
\]

Proposition 4: Consider the following convex optimization problem:

\[
\min_{x \in \mathbb{R}^n} f(x) \quad \text{subject to} \quad g_i(x) \leq 0, \quad i = 1, \ldots, m,
\]

where \( f: \mathbb{R}^n \rightarrow \mathbb{R} \) is a convex function, and \( g_i: \mathbb{R}^n \rightarrow \mathbb{R} \) are convex functions. Let \( x^* \) be the optimal solution to this problem. Then, for any \( x \in \mathbb{R}^n \):

\[
 f(x) \geq f(x^*) + \sum_{i=1}^m \nabla f(x^*)^T g_i(x) + \frac{1}{2} \sum_{i=1}^m (g_i(x) - g_i(x^*))^T \nabla^2 f(x^*) g_i(x) - g_i(x^*) \nabla^2 f(x^*) g_i(x^*)^T (g_i(x) - g_i(x^*)) + \sum_{i=1}^m \frac{1}{2} (g_i(x) - g_i(x^*))^T \nabla^2 g_i(x^*) (g_i(x) - g_i(x^*)).
\]

Proposition 5: Consider the following convex optimization problem:

\[
\min_{x \in \mathbb{R}^n} f(x) \quad \text{subject to} \quad g_i(x) \leq 0, \quad i = 1, \ldots, m,
\]

where \( f: \mathbb{R}^n \rightarrow \mathbb{R} \) is a convex function, and \( g_i: \mathbb{R}^n \rightarrow \mathbb{R} \) are convex functions. Let \( x^* \) be the optimal solution to this problem. Then, for any \( x \in \mathbb{R}^n \):

\[
 f(x) \geq f(x^*) + \sum_{i=1}^m \nabla f(x^*)^T g_i(x) + \frac{1}{2} \sum_{i=1}^m (g_i(x) - g_i(x^*))^T \nabla^2 f(x^*) g_i(x) - g_i(x^*) \nabla^2 f(x^*) g_i(x^*)^T (g_i(x) - g_i(x^*)) + \sum_{i=1}^m \frac{1}{2} (g_i(x) - g_i(x^*))^T \nabla^2 g_i(x^*) (g_i(x) - g_i(x^*)).
\]

Proposition 6: Consider the following convex optimization problem:

\[
\min_{x \in \mathbb{R}^n} f(x) \quad \text{subject to} \quad g_i(x) \leq 0, \quad i = 1, \ldots, m,
\]

where \( f: \mathbb{R}^n \rightarrow \mathbb{R} \) is a convex function, and \( g_i: \mathbb{R}^n \rightarrow \mathbb{R} \) are convex functions. Let \( x^* \) be the optimal solution to this problem. Then, for any \( x \in \mathbb{R}^n \):

\[
 f(x) \geq f(x^*) + \sum_{i=1}^m \nabla f(x^*)^T g_i(x) + \frac{1}{2} \sum_{i=1}^m (g_i(x) - g_i(x^*))^T \nabla^2 f(x^*) g_i(x) - g_i(x^*) \nabla^2 f(x^*) g_i(x^*)^T (g_i(x) - g_i(x^*)) + \sum_{i=1}^m \frac{1}{2} (g_i(x) - g_i(x^*))^T \nabla^2 g_i(x^*) (g_i(x) - g_i(x^*)).
\]

Proposition 7: Consider the following convex optimization problem:

\[
\min_{x \in \mathbb{R}^n} f(x) \quad \text{subject to} \quad g_i(x) \leq 0, \quad i = 1, \ldots, m,
\]

where \( f: \mathbb{R}^n \rightarrow \mathbb{R} \) is a convex function, and \( g_i: \mathbb{R}^n \rightarrow \mathbb{R} \) are convex functions. Let \( x^* \) be the optimal solution to this problem. Then, for any \( x \in \mathbb{R}^n \):

\[
 f(x) \geq f(x^*) + \sum_{i=1}^m \nabla f(x^*)^T g_i(x) + \frac{1}{2} \sum_{i=1}^m (g_i(x) - g_i(x^*))^T \nabla^2 f(x^*) g_i(x) - g_i(x^*) \nabla^2 f(x^*) g_i(x^*)^T (g_i(x) - g_i(x^*)) + \sum_{i=1}^m \frac{1}{2} (g_i(x) - g_i(x^*))^T \nabla^2 g_i(x^*) (g_i(x) - g_i(x^*)).
\]
recommended maximum allowable overall delay as 400ms. In order to show the possibilities to meet the requirement of propagation delay, the delay involved in mobile satellite communications [20][21] given in Figure 2-3. Voice is the most sensitive service to delay and thus the lower the delay (hence altitude) the less the echo cancellation required.

Figure 2-3: Propagation delay variation with satellite altitude

- **Minimum elevation angle and diversity**

Due to the blockage of buildings and vegetation in the surrounding user environment, the signal will be attenuated. So the blockage can be reduced if the minimum elevation angle is selected as large as possible. The minimum elevation angle selection depends on the propagation environment, link margin restriction and coverage diversity. The quality of service can be increased using visibility of more than one satellite from the user. This is very important if CDMA access schemes are used since one of the most important advantages of the terrestrial cellular CDMA is the capability of constructively combating multipath via RAKE receivers [22]. This is not possible in the mobile satellite environment due to the small delay spreads associated with such environments. The satellite diversity overcomes this problem by introducing multipath via different satellites as well as improving the performance of the power control [14].

- **Satellite coverage and intersatellite links**

Coverage of the MSS not only depends on the satellite constellation geometry but also depends on the geographical nature of the earth and the type of links deployed between two ground terminals. A single satellite coverage area depends on the required minimum elevation angle and the altitude of the satellite. The coverage of the whole constellation depends on the inclination of the satellite
orbit, the type of ground-to-ground connection (via intersatellite links or only via FESs). If it is only via FESs, the connectivity cannot be guaranteed in some parts of the earth particularly in middle of the big oceans [23]. The reason is that the guaranteed coverage area (GCA) (see section 3.2.2) associated with the FES layout cannot be sufficiently large.

2.2 Constraints

- **Procession due to the oblateness of the earth and other external force**

![Figure 2-4: Effect on orbit due to procession](image)

Other forces act on the satellite besides the centrifugal and earth gravitational to perturb it away from its nominal orbit. These are termed as secular variations, the effect of which is continuous rather than periodic.

- Primary forces arise from third bodies such as the sun, moon and the non-spherical mass distribution of the earth.
- Earth oblateness perturbation causes the largest magnitude effect for LEO, MEO and even GEO altitudes

The oblateness of the earth has a threefold effect on satellite orbits.

1. Rotation of the major axis within the orbit plane
2. Reduction of the period
3. Rotation of the orbit plane about the earth's axis

Since circular orbits only are considered in our analysis, the rotation of the major axis is not pertinent. Only the third effect of the earth's oblateness must be taken into account. The rate of drifts of the right ascension of the ascending node \( \dot{\Omega} \) (degree per day) is given by equation (2-2) [5].
Chapter 2. Characteristic of Satellite Constellations

\[
\Omega = - \frac{9.964}{(1 - e^2)^{9/2}} \left( \frac{R_E}{R_E + h} \right)^{15} \cos(\beta)
\]

(2-2)

Where \( \beta \) is the orbit inclination and 'e' is the eccentricity (Refer Figure 2-13 for rest of the notations). The ascending node drifts westward for direct orbits or prograde orbits \((\beta < 90)\) as shown in Figure 2-13 and eastward for retrograde orbits \((\beta > 90)\). For polar orbits \((\beta = 90)\) the ascending node remains fixed.

- **Constellation radiation environment**

![Figure 2-5: Radiation pattern above the earth [24]](image)

Three particular radiation types of the earth space are, galactic, solar and trapped earth (Van Allen radiation belts as shown in Figure 2-5). The trapped earth radiation has most influence on the choice of satellite orbit altitude. Altitudes between 600km and 2000km experience acceptable level of radiation allowing for a respectable satellite lifetime without significantly increasing satellite cost. Between 2000km and about 9000km radiation levels are considered particularly high and preferably to be avoided. Above 9000km the levels are again low enough to allow lower cost constellations.

Orbit inclination, the angle between the earth’s equatorial plane and the ascending node of the satellite orbit plane, also influence the radiation level. Another important factor is the activity cycle of the sun, resulting in radiation level peaks approximately every 11 years.

Radiation affects a satellite in a number of different ways such as damage to solar panels logic upsets on satellite electronic chips and reduced power generating capacity of the solar arrays.

Spacecraft shielding and careful positioning of the most vulnerable components can help mitigate these detrimental effects. So radiation resistant electronic devices such as gallium-arsenide solar
cells can be used. But, these approaches complicate the overall spacecraft design and can increase costs by a substantial amount.

### 2.3 Type of Orbits

![Figure 2-6: Type of orbits](image)

There are four types of orbits currently in use. They are LEO (Low earth orbit), MEO (Medium earth orbit) or ICO (Intermediate circular orbit), GEO (Geostationary orbit) and HEO (Highly elliptical orbit). Details about these orbits are given in Table 2-1 based on [26]. Additional communication technical details about the individual satellite personal communication system can be found in [27].

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>LEO</th>
<th>MEO</th>
<th>HEO</th>
<th>GEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height/(km)</td>
<td>&lt;2000</td>
<td>2000-36000</td>
<td>-</td>
<td>35786</td>
</tr>
<tr>
<td>Maximum propagation delay*/(ms)</td>
<td>20-60</td>
<td>80-120</td>
<td>200-310</td>
<td>280</td>
</tr>
<tr>
<td>Satellite handover during call</td>
<td>Every 10 minutes</td>
<td>Every 2 hours</td>
<td>Every 4-8 hours</td>
<td>No</td>
</tr>
<tr>
<td>Delay jump on handover (ms)</td>
<td>4</td>
<td>24</td>
<td>12</td>
<td>none</td>
</tr>
<tr>
<td>Doppler shift* (kHz)</td>
<td>±200</td>
<td>±100</td>
<td>±50</td>
<td>±1</td>
</tr>
<tr>
<td>Doppler jump on Handover (kHz)</td>
<td>400</td>
<td>200</td>
<td>100</td>
<td>none</td>
</tr>
<tr>
<td>Multipath delay spread in-building (ns)</td>
<td>200</td>
<td>200</td>
<td>&lt;100</td>
<td>200</td>
</tr>
<tr>
<td>Range of Elevation angle (deg)</td>
<td>&gt;10</td>
<td>&gt;10</td>
<td>&gt;40</td>
<td>0-45</td>
</tr>
<tr>
<td>Approx. number of FES* for global coverage</td>
<td>50</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Number of Satellite for near global coverage</td>
<td>&gt;48</td>
<td>10-15</td>
<td>5-12</td>
<td>3</td>
</tr>
</tbody>
</table>

* Ground to ground delay is mentioned here (Figure 2-3) assuming no inter-satellite links.
* Values are based on C-band link (4-6 GHz). But the values in Figure 2-9 to Figure 2-12 are based on 2GHz.
* Inter-satellite links can reduce the number of FES for global coverage.
Approximate cost involved in satellite constellation from [20], visibility duration (The maximum duration where a satellite is visible with the required minimum elevation angle from a point on the earth, is called as maximum visibility duration. Here the satellite crossed the point) of the satellite, delay variation and Doppler variation with different orbit altitudes are given in Figure 2-7 –Figure 2-10. It is noticeable that the delay variation and Doppler variations are significant compared to terrestrial systems.

![Graph showing variation of cost, launch cost and total cost with altitude per satellite](image)

**Figure 2-7:** Variation of cost, launch cost and total cost with altitude per satellite [20]

![Graph showing visibility time versus orbit altitudes](image)

**Figure 2-8:** Visibility time versus orbit altitudes
Chapter 2. Characteristic of Satellite Constellations

The reason for the change in trend of the curves for Doppler and delay around 5500th second in the above two figures is due to the occurrence of satellite handover at that point.

Figure 2-9: Delay variation with time for LEO-66 at L-band

Figure 2-10: Doppler variation with time for LEO-66 at L-band
Chapter 2. Characteristic of Satellite Constellations

2.3.1 Geosynchronous orbit or resonant orbit

A geo-synchronous orbit is any type of orbit, which produces a repeating ground track. This is achieved with an orbit period which is approximately an integer multiple or sub-multiple of a sidereal day (NOTE: The word "approximately" is used because there is a need to correct for the node regression due to the precession of the satellite orbit).

This concept has been explained in more detail by Walker [28]. If \( \Omega_R/360 \) (\( \Omega_R \) is the rotation of the Earth relative to the orbital plane in one nodal period) is equal to \( M/L \) where \( M \) and \( L \) are mutually prime integers, then the earth track is repetitive after completion of \( L \) orbits in \( M \).
sidereal days, having covered 360(L-M) deg of geographical longitude. Walker described this condition as L:M resonance.

Advantage of resonant orbits

1. Network connectivity and control between the space segment and the ground segment can be optimised due to the repetitive coverage geometry.

2. The use of resonant orbits allows for optimisation of the mapping between constellation frequency management and traffic demand, hence reducing network control complexity.

The constellation design described in our previous work [29] is also based on a resonant orbit.

2.3.2 Sun-Synchronous Orbit

In a Sun-synchronous or Helio-synchronous orbit, the angle between the orbital plane and the Sun remains constant, which results in consistent light conditions of the satellite. This can be achieved by a careful selection of orbital height, eccentricity and inclination, which produces a precession of the orbit (node rotation) of approximately one degree eastward each day, equal to the apparent motion of the sun. This condition can only be achieved for a satellite in a retrograde orbit. A satellite in sun-synchronous orbit crosses the equator and each latitude at the same time each day. This type of orbit is therefore advantageous for an Earth Observation satellite, as it provides constant lighting conditions.

2.4 Satellite Orbit Patterns

2.4.1 Satellite orbit parameters

Figure 2-13: Definition of satellite orbit parameters

\( \beta_k \) - Inclination angle (\( \beta_k=\beta \) for all \( k \), since only equally inclined orbits are considered for satellite constellation design here, to avoid the procession effect)
\( \gamma \) - Initial phase angle of the \( k \)th satellite in its orbit plane at \( t=0 \), measured from the point of RAAN.

\( \alpha_k \) - Right Angle of Ascending Node (RAAN) for the \( k \)th orbit plane

\( k \) - Orbit number

\( \theta \) - Suspended angle at the centre of the earth

\( h \) - Altitude of the satellite

\( \varepsilon \) - Minimum elevation angle

\( R_E \) - Radius of the earth

\( t_{sh} \) - Orbit period in sidereal hours

General orbit pattern and related parameters are shown in Figure 2-13. The relation of elevation angle, observer's geocentric angular distance, radius of the earth and radius of the satellite orbit and orbit period in sidereal hours are given in (2-3) from [31].

\[
\frac{\cos \sigma}{\cos(\theta + \sigma)} = \frac{h + R_E}{R_E} = 0.975t_{sh}^{2/3}
\]  

(2-3)

### 2.4.2 Star pattern

A star pattern consists of orbits, which go through the same intersection points. The star pattern was referred to by Vargo [30] as a \( \lambda \) - type pattern, where the orbits go through the same right ascension node with different inclinations. Walker [31] considered the orbits, which go through the poles, as star patterns. The star pattern referred to by Vargo [30] undergoes perturbation effects, since the inclinations are different. Therefore the star pattern with the orbits, which go through the poles, is the better arrangement with respect to orbit keeping.

### 2.4.3 Delta pattern

Delta patterns consist of orbits with equal inclination angles (not equal to 90 degrees) to the reference plane. If the inclination is 90 degrees, the pattern becomes star. It was referred to as an L-type pattern by Vargo [30]. Their views, perpendicular to the reference plane, are shown in Figure 2-14. It has been identified in [32] that inclined orbits with odd number of planes do better in terms of global coverage (with lesser number of satellites) than orbits with even number of planes. The distance between the orbit planes along the equator for the odd number of orbits case is more uniformly distributed as shown in Figure 2-14 (b) and (c). But for the even case two planes cross at the same point around the equator.

From equation (2-2), it can be concluded that interorbit spacing of the identically inclined equal orbits does not change due to the perturbation resulting from earth oblateness if the reference
Chapter 2. Characteristic of Satellite Constellations

2.5 Comparison of different constellations and their design methods

2.5.1 Comparison of development cost of satellite constellations

Using Figure 2-7 & Figure 2-15 the altitude versus total satellite cost plotted as shown in Figure 2-16 for the street of coverage method. From Figure 2-16, it can be identified that the cost reduces until around 9000km height and thereafter increases slowly. Therefore the results clearly indicate that LEO constellation is very expensive compared to MEO and GEO. Even though it looks in the Figure 2-16 that MEO constellation cost is slightly lower than GEO, it is difficult to come to the conclusion that MEO is optimal. The reason is that the cost curve shown in Figure 2-7 is very

1 The reference plane mentioned here is not directly applicable to the Vargo [30] pattern
rough one and it is also possible to show that slight variation in satellite and launch cost will decrease the GEO constellation total cost.

2.5.2 Visibility and coverage

Visibility statistics of some popular satellite constellation are shown in Figure 2-17, to Figure 2-19. Figure 2-17 polar obit constellation and the other two are inclined orbits. The figures also show dual satellite visibility, which is essential for diversity concept in satellite systems. Each constellation arrangement has its own regional coverage advantages. For instance, polar orbits have good coverage over polar regions and inclined orbits have good cover around their intersection points which can be designed for particular area coverage. Therefore constellations that have equally inclined orbits, cannot be considered as optimal in terms of numbers of satellites for global coverage. Actually constellations that have distributed intersection points around the globe (as shown in Figure 2-20) can be better than equally inclined orbits for global coverage. This concept is also mentioned in [34]. This can be partially proved by the combined dual coverage capacity of the above three satellites constellations (Figure 2-17 to Figure 2-19). That is,
the LEO-66 has dual coverage above 58° altitudes, LEO-48 has dual coverage in between 24° and 50° altitudes and MEO-10 has dual coverage from 0° to 12° altitudes. Hence the global dual coverage can be achieved if a constellation is formed combining these three constellations with modifications of altitude and orbits inclination. But dynamic nature of the orbits and the differences in the orbit inclination angle make the orbit keeping difficult compared to the equally inclined orbits.

For the MEO type constellation, the push has to be much compared to GEO but LEO gives lowest push loss. If the eccentricity of the orbit increases lower. Hence, they need inter-satellite links in order.

Figure 2-20: Polyhedron orbits

Figure 2-21: Comparison of design methods from [32] based on single global coverage

Figure 2-21 is reproduced from Rider’s paper [32] for single global coverage. It shows that odd number of planes do better than even number of planes as mentioned in section 2.4.3 and polar phased orbits are better than polar unphased orbits. It also shows that polar orbits do well up to
approximately 3000km altitude compared to inclined orbits (for the street of coverage method), but above 3000km inclined orbits (using spherical method) do well compared to the polar orbits as mentioned in the paper [36] (The explanation for street of coverage method and spherical triangle method is given in Appendix B).

2.5.3 Other factors influencing the satellite constellation selection

For the MEO type constellation, the path loss is moderate compared to GEO, but LEO gives lowest path loss. If the connectivity of the network is considered, it is obvious that low altitude orbits lose ground connectivity. This is worse when the altitude becomes lower. Hence, they need inter-satellite links, in order to maintain the connectivity. One example of this is the Iridium system. Even though, higher altitude LEO constellations can have ground connections, they need a considerable number of fixed earth stations to maintain the connectivity, if they do not have inter-satellite links. MEO can always have ground connections with reasonable number of FESs. With inter-satellite links, the propagation delay will increase. From the delay point of view, MEOs satisfy the CCITT specification for voice as well. Minimum elevation angles for MEOs can also be kept reasonably high compared to other constellation types. The possibility of collision due to space junk is also low for MEO constellation and they spend about 90% of their time illuminated by the sun. Atmospheric drag is also low for MEO. So MEOs have advantages over LEO and GEO. Ramesh [40] showed that the probability of seeing unshadowed satellites is always greater for MEO even though inclined LEO orbits do better around latitudes of the inclination and polar LEO orbits do better around the polar regions. Finally, from Figure 2-16 and [20], the cost of the constellation is minimum for MEO constellations compared to LEO and it is comparable with GEO satellite constellation cost. The only disadvantage of MEO is the low channel capacity compare to LEOs. Success and failure of first and second generation mobile satellite systems have already given us a clear picture that satellites can only target a small size market. Therefore the capacity difference between LEO and MEO is not really significant. Considering all the above aspects, it can be concluded that expanding the satellite communications from GEO to MEO, may happen in S-UMTS if S-UMTS targets mass market (services targeting urban, suburban and highway environment) and niche market (Aviation, maritime and peace keeping mission applications) together. However the services trend nowadays to target the mass market is going for broadcast and multicast services. Therefore GEO can dominate the S-UMTS as well as it is doing with the traditional satellite communication systems provided the system is augmented by terrestrial gap fillers to allow urban/suburban and indoor coverage. It is also important to mention here that even with one GEO satellite, it is possible to deliver continuously the services to the required area. That is, the initial deployment cost is very low compared to non-GEO case where
all satellites or part of them should be in the space before delivery of the services to the particular area.

2.6 Summary and conclusions

From the literature survey, it has been found, that the street of coverage method for polar orbits with phased orbits is better than with un-phased orbits. Polar orbits do well for low altitude orbits and inclined orbits do well for the higher altitude orbits. It has been found that odd numbers of planes for inclined orbits are more efficient compared to even number of planes. It has also been shown by Rider that the spherical triangle design method is better for higher altitude orbits compared to the street of coverage method.

It has been shown that MEO may be better selection if the non-GEO satellites are considered for real time applications. However recent research shows that GEO with gap filler concept can serve required service.
Chapter 3

3 PCN network architecture and signalling

In this section we discuss the network architecture and signalling of the terrestrial personal communication network (T-PCN) as a platform on which to analyse and expand to a satellite personal communication network (S-PCN). Specifications unique to the T-PCN are identified and modified or replaced by the new proposal in order to overcome the problems that arise due to the special characteristics of the S-PCN space segment, particularly the dynamic nature of the satellite constellation and increased delays.

Even though radiotelephones have been used for public safety purpose for many decades, they were not commercialised due to capacity limitations within the limited frequency band available for the services. This problem was solved by the introduction of cellular network concept where the same frequencies are re-used in multiple cells in 1960s [41]. Cellular networks became more feasible by the end of 1970s [42] due to the technological development of radio frequency control, the microprocessor, and software technologies. The most important characteristics of the cellular system are listed below.

- Frequency reuse in the cellular systems provides an increase in the number of communication channels.
- Automated intercell transfer (handover) ensures continuity of communication when there is a need to change between base stations (BS)
- Continuous monitoring of communication between the mobile and BS to verify quality and identify the need for a cell handover
- Automatic update of mobile stations location within the network ensures that calls can be routed to mobiles.
- Mobile stations continuously listen to a common channel (broadcast channel) of the network in order to receive a call.
- The functions required of all telecommunication networks—such as operation, maintenance, and invoicing—are consistent with cellular systems.

The early cellular technologies were analogue, where frequency modulation (FM) techniques were used and are referred as first generation (1G) cellular systems. Here, the frequency band is divided into channels to handle the individual calls and the radio access principle is called FDMA (frequency division multiple access) [41][43] [44]. Advanced mobile phone system (AMPS) in
USA, Nordic mobile telephone (NMT) in Nordic countries and Total access communication system (TACS) in UK were the typical examples of 1G cellular systems. Second generation (2G) [41][43][44] cellular systems in the 80/90's moved to digital modulation techniques with advanced call processing capabilities. The advantage of the digital cellular over analogue cellular is that the digital modulation system can operate with a lower signal to noise ratio (SNR) for the same service quality [45]. Therefore it allowed smaller reuse distances and thus provided higher spectrum efficiency. Examples of 2G are global system for mobile (GSM) with time division multiple access (TDMA) scheme in Europe and most of the world, personal digital cellular (PDC) in Japan and narrowband CDMA (N-CDMA) or interim standard-95 (IS-95) system in USA using code division multiple access (CDMA) schemes.

The difference between 1G and 2G in terms of architecture, was the introduction of the base station controller (BSC), which was inserted between several base stations (BS) and the mobile switching centre (MSC) which provides connectivity between the public switched telephone network (PSTN) and a number of BS so as to reduce the computational burden of the MSC [46]. 1G is mainly based on voice application. But 2G has extended to data applications such as paging, facsimile etc.

Third generation (3G) is now evolving from mature 2G systems with the aim of providing data and multimedia applications anywhere, anytime whilst improving the spectral efficiency and reducing cost. In order to achieve this goal, the standardisation bodies tried to define a single set of standards through different working groups and projects (3GPP, 3GPP2, IWTF etc.). What has emerged is a family of standards under the heading IMT2000. This embraces UMTS (Europe), CDMA2000 (USA) and NTT DoCoMo (Japan).

One of the important features of the 3G network architecture is clear separation between core network (CN) and access network (AN) [47], where an access network comprises all functions that enable a user to access services and the core network includes the switching network and service network. A switching network includes all the functions related to call and bearer control for fixed transmission and the service network includes all the functionalities for the support services including location management. This concept helps in the design of the core network independently from the access network since most of the radio related parts are located in the access network and therefore the core network has little impact from the new radio interface. For example the BSS and NSS in Figure 3-1 can be considered as the access network and core network respectively. Further 3G architecture details can be found in [48][49][50][51].

Since the analysis in this thesis is based on the GSM architecture, the following sections explain the network architecture of GSM and the new entities required by the S-PCN.
3.1 System architecture of GSM network and signalling

Figure 3-1: GSM system architecture

Figure 3-1 shows the GSM network architecture with different physical entities and interconnecting interfaces. The GSM system can be divided into four main parts, mobile station (MS), base station subsystem (BSS/access network in UMTS terminology), network subsystem (NSS) and network management subsystem (NMS). BSS controls the radio link with the MS, NSS performs the switching of calls between the mobile users, and mobile and fixed network users and NMS looks after the operation and set-up of the network. This network architecture is mapped on to the geographical areas, which are structured hierarchically as shown in Figure 3-2. Here, location area (LA), which is made up of one or more cells, is a virtual administrative division to handle the mobility of the terminal in idle mode. Therefore it can be smaller or larger than BSC area or even bigger than MSC/VLR area. But in GSM, LA is smaller than the MSC service area. The decision on the size of the LA, depends on the signalling involved during the idle mode of the terminals and this is discussed in detail in section 3.3 and chapters 4, 5 & 6. Each LA can uniquely be identified by a location area identity (LAI). The LAI format is (LAI = MCC-MNC-LAC). Where LAC - location area code, MCC - mobile country code and MNC - mobile network code. The PLMN can be identified using MCC and MNC.

PLMN (GSM) service area

Figure 3-2: GSM service area partitioning
The following sub-sections provide an overview of the GSM architecture with explanation of the physical entities, protocol architecture and functional entities, radio channel structure and signalling procedures.

### 3.1.1 Physical entities

This section explains some of the physical entities particularly BSS, MSC, HLR, VLR, AuC, EIR which are mainly involved in mobility management. These four database elements (HLR, VLR, AuC, EIR) are called service control points (SCP) in the terminology of the intelligent network (IN).

#### 3.1.1.1 Base station subsystems (BSS)

The BSS consists of base station controller (BSC) and base station transceiver station (BTS). The radio resource management functions are mainly dealt with by the BSS and in particular by the BSC. The BTS comprises the infrastructure's radio transmission and reception devices. One of BTS main feature is the transcoder/rate adaptor unit (TRAU), where the GSM speech encoding and decoding is carried out as well as rate adaptation between the 13kbps voice channel used over the radio link and the standard 64kbps channel used by the PSTN or ISDN.

#### 3.1.1.2 Mobile Switching Centre (MSC)

The MSC is basically an ISDN-switch with additional functions for handling radio resources and mobility of the users. Its main function is to co-ordinate the setting-up of calls from GSM users. It also handles the functions of location registration and handover. Some of the MSCs, called gateway mobile switching centre (GMSC) act as the door for entering and leaving the call from and to other networks, e.g. PSTN. In order to direct the calls from outside GSM network to the correct MSC, the outside network requests the routing information from the HLR via the GMSC. According to the service point of view, the greater the density of GMSCs the better, because the call can be routed efficiently if the interrogation point is closer to the calling party. There is a functional unit called the interworking function (/WF) to facilitate the interworking of the PLMN with fixed networks (ISDN, PSTN etc.).

#### 3.1.1.3 Home Location Register (HLR)

The HLR is typically a standalone computer, without switching capability. HLR is the main database for the management of the MS. There may be one or more HLRs in a PLMN according to the capacity of the equipment and the size of the network. Normally there is one HLR in a PLMN. Two important items of data are International Mobile Station Identity (IMSI) and the mobile station ISDN number (MSISDN) and are stored in the HLR. The number dialled for the MS points to a record in its HLR. The first digit of the GSM directory number is enough to verify whether it
Chapter 3. PCN network architecture and signalling

is a GSM directory number or not and is also used to identify the operator with, which the subscription is held. This is called an MSISDN. From this number the GMSC gets the Mobile Station Roaming Number (MSRN) from the HLR. This is used by the GMSC to identify the visited MSC. After the call is received by the MSC, it will retrieve the IMSI, which is then used for signalling within the GSM network and between different GSM networks to identify the terminal and its HLR. The VLR stores the LAI and the HLR stores the VLR identifier. Location updating exchange mainly uses the SDCCH (see section 3.1.3.3)

3.1.1.4 Visitor Location Register (VLR)

This database is linked to one or more MSCs. It handles the data management of the mobile stations roaming in a MSC area, remote from their home MSC area. Thus the VLR keeps the more precise location information regarding the MS compare to the HLR. The main functions of the VLR are:

- Organization of subscriber data
- Management and allocation of the local identity codes in order to avoid frequent use of global identity on the radio path and for security reasons.
- Location registration and call handling
- Authentication
- Support of encryption
- Handling of supplementary services
- Support short message service

3.1.1.5 Authentication Centre (AuC)

The AuC stores the security data (subscriber-specific security key, encryption algorithms, and a random generator) of subscribers. The AuC gives the subscriber-specific key to the HLR, which distributes them to the VLR. The same subscriber-specific key and algorithms are stored in the subscriber identity module (SIM).

3.1.1.6 Equipment Identity Register (EIR)

The EIR enables the MSC to check the validity of the equipment since it contains information about the MS equipment. There is a white list for serial numbers of terminals that are allowed to use the service, a grey list for terminals that need to be held under surveillance, and a black list for stolen and faulty MSs. Those terminals that are found on the black list are not allowed to use the network. The IMSI is used to interrogate the EIR.
3.1.2 Functional entities and protocol architecture

In 2G mobile communication systems, there are five generic functional entities that can be identified as follows:

- **Transmission**: This is needed for the transmission of user and signalling information. MS, BTS and BSC are involved with transmission, whilst HLR, VLR, EIR and AuC are only concerned with transmission for signalling purposes.

- **Radio resources management (RR)**: The role of the RR is to establish, maintain and release communication links between MS and MSC with the help of the following tasks [52][43][47]. It is also responsible for cell selection in idle mode and for monitoring BCCH and CCCH.
  - Admission control
  - Channel assignment
  - Load control
  - Power control
  - Handover

- **Mobility management (MM)**: This is related to tracking of the MS in the idle mode within the home network and when roaming, e.g. when in a network other than the MS's home network. The tasks specific to MS tracking are:
  - Location update: This is the procedure to inform the network about the LA or any network change or switching in the MS.
  - Paging: This is the procedure to find the exact position of the MS within the LA.
  - Cell and network selection

Since mobility management is the main topic of this thesis, it will be revisited in section 3.3.

- **Communication management (CM)**: This is responsible for setting up, maintaining and releasing calls between users (call control-CC). It also handles supplementary services (SS); call forwarding, call waiting and call hold and short message services (SMS).

- **Operation, Administration and Maintenance (OAM)**: It is related to monitoring and controlling of the system. The tasks include billing and accounting, and collecting performance data.

The functions explained above, are mapped onto the network architecture (Figure 3-1) and protocol architecture (Figure 3-3). This mapping is the basis for the detailed protocol and interface specification.
Wireless network protocol architectures are a combination of *OSI* and *ISDN PRM* (protocol reference model) models where the *OSI* model forms the basis for vertical protocol division, whilst the *ISDN PRM* model forms the basis for defining different protocols for user and control planes [43][47]. Therefore, there are usually two different protocol stacks, the user and control plane (sometime called signalling plane), which defined in wireless networks. This section only discusses the signalling protocol stack and the functional entities that relate to it.

**Physical Layer (Layer 1):** This has all the functions necessary for the transmission over the physical medium, RF channels between MS and BSS, that also contain signalling channels (*SACCH*, *FACCH*, *BCCH*, *SCH*, *FCCH*, *PAGCH*, *RACH* and *SDCCH*) and the traffic channel (*TCH*), and the multiplex standard TDM slots implemented on 64kbps or 2048kbps links (*E1* trunks) [43][45][53] between MSC and BSS.

**Data Link Layer (Layer 2):** The data link layer protocol between the MS and the BSS is *LAPDm*, which is a modified version of the link access protocol for the D-channel of DSSI[53]. It is similar to *HDLC*. The DLL between MSC and BSS consists of the message transfer part level 2 (*MTP2*) of signalling system No.7 (*SS7*)

**Message Layer (Layer 3):** This layer in the MS, is divided into three sublayers, radio resources management (*RR*), mobility management (*MM*) and connection management (*CM*). The *RR* in the MS communicates with its peer in the BSS. The *MM* and *CM* in a MS communicate with their peers at the MSC. The base station subsystem application part (*BSSAP*) is present at the MSC and BSS and uses the signalling connection control part

---

**Figure 3-3:** GSM signalling protocol architecture

Figure 3-3 shows the interfaces and protocols for signalling between *PLMN* entities. *GSM* define 3-layer architecture, which is different from the *OSI* architecture.
(SCCP) of SS7. BSSAP has two parts; direct transfer application part (DTAP) and BSS management application process (BSSMAP). The BSSMAP at BSS and MSC handles the transfer of RR-related BSSMAP messages. At a BSS, RR and BSSMAP communicate with each other. The DTAP at a BSS transparently transfers MM and CM messages, received on dedicated radio channels, to a SS7 data link, which transports them to the MSC [53].

3.1.3 Radio channel structure

The radio channels between BTS and MS can be considered as a physical channel and logical channel [52]. One of the time slots of a TDMA frame on one carrier is referred to as a physical channel. There are eight time slots in GSM, so eight physical channels per carrier. Even though these physical channels are used for radio interface, they are further divided into so many virtual channels according to the information content (e.g. just data or controlling signal etc). These are called logical channels. There are two types of logical channel, called traffic channel (TCH) and control channel (CCH) [52][46]. Traffic channels carry digitally encoded user speech or user data and have identical functions on both the forward and reverse links. Control channels carry signalling and synchronising commands between the base station and the mobile station. There are six different types of TCHs. There are three main control channels called broadcast channel (BCH), the common control channel (CCCH) and dedicated control channel (DCCH). GSM PLMN uses 124 duplex carrier frequencies within the allocated frequency range 890-915MHz for uplink and 935-960MHz for downlink with carrier spacing of 200kHz. The control channels only are discussed here.

3.1.3.1 Broadcast Channels (BCH)

- **Broadcast Control Channel (BCCH):** This is a forward link unidirectional channel. It broadcasts general information regarding the cells and network identity, operating characteristics of the cell (current control channel structure, channel availability, and congestion), and the channels currently in use within the cell.

- **Frequency Correction Channel (FCCH):** The FCCH allows each subscriber unit to synchronise its local oscillator frequency to the exact base station frequency.

- **Synchronisation Channel (SCH):** This is used to identify the serving base station while allowing each mobile to synchronise the frame with the base station. The frame number (FN) is sent with the base station identity code (BSIC) during the SCH burst. This carries coarse time advancement commands from the base station.
3.1.3.2 Common Control Channel (CCCH)

- Random Access Channel (RACH): This is an uplink unidirectional channel used by the mobile station for access requests to the network. The reason for the access request can be categorised as follows;
  - Response to paging
  - Normal location update, periodic location update, and IMSI attach.
  - All other cases such as call set up, short message transmission, supplementary service management etc.

This channel is required to provide high throughput and low delay. Its performance is impacted by the signalling delay in S-PCN. Since, the mobile stations choose their emission on this channel in a random manner, it is called RACH. Thus there are possibilities for collision between the transmissions of several mobile stations.

- Paging and Access Grant Channel (PAGCH): This is a combination of the Paging Channel (PCH) and Access Grant Channel (AGCH). Paging messages and messages indicating the allocated channel upon prime access, are transmitted on this channel. The PCH transmits the IMSI of the called mobile user with a request for acknowledgement from the MS on the RACH. The AGCH is used by the base station to respond to a RACH request sent by the MS. It carries data, which instructs the mobile to operate in a particular physical channel with a particular dedicated control channel.

3.1.3.3 Dedicated Control Channel (DCCH)

There are three types of dedicated channels all of which are bi-directional.

- Stand alone dedicated channel (SDCCH): This can be considered as an intermediate temporary channel which maintains the contact between the base station and the MS until base station and MSC verify the subscriber unit and allocate resources to the mobile. It carries the authentication and alert messages as the mobile synchronises itself with the frame structure.

- Slow associated control channel (SACCH): This is used to send slow but regular information such as transmit power level instructions and specific timing advance instructions to each user in the forward link. The reserve SACCH carries information about the received signal strength and the quality of the TCH and BCH measurement results from neighbouring cells.
• **Fast associated control channel (FACCH):** This carries urgent messages and it contains the same type of information as the SDCCH. A FACCH is assigned whenever a SDCCH has not been dedicated to a particular user and there is an urgent message such as a hand off request. A stealing flag in the time slot is identification for the FACCH in the time slot.

### 3.1.4 MM signalling in GSM network

Signalling is used for establishing and maintaining the communication link between end terminals and management of the network. In the fixed network, there is no signalling between the end terminal and the network when the terminal is in the inactive state. In contrast to this, there is always (active and idle mode) signalling exchange between the terminal and network if the terminal is switched on. When a MS is switched on, it needs to locate the RF carrier, which carries the CCCH to achieve synchronisation with the BCCH, PAGCH and RACH. This procedure enables the terminal to listen to broadcast and paging messages, to access the network for location updating and originating calls. Mobiles in the idle mode, periodically compare the signal strength of the RF carrier with the CCCH channel in their cell to counter parts in adjacent cells. If any of the adjacent cell RF carriers is stronger than the current carrier the MS will switch to strongest one. The signalling procedures in mobile networks can be divided into two groups, signalling over the air-interface and signalling amongst fixed network entities. In this section signalling procedures for location update and registering, originating calls, and terminating calls are explained.

#### 3.1.4.1 Location update and registration

Registration is only performed when a MS moves from one PLMN to another PLMN and the location update is done when a MS moves from one LA to another LA. The location updates can also occur periodically, independent of the current location. The time interval required for the periodic location update is broadcast on the BCCH. During the registration, a VLR in the current network issues a TMSI to the subscriber. This TMSI is stored by the MS in its non-volatile SIM storage. Therefore there is no need for registration just after it is switched on if it is in the same network before and after the switch on. The normal location update procedure is sufficient. The complete location registration procedure is shown in Figure 3-4 and location update procedures for the LA crossing inside the same VLR and for different VLRs are shown in and Figure 3-5 and Figure 3-6 respectively. The difference between location registration and location update is that the MS has already been assigned a valid TMSI in the location update case. The common procedures involved in these three procedures are location update, authentication, ciphering, TMSI reallocation, assigning a new MSRN and obtaining additional information about the subscriber (e.g. the MS category or configuration parameters for supplementary services).
Chapter 3. PCN network architecture and signalling

Authentication

Ciphering mode setting

RR connection release

Figure 3-4: Registration procedure in GSM

Figure 3-5: Location update procedure in GSM (LA change within the same VLR)
3.1.4.2 Mobile calls

Here a call to the MS from outside the PLMN and a call from the MS to outside the PLMN are explained in Figure 3-7 and Figure 3-9 respectively. For the first case, the number dialled (MSISDN) does not contain information about the current location of the MS. Therefore the GMSC contacts the HLR to get the routing address of the called MS MSRN which is assigned by the currently serving VLR of the MS. Using the MSRN, the GMSC can forward the call to the local MSC which will take care of the remaining procedures as shown in Figure 3-7. The important process here is paging to find the exact location of the MS. The international switching centre (ISC) will be involved if the call comes from outside the home country of the called MS. The involvement of ISC and PLMN entities in a call set-up procedure are shown in Figure 3-8. In this particular example, the calling party is in country 1 (e.g. UK), the home PLMN of MS is in country 2 (e.g. France), and the MS is currently visiting a PLMN in country 3 (e.g. Germany). In the MS initiated calls, there is no paging procedure. The call is forwarded to the GMSC if the called party is outside the home PLMN of the calling party.
Figure 3-7: MS terminated call set-up

Figure 3-8: International connection to called mobile
3.2 S-PCN system architecture

We now look at how this GSM networking maps onto the satellite case. Referring to Figure 3-10, each satellite covers a circular area on the earth’s surface and this is called its footprint. Its size...
depends on the minimum elevation angle and the height of the orbit. Each footprint is further divided into larger number of spotbeams in order to reuse the frequency band, as in the terrestrial case. Each spotbeam can be considered as the equivalent of a terrestrial cell and therefore each spotbeam requires at least one set of control channels. In order to maintain the connectivity and control each satellite, fixed earth stations are placed around the globe. Some systems use fewer number of FESs by using intersatellite links e.g. Iridium.

Each FES is accompanied by a mobile satellite-switching centre (MSSC) and forms the gateway, which is connected to the terrestrial fixed network via the international switching centre (ISC). The network control centre (NCC) is the network element central to the network management system and is equivalent to the operation and maintenance centre (OMC) in terrestrial systems. Amongst other tasks [54] it allocates spotbeam frequencies and distributes routing tables to the satellites. The satellite control centre (SCC) is responsible for orbit keeping via telemetry, tracking and command (TT&C) links to the satellite. VLR, HLR, EIR and AuC have the same roles as in GSM.

3.2.1 Fixed Earth Stations (FES)

The obvious difference between the terrestrial system and the satellite system is that, the ground based transmitter and receiver antenna act as the BTS but in the satellite system the transmitter and receiver antenna in the satellite act as the BTS, so there is no fixed cable connection between the BTS and BSC in the satellite system. Instead a dynamically changing wireless connection is maintained between them.

There are two types of fixed earth station, which have been identified in [55][56][57]. These are called the Gateway Earth Stations (GESSs) / Primary Earth Stations (PESs) and Traffic Earth Station (TESs). The main reasons for using different type of FESs are to reduce the FES cost, and ease the route choice during route optimisation as well in some cases for political reasons.

Figure 3-11: Similar functional elements in terrestrial and satellite systems
3.2.1.1 Primary Earth Station (PES)

The FES has the capability to handle the resource management and to control the satellites in the constellation. It performs allocation of the satellite traffic channels and common and dedicated signalling control channels. The number of PES’s needed is a function of the constellation altitude and the service area. PESs contain HLRs and VLRs. PESs also act as TES’s when the suitable TES for call maintenance is the PES. From the control viewpoint, the GES combines MSC and BSS role. The GES is responsible for database management, including security, mobility management, service, authentication and equipment registers. The interface between the GES and the registers is similar to that in GSM. Air interface route optimisation is a more complex function for S-PCN’s compared with GSM and it is the responsibility of the GES. Distribution of PESs around the globe depends mainly on the guaranteed coverage area (GCA) (see section 3.2.2)

3.2.1.2 Traffic Earth Station (TES)

TESs only handle traffic channels and associated control channels via TCHs. Actually, TESs works under direction of the PES’s. Call set up, channel allocation and selection of suitable TES are performed by the PES. Even though, the TESs can be considered as the counter part of the BSS in GSM, it has the ability to interface directly with external networks (ISDN, PSTN and GSM) since the distance between the FESs is large, where as in GSM this is implemented via MSCs. In GSM the BSS has control over its own channels but not the TES. This difference is a direct consequence of dynamically changing constellation connectivity. TES’s may be distributed country by country depending on country size, population and traffic competition in that region.

3.2.2 Guaranteed coverage area (GCA)

The area around an FES, for guaranteed connection to an MS with required minimum elevation angle on both sides of the link (FES to Satellite and MS to Satellite), is defined as the guaranteed coverage area (GCA) [58][59]. The GCA shape and size depends on the satellite constellation characteristics and the FES latitude position. Figure 3-12 shows the GCA in different latitude positions for a LEO-48 calculation.
Chapter 3. PCN network architecture and signalling

3.3 Mobility Management

Mobility management takes care of the position of MSs when in idle and active modes. The mobility functions can be categorised into two main parts called handover (Radio Mobility) and Location Management (Network Mobility). The full literature can be found in [60][61][62][63][64][65][66]. Handover occurs, in order to provide continuity of a call and support a specified QoS, when users moves from the coverage area of one base station to another base station or from one spotbeam to another spotbeam. Location management however, handles tracking of MSs and routing the incoming calls to the mobiles. This thesis concentrates mainly on location management aspects.

Location information is maintained and used by the network for call routing purposes. Due to the mobility of the users, this information should be updated regularly. This requires location update and registration process by the mobiles. Since this data only contains the area identification, where user can be found, the network performs a paging operation to alert a mobile of an incoming call. In the location updating technique, LA size, paging area (PA) size and methods and database management need to be optimised together so as to minimise the undesirable effects on the resources and QoS (spectrum, satellite and terminal power, call set-up delay). Location management is based on the user's mobility and incoming and outgoing call rate characteristics.

3.3.1 Location tracking schemes in terrestrial systems

Location update is the process of informing the network about the position of MSs for the purpose of optimum call routing. The location update methods can be divided into two categories, called Fixed Location Area methods (FLA) and Dynamic Location Area methods (DLA) [70]. In the FLA method (Figure 3-14-(a)), a certain number of cells are grouped into an LA. Whenever a MS...
crosses the boundary of one LA to another, the MS informs the network about its new location with a LAI. When a call arrives for a MS, the network searches all, or a subset, of the cells, called the paging area (PA), belonging to the particular LA, by sending a message in the paging channel. The FLA method has a number of inefficiencies associated with;

1. Switching between two LAs, due to the random walk of MSs at an LA border.

2. Traffic loading due to the location tracking being concentrated in the LA bordering cells.

3. High location update rate (LUR) due to cell selection switching, caused by radio propagation effects.

4. The mobility and call arrival patterns of MSs vary, and thus in generally it is difficult to select an LA size that is optimal for all users.

In order to overcome these problems, a multi-layer location update method has been proposed in [71][72]. However this is not fully optimised for all parameters, which change with time and individual situation. Therefore, the DLA method (Figure 3-14-(b)) was proposed in [73], where the size of the LA for a user is not fixed, but optimised according to its current call arrival rate (CAR or \( \lambda \)) and mobility. The DLA method was investigated in [74] for time based, movement based and distance based approaches [75] and it was shown that distance based was optimum. Intelligent paging was introduced in [76] and [77] to further reduce signalling load due to location management. In this method, the LA is further divided into small areas called paging areas (PA) as shown in Figure 3-13. The number of PAs and their size are optimised using several attributes such as CAR, the user’s degree of mobility, recent interaction point, MS attraction point (e.g. cinema, leisure centre etc), mobility time slot in a day etc. The full procedure involved in intelligent paging is shown in Figure 3-15. The reverse virtual call set-up (RVC) method proposed in [78] reduces the LUR, signalling and call set-up delay.

![Figure 3-13: Location area and paging area arrangement in terrestrial system](image)
The DLA method performs location updates based on the mobility of the MSs and frequency of incoming calls. Three main dynamic location update methods for terrestrial mobile communications systems have been proposed [74][75].

1. **Time based**: Each mobile user updates its location periodically. The drawback is that, the location update is performed even if a terminal has not moved.

2. **Movement based** [75]: This depends on the number of boundary crossings between the cells. If the number of crossings of cell boundaries is exceeded by a specified number of the MS will send an update message.

3. **Distance based**: In this method, the user tracks the distance in terms of cells. User will send update message whenever the distance exceeds a pre-specified distance threshold as shown in Figure 3-14(b). This requires an intelligent paging scheme, to identify the location of the terminal using the point of last contact with the network and the distance it might have travelled thereafter.

![Figure 3-14: Location update points of FLA and DLA methods for the same movement MS](image)

3.3.2.1 Fixed location area methods in MSN

When the FLA method is used in satellite systems, the problem is to define the fixed location area with the dynamic constellation. In terrestrial mobile systems, the cells are divided into segments of the fixed size. However, in mobile satellite systems this cannot be directly applied due to the dynamic nature of the spacecraft. The following sub-section explains this in detail.

- **BICCH based FLA method**

A set of LAs can be defined on the same as in Figure 3-16, by distributing LAs using a broadcast control channel for each spacecraft (BCC). Therefore, a location update is necessary, when the quality of the received broadcast channel is lower than a specific threshold. On report channel exception, the network calculates the spacecraft that provides coverage over the LA and pagers the mobile via these subscribers. There are problems in defining boundaries in the system.
3.3.2 Location tracking schemes in satellite systems

The location update for the mobile non-GEO satellite system will be different from the terrestrial system, due to the fast movement of the satellites (7km/s for LEO and 2km/s MEO). That is, the cells (spotbeams) are not fixed relative to the surface of the Earth. So it is difficult to define a fixed location area based on grouping of a number of spotbeams.

3.3.2.1 Fixed location area methods in MSS

When the FLA method is used in satellite systems, the problem is to define the fixed location area with the dynamic constellation. In terrestrial system, cells are used to define the LA with a unique LAI. However, in mobile satellite systems this cannot be directly applied due to the dynamic nature of the spotbeams. The following sub-sections explain this in detail.

- **BCCH based FLA method**

A set of LAs can be defined on the earth, as in Figure 3-16, by transmitting LAI's using a broadcast control channel for each spotbeam [56][57]. Therefore a location update is necessary, when the quality of the received broadcast channel is lower than a specific threshold. On paging channel reception the network calculates the spotbeams that provide coverage over the LA and pages the mobile via these satellites. There are problems in defining boundaries. In the case
shown in Figure 3-16(a), three spotbeams cover an LA and broadcast the LAI associated with the LA. The same spotbeams cover at least two more LAs. So, they have to broadcast the LAIs of at least three different LAs. This is the case for the LA being smaller than a spotbeam. In the case where, the LA is greater than the spotbeam size, it is possible to fix the LA with an exact number of spotbeams at a particular time, as in the terrestrial systems. However, there is then a problem due to the movement of spotbeams as shown in Figure 3-16(c). Initially, the LA is covered by a unique number of spotbeams but after a while some spotbeams will belong to two or three different LAs. Spotbeams 1 and 2 are examples. In this case, spotbeams sometimes have to broadcast two or three LAIs. When a MS leaves its current LA and enters a new LA through one of these spotbeams, which broadcast two or three LAIs, then it cannot effectively determine the LAI of the new LA. This feature leads to redundant location updates. One possible solution to this problem is for the network to calculate the position of a mobile during the location update signalling and then provide the mobile with this information. This problem is further reduced as the LA size increases. However, the decision on LA size not only depends on the location update method but also on the paging method.

![Diagram of location area boundaries](image)

a) LA size < spot size  
b) LA size > spot size  
c) Relative movement between spots and LA

**Figure 3-16: FLA using location area identity (LAI)**

- **FES based FLA method**

This method is based on the *guaranteed coverage area* (GCA) technique. This is similar to the scheme used for terrestrial cellular systems such as GSM. It is based on the monitoring of the BCCH channel of the spotbeams that overlap the GCA. The spotbeams within the FES GCA, broadcast the same FES identification on the BCCH. A location update occurs when the MS receives the BCCH with a new FES identifier with better quality than the current one. This should happen close to the GCA border. Therefore, the MS is responsible for triggering the location update. It is required that some overlap of adjacent GCAs occur, in order to allow the MS to register with a new FES when it is moving from one GCA to another. In these overlap areas the
MS detects more than one FES identifier. When the BCCH channel, with the identifier of the improved FES is received, the MS informs the new FES that it wishes to perform a location update. Consequently, the new FES updates the network database.

3.3.2.2 Dynamic location area method in MSS

Time based methods have the same advantages and disadvantages as with terrestrial systems. A movement-based method is not suitable for non-GEO satellite systems due to the fast movement of the spot beams. For the distance-based case, in terrestrial system, the distance is measured in terms number of cells covered. However, this is not practical in non-GEO mobile satellite systems, due to the rapid movement of the spotbeams. Measurement of real distance is possible using GPS as mentioned in [57][56] or via other methods proposed in [81] (using delay and Doppler without any additional signalling transfer between the user terminal and the network). But, the problems are that the S-PCN system relies on other extend systems and/or the MS needs additional hardware (for example GPS receiver combined with MS) to calculate the user position. This may therefore lead to a complication in terminal design. In the method proposed herein the user terminal provides its position information (in terms of latitude and longitude). To define the location of a MS with time verification, a circle is defined whose radius increases with time at a certain rate (which could be fixed or variable for different terminal types) as shown in Figure 3-17.

![Figure 3-17: Variation of paging area radius with time](image)

The centre of this circle has the coordinates of the last mobile position. The mobile needs to update its position after travelling a certain (pre-defined) distance called location area radius (LAR), as shown in Figure 3-18. Between ‘a’ and ‘e’ the terminal makes location update at points ‘b’, ‘c’ and ‘d’ as at these points it has reached the edge of its LA.
In [57], it has been shown that there is no reduction in location update rate in the FLA method due to user terminating call or initiating calls statistics. In the FLA method the location update is only performed when the user crosses the LA boundary. So the location update is purely dependent on the crossing of a fixed boundary. But for the DLA method, the LA boundary changes with time. If a call arrives, then the boundary is centred around that position. This is one of the advantages for the dynamic location area update method. But as mentioned in [82], large overlaps occur with this method and this is a downside.

### 3.3.3 Paging in satellite systems

Unlike terrestrial system, in satellite systems, the number of spotbeams overlapping in the LA depends on the type of constellation, size of the LA and latitude and longitude of the LA. Reducing the number of spotbeams for efficient paging is highly desirable as this can save valuable satellite power, increases the system capacity and also reduces interference. A multiple step paging method can be used to reduce the number of spotbeams. However whatever the paging technique used, in practice a significant amount of redundant signalling occurs. Figure 3-19 shows paging of a larger area outside the LA and it is difficult to avoid such scenario in practice.

Multiple satellite visibility will also lead to paging redundancy as shown in Figure 3-20. But this can easily be overcome as follows;
Optimal satellite paging: Only paging to the highest elevation angle satellite

Satellite diversity paging: This is only used when probability of both channel will be high

Hybrid satellite paging: In this case, paging is performed through the highest elevation angle satellite in the first instance and only if failure occurs, the second highest satellite is used for paging

3.4 Comparison of different location update and paging methods

The comparison between different location update methods and paging methods are given in Table 3-1 and Table 3-2. The discussions are based on both terrestrial and satellite systems. The references related to the methods are also given inside the table.
Chapter 3. PCN network architecture and signalling

3.4 Comparison of different location update and paging methods

The comparison between different location update methods and paging methods are given in Table 3-1 and Table 3-2. The discussions are based on both terrestrial and satellite systems. The references related to the methods are also given inside the table.

- **Optimal satellite paging**: Only paging to the highest elevation angle satellite
- **Satellite diversity paging**: This is only used when probability of both channel will be high
- **Hybrid satellite paging**: In this case, paging is performed through the highest elevation angle satellite in the first instance and only if failure occurs, the second highest satellite is used for paging
### Table 3-1: Comparison of different location update methods

<table>
<thead>
<tr>
<th>Methods</th>
<th>Fixed Location Area (FLA) Method [70]</th>
<th>Dynamic Location Area (DLA) Method [70]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Descriptions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cells are grouped into LA with out LA overlap</td>
<td>Cells are grouped into LA with some amount of LA overlaps</td>
</tr>
<tr>
<td></td>
<td>Common LA for all users</td>
<td>Common LA for all users</td>
</tr>
<tr>
<td></td>
<td>Cells broadcast LAI in BCCH</td>
<td>Cells in overlapping region broadcast all the LAI of all the overlapping LAs</td>
</tr>
<tr>
<td></td>
<td>$MS$ does location update whenever $MS$ crosses the LA</td>
<td>$MS$ does location update whenever $MS$ crosses the LA</td>
</tr>
<tr>
<td><strong>Advantages &amp; disadvantages</strong></td>
<td>Not optimal for all users mobility and call pattern</td>
<td>The second problem mentioned in single layer case is solved in this method</td>
</tr>
<tr>
<td></td>
<td>Possibilities for frequent location update by users those movement is around the LA boundary</td>
<td>But the paging signalling will increase due to the LA overlapping.</td>
</tr>
<tr>
<td></td>
<td>Location update traffic is concentrated in the cells located around the LA</td>
<td></td>
</tr>
<tr>
<td><strong>Applicability in terrestrial systems</strong></td>
<td>It is being used in GSM</td>
<td>Yes, possible</td>
</tr>
</tbody>
</table>
Chapter 3. PCN network architecture and signalling

<table>
<thead>
<tr>
<th>Methods</th>
<th>Fixed Location Area (FLA) Method</th>
<th>Dynamic Location Area (DLA) Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single Layer</td>
<td>Time Based</td>
</tr>
<tr>
<td></td>
<td>Multi-layer</td>
<td>Movement Based</td>
</tr>
<tr>
<td></td>
<td>Distanced Based</td>
<td></td>
</tr>
<tr>
<td>Applicability in non-GEO systems</td>
<td>Difficult due to movement of spotbeams and not optimal. E.g.: BCCH based FLA &amp; FES based FLA (section 3.3.2.1)</td>
<td>Yes possible and very simple. But this is not the optimal one.</td>
</tr>
<tr>
<td></td>
<td>Not very realistic due to the movement of spotbeams</td>
<td>It is not possible due to the movement of spotbeams.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Possible. But MS needs a positioning method to calculate the distance.</td>
</tr>
</tbody>
</table>

Table 3-2: Comparison of different paging methods

<table>
<thead>
<tr>
<th>Methods</th>
<th>Traditional paging method [43]</th>
<th>Intelligent/Step paging method [76][77]</th>
<th>Reverse virtual call set-up paging method [78]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Descriptions</td>
<td>All the cells in the LA are paged.</td>
<td>Selected cells in the LA are paged</td>
<td>This is suitable for hierarchical cell arrangement where macrocells overlay on top of micro cells.</td>
</tr>
<tr>
<td>Advantages and disadvantages</td>
<td>Simple to implement, There is no big paging delay like intelligent paging, Wastage of paging signal due to the paging of all the cells overlap with LA.</td>
<td>Complicated compared to traditional method since there is computational overhead for probability calculation of PA and selection procedures involved.</td>
<td>Paging delay is lower than other two methods.</td>
</tr>
<tr>
<td>Applicability in terrestrial system</td>
<td>It is being used in GSM</td>
<td>Possible</td>
<td>Possible if there is hierarchical cellular structure</td>
</tr>
<tr>
<td>Applicability in non-GEO systems</td>
<td>It is being used in 2G MSS</td>
<td>Possible and it can be used to remove the satellite and spotbeam redundancies in MSS</td>
<td>There are possibilities, it should be investigated</td>
</tr>
</tbody>
</table>
3.5 Summary and conclusions

The cellular concept has been reviewed with 1G, 2G and 3G mobile communication systems. System architecture of the GSM system has been explained together with its physical and functional entities. Its protocol architecture has also been described and the radio channel structure presented. The signalling procedures involved in location update and call handling have been illustrated based on the GSM architecture. S-PCN system architecture has been described with the additional physical entities required for MSS over and above the terrestrial GSM system. The different requirements of mobility management techniques between terrestrial and satellite system have been highlighted and some potential solutions outlined for the satellite case.
Chapter 4

4 Location area planning and positioning

Due to the dynamic nature of the satellites in the non-GEO satellite constellation, it is difficult to use the spotbeams, which are equivalent to the cells in terrestrial system, to define the LA on the ground. It is possible to use DLA's together with position reporting schemes based upon GPS but such scheme can complicate the terminals. Thus in this chapter we investigate a new FLA scheme together with a new positioning scheme for location updating.

4.1 A new methodology for defining fixed location area

Comparing the two location area methods, FLA and DLA, the DLA method is most often proposed for MSS in the literature due to the fact that it is difficult to define a FLA using moving spotbeams. In this chapter we show that with a new method called latitude/longitude partitioning FLA (LatLongFLA) it is possible to define an FLA for the MSS system to satisfy the same requirements as provided by the DLA method. This method also needs a positioning scheme to determine the MS position as in the DLA method explained in section 3.3.2.2 and this will also be addressed.

4.1.1 Defining layout of the LatLongFLA on the earth

Figure 4-1: LatLongFLA layout in MSS

In the LatLongFLA method, the earth's surface is divided into a number of strips with equal width “θ” as shown in Figure 4-1 and the rows are numbered as 1,2,...,Ir,Nr (defined as row number)
from -90° latitude. Each strip is divided into small cells of equal width "ξ(I)" and numbered as 1,2,...,I,N, (defined as column number) from -180° longitude. Now the LA can be identified using row number and column number. The procedures for determining the LA of a MS and performing the location tracking are explained below together with a method for calculating θ and ξ(I) explained in the following section.

1. Determine the MSs position using a positioning scheme, say 
\( (MS.\text{Latitude}, MS.\text{Longitude}) \)

2. Then determine, in which row the MS is located.
\[
\text{Row Number, } I_r = \text{round}\left\{ (MS.\text{Latitude}+90)/\theta_{\text{new}} \right\}
\]
\( \text{round}\{ \} \) - an operator to round a value to the nearest integer

3. Determine the cell width "ξ(I)" (explained in section 4.1.2)

4. Finally determine in which cell of that row, the MS is located
\[
\text{Column Number, } I_c = \text{round}\left\{ (MS.\text{Longitude}+180.0)/\xi(I) \right\}
\]

5. These two values are compared with the previously calculated values to monitor the change in the LA.

6. If there is a change, the MS deletes the previous values, stores the new values and informs the network of the new values.

7. When a call arrives at the MS, the network identifies the LA of the MS using the stored data regarding the MS during location update and sends the paging signal through the spotbeams, which overlap with the LA.

Only two variables and very simple software need to be stored in the MS, so the scheme is very efficient.

### 4.1.2 Determine the LatLongFLA size

From Figure 4-2, the area of the strip 'Δ' is described by equation (4-1).

\[
\Delta = 2\pi R_s^2 \{\sin(\theta_2)-\sin(\theta_1)\} = 2\pi R_s^2 \{\sin(\theta_1+\theta)-\sin(\theta_1)\}
\]  

(4-1)

The required size of the LA, 'Π', is defined as \(\pi r^2\), where r is the radius of the circular LA equivalent to that in Figure 4-2. The number of cells in the strip \(N_{\text{Cells Strip}}\) can be calculated using equation (4-2);

\[
N_{\text{Cells Strip}} = \Delta/\Pi = 2K\times\cos((\theta_2+\theta_1)/2)\sin(\theta/2)
\]  

(4-2)

Where \(K = 2\times R_s^2/r^2\). In order to have cost effective paging, the shape of the LA should be closer to a circle. Hence, the width of the strip "\(R_s\theta\)" and the width of the cell "\(r_\xi\)" should be equal,
where $r_s$ is the radius of the strip. The possible number of cells in a strip $N_{Cells, Strip}$ is given as follows.

$$N_{Cells, Strip} = 2\pi \cos((\theta_2 + \theta_1)/2)/\theta$$  \hspace{1cm} (4-3)

Equating (4-2) and (4-3), the following result can be derived.

$$(\theta/2)\sin(\theta/2) = \pi/(2\sqrt{N})$$  \hspace{1cm} (4-4)

The above (4-4) is only a function of strip width $\theta$. Solving equation (4-4) numerically $\theta$ can be determined for different values of $r$ as shown in Figure 4-3.

### Figure 4-2: Geometry of the LatLongFLA on the earth surface

![Figure 4-2: Geometry of the LatLongFLA on the earth surface](image)

### Figure 4-3: Strip width versus LAR for defining LatLongFLA in MSS

![Figure 4-3: Strip width versus LAR for defining LatLongFLA in MSS](image)
From the calculated value of $\theta$, the actual number of strips $N_{strip}$, recalculated value of $\theta$ $\theta_{new}$, actual number of cells in the $i^{th}$ strip and cell width $\xi(i_t)$ can be calculated using equations (4-5)-(4-8) respectively.

$$N_{strip} = 2 \times \text{round}(0.5 \times \pi / \theta) \quad (4-5)$$

$$\theta_{new} = \pi / N_{strip} \quad (4-6)$$

$$N_{cells\_strip}(i_t) = \text{round}(2\pi \cos((2j-1) \frac{\theta_{new}}{2}) / \theta_{new}) \quad (4-7)$$

$$\xi(i_t) = 2\pi / N_{cells\_strip}(i_t) \quad (4-8)$$

$$\text{If} \ (i_t <= N_{strip}/2) \ j = N_{strip}/2 - i_t + 1; \text{ Else } j = i_t - N_{strip}/2; \quad (4-9)$$

The single most important parameter in this method is $\theta$. Hence, the network should inform the value of $\theta$ to the MS whenever it changes the LA size. The easiest way of determining $\theta$ for the required LA size is to have the coefficients of the equation of the curve in Figure 4-3 in the network database.

### 4.1.3 Comparison of LatLongFLA with DLA

Table 4-1: Comparison of new LatLongFLA against DLA

<table>
<thead>
<tr>
<th>Descriptions</th>
<th>New FLA</th>
<th>DLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positioning method required</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>LA size is dynamically changeable</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>LA size can differ from user to user</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Number of logic/math operations in MS</td>
<td>$= 9$</td>
<td>$= 2$</td>
</tr>
<tr>
<td>Number of parameters needed for location update</td>
<td>2 (column &amp; row No.)</td>
<td>2 (lat &amp; longitude)</td>
</tr>
<tr>
<td>LA index needed in BCCH channel</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Impact on performance due to location update on call arrival</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Shape of the LA (Spherical)</td>
<td>Trapezium</td>
<td>Circle</td>
</tr>
</tbody>
</table>

Table 4-1 compares the LatLongFLA method with the DLA method. The features are similar, except the number of logic operations in the MS and the shape of the LA. Since the number of logic operations in the MS for both methods is low, the LatLongFLA and DLA methods are similar in complexity. The average number of spotbeams (including redundant ones) overlapping with the LAs of the LatLongFLA and DLA methods along the equator has been derived via simulation for LEO-48, MEO-10 and global GEO constellations [2] and the results are given in Figure 4-4. The method of selecting overlapping spotbeams with LatLongFLA is explained in Appendix E. The difference between the number of spotbeams overlapping with the new FLA and the DLA is small for LEO and MEO. It is larger for GEO because the trapezium shaped LA overlaps with more
redundant spotbeams compared to the circular shaped LA when the footprint overlap area is large. This is the case with GEO where bigger footprint sizes with only 4 satellites create larger overlap regions. Hence, removal of redundancy (chapter 5) will reasonably reduce this difference.

![Graph showing the relationship between Equivalent circular shape LA radius and number of spotbeams for paging versus LAR.](image)

**Figure 4-4: Number of spotbeams for paging versus LAR**

### 4.2 Positioning

Positioning is a major service nowadays in military, navigation and civil applications and is especially important for multimedia applications in mobile satellite communication systems. Emergency services, geographical dependant services, tariff, guiding a person towards nearest gas station or tourist attraction point etc., in unfamiliar surrounding, crime detection, earth exploration and mobility management in mobile satellite system, are some of the applications of positioning. The terminal positioning technique proposed here is mainly developed for mobility management applications in mobile satellite systems.

As explained in section 3.3.2.2, DLA method needs a positioning method and most of the research carried out in location tracking [56][57][83] has assumed that the mobile position can be determined using other means such as GPS. This increases the size and the complexity of the MS and produces dependence on another system for position determination. It is evident that a self-dependant positioning method will reduce the complexity and cost of the MS design. Even though, the methods given in [84][81] are self-dependant, the complexity is considerable due to the requirement of a very accurate oscillator to measure delay and Doppler and a very efficient filter to remove the noise. With this in mind, two novel positioning methods are proposed here,
Spotbeam Boundary Crossing Method and Averaging Method, which are simple yet effective for the application in hand.

### 4.2.1 Existing positioning methods

GPS\[85][86\] provides highly accurate positioning information. The idea behind GPS is, that one’s position \((x,y,z)\) can be determined with the distance values from three different known positions by the triangulation method. The corresponding geometry with satellites and an equation for the distance between a satellite and a MS position on earth are given in Figure 4-5-(a) and (4-10) respectively. The satellite position and its direction of movement are known parameters. The distance is measured in terms of delay, where an accurate clock at the receiver measures the time delay between the signal leaving the satellite and arriving at the receiver. Four simultaneous delay measurements from four satellites are required to solve three unknowns \((x,y,z)\) and the user’s clock offset \((\xi)\). Some proposals for positioning, using one or two satellites, were presented in [84][81] based on recently proposed mobile satellite systems using delay, Doppler and spotbeam ID. The geometry and an equation relating to the speed of the satellite \((V_s)\), angle between the direction of the satellite movement and the line connecting to the satellite position and the MS position \((\theta)\) are given in Figure 4-5-(b) and by equation (4-11). From the delay the distance can be found and the equation will give the value for \(\theta\). Using these two parameters, the possible two positions of the MS can be calculated. Using the spotbeam ID the appropriate one can be selected. Errors in positioning due to the inaccuracy in delay and Doppler measurement are also explained in this paper. Precise clock and a stable space platform are the two important aspects of the above-mentioned positioning methods.

\[
R_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2 - \xi}
\]  

\[
fdl = (V_s f/c) \cos \theta
\]

Where \(f\) is carrier frequency and \(c \ (=3\times10^8)\) is the speed of light.
4.2.2 Newly proposed positioning methods

In the technique proposed herein, it has been assumed, that the Broadcast Control Channel (BCCH) carries the information about the centre position of each spotbeam in the form of latitude and longitude, spotbeam ID and satellite ID. We present two methods to estimate the position of the terminal using the above three pieces of information.

4.2.2.1 Averaging Method

![Averaging phenomena](image)

![Flow chart for satellite selection in position determination procedures](image)

From Figure 4-6, it can be seen that the individual sensor reads and average duration. For LEO-66, error decreases very sharply up to 400 ms, whereas sharply thereafter. For LEO-48, error decreases sharply up to 300 ms, and then remains steady thereafter. Therefore, the averaging duration can be increased up to 100 ms for LEO-48 and 300 ms for LEO-66. This interval between the two position data collection, is considered as one second step time. The determination that the time interval between two positions data collection, is considered as one second step time. The determination that the time interval between two position data collection, is considered as one second step time. The determination that the time interval between two position data collection, is considered as one second step time. The determination that the time interval between two position data collection, is considered as one second step time. The determination that the time interval between two position data collection, is considered as one second step time. The determination that the time interval between two position data collection, is considered as one second step time. The determination that the time interval between two position data collection, is considered as one second step time.
In this method, the MS collects a number of spotbeam centre positions over a certain period of time as shown in Figure 4-6 and averages them. The selection process for the satellite and the spotbeam is shown in Figure 4-7. The position is calculated as the average of the stored positions. The averaging duration has considerable impact on the accuracy obtained. The error for different averaging duration is given in Figure 4-8 for different latitude positions. For example, the position information is taken from the BCCH channel in 1 second intervals for 120 seconds. At the end of 120 seconds, there are 120 data points for the positions. The values are averaged and the averaged value gives the approximate position of the MS. In 121st second, the first stored data is disregarded and the new value is stored and the average value is recalculated again. After the first calculation for position, the position can be calculated in each second interval. Handling for the data for this method is shown in Figure 4-9. Each box indicates a storage memory in the MS. The required storage memory depends on the averaging duration and the time interval between the two receiving spotbeam position data. The time interval between two positions data collection, is considered as one second in Figure 4-8. It has been found from simulation that the time interval between two positions data collection can be as high as 20 seconds without significant increase in position error.

From Figure 4-8, it can be seen that the error decreases with increased average duration. For LEO-66, error decreases very sharply up to 200 seconds and decreases slowly thereafter. For LEO-48, error decreases sharply up to 400 seconds and decreases slowly thereafter. Therefore, the averaging duration can be taken as 250s for LEO-66 and 500s for LEO-48 with 5s interval between the two position data collections. Thus the required memory locations for the averaging method are 50 for LEO-66 and 100 for LEO-48.

![Figure 4-8: Position Error versus averaging duration in different altitudes](image)

(a) LEO-66  
(b) LEO-48
4.2.2.2 Spotbeam boundary crossing method

In this method, the MS monitors the spotbeam ID and satellite ID at regular intervals (e.g. 1 second). When the terminal encounters different spotbeam ID or satellite ID, it stores the current spotbeam position and calculates the previous spotbeam position. Using these two positions, the MS calculates the middle of the spotbeams intersection area as shown by the shaded area in Figure 4-10. During the spotbeam boundary crossing time, the MS will be in the shaded area. With this concept, the position of the MS can be determined with an accuracy that is sufficient for location update. A flow chart for selecting the satellite and the spotbeam in simulation is given in Figure 4-7. Using a simulation, the positioning error with Latitudes in this method is calculated for LEO-66 and LEO-48 constellations (Appendix G). The results are given in Figure 4-11. Maximum error for LEO-66 is 188km (Diameter of spotbeam 600km) and for LEO-48 is 460km (Diameter of spotbeam 1642km). Error levels with percentage of time are also given in Figure 4-13.
4. Location area planning and positioning

Maximum error for the LEO-66 is found to be 188km (for 600km diameter spotbeams) and for LEO-48 is 460km (for 1642km diameter spotbeams). Statistics of these errors are also given in Figure 4-13.

4.2.3 Comparison between the two newly proposed positioning methods

Figure 4-12 shows the error variation with time (i.e., different constellation position with respect to a fixed point on the earth) for duration of 2hours. From this figure, it is evident that the averaging method gives better error performance than the boundary crossing method. This is further strengthened by the result in Figure 4-13, which shows the percentage of time versus error threshold. For the averaging method for 90% of the time, the error is less than 100km for LEO-66 and 275km for LEO-48, but for the spotbeam boundary crossing method, only 55% of the time error is less than 100km for LEO-66 and only 55% time, the error is less the 275km for LEO-48. The performance of the boundary crossing method depends on the power level fluctuation of the signal near to the spotbeam boundary and it needs satellite ID and spotbeam ID information. But the averaging method doesn’t require the satellite ID or spotbeam ID information.
Chapter 4. Location area planning and positioning

4.2.4 Evaluation of positioning method against location update and paging

Using a very simple mobility model (see Appendix D) the actual position of the MS has been calculated with time. The positions of the MS are calculated using the proposed averaging method with the help of in house constellation software called “simulation package of orbit constellation” (SPOC). The number of spotbeams per location area has been calculated. Using the number of spotbeams and other data (bit required for paging and location update, call arrival rate and terminal speed) optimal location area size has been calculated as explained in section 5.3.3. The calculated optimal location area radius is used for location update. It is also assumed that the MS performs a location update during mobile terminating calls and mobile initiating calls. With the above location update methods, the following paging strategies were investigated with the simulated model for different mobile speeds (four different speeds are considered, car {50km/h}, high speed train {250km/h}, plane {800km/h}, concord {2200km/h}) and call arrival rate. Simulated mobile terminal movement on the earth, location updates positions, call arrival positions and paging failure positions are shown in Figure 3-15 for the following scenarios (refer Figure 4-14). The case of paging circular area with radius of location area radius and position error is not considered here since it is obvious, there would be no paging failure possible.

- Case I: Whole location area has been paged
- Case II: The paging area grows with time according to the mobile velocity from the location update position if the expected distance of travel of the mobile terminal is greater than positioning error.

\[
\text{If } ( \text{PosErr} < \text{Time elapsed} \times \text{Max MS Velocity} ) \\
\text{Then } \\
\\text{PAR} = \text{Time elapsed} \times \text{Max MS Velocity} \\
\text{else}
\]
Chapter 4. Location area planning and positioning

PAR = PosErr

- Case III: The paging area grows with time according to the mobile velocity from the location update position.

\[ PAR = \text{Time elapsed} \times \text{Max MS Velocity} \]

PosErr – Position error

PAR – Paging area radius

Figure 4-14: Paging areas representing different paging scenarios used for the simulation

Figure 4-15: Relative positions of location update, call arrival and paging failure for LEO-48
The above figure shows the sample of the simulation model with LEO-48 constellation used in the investigation. In that particular sample, there is no paging failure in the case I. That is the reason for no showing any failure points for case I in the figure.

The simulation results for four different speeds are given in Figure 4-16 to Figure 4-19 for LEO-66 and LEO-48 constellations. The simulation ran for 100 call arrival times. From the simulation results, the paging failure rate is very low for Case I compare to Case II & III. Paging failure increases remarkably with call arrival rate for Case II & III. Except for a speed of 2200km/h, for all other speeds, paging failure is less than 10% with call arrival rate of 0.1 calls/h or less and it is almost zero for Case I. Therefore the proposed positioning method is useful for the mobile satellite systems when the expected call arrival rate are less than 0.1 calls/h/user. It is possible to observe from Figure 3-15, that most of the failure occurs if calls arrive just after the location update. There will be no paging failure if the PA radius is greater than the notional LA radius plus the position error.

![Graphs showing simulation results for different speeds and constellations.](image-url)

**Figure 4-16:** Probability of paging failure versus call arrival rate for MS speed of 50km/h

**Figure 4-17:** Probability of paging failure versus call arrival rate for MS speed of 250km/h
Chapter 4. Location area planning and positioning

4.3 Summary and conclusions

A new methodology for defining FLA layout in MSS has been proposed with only a single parameter strip width and very simple software in the MSs and the network. Since the LAs are virtually defined, the size of LAs is variable according to the mobility of the users and call arrival rate. The size of the LA can also differ from user to user. The comparison with a DLA method demonstrated that the new FLA method has similar performance features to the DLA method whilst solving the problems of higher overlapping between two consecutive LAs and the common LA for all the users in DLA.

A new application oriented simple positioning method has been proposed for location tracking. Its effectiveness has been verified against the dynamic location update method and it has been found to perform well up to call arrival rates of 0.1 calls/h/user except at extremely high speed (MS flies in Concord). It also performs well for higher call arrival rates when the PA is comparable with the
LA size. Therefore it can easily be adapted for mobile satellite systems provided the additional bits for transmission of latitude and longitude can be accommodated in the BCCH channel.
Chapter 5

5 Mobility management signalling over the air-interface in MSS

In an MSS system there is considerable signalling load on the air interface and fixed network, due to the MS tracking procedures as mentioned in section 4.1.4. Handling signalling over the air-interface is more stringent than that for a fixed network due to the spectrum limitation and direct impact on MS and satellite. Hence it is important to optimise the mobility management protocol to use the available spectrum effectively and save MS and satellite power whilst retaining the signalling load on the fixed network to a reasonable level in order to achieve the required QoS. Therefore this chapter investigates different location tracking scenarios in order to achieve this objective and in the next chapter we analyse the possible impact of the different location tracking scenarios back on the fixed network.

The general idea of mobility management and the advantages of introducing intelligent paging in mobile communication system was addressed in section 3.3. The following sections address the implementation of intelligent paging in MSS systems. A new paging method is proposed to overcome some problems with existing intelligent paging schemes [57]. Different combinations of location update and paging methods are investigated against different performance metrics such as signalling load, terminal power, satellite power, and processing delay.

5.1 Intelligent paging in MSS

As mentioned in section 3.3, the main purpose of introducing intelligent paging is to reduce the over air-interface signalling. Due to the computation complexity and the long propagation delay associated with MSS, intelligent paging may introduce more delay on call set-up. This section explains the relationship between signalling load and delay, probability calculations of paging areas and the implementation of intelligent paging in MSS, plus a new paging method.

5.1.1 Calculation of number of spotbeams for paging and paging delay

The first step toward finding signalling load in MSS is to calculate the number of spotbeams required for paging. This is little bit complicated in MSS compared to the terrestrial system. The reason is that the spotbeams are not overlapped with the LA uniformly. The following figure
shows the arrangement of location area, paging area and spotbeams. Here the location area is divided into eight paging areas.

In order to find the number of spotbeams required for paging, we need to introduce a number of relevant parameters as follows:

\[ N_{Sb} \] : Number of spotbeams within a LA. It can be calculated via simulation using the appropriate constellation parameters

\[ N_{PA} \] : Number of PA in an LA

\[ N_{Sb-p} \] : Average number of spotbeams for step paging.

\[ AiDly \] : Delay involved in the air interface for single (FES->MT->FES).

\[ AiDly_{sp} \] : Delay involved in the Multi-step paging.

\[ K_{Sb}(i) \] : Number of spotbeams in the \( i^{th} \) PA

\[ P_{PA}(i) \] : Probability of a MT being in the \( i^{th} \) PA.

In order to achieve success in the initial paging step, the PAs should be paged in descending order of the probability. The average number of spotbeams \( (N_{Sb-p}) \) for step paging and paging delay are given logically by (5-1) & (5-2) respectively. The reason for the factors \( \sum_{j=1}^{n} K_{Sb}(j) \) and \( \sum_{j=1}^{n} j \) in equations (5-1) and (5-2) respectively, is that the system would have paged 'i' paging areas step by step if the paging is succeeded in \( i^{th} \) attempt. That is the number of PAs paged is 'i' and the delay encountered is addition of all delay happened in each paging steps up to \( i^{th} \) attempt.

\[
N_{Sb-p} = \sum_{i=1}^{n} P_{PA}(i) \sum_{j=1}^{n} K_{Sb}(j)
\]  

\[
AiDly_{sp} = AiDly \times \sum_{i=1}^{n} P_{PA}(i) \sum_{j=1}^{n} j
\]
For example, assume $P_{PA}(i) = 1/N_{PA}$ for all $i$ and $K_S(i) = K_S(2) = \ldots = K_S(N_{PA}) = N_{SA}/N_{PA}$. Then equations (5-1) & (5-2) simplify as follows;

\[ N_{SA,SP} = 0.5 \times N_{SA} \times (N_{PA} + 1)/N_{PA} \]  \hspace{1cm} (5-3)

\[ AiDly_{SP} = 0.5 \times (N_{PA} + 1) \times AiDly \]  \hspace{1cm} (5-4)

For large values of $N_{PA}$, the average number of spotbeams to be paged is reduced by half, whilst the paging delay increases by $0.5 \times (N_{PA} + 1)$ times. Therefore the number of steps should be decided, based upon maximum allowable call set-up delay ($C_{SuDiY_{Max}}$). We have assumed $C_{SuDiY_{Max}} = 1.5s$ in line with ITU recommendation for demonstration purposes.

### 5.1.2 Implementation of intelligent paging in MSS

A virtual paging cell (VPC) method to select the appropriate spotbeams for paging in MSS was proposed in [57]. But herein there was no mentioned of the method of implementing VPC's for an MSS system. Therefore this section introduces such a method of implementing VPC's, which is quite general.

The implementation steps are as follows;

1. Divide the $LA$ into a number of equal size cells as shown in Figure 5-2.
2. Find each VPC position in terms of latitude and longitude (see Appendix C).
3. Determine the probability of the MT being in the $i^{th}$ VPC ($P_{VPC(i)}$). (see section 5.1.3).
4. Determine overlapping footprints with the $LA$ and remove the redundant footprints.
5. Select the overlapping spotbeams of the selected footprints within the $LA$.
6. Find the overlapping VPCs with each selected spotbeam and $P_{Sh(i)}$ using (5-5) & (5-6).

\[ SA(i) \cap LA = \{ \text{collection of ID}_{VPC} \} \]  \hspace{1cm} (5-5)

\[ P_{Sh(i)} = \sum_{ID_{SpotArea}(i) \cap LA} P_{VPC}(ld) \]  \hspace{1cm} (5-6)

$SA(i)$ is the coverage area of the $i^{th}$ spotbeam, $ID_{VPC}$ is the identity of the VPC and $P_{Sh(i)}$ the probability of the MT being in the $i^{th}$ spotbeam. e.g. $SA(i) \cap LA = \{1,3,7,12,15\}$, that is $1^{st}$, $3^{rd}$, $7^{th}$, $12^{th}$ and $15^{th}$ VPCs overlap with $i^{th}$ spotbeam coverage area and $P_{Sh(i)} = p(1) + p(3) + p(7) + p(12) + p(15)$.

7. Sort the spotbeams in descending order of probability.
8. Select the spotbeams having the highest probability $P_{Sh(i)}$. 

---

65
9. Check the overlap between this spotbeam and other spotbeams, using the VPCs ID and find the new probability of each spotbeam as explained below. e.g. $SA(k) \cap LA = \{2, 5, 7, 10, 13\}$, $P_{SA}(k) = p(2) + p(5) + p(7) + p(10) + p(13)$. VPC 7 is common for both. Assuming $P_{SA}(i) > P_{SA}(k)$ where $k$ is any values except $i$. $P_{SA}(k)_{new} = P_{SA}(k) - p(7)$.

10. Sort in descending order of probabilities, and select the spotbeam, which has the next highest probability. Then, repeat step 9 for the remainder of the spotbeams.

Using this procedure, overlapping spotbeams within the same LA can be identified and removed. As shown in Figure 5-3(a), the LA can be covered by two or more different satellites. In this case, the selection of footprints and spotbeams depends on the spotbeam or footprint handover, FES handover and ease of call routing.

**Figure 5-3: Layout of footprints, spotbeams and VPCs on top of the LA**
5.1.3 Calculation of probability of the virtual paging cells

Figure 5-4 shows a LA with a ring arrangement and mapping of probability density function (PDF) of the distance derived from the mobile velocity (v) distribution. The network can calculate the speed of MTs since MT's determine their position from time to time for location tracking purposes (but this is not available to network). Accordingly with the above assumptions, the probability distribution $P_{VPC}(i)$ for the VPCs is based on the velocity distribution of MTs and is given by a combination of equations (5-7) & (5-8).

\[
P_{\text{ring}}(R_{\text{index}}) = T \int_{W \cdot R_{\text{index}}/T}^{W \cdot (R_{\text{index}}+1)/T} f(v) \, dv
\]

\[
P_{\text{ring}}(R_{\text{index}}) = T \int_{W \cdot R_{\text{index}}/T}^{W \cdot R_{\text{index}}/T} f(v) \, dv \quad \text{for } R_{\text{index}}=N_{\text{rings}} \quad \text{only if } T \cdot \nu_{\text{max}} > \text{LAR}
\]

\[
P_{\text{VPC}}(j) = P_{\text{ring}}(R_{\text{index}}) \quad \text{for } j = 1
\]

\[
P_{\text{VPC}}(j) = P_{\text{ring}}(R_{\text{index}})/N_{\text{VPC}}(R_{\text{index}}) \quad \text{for } j = (N_{\text{VPC}}(R_{\text{index}}-1) + 1) \cdot (N_{\text{VPC}}(R_{\text{index}}-1) + N_{\text{VPC}}(R_{\text{index}}))
\]

$T$ is the elapsed time from the last update.

Figure 5-4: Mapping of PDF of MS speed onto LA for VPC probability calculation

5.2 Footprint based paging method (FBP)

Figure 5-5: Paging and paging response in FBP
The number of VPCs used depends on the average number of overlapping spotbeams within the LA and the LA size. When the LA increases, the required number of VPCs also increases. This means higher processing time for spotbeam selection. Therefore we propose a new paging method called footprint based paging scheme (FBP), not only to overcome this problem, but also to reduce the location update rate (LUR), paging load, signalling cost in the fixed network and call set-up delay, shown in a later section. In this scheme, the MS is paged using a single beam representing the footprint and the MS response is received by the nearest spotbeam as shown in Figure 5-5. But, there is a need for an additional antenna on the satellite. In this thesis, paging through an individual spotbeam is called spotbeam based paging (SBP).

5.3 Signalling cost calculations

Average air interface cost per call $AC_{\text{Call-AI}}$ for location tracking can be given by (5-9).

$$AC_{\text{Call-AI}} = N_{\text{Sp-p}} \times NB_{\text{PAGE}} + LUR \times NB_{\text{LUP}} / \lambda$$

(5-9)

Where $N_{\text{Sp-p}}$ is given by equation (5-3), $NB_{\text{PAGE}}$ (=152 bits) and $NB_{\text{LUP}}$ (=1196 bits) are number of bits for paging in one spotbeam and location update respectively and $LUR$ is given by equation (5-11) and equation (5-16). In the case of the FBP method, $N_{\text{Sp-p}}$ will be replaced by the number of footprints ($N_{\text{Fp-p}}$), which can be derived in the same way as $N_{\text{Sp-p}}$.

5.3.1 Location update rate in FLA method

$LUR$ in the FLA method depends on the flow of MTs between the LAs. The number of incoming MTs to a LA ($N_{\text{I-MTs}}$) in unit time is given by equation (5-10). $S$ is the perimeter of the LA, $\rho$ is density of MTs per unit area, $E(v)$ is mean velocity of MTs and $v$ is the mean velocity of individual users.

$$N_{\text{I-MTs}} = \rho SE[v] / \pi$$

(5-10)

Assuming that, the number of incoming and outgoing MTs is equal and $LAR$ is the LA radius,

$$LUR = 2 \times E[v] / (\pi \times LAR)$$

(5-11)
5.3.2 Location update rate in DLA method

Referring to Figure 5-6, the LUR is given by (5-12) for the case of no update on call arrival.

\[ LUR = \frac{u}{LAR}. \]  

(5-12)

For the case of update on call arrival, the derivation for LUR is given below, assuming that the PDF of the originating and terminating calls is Poisson distributed \( P(N) = (\lambda t)_N e^{-\lambda t}/N! \). Referring to Figure 5-7, inter-call arrival times \( \tau_1, ..., \tau_n \) should be greater than \( T (= LAR/u) \), in order to have location update, only after a call initiation. The number of location updates followed by calls (\( N_{AC} \)) in unit time is given by equation (5-13). The relationship between probabilities of location update after call (\( P_{AC} \)) and after location update (\( P_{AL} \)) is given by equation (5-14)

\[ N_{AC} = \lambda e^{\lambda (LAR/u)} \]  

(5-13)

\[ P_{AC} + P_{AL} = 1 \]  

(5-14)

In order to find the probability of having a location update after a location update (not after a call), the case where there are not any calls in between two consecutive location updates, should be considered. Then referring to Figure 5-8, \( P_{AL} = e^{-\lambda T} \), \( P_{AC} = 1 - e^{-\lambda T} \) and \( N_{AC} \) is given by (5-15).

\[ T = \frac{LAR}{v} \]

Figure 5-8: Time diagram for Location Update
By combining (5-13) & (5-15) 

\[
LUR = \frac{\lambda e^{-\lambda R^2}}{(1-e^{-\lambda R^2})}
\] (5-16)

It can also be shown that equation (5-16) reduces to equation (5-12) when \( \lambda_{\text{mean}} = 0 \).

### 5.3.3 Determination of optimal location area

Decisions on the \( LA \) size, depends on the number of bits required for paging and location update, \( MS \) speed and its location, spotbeam size, rate of incoming and outgoing calls and channel characteristics. In this thesis the impact of the channel condition is not considered. It has been considered elsewhere in Surrey work [57].

Combining (5-9) and (5-12) or (5-16), the total cost for location tracking can be derived for \( FLA \) or \( DLA \) methods respectively. It is possible to find the number of spotbeams within a \( LA \) radius using \( SPOC \) and this is given in Figure 5-9 for \( LEO-66 \) and \( LEO-48 \) (Appendix G). Figure 5-9(a) shows the required number of spotbeams for paging, versus \( LA \) at a particular position of the \( MS \) on the earth's surface and Figure 5-9(b) shows the average number of spotbeams taken from a quarter of the earth surface. Results show that spotbeams are not uniformly distributed over the earth's surface and vary with latitude and longitude position. Further the number of spotbeams required to page is not necessarily the same as shown in Figure 5-9, because there is the possibility of spotbeam/footprint overlaps as shown in Figure 5-3. Therefore the minimum number of spotbeams should be selected for optimum paging and this is discussed in section 5.4.

Using equation (5-9), and data from Figure 5-9(b), the signalling load for location tracking with \( LA \) size can be derived and the results are shown in Figure 5-10 for two different satellite constellations. Using the same procedure, optimal \( LAR \) and optimal number of spotbeams for paging can be found for different \( MS \) speeds and different call arrival rates. The variation of optimal \( LAR \) and optimal number of spotbeams with \( MS \) speed are shown in Figure 5-11 (a) and (b) respectively for two different call arrival rates. The higher the call arrival rate, the lower the optimal \( LA \) radius becomes. There is no significant difference between the location update on call arrival and no location update on call arrival in terms of number of spotbeams. This indicates that there will be no reduction of the paging cost unless an intelligent paging scheme is deployed. However it does yield a reduction in location update rate and this is discussed in the next section.
5.4 Performance evaluation of location tracking schemes

Eight different cases (P1-P8) for paging, two different cases (D1-D2) for DLA method and only one case (FA) for FLA are considered for the performance analysis with two values of call arrival...
rate ($\lambda$), CR1=0.01 and CR2=1.0 calls/hour. Cases P1-P5 are spotbeam based paging (SBP) and cases P6-P8 are footprint based paging (FBP).

P1 : Page all spotbeams overlap with the LA

P2 : Page all spotbeams overlap with the LA without satellite redundancy.

P3 : Page minimum number of spotbeams for 100% successful paging.

P4 : Two step spotbeams paging with 90% success in first step.

P5 : Spotbeams step paging with infinite delay.

P6 : Page all footprints overlap with the LA

P7 : Page minimum number of footprints for 100% successful paging

P8 : Footprints step paging with infinite delay.

D1 : DLA method with no location update on call arrival

D2 : DLA method with location update on call arrival

FA : FLA method

Initially, the number of spotbeams for paging with the all paging method was found for three different constellations. They show the same (Figure 5-12, Figure 5-13 and Figure 5-14) paging trends. Hence only the LEO-66 constellation is considered for further analysis. Using the number of spotbeams calculated and the method explained in section 5.3.3, optimal LA size, optimal signalling load and optimal location update rate were found. The optimal LAR variation is shown in Figure 5-15 for two different cases and the signalling load and LUR variations are shown in Figure 5-16 to Figure 5-21. The reason for the flattening in the curve at 11,100km is that the maximum LAR size considered is 11100km. However, the curves have the same trend with speed.

**Figure 5-12: Number of spotbeams or footprints versus LAR for LEO-48**

**Figure 5-13: Number of spotbeams or footprints versus LAR for LEO-66**
5.4.1 Signalling load and location update rate

Figure 5-14: Number of spotbeams or footprints versus LAR for MEO-10

Figure 5-15: Optimal location area versus MS speed

Figure 5-16: Signalling load versus MS speed for case P1 and P6

Figure 5-17: Signalling load versus MS speed for case P3 and P7
Chapter 5. MM signalling over air-interface

From the results shown in Figure 5-12 to Figure 5-21, the following conclusions can be made.

- The minimum number of spotbeams or footprints required to have 100% of paging success in the first paging step is much lower than the number of spotbeams or footprints overlap with the LA (see cases P1 & P3 for spotbeam and cases P6 & P7 for footprint in Figure 5-12 to Figure 5-14). Therefore the need for removal of redundant footprints or spotbeams is paramount.

- Signalling load for location tracking and LUR decrease with the amount of intelligence in the paging.

- Average number of spotbeams or footprints decreases with increased number of paging steps.

- In the spotbeam based non-intelligent paging, the FLA method requires less signalling load compared to the DLA (D1&D2) method at higher $\lambda$, in most of the speed range.

- $LUR$ of case D2 is always low compared to D1 and FLA at higher $\lambda$.
• The difference between FLA and DLA values for LUR and signalling load for location tracking are small at lower $\lambda$.

• There is no difference in terms of LUR and bandwidth requirement between DLA with and DLA without update on call arrival at lower $\lambda$.

• Signalling load is always low for the FLA method compared to the DLA method at low $\lambda$.

• The footprint based paging always requires fewer number of footprint for paging, much lower bandwidth and less frequent LUR compared to spotbeam based paging.

• The bandwidth required for footprint-based paging is always lower for case D2 compared to case D1 & FLA at higher $\lambda$.

• With intelligent paging, the bandwidth requirement is almost the same for FLA and DLA with update on call arrival.

The results shown in Figure 5-16 to Figure 5-21 represent the individual mobiles influence on the system. Therefore conclusions drawn from them do not reflect the total impact of the mobile population on the system. Therefore overall average signalling load and LUR seen by the system are derived below.

Optimal signalling load variation ($SW(\nu, \lambda)$) shown in Figure 5-16, Figure 5-17 and Figure 5-18 and LUR variation ($LUR(\nu, \lambda)$) shown in Figure 5-19, Figure 5-20 and Figure 5-21 can be considered as a function of velocity ($\nu$) and call arrival rate ($\lambda$). Considering the overall MSS, the average signalling load ($SW_{Avr}(\lambda)$) and LUR ($LUR_{Avr}(\lambda)$) for each user can be expressed by equations (5-17) and (5-18) respectively. Where $Dis_{v}(\nu)$ is the velocity distribution of the mobile population. The results are shown in Figure 5-22.

$$SW_{Avr}(\lambda) = \sum_{i=1}^{N_{user}} SW(\nu, \lambda) \times Dis_{v}(\nu)$$

$$LUR_{Avr}(\lambda) = \sum_{i=1}^{N_{user}} LUR(\nu, \lambda) \times Dis_{v}(\nu)$$

From the results shown in Figure 5-22, it is clear that the DLA method with location update on call arrival (D2) is performed to the other two for all call arrival rates. But the FLA method (FA) is better than the DLA method without update on call arrival (D1). However, selection of D2 may not be beneficial for some mobiles with speeds that do not show better perform with D2. This happens at lower call arrival rates which will be the most possible case with MSS. Therefore user controllable FLA as proposed in section 4.1 may be the better solution. The observation further strengthens the advantage of adapting a footprint based paging method.
5.4.2 Comparison of processing time for paging

The major constraint in using intelligent paging is the processing time and complexity on the network side. In order to achieve good paging results, the number of VPCs should be as high as possible. Equation (5-19) is used to evaluate the number of VPCs \((N_{VPC}(LAR))\) in the simulation. However \(N_{VPC}(LAR)\) should be as given in equation (5-20) in order to have the same accuracy for all \(LA\) sizes, assuming that \(N_{VPC}(50)=50\). From the simulation result, it has been found that the number of VPCs should be four or five times the maximum number of spotbeams for the particular \(LA\) in order to have moderate accuracy in intelligent paging.

\[
N_{VPC}(LAR) = \text{ceil} (0.0955 \times LAR + 90.45)
\]

(5-19)

\[
N_{VPC}(LAR) = 50 \times LAR^2
\]

(5-20)

Assuming that the number of spotbeams overlapping with a \(LA\) is \(N_{\text{SBP-LA}}(LAR)\), the number of footprints overlapping with an \(LA\) is \(N_{\text{FBP-LA}}(LAR)\), the time for one spotbeam or footprint scanning through one VPC is \(T_{\text{SB}}\) units and time for one single operation in sorting is \(T_{\text{Sr}}\), the total time for spotbeam scanning \(T_{\text{SB}(SBP)}\) and the total time for footprint scanning \(T_{\text{SB}(FBP)}\) are given by equations (5-21) & (5-22) respectively. After scanning, the spotbeams or footprints should be sorted for probability to remove the redundant spotbeams or footprints. Hence, sorting time should be included in the processing time. Heapsort [87] was selected for sorting, because it required very low processing time \((N_{\text{Data}} \log_2 N_{\text{Data}}\) where \(N_{\text{Data}}\)–Number of data). The sorting time for spotbeam and footprint are given by equations (5-23) & (5-24). Then the ratios of time for

Figure 5-22: Overall average of signalling load and location update rate per user

(a) LUR\(_{Av}\) for D1 & FA

(b) SW\(_{Av}\) for D1 & FA

(c) LUR\(_{Av}\) for D2

(d) SW\(_{Av}\) for D2

\[
T_{\text{SB}(SBP)} = N_{\text{SBP-LA}}(LAR) \times T_{\text{SB}}
\]

(5-21)

\[
T_{\text{SB}(FBP)} = N_{\text{FBP-LA}}(LAR) \times T_{\text{FBP}}
\]

(5-22)

\[
T_{\text{Sr}(SBP)} = N_{\text{SBP-LA}}(LAR) \times T_{\text{Sr}}
\]

(5-23)

\[
T_{\text{Sr}(FBP)} = N_{\text{FBP-LA}}(LAR) \times T_{\text{Sr}}
\]

(5-24)
scanning and sorting between SBP and FBP are given by equations (5-25) and (5-26) respectively. The simulation results based upon these equations are given in Figure 5-23.

\[ T_{St}(SBP) = N_{VPC}(LAR) \times N_{(Sh \rightarrow LA)}(LAR) \times T_{Sn} \]  
\[ T_{St}(FBP) = N_{VPC}(LAR) \times N_{(Fp \rightarrow LA)}(LAR) \times T_{Sn} \]  
\[ T_{Sr}(SBP) = N_{(Sh \rightarrow LA)}(LAR) \log_2 N_{(Sh \rightarrow LA)}(LAR) \times T_{St} \]  
\[ T_{Sr}(FBP) = N_{(Fp \rightarrow LA)}(LAR) \log_2 N_{(Fp \rightarrow LA)}(LAR) \times T_{St} \]  
\[ \frac{T_{Sr}(FBP)}{T_{St}(FBP)} = \frac{N_{(Fp \rightarrow LA)}(LAR)}{N_{(Sh \rightarrow LA)}(LAR)} \]  
\[ \frac{T_{Sr}(FBP)}{T_{St}(SBP)} = \frac{N_{(Fp \rightarrow LA)}(LAR) \log_2 N_{(Fp \rightarrow LA)}(LAR)}{N_{(Sh \rightarrow LA)}(LAR) \log_2 N_{(Sh \rightarrow LA)}(LAR)} \]

![Figure 5-23: Processing time for intelligent paging](image)

The processing time required by the footprint based intelligent paging is less than 25% of the spotbeam based intelligent paging. Therefore FBP is better in terms of time delay in intelligent paging.

### 5.4.3 Comparison of satellite power consumption for paging

We have reported the bandwidth and processing time comparisons in previous sections. In this section, power comparison is made for spotbeam and footprint based paging. From [88], the gain of the antenna is given by the following equation.

\[ G = 44.3 - 10 \log(\theta^2) \]  

Where \( \theta \) is antenna beamwidth and given by the following equation.
\[ \theta \approx \frac{21}{(f_{\text{GHz}} \cdot \mathcal{D})} \quad (5-28) \]

Where \( f_{\text{GHz}} \) is the carrier frequency in GHz, \( \mathcal{D} \) is the diameter of the antenna and \( \theta \) is in Deg. Reduction from the peak gain, due to the offset from the centre of the spotbeam is given by (5-29).

\[ L_\theta = -12(\chi/\theta)^2 \quad (5-29) \]

Where \( \chi \) is the pointing error. Here only the edge of the spotbeam and footprint is considered for this analysis. Hence, the gain at the edge of the beam is given by equation (5-30).

\[ G_{\text{at edge}} = 32.3 - 10 \log(\theta^2) \quad (5-30) \]

Assuming that the required amount of power density at the receiver is \( P_{\text{Den}} \) and the distance between the MS and satellite is \( D_{\text{SatMT}} \), the power required by a satellite to maintain the required power density at the MS receiver for both spotbeam and footprint based paging is given by the following equations.

\[ P_{\text{Tn-Fp}} = P_{\text{Den}} \times 4\pi D_{\text{SatMT}}^2 / G_{\text{fp}} \quad (5-31) \]

\[ P_{\text{Tn-Sb}} = P_{\text{Den}} \times 4\pi D_{\text{SatMT}}^2 / G_{\text{Sb}} \quad (5-32) \]

From (5-30), \( G_{\text{fp}} = 32.3 - 10 \log(\theta_{\text{FM}}^2) \) and \( G_{\text{Sb}} = 32.3 - 10 \log(\theta_{\text{SHA}}^2) \). Assuming that the number of spotbeams required to page is \( N_{\text{Sb}} \) and number of footprints required to page \( N_{\text{Fp}} \), the power ratio \((P_{\text{WR}}(\nu, \lambda))\) between these two cases (FBP and SBP) is given by equation (5-33). Initially power ratio variation with LAR was found and shown in Figure 5-24.

\[ P_{\text{WR}}(\nu, \lambda) = \frac{N_{\text{Fp}} \times P_{\text{Tn-Fp}}}{N_{\text{Sb}} \times P_{\text{Tn-Sb}}} = \frac{N_{\text{Fp}} \times G_{\text{fp}}}{N_{\text{Sb}} \times G_{\text{Sb}}} = \frac{N_{\text{Fp}} \times \theta_{\text{FM}}^2}{N_{\text{Sb}} \times \theta_{\text{SHA}}^2} \quad (5-33) \]
This only represents the power required to page the same LA using a particular paging method and not the power required by the particular location tracking scheme since the optimal LA size depends on the location tracking scheme. Therefore the power ratio between two different location tracking schemes is functions of speed of the MS and call arrival rate as shown in Figure 5-25. Hence the total power ratio (between spotbeam based method and footprint based method) is given by equation (5-34) and the result is shown in Figure 5-26. The result in Figure 5-26 shows that the footprint based paging method is not beneficial in terms of satellite power.

\[
\bar{PW}_{\text{usr}}(\lambda) = \sum_{i=1}^{n_{\text{spwr}}} PW_{\text{usr}}(v_i, \lambda) \times D(v_i)
\]  

(5-34)
5.5 Summary and conclusions

Different location tracking schemes with intelligent paging have been investigated against signalling load in the air-interface, terminal power, satellite power, and processing delay for intelligent paging for different mobile speeds and call arrival rates. Three main location update methods considered in this chapter are fixed location area, dynamic location area without location update on call arrival and dynamic location area with location update on call arrival. The different paging methods considered are spotbeam based paging and footprint based paging.

Signalling load, processing delay and the trade off between these two parameters have been investigated in intelligent paging and it has been shown that reduction of signalling load through intelligent paging increases the processing delay. A method of implementing intelligent paging using virtual paging cell (VPC) method in MSS has been explained with probability calculation of VPCs. Downsides of the intelligent paging have been identified and a new paging method has been proposed in order to overcome them. Signalling cost calculations were made for general location tracking scheme and the method of calculating optimal location area radius has been explained.

Performance evaluation of different combinations of location update methods and paging methods has been done using simulation and the following observations were made.

- There is a large amount of redundant spotbeams overlap with the location area. Therefore they have to be removed for effective and efficient usage of satellite, terminal and radio resources.
- Footprint based intelligent paging shows better performance in most of the cases except for satellite power usage.
When the overall system is considered, the DLA method with location update on call arrival is the best, but this may not be optimal for some individual mobiles which have low speed and low call arrival rate. Therefore the adaptive location update method with FLA and DLA according to the speed may be one possible solution. The main disadvantage with the traditional FLA method is the fixed and common LA for all the mobiles and the problem with the DLA is the higher overlap between consecutive LAs. These two problems can be solved by using the LatLongFLA method proposed in section 4.1.

Intelligent paging reduces the signalling load. But higher number of paging steps increases the delay in paging and leads to long delay in call set-up. Therefore the number of steps should be selected carefully.
Chapter 6

6 Mobility management signalling on fixed network in MSS

The mobility management signalling in the fixed network is not really limited by the capacity of the connections as in the case of capacity of the radio channel (which is spectrum limited), since there are high-speed connections such as optical fibres. But limitations come from the required call set-up delay, which depends mainly on the database architecture and the processing power of the databases. In this chapter, the performance of the fixed network is investigated against different location tracking schemes.

Call set-up delay is one of the metric determining the performance of different location tracking schemes. The degree of intelligent paging (which is part of the location tracking mechanism and has the capability to reduce the utilisation of satellite, terminal and air interface resources) implementation in the mobile satellite system is limited by call set-up delay, due to the long delay on the air interface. On the other hand, intelligent paging helps to reduce location update rates of the mobile users. This leads to a reduction in signalling traffic, which eventually reduces the delay in the fixed network. This phenomenon is investigated in this chapter by simulation via which we show the optimal number of steps possible.

6.1 Signalling network architecture and layout

![Diagram of MSS signalling network architecture](image)

RSTP – Regional signalling transfer point, LSTP – Local signalling transfer point
RMSC – Remote MSC

Figure 6-1: MSS signalling network architecture.
The database architecture, which combines hierarchical, distributed, replicated and pointer forwarding is shown in Figure 6-1. This architecture is selected considering the call set-up delay, fixed network signalling and HLR server processing and memory capacity. In this system, MSs are registered with one of the six HLRs. When a MS moves from its home HLR (H-HLR) to a remote HLR (R-HLR) or from a R-HLR to another R-HLR, it informs the new R-HLR which in turn informs the change via the R-HLR ID to the H-HLR and requests the MS profile information. Then the R-HLR stores the MS's profile information for future authentication purposes. If there is any LA change inside the R-HLR region, the R-HLR does not inform the H-HLR. When a call arrives at the MS from inside the R-HLR region, the R-HLR handles it without referring to the H-HLR. Otherwise the H-HLR requests a route from the R-HLR, then the R-HLR asks the corresponding VLR and assigns a TLDN (temporary location directory number) and sends it to the H-HLR. The remaining procedures are explained in sections 6.2 and 6.3.

The signalling messages indicated with an arrow in between network entities (see Figure 6-3 to Figure 6-9), are used for the simulation model development. For example "RtRqBCpRsp" corresponds to route (Rt) request (Rq) message to the called MS's residing region RSTP or MS's previous residing region RSTP (Cp) and RSTP (Rsp). Here B represents a connection between two RSTP's.

The above architecture shown in Figure 6-1 is mapped onto the surface of the earth as shown in Figure 6-2 based on GCA shape & size and geographical borders. For example, HLR-1 is placed on the west coast of USA to cover north American countries. The following assumptions are made for the network analysis.
1. Each FES associated with a MSC/VLR
2. FESs at edge of the landmarks, cover the oceans.
3. Regional signalling transfer point (RSTP) is associated with the HLR
4. Normally each terminal is registered with the local H-HLR.
5. Other HLRs with respect to a particular terminal are called remote HLR’s.
6. Only RSTPs are connected to the gateway mobile switching centres, which are in turn connected to the PSTN/PLMN. (In practise, most of the FESs are connected to the gateways).
7. Temporary local directory numbers (TLDN) are assigned by the HLR not by the VLR.

Based on the above assumptions, the signalling procedure for location update and paging are explained in the next section for different scenarios. The notation used in the cost analysis is given in Table 6-1.

### Table 6-1: Notations for database access cost and link cost

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_{VLR})</td>
<td>Access cost of VLR</td>
</tr>
<tr>
<td>(C_{HLR})</td>
<td>Access cost of HLR</td>
</tr>
<tr>
<td>(C_{LSTP})</td>
<td>Routing cost through LSTP</td>
</tr>
<tr>
<td>(C_{RSTP})</td>
<td>Routing cost through RSTP</td>
</tr>
<tr>
<td>(C_{RMSC})</td>
<td>Routing cost through RMSC</td>
</tr>
<tr>
<td>(C_{C-Link})</td>
<td>Routing cost through C-Link</td>
</tr>
<tr>
<td>(C_{A-Link})</td>
<td>Routing cost through A-Link</td>
</tr>
<tr>
<td>(C_{D-Link})</td>
<td>Routing cost through D-Link</td>
</tr>
<tr>
<td>(C_{RA-Link})</td>
<td>Routing cost through remote A-Link</td>
</tr>
<tr>
<td>(C_{RE-Link})</td>
<td>Routing cost through remote E-Link</td>
</tr>
<tr>
<td>(C_{LUi})</td>
<td>Cost for i(^{th}) location update scenario.</td>
</tr>
<tr>
<td>(C_{CDi})</td>
<td>Cost for i(^{th}) call delivery scenario.</td>
</tr>
</tbody>
</table>

### 6.2 Signalling procedures in location update

The MS communicates with the VLR via the nearest satellite and the corresponding FES. Since it has been assumed that the VLR is collocated with the FES, the FES is not shown in the signalling procedures. Based on the signalling procedures, the cost functions \(C_{LUi}\) are defined as follows;

**LU1. LA crossing inside the same VLR region** (Figure 6-3)

1. MS informs the VLR about LA change with LAI.
2. The VLR updates the MS information and sends the registration message to the H-HLR
3. The H-HLR sends the registration acknowledgement message (RegAckVlr) to the VLR.

\[
C_{LU} = C_{VLR} + C_{HLR} + 2C_i \quad (6-1)
\]
\[
C_i = C_{LSTP} + C_{RSTP} + C_{A-Link} + C_{D-Link} + C_{RA-Link} \quad (6-2)
\]
Chapter 6. MM signalling on fixed network

Figure 6-3: Signalling flow for cases LU1 & LU5

LU2. LA crossing inside the same H-HLR region (Figure 6-4)

1. MS informs the VLR about LA changes via LAI.
2. The new VLR updates the MS information and sends the registration message to the H-HLR.
3. The H-HLR sends the registration acknowledgement message (Ack) message to the new VLR together with a copy of the user profile.
4. The H-HLR sends a registration cancellation message (RegCanVlr) to the old VLR.
5. The old VLR removes the MS records and sends the cancellation Ack to the H-HLR.

\[ C_{LU2} = C_{LU3} = C_{LU6} = C_{LU7} = 3C_{VLR} + 2C_{HLR} + 4C_I \]  

Figure 6-4: Signalling flow for cases LU2, LU3, LU6, & LU7

LU4. LA crossing from H-HLR to R-HLR (Figure 6-5)

1. MS informs the VLR regarding LA changes via LAI.
2. The new VLR updates the MS information and sends the registration message to the R-HLR.
3. The R-HLR updates the MS information and forwards the message to the H-HLR.
4. The H-HLR updates the MS information and sends the registration Ack message to the R-HLR together with a copy of the user profile.
5. The R-HLR takes the copy of the user profile and forwards Ack with the subscriber’s user profile to the new VLR.
6. The H-HLR sends a RegCanVlr to the old VLR.

85
7. Old VLR removes the MS records and sends the cancellation Ack to the H-HLR.

\[ C_{LU4} = 3C_{VLR} + 3C_{HLR} + 4C_I + 2C_H \]  

(6-4)

The expression for \( C_H \) in equation (6-4) is given by equation (6-5)

\[ C_H = 2C_{RSTP} + 2C_{RA-Link} + C_{RR-Link} \]  

(6-5)

The expression for \( C_{RR-Link} \) in equation is given by (6-6)

\[ C_{RR-Link} = 2C_{RMSC} + 2C_{C-Link} + C_{RE-Link} \]  

(6-6)

---

**Figure 6-5: Signalling flow for cases LU4**

LU8. LA crossing from R-HLR to another R-HLR (Figure 6-6)

1. MS informs the VLR about LA change via LAI.
2. New VLR updates the MS information and sends the registration message to the new R-HLR.
3. The new R-HLR updates the MS information and forwards the message to the H-HLR.
4. The H-HLR updates MS data and sends the registration Ack to R-HLR.
5. The R-HLR forwards the Ack to the new VLR.
6. New R-HLR sends a registration cancellation message to the old R-HLR.
7. The old R-HLR forwards the RegCanVlr to the old VLR.
8. The old VLR removes the MS records and sends the cancellation Ack to the R-HLR.
9. The old R-HLR forwards the cancellation ACK to the new R-HLR.

\[ C_{LU8} = 3C_{VLR} + 3C_{HLR} + 4C_I + 4C_H \]  

(6-7)
6.3 Signalling procedures in call delivery

CD1. Calling MSs inside the called H-HLR region (Figure 6-8)

1. The MS sends the initiation signal to the nearest VLR.
2. The VLR forwards the signal to the H-HLR.

3. The HLR sends the paging signal to all the VLRs serving the LA (LA may overlap only with H-HLR region or only with a R-HLR region or with number of HLRs as shown in Figure 6-8).

4. The H-HLR receives the response from a VLR directly or via the R-HLR.

5. Based on the response from VLRs, the H-HLR assigns a TLDN and sends to the calling VLR.

\[ C_{CDI} = C_{cdl} + f_i(C_i, C_{H-HLR}) \]  
\[ C_{cdl} = 2C_{VLR} + 2C_{HLR} + 2C_i \]  
\[ f_i(C_i, C_{H-HLR}) = N(i)_{R-HLR} \times (2C_i + C_{HLR}) + N(i)_{VLR} \times (2C_i + C_{VLR}) \]

\[ \text{N}(i)_{R-HLR} \] and \[ \text{N}(i)_{VLR} \] are number of R-HLRs and VLRs accessed for paging.

D2. Calling MSs outside the called H-HLR region (Figure 6-9)
The block shown in Figure 6-9 to represent the paging signalling procedure is same as in Figure 6-8 except the changes in $N(i)_{R-HLR}$ and $N(i)_{VLR}$.

1. The MS sends the initiation signal to the nearest VLR.
2. The VLR forwards the signal to the R-HLR.
3. The R-HLR forwards the message to the H-HLR.
4. The HLR sends the paging signal to all the VLR serving the LA.
5. The HLR receives the response from a VLR directly or via the R-HLR.
6. Based on the response from VLRs, H-HLR assigns a TLDN and sends to the calling R-HLR.
7. R-HLR forwards the TLDN to calling VLR. The calling MSC can set up the call now.

$$C_{CD2} = C_{cd2} + f_{L}(C_{VLR}, C_{VLR}, C_{HLR})$$  \hspace{3cm} (6-12)

$$C_{cd2} = 2C_{VLR} + 2C_{HLR} + 2C_{I} + 2C_{II}$$  \hspace{3cm} (6-13)

Figure 6-9: Signalling in call delivery for the case of calling MS outside the called MS’s H-HLR

### 6.4 Signalling cost calculations

A simulation model was developed based upon the signalling network and LA layout with a simple mobility model (Appendix D) for the MSs. Using the simulation model, $N_{LUI}$ (number of location update during the unit time for the $LU_i$ case) $N(i)_{R-HLR}$ and $N(i)_{VLR}$ are computed. Using these values and equation (6-17) the average fixed network cost per call “$AC_{Call\_FN}$” is calculated. The total location update cost “$TC_{LU}$” and call delivery cost “$TC_{CD}$” are given by equations (6-14) and (6-15) respectively. $C_{LUI}$ and $C_{CDI}$ are given from section 6.2 and 6.3 respectively. Where $P_{CD(i)}$ is the probability of the calling MS’s location position with respect to the called MS’s H-HLR and “$N_{Calls}$” is number of calls arrived within a particular time interval. By substituting equations (6-14) and (6-15) into equation (6-16), a simplified version equation (6-17) is derived. Assumption made for access costs of network entities and links with respect to VLR are given in Appendix H.
Chapter 6. MM signalling on fixed network

\[ TC_{LU} = \sum_{i=1}^{\nu} N_{LUi} \times C_{LUi} \] (6-14)

\[ TC_{CD} = N_{Calls} \times \sum_{i=1}^{2} (P(i) \times C_{CDi}) \] (6-15)

\[ AC_{Call-FN} = \frac{(TC_{LU} + TC_{CD})}{N_{Calls}} \] (6-16)

\[ AC_{Call-FN} = \left( \sum_{i=1}^{\nu} N_{LUi} \times C_{LUi} + N_{Call} \sum_{i=1}^{2} (P_{CD}(i) \times C_{CDi}) + (2C_{A} + C_{M,R}) \sum_{i=1}^{2} N(i)_{M,RA} + (2C_{F} + C_{V,L,R}) \sum_{i=1}^{2} N(i)_{V,LR} \right) / N_{Calls} \] (6-17)

### 6.5 Combined cost analysis

Using equation (5-9) from chapter 5 and equation (6-17), the signalling cost in the air interface and in the fixed network with LAR are calculated for two different mobile speeds and shown in Figure 6-10 and Figure 6-11. Here no update on call arrival is considered. The rate of change of signalling load with LAR for air-interface case is higher than that of the fixed network case around optimal LAR. This feature may give more flexibility to select the optimal LAR since the air-interface resources are more stringent than the fixed network resources. Optimal LAR choice considering only the air interface is not equivalent to the optimal LAR choice considering just the fixed network. Therefore the optimal LAR should be determined using equation (6-18) for the combined cost \( AC_{Call_AiFx} \). Where \( F_{value} \) is a valuation factor based on the fixed network access cost with respect to the air interface access. This is determined by the resource availability in the air interface as well as the fixed network and QoS (call set-up delay).

\[ AC_{Call_AiFx} = AC_{Call_Ai} + F_{value} \times AC_{Call_AiFx} \] (6-18)

Figure 6-10: Signalling cost versus LAR for \( \nu=100\text{km/h} \)
A simple analytical and simulation queuing model for a GSM type network is explained in this section. The basic message flow between the network entities during call set-up and location update is shown in Figure 6-12 and Figure 6-13. Here, it is assumed that the length of each message is equal and the processing time for all messages arriving to an entity is also equal. Therefore each network entity (HLR & VLR) is considered as an M/D/1 queue. The queuing network architecture is shown in Figure 6-14 with parameter descriptions in Table 6-2.

In the equilibrium state, by Burke’s theorem [90], relationship between the message arrival rates to entities can be expressed by equations (6-19) and (6-20) for location update and call arrival cases.

\[ \lambda_{AU} = \lambda_{RC} = \lambda_{RA} = \lambda_{U} \]  

(6-19)
\[ \lambda_{LR} = \lambda_{RR} = \lambda_{SI} = \lambda_{FI} = (N_{VLR}-1)\lambda_C/N_{VLR} \]  

(6-20)

Where \( N_{VLR} \) is the number of VLR/FEs and we assumed that the probability for called terminal and calling terminal in the same VLR is \( 1/N_{VLR} \) and the probability of being in different VLRs is \( (1-N_{VLR})/N_{VLR} \).

The total delay in any communication network \( (D_T) \) is given by equation (6-21).

\[ D_T = D_W + D_P \]  

(6-21)

Where

\( D_W \) - Waiting delay in the queue

\( D_P \) - Processing delay

According to Little’s formula [93][94], delay in a system is given by equation (6-22) for M/D/1.

\[ D_T = (2\mu-\lambda)/(2\mu(\mu-\lambda)) \]  

(6-22)

Where, \( \lambda \) is the arrival rate and \( \mu \) is the service rate of a system.

Table 6-2: Notations for signalling message arrival rates

<table>
<thead>
<tr>
<th>Description</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_C )</td>
<td>Call arrival rate</td>
</tr>
<tr>
<td>( \lambda_{LR} )</td>
<td>Location request rate</td>
</tr>
<tr>
<td>( \lambda_{RR} )</td>
<td>Route request rate</td>
</tr>
<tr>
<td>( \lambda_{SI} )</td>
<td>Arrival rate of TLDN to HLR</td>
</tr>
<tr>
<td>( \lambda_{FI} )</td>
<td>Arrival rate of TLDN to VLR</td>
</tr>
</tbody>
</table>

6.7 Call set-up delay comparison

The overall call set-up delay \( (D_{set-up}) \) for the process under examination can be given by equation (6-26). Where \( T_{set-up} \) and \( T_{call} \) are the process under examination respectively and \( N_{VLR} \) is the number of stages in the diagram that can be given in equation (6-27) referring to Figure 6-14. Let \( \lambda \) and \( \mu \) be the arrival rate and service time of the process of interest. A method of considering these elements is given in the following equation.
For the VLR, $\lambda = \lambda_v = \lambda_C + \lambda_{RR} + \lambda_{AI} + \lambda_{AU} = (3N_{VLR} - 2) \lambda_C/N_{VLR} + 3\lambda_{AU}$ and $\mu = \mu_v$.

$D_{TV} = (2\mu_v - \lambda_v)/(2\mu_v(\mu_v - \lambda_v))$ \hspace{1cm} (6-23)

For the HLR, $\lambda = \lambda_h = N_{VLR}(\lambda_{LR} + \lambda_{SI} + \lambda_{AI} + \lambda_{CA}) = 2(N_{VLR} - 1) \lambda_C + 2N_{VLR}\lambda_{AU}$ and $\mu = \mu_h$.

$D_{TH} = (2\mu_h - \lambda_h)/(2\mu_h(\mu_h - \lambda_h))$ \hspace{1cm} (6-24)

Therefore the mean call set-up time is given by equation (6-25).

$T_{Call\ set-up} = D_{TV}/N_{VLR} + (N_{VLR} - 1)(2D_{TH} + 3D_{TV})/N_{VLR}$ \hspace{1cm} (6-25)

Using the queuing network in Figure 6-14, the call set-up delay is calculated theoretically and checked via simulation. The processing power of each component is given in Appendix H. The results are shown in Figure 6-15. The curves for the mean delay from simulation and the analytical results show good agreement and represent validation for the simulation model.

### 6.7 Call set-up delay comparison

The overall call set-up delay ($CsuDly$) between two MSs in the general case is given by equation (6-26). Where $FxDly$ and $AiDly$ are fixed network delay and delay in the air interface respectively. $N_{steps}$ is the number of steps in step paging. $AiDly$ can be given by equation (6-27) referring to Figure 6-16. $T_{MI-SI}, T_{SI-F1}, T_{F2-S2}$ and $T_{S2-M2}$ depend on the position of the FESs and MSs with respect to the satellite footprint and they are denoted by $Dly(i)$. Where $i$ will take a value between 1 and $N_{strips}$ according to the MSs and FESs positions. A method of calculating these parameters is given in the following sections.
\[ C_{suDly} = FxDly + (N_{step} + 1) \times AiDly/2 \]  
\[ AiDly = 2(T_{M1-S1} + T_{S1-F1} + T_{F2-S2} + T_{S2-M2}) \]  

**6.7.1 Propagation delay**

The satellite footprint is divided into a number of strips as shown in Figure 6-18. The probability of finding a terminal inside the \( i \text{th} \) strip is given by equation (6-28) and the delay \( Dly(i) \) is given by equation (6-29).

\[ P(i) = \frac{SL(i)}{\sum_{k=1}^{N_{strip}} SL(k)} \]  
\[ Dly(i) = \frac{L(i)}{3 \times 10^8} \]  

Where, \( SL(i) = 2\pi R_s \sin(\beta_i) \) is the \( i \text{th} \) strip length measured along the dot-dot line (middle of the strip), \( \beta_i = 0.5 \times (2i-1)\theta_{FHA} / N_{strip} \) and \( \theta_{FHA} \) is footprint half angle. \( L(i) = (H_s + R_e)^2 + R_e^2 - 2(H_s + R_e)R_e \cos(\beta_i) \)^{1/2}. Here the strip width is very small such that the delay difference between the two edges is negligible. In the call set-up procedure, two MSs and two FESs are involved. They
can be in any one of the strip areas, therefore there are \((N_{Strip})^4\) combinations for their relative positions. So the probability of one of the combination \(P_c(i_1, i_2, i_3, i_4)\) is given by the equation (6-30) and the total delay is given by equation (6-31).

\[
P_c(i_1, i_2, i_3, i_4) = P(i_1) \times P(i_2) \times P(i_3) \times P(i_4)
\]  

(6-30)

Where \(i_1, i_2, i_3, i_4 \in \{1, \ldots, N_{Strip}\}\).

\[
AiDly(i_1, i_2, i_3, i_4) = 2 \{ Dly(i_1) + Dly(i_2) + Dly(i_3) + Dly(i_4) \}
\]  

(6-31)

Therefore the average delay can be expressed as follows;

\[
AiDly_{Av} = \sum_{i_4=1}^{N_{Strip}} \sum_{i_3=1}^{N_{Strip}} \sum_{i_2=1}^{N_{Strip}} \sum_{i_1=1}^{N_{Strip}} AiDly(i_1, i_2, i_3, i_4) \times P_c(i_1, i_2, i_3, i_4)
\]  

(6-32)

Distribution of air interface delay \((AiDly)\) and average delay involved in call set-up (Figure 6-12) are shown in Figure 6-19.

![Figure 6-19: Propagation delay distribution in air interface](image)

From Figure 6-19, it is seen that the probability of having a particular delay increases with propagation delay. This is because the area of a strip increases with distance from the centre of the footprint. The fluctuation shown in Figure 6-19 occurs due to the total delay being a combination of four separate delays as mentioned in equation (6-27).

### 6.7.2 Fixed network delay

A simulation model for S-PNC based on the network layout in Figure 6-2 and signalling procedures explained in sections 6.2 and 6.3 was developed as an extension of the model given in Figure 6-14. The call delivery process starts when a VLR receives a call originating message \((CalArvVlr)\) from a MS and ends with reception of TLDN \((FwdMldVlr)\) in the VLR. The location
update process starts when a VLR receives a location update message (LocUpdVlr) from a MS and ends when the VLR receives a registration acknowledgement message (RegAckVlr) and the HLR receives a cancellation acknowledge message (CnAkHmHlr). Therefore two main input parameters to the simulation model are the arrival rate of the location update message (AR_LaMsg(λ)) and the call origination messages (AR_CoMsg(λ)) to the VLRs and they are given by equations (6-33) and (6-34) respectively, where NVLR is the number of VLRs in the system, NUsers is the total number of subscribers and λ is the call arrival rate.

\[ AR_{LaMsg}(\lambda) = N_{Users} \times LUR_{Avr}(\lambda)/N_{VLR} \]  
(6-33)

\[ AR_{CoMsg}(\lambda) = N_{Users} \times \lambda/N_{VLR} \]  
(6-34)

The derivation of \( LUR_{Avr}(\lambda) \) is explained in section 5.4.1.

The call set-up delay for different paging and location update scenarios (section 5.4) with the parameter in Appendix H is calculated using the above model and the results are shown in Figure 6-21 (The legend descriptions can be found in section 5.4). It is also assumed that there are 2 million subscribers (worst case [89]).
Figure 6-21: Call set-up delay versus call arrival rate for different location tracking scenarios

The maximum fixed network delay for DLA method with location update on call arrival with \( \text{CAR} = 0.2 \) is around \( FxDly_{\text{Max}}(D2)=750\text{ms} \) but for the FLA method is around \( FxDly_{\text{Max}}(FA)=1000\text{ms} \). The call set-up delay \( (CsuDly) \) is given by equation (6-35). Therefore the possible number of steps for set paging is given by equation (6-36). Then \( N_{\text{Step}}(D2) = (1500-750-44.8)/44.8 \equiv 16 \) and \( N_{\text{Step}}(FA) = (1500-1000-44.8)/44.8 \equiv 10 \). Calculated values for different cases, are given in Table 6-3.

\[
CsuDly = FxDly + (N_{\text{Step}}+1)/AiDly/2
\]  
\[
N_{\text{Step}} = (CsuDly_{\text{Max}}-AiDly_{\text{Max}}-FxDly_{\text{Max}})/AiDly_{\text{Max}}
\]  

<table>
<thead>
<tr>
<th>Methods</th>
<th>( N_{\text{Step}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBP method</td>
<td></td>
</tr>
<tr>
<td>D1-P3</td>
<td>8</td>
</tr>
<tr>
<td>D2-P3</td>
<td>17</td>
</tr>
<tr>
<td>FA-P3</td>
<td>10</td>
</tr>
<tr>
<td>FBP method</td>
<td></td>
</tr>
<tr>
<td>D1-P7</td>
<td>17</td>
</tr>
<tr>
<td>D2-P7</td>
<td>19</td>
</tr>
<tr>
<td>FA-P7</td>
<td>17</td>
</tr>
</tbody>
</table>

The call set-up delay is low for the FBP method compared to the SBP method. This advantage gives more flexibility to decide on the number of steps for step paging and leads to further reduction in call set-up delay. The DLA method with update on call arrival \( (D2) \) performs better than the other two in terms of call set-up delay. Therefore FBP with DLA (with update on call arrival) gives better performance in terms of QoS.
6.8 Summary and conclusions

A signalling network architecture has been defined considering different advantages from different database architecture, e.g. hierarchical, distributed, replicated and pointer forwarding, and the network layout for a LEO-48 constellation was planned considering the GCA and the network architecture. Signalling procedures for location update and paging with this architecture have been explained for different scenarios. Using a simple mobility model, the fixed network signalling load has been calculated and it is observed that it has the same trend as signalling load on the air-interface except for the fact that it is flatter around optimal LAR compare to the air-interface signalling load. This reduces sensitivity of the network-signalling load and makes it simpler to select an optimal LAR. A simulation model was developed based on M/D/1 queues to calculate the fixed network delay of different location tracking scenarios. A simple method has been introduced to calculate the mean propagation delay over the air-interface.

It has been observed from the simulation results that the FBP method is better than the SBP method and DLA with location update on call arrival (D2) is better than the other two (FA and D1) in term of call set-up delay. It has also been shown that intelligent paging further reduces overall call set-up delay although the delay in the air interface increases. Therefore footprint based intelligent paging with DLA and with location update on call arrival is the best overall combination to reduce the call set-up delay reasonably.
Chapter 7

7 Conclusions and future work

7.1 The research rationale and critical issues

The prominent feature of the mobile satellite systems is the movement of the satellites. This movement leads to the movement of the spotbeams, which are analogous to the cells in terrestrial systems, and the rapid change of elevation angle. These two problems have driven the two main research areas of this thesis, mobility management and satellite link modelling.

The movement of the spotbeams makes the location area planning much more difficult in MSS than for terrestrial systems. Therefore there is a need for a location tracking scheme which is different from the schemes used in terrestrial cellular systems to manage this new feature.

The location-tracking scheme consists of three main elements, location area (LA), location update and paging. Location area definition acts as the base for the other two operations, location update and paging. Therefore the location area planning was selected as the first research issue in this thesis. Further investigation on location area planning has led to the second research issue positioning.

The two operations, location update and paging have direct impact on mobile power and size, satellite power, signalling load on the air-interface and QoS. All of these needed investigations as a comprehensive study of mobility management in MSS had not been made at the time of starting our research.

The power consumption of the MS depends on the number of operations carried out in the MS and the path loss between the satellite and the terminal, which is determined by the type of satellite constellation. In this respect, there are two operations related to location tracking, request from MS to the network for location update and the paging response sent by the MS to the network. The frequency of the later operation cannot be reduced since it purely depends on the call arrival rate. However the frequency of the first operation (location update rate-LUR) can be reduced by correct selection of a location-tracking scheme. Hence a third research issue has been identified as reduction of the location update rate.
Chapter 7: Conclusion and Future Work

The size and complexity of the terminal is driven by the method of defining the location area (since some location tracking schemes may use n external positioning method) and the required battery capacity to handle the operations in the terminal. Again it is obvious that the reduction of location update rate would help to reduce the power requirement of the terminals and would eventually reduce the size of the terminal.

The satellite power consumption is influenced by the operations related to location tracking, update and paging, and path loss. Thus, once again, the location update rate is one of the key elements together with paging and satellite constellation. So paging and related issues were recognized as the fourth research issue in this thesis.

Location tracking signalling load over the air-interface is also contributed to by location update and paging operations and it is desirable to reduce this signalling due to the bandwidth and power limitations.

call set-up delay limits have also been studied in the location-tracking scheme. This depends on the paging strategy and the database architecture. The paging has been included as the fourth research issue and the problem related to database architecture, have been identified as the fifth research issue for investigation in the thesis.

From the argument made so far it is obvious that the type of satellite constellation (LEO/MEO/GEO) is key to the whole MSS system. Hence we perceived a need to investigate the constellation aspects in the context of mobility management and this is the sixth research issue in this thesis.

7.2 The research work completed

The satellite constellation aspects have been addressed in chapter 2. Path loss, propagation delay, Doppler, diversity, coverage and ground connectivity, cost and number of satellites, were considered as important parameters to be investigated. It has been shown that the low altitude satellite constellations are better in term of path loss and delay since the satellite and terminal power consumption depends on path loss, and synchronisation, power control, etc depend on delay. On the other hand they have negative impact on frequency tracking due to the Doppler variation and handover due to short period of visibility at low attitude. It has been shown that satellite altitudes of around 9000km would be most favourable in terms of implementation cost of the satellite constellation. It has also been shown that constellations with this altitude have advantages in radiation zones, solar eclipses, space junk collision, and atmospheric drag. In terms of ground connectivity higher altitude satellites would be better and intersatellite links are required for low altitude constellation to maintain the operability in ground connectivity.
Therefore, expanding satellite communications from GEO to MEO would be advisable for S-UMTS rather than going to LEO, which has the advantage on capacity and other aspect mentioned above. In addition total system cost for LEO has been shown to be a major financial problem (Iridium/Globalstar). History has clearly shown us that the MSS cannot compete with terrestrial systems and can only target limited market areas. Therefore the capacity difference between MEO and LEO would not be a big problem.

Streets of coverage and spherical triangle constellation methods have been explained and it has been observed that the street of coverage method would be suitable for star constellation patterns and the spherical triangle method is suitable for delta constellation patterns. It has also been illustrated that star patterns would be efficient for LEOs and delta patterns would be efficient for MEOs. It has been further shown that delta patterns with odd number of planes would be better than delta pattern with even number of planes.

The PCN network architecture and signalling has been discussed in chapter 3. The cellular concept has been described and the historical development stages of mobile systems 1G 2G and 3G have been discussed. GSM architecture and signalling concepts have been explained as well as its limitations to apply to MSS. S-PCN architecture with some additional physical entities added to the basic GSM idea has been described. The available location tracking mechanisms in terrestrial and satellite system have been investigated and the difficulties of applying terrestrial methods using LAI on the BCCH channel in MSS, due to the movement of satellites has been highlighted. Two available location update method based on fixed location area (FLA) and dynamic location area (DLA) have been described. The basic concept of intelligent paging has been explained and the steps need to be followed in MSS to avoid the redundant paging have been outlined.

Location area planning and positioning have been investigated in chapter 4. The need for a method of definition of fixed location area on the earth’s surface in MSS has been stressed. A new methodology for defining FLA called ‘LatLongFLA’ has been proposed and compared with the existing proposed DLA method. It has been shown that the LatLongFLA method has similar features to the DLA method. Hence the decision on applying the new method for MSS depends purely on other factors. Existing position methods have been reviewed and the disadvantages in applying these methods in MSS terminals have been pointed out. Hence two new positioning methods have been proposed for mobility management purpose. Their error performance has been investigated. Even though the positioning error is large compared to GPS etc, it has been shown through simulation that the accuracy would be sufficient if the average call arrival rate of the system is less than 0.1calls/h/user.
Issues related to location update and paging signals over the air-interface have been discussed in chapter 5. Limitation on radio resources have been highlighted and the need for optimal location tracking techniques has been understood. The concept of intelligent paging has been described and the trade off between reduction of signalling load through intelligent paging and increase in paging delay has been investigated. Location tracking signalling cost calculations have been made and a method of calculating an optimal location area based on signalling load has been presented. A method of implementing intelligent paging using a virtual cell paging method has been introduced and the problem with existing implementation methods has been identified as the processing delay. In order to overcome this problem, a new paging method called 'footprint based paging' has been proposed. Performance evaluation of combination of different location update methods (DLA with and without update on call arrival & FLA) and paging methods (FBP and SBP with and without intelligence on paging) has been performed via simulation. It has been shown that footprint based paging (FBP) performs well compared to spotbeam based paging methods (SBP) except for satellite power consumption. It has also been illustrated that using intelligence in paging would always be beneficial in terms of signalling load and location update rate if the number of steps involved in the intelligent paging is selected carefully.

Signalling loads created by the MS at speeds below 130km/h, are lower for the DLA method (both cases, with and without update on call arrival) compared to the FLA method for all the paging combinations considered. Location update rate (LUR) of the DLA method (without update on call arrival) was higher than that of the FLA method whenever the speed of MS is lower than 1000km/h. This is also the case with the DLA method (with update on call arrival) whenever the call arrival rate is low. However the DLA method (D2-with update on call arrival) performs better than the FLA if the call arrival rate is high. When the overall system is considered, the performance of the DLA method (D2-with location update on call arrival) is the best compared to the other two DLA (D1-without location update on call arrival) and FLA (FA), and FLA (FA) is better than DLA (D1-without location update on call arrival). In practice, the call arrival rate in MSS would be very much lower than in terrestrial systems, therefore there would be very little difference in performance between FLA and DLA (D1&D2) methods. The main disadvantage of the FLA method compared to the DLA method is common and fixed location areas for all users and this feature limits further improvement. On the other hand the disadvantage with the DLA method compared to the FLA is the large overlap region between two consecutive location areas. Thus the newly proposed fixed location area method, 'LatLongFLA' would overcome the problems with the existing FLA and DLA methods and provide better performance.

QoS issues in terms of call set-up has been analysed in chapter 6. A database architecture and its layout on the surface of earth have been introduced. Location updates and call set-up procedures
have been identified based on that network architecture. Signalling cost calculations have been made and comparisons have been made between optimal location areas derived for air-interface signalling and fixed network signalling. It has been concluded that more weight should be given to the air-interface signalling since the radio resources are more limited compared to fixed network resources and the trend of the signalling load curve with \( LAR \) for the air-interface was shown to be steeper on both sides of the optimal point than for fixed network signalling. A signalling network model has been developed to calculate the call set-up delay. It has been shown that the \( FBP \) method is better than the \( SBP \) method in terms of call set-up delay. Not much difference in performance has been observed between the \( DLA \) and \( FLA \) methods when the \( FBP \) method was used for paging. But there has been significant difference in performance between \( FLA \) and \( DLA \) (with update on call arrival), when the \( SBP \) method was used for paging.

### 7.3 Implications of the research work

This is an in depth evaluation of mobility management in a complete MSS system using dynamic satellite constellations. The general lessons learnt can be applied to all new system designs.

As an overall conclusion, location area planning, positioning, location update method, paging method, signalling over the air-interface, call set-up delay, satellite link modelling and satellite constellation design have been identified as issues arising from the special feature of the dynamic nature of the mobile satellite system. In our research we have investigated in depth these issues and made the following proposals as a result.

- The footprint based intelligent paging method accompanied with newly proposed location update method, ‘\( Lat\LongFLA \)’ can resolve most of the problems with the existing location tracking schemes.

- The newly proposed positioning method can help to produce low cost and small size terminal if the positioning accuracy is not a major issue.

### 7.4 Future research issues

Some possible research issues have been identified for future study and are given below.

- Improvement in terms of processing time and complexity for the implementation of intelligent paging.

- The main difference between the newly proposed \( LA \) method, ‘\( Lat\LongFLA \)’, and existing \( LA \) methods is shape of the \( LA \). Therefore the impact of the shape of the \( LA \) on the performance of the location-tracking scheme has to be investigated.
The issues discussed on mobility management in this thesis, are based on circuit switched (CS) network. Most of the concepts discussed and proposed here can be applied to packet switched (PS) network. However there are still some topics like database architecture, call handling etc. that are different in PS. Therefore the extension of the CS ideas to PS could be useful so that the work can be applied to new PS systems.
References


[21] Roger J. Rusch; ODYSSEY, An optimized personal communications satellite system; AIAA-94-1136-CP.


[26] Draft ETSI TR 000054 V0.1.0 (2000-12); Satellite Component of UMTS/IMT2000; General Aspects and Principles; TC SES/S-UMTS.


[28] Walker J.G; Continuous whole-earth coverage by circular-orbit satellite patterns; Royal aircraft establishment, Technical report 77044, Received for printing 24 March 1977.

References


[32] Rider L; Analytical design of satellite constellations for zonal earth coverage using inclined circular orbits; The journal of the astronautical sciences, Vol. 34, No. 1, Jan-Mar 1986, pp 31-64.


[35] Ullock M.H and Schoen A.H; Optimal Polar Satellite Networks for Continuous Earth Coverage; AIAA Journal; VOL 1 NO 1, Jan 1963.


[38] Walker J.G; Circular orbit patterns providing continuous whole earth coverage; Royal aircraft establishment Technical report 70211; Nov 1970.


[40] Ramseh R; Availability Calculations for Mobile Satellite Communication Systems; VCT96.

[41] Anttalainen T; "Introduction to Telecommunications Network Engineering"; 1999 Artech House, Inc.


[43] Eberspacher J and Vogel H; "GSM switching, services and protocols"; 1999 John Wiley & Sons Ltd.

[44] Zeng M, Annamalai A and Bhargava V.K; "Recent advances in cellular wireless communications"; IEEE communication magazine, Sept 1999.


[49] “Architecture for an all IP network”; 3G TR 23.922 v1.0.0 (1999-10); 3GPP technical report.
[52] Michel Mouflle and Marie-Bernadette Pautet; The GSM System for Mobile Communication;
[55] Cionaith Cullen; Network and signalling aspects of satellite personal communication Networks; PhD thesis ; University of Surrey 1995.
[56] Manuel Dinis and Jose Neves; Mobility Management Signalling in Satellite Mobile Networks; IUCPC 95.
[57] Christoper Meenan; Advanced Mobility Management Techniques for Satellite Mobile Communication Networks; PhD thesis; University of Surrey Feb 1998.
[59] Robert J Finean; “Satellite access in FPLMTS”; PhD thesis; CCSR/CSE, University of Surrey may 1996.
[63] Sami Tabbane; Location management methods for third-generation mobile systems; IEEE Communications Magazine, August 1997.
[66] Sami Tabbane; Location management methods for third-generation mobile systems; IEEE Communications Magazine, August 1997.
[70] Joseph S.M.Ho and Ian F.Akyildiz; Mobile user location update and paging under delay constraints; Wireless Networks 1(1995) 413-425.
[73] Hai Xie, Sami Tabbane and David J.Goodman; Dynamic Location Area Management and Performance Analysis; IEEE VTC 93.
[75] IAN F.Akyildiz, S.M.Ho and Yi-Bing Lin; Movement-Based Location Update and Selective paging; IEEE/ACM Trans. On Networking, Vol. 4, No. 4, Aug 96.
[81] Zhao W, Taffazolli R and Evans B.G; A UT Positioning Approach for Dynamic Satellite Constellations; IMSC95.
[83] Sammut A, Cullen C, Tafazolli R, Evans B.G; “Mobility Management Related Signalling For MAGSS-14 Based Satellite Personal Communications Network(S-PCN)”.
[92] Jyh-Kong Wey, Wei-Pang Yang, Yi-Bing Lin; “Mobility traffic analysis for PACS using various subscriber profiles”; 7th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC’96), vol.1, 1996, pp.133-7 vol.1. New York, NY, USA.
[95] Stremeller F.G; Introduction to communication systems; 3rd edition. 1990 by Addison-Wesley Publishing company.


[99] Axel Jahn, Hermann Bischl, Gunter Heiss; Channel Characterisation for Spread Spectrum Satellite Communications; ISSSTA 96 IEEE.


[103] Saunders, Simon R; "Antennas and propagation for wireless communication systems"; John Wiley & Sons, 1999


Publications

1. K. Narenthiran, R. Tafazolli and B. G. Evans; "New methodology for defining fixed location area in mobile satellite communication systems", To be presented in vehicular technology conference 2001 falls.


7. B. G. Evans, R. Tafazolli and K. Narenthiran; "SATELLITE-UMTS IP-BASED NETWORK (SATIN)", AIAA 19th International Communications Satellite Systems Conference (ICSSC) and Exhibit.
Appendix A: Characteristics of satellite link and modelling

In this thesis, mobility management related issues (which are related to layer 3) have been investigated assuming that the lower layers are functioning perfectly. In reality this is not the case, because the effective functioning of each layer’s protocols, particularly of the physical layer (hence layer two and three) depends on the channel conditions of the particular environment. Even though channel coding, modulation, interleaving and power control functionalities of the system are designed in such a way to counteract channel variation and to give better system performance, the impact of channel variations cannot be fully decoupled from the upper layers and hence will influence the functionalities of the upper layers such as mobility management, where handover and paging are main functions influenced by the channel conditions. Handover between two satellites in the non-GEO case not only depends on the path loss variation but also depends on the variation of channel conditions due to the local environment. In order to provide a reasonable level of QoS, it is important to reduce the number of handovers throughout the call duration and the handover should be as smooth as possible to avoid interruption during a call. Therefore the impact of the channel on handover directly impacts the QoS. On the other hand, bad channel condition can lead to paging failure, which contributes to the call set-up delay. The number of paging failures increases the signalling load for paging and therefore has an impact on location area planning where the location area size is decided based on the optimal location tracking signalling as explained in section 5.3.

The above arguments clearly indicate the importance of understanding the radio channel characteristics in designing the system more efficiently. Therefore in this appendix the channel characteristics is investigated and methods of modelling the channel to evaluate different functionalities of the system.

A.1 Overview of the satellite radio channel

The general propagation environment for a mobile satellite communication system is shown in Figure A-1. The radio channel is seen to be very hostile and its characteristics vary with time very rapidly compared to fixed links. The channel is one of the basic subsystems [95] (transmitter, receiver and channel) in a model of the communication system. The basic elements of a physical satellite link are shown in Figure A-2.
Appendix A: Characteristics of satellite link and modelling

In digital communications, service quality is mainly expressed in terms of bit error rate (BER). In a radio system BER rate depends on the carrier to noise density ratio ($C/N_0$). According to the normal standard, the BER should be lower than $10^{-4}$ for voice communications. The service reliability is expressed in terms of service availability, which is the percentage of time the link has the specified $C/N_0$. The $C/N_0$ in turn depends largely on the channel characteristics. In the transmitter site the signal must be conditioned in such a manner that distortions introduced by the channel can be overcome. This task involves coding, pulse shaping and modulation. At the receiver the task is to extract the information signal from the received signal by implementing all the available techniques such as equalisation, demodulation, error correction, error detection and decoding. These tasks in the two major parts require knowledge of the mobile channel in order to design the techniques related to the satellite link. Therefore the importance of understanding channel characteristics cannot be underestimated.

A channel model is a set of mathematical equations that allow reproduction of the actual channel characteristic usually derived from measurements. The model can then be used in either simulation or empirical work to develop a channel model that may be used in a mobile satellite link. The parameters to be considered in the channel model are shown in Figure A-1.

- Non linearity of the payload
- Pathloss, Propagation delay, Doppler shift
- Shadowing
- Multipath fading
- Multiple access interference
- Gaseous absorption & Ionospheric effects

Figure A-1: Propagation environment for land mobile satellite system

Figure A-2: Basic elements of a satellite link
Appendix A: Characteristics of satellite link and modelling

design the techniques reliably. Also for any power control system that may be used on a mobile satellite link, typical channel information is essential for its reliable design. Apart from this, carrier recovery, bit timing, and frame synchronisation have to be carefully matched to the channel behaviour.

Hence, the reliability and QoS of a communication system can be significantly influenced by the characteristic of the transmission channel between the transmitter and the receiver. This has indirect impact on the design of the transmitter and receiver. Therefore the importance of understanding the transmission channel characteristics and having realistic models cannot be underestimated.

A channel model is a set of mathematical expressions, which allow reproduction of the actual channel characteristic usually derived from propagation measurements. The model can then be used in either simulation or emulating system. The steps involved in developing a channel model are shown in Figure A-3.

![Figure A-3: Channel model development process](image)

A.2 Characteristics of mobile satellite channel

As shown in Figure A-1, the signal arrives at the receiver via different paths and undergoes different types of path losses and frequency shift. The following sections discuss these characteristics of the channel in terms of path loss, Doppler shift, multipath fading and shadowing.

A.2.1 Path losses

The propagation of the direct path is affected by free space attenuation, and other losses as given in equation (A-3), which includes absorption and scattering by rain, hail, snow, fog and clouds, gaseous absorption and ionospheric effects such as faraday rotation and ionospheric scintillation.

Up to about 5GHz, the propagation is not affected by rain. The main regions for high gaseous absorption are around 22GHz for water vapour and 60GHz for oxygen. The main ionospheric effects occur in the region 80-1000km above the earth and are faraday rotation reduces as $1/f^2$ with significant effect limited to range below 2GHz.
Appendix A: Characteristics of satellite link and modelling

The free space loss equation is as follows;

\[ P_{r} = \frac{P_G}{4\pi d^2} \left( \frac{\lambda^2 G_L}{4\pi} \right) \]  \hspace{1cm} (A-1)

And expansion in dB terms as;

\[ P_r[dB] = P_t[dB] + G_t[dB] + G_r[dB] - 20\log_{10}(4\pi d/\lambda) \]  \hspace{1cm} (A-2)

With additional loss terms this comes


Where

\[ G_t \] - Transmitter antenna gain
\[ G_r \] - Receiver antenna gain
\[ P_t \] - Received carrier power
\[ P_t \] - Transmitted carrier power
\[ d \] - Distance between the transmitter and receiver
\[ \lambda \] - Wavelength of the carrier
\[ L_a \] - Other losses such as atmospheric absorption
\[ L_p = 20\log_{10}(4\pi d/\lambda) \] - Free space path loss

A.2.2 Doppler shift

The signal travels different distance from the satellite to the mobile as shown in Figure A-4. The movement of the vehicle and the satellite leads to the Doppler shift in the received frequency. There is a continuous change in the electrical length of every propagation path and thus the relative phase shifts between them changes as a function of spatial location. The time variation or dynamic change in the propagation path length can be related directly to the Doppler effects. The rate of change of phase due to motion is called the Doppler frequency shift and it given as follows;

\[ f_{dm} = \frac{(vf/c)\cos\theta}{\lambda} \]  \hspace{1cm} (A-4)

So the frequency shift range is \( \pm f_m \)

Where \( f_m = (vf/c) \) is called the fade rate

The Doppler due to the movement of the satellite is much higher in LEO and MEO constellations than for the mobile. But in a GEO case it will be the mobile velocity that will predominate
Appendix A: Characteristics of satellite link and modelling

So the Doppler due to the movement of the satellite \( = f_d \).

Therefore the total Doppler shift \( = f_d + f_{\text{im}} \).

### A.2.3 Multipath propagation

The received signal at a mobile is made up from numerous attenuated, reflected or diffracted versions of the original signal as shown in Figure A-5. This is called multipath propagation. If the direct signal is blocked as shown in Figure A-5(a), it is called non line of sight (NLOS) and the received signal is the summation of reflected signals from all directions. If there is a line of sight signal, it is called a 'line of sight' (LOS) case. Two ray models for both cases are shown in Figure A-6. Depending on the phase different between the echoes, the resultant signal may be higher than any of the individual echoes or indeed less and this will vary with time. This phenomenon is called multipath fading. In the NLOS case, the amplitude of each reflected component will be approximately equal, but the phases are uniformly distributed between 0 and \( 2\pi \). The envelope of the received signals undergoes fading with a Rayleigh statistical distribution defined as follows.

\[
P(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right)
\]

(A-5)

- \( r \) – Received signal envelope
- \( 2\sigma^2 \) – Mean power of the signal due to reflected component only

In the LOS case, the direct signal has more power than the multipath components and hence tends to dominate the resulting signal power as shown in Figure A-6(b). Hence the envelope of the received signal is more deterministic and follows a Rician probability density function defined as follows.

\[
P(r) = \left(\frac{r}{\sigma^2}\right) \exp\left(-\frac{r^2 + A^2}{2\sigma^2}\right) \frac{rA}{2} \]

(A-6)

where \( r \) & \( \sigma^2 \) are as in (A-5) and ‘\( A \)’ is the amplitude of the direct path component. As shown in Figure A-6 for a two ray model, for the Rician case, the resulting amplitude and phase transients are less severe compared to the Rayleigh case. The degree of variation between direct and reflected components is defined by a constant known as \( \text{K-factor or Rician factor} \). Mathematically the \( \text{K-factor} \) is defined as follows;

\[
K = 10\log\left(\frac{A^2}{2\sigma^2}\right)
\]

(A-7)

and it is the ratio of the directly received component to the sum of the power in the multipath component. Lutz mentions in his paper [96] that the \( \text{K-factor} \) can vary from 3.9dB to 18.1dB in a mobile satellite system. In [97], it is mentioned that \( \text{K-factor} \) varies between 10-20dB in
measurements taken in America and 15-20dB in the measurements taken in Australia in open areas. In land mobile systems, variation usually in between 5 and 10dB in urban case.

Figure A-5: Multipath propagation in satellite systems

(a) Non line of sight

(b) Line of sight

Figure A-6: Two ray model for multipath signal construction

(a) Rayleigh

(b) Rician

Figure A-7: Impact of multipath propagation on wideband and narrowband signal

(a) Inter-symbol interference

(b) Notches in channel frequency response

The impact of multipath propagation on the signal in the time and frequency domains is shown in Figure A-7. For narrowband communications, multipath effects provide amplitude and phase variations to the carrier signal. However, as the bandwidth of the waveform increases, the
different in the electrical lengths of the different frequencies within the waveform become larger and so, their amplitude and phase variation become less similar. This is known as frequency selective fading. The extent of frequency separation before correlation between two signal components becomes less than a given factor (usually 0.5 or 0.9), and is known as the coherence bandwidth. Thus, for wideband modulation techniques such as CDMA, where the coherence bandwidth is exceeded, frequency selective fading causes problems and must be considered. The coherence bandwidth can be expressed in terms of rms (Root Mean Square) delay ($\tau_{rms}$) as follows:

\[ \text{Coherent bandwidth} = \frac{1}{6\tau_{rms}} \]  \hspace{1cm} (A-8)

where $\tau_{rms} = \left[ \frac{\sum [\tau_k - \tau_a]^2 \alpha_k^2}{\sum \alpha_k^2} \right]^{1/2}$, with $\tau_a = \frac{\sum \tau_k \alpha_k^2}{\sum \alpha_k^2}$

$\alpha_k$ – amplitude of the $k^{th}$ ray with time delay $\tau_k$

A more general tap delay line model [98] shown in Figure A-9 can be used to represent the multipath propagation. The mathematical expression is given by (A-9).

\[ h(t) = \sum \alpha_k \delta(t - \tau_k) e^{j\theta_k} \]  \hspace{1cm} (A-9)

Where $\alpha_k$ – Amplitude of the $k^{th}$ path component, $\theta_k$ – Phase of the $k^{th}$ path component

The characteristics of the echoes have been discussed in [99] and herein the author proposes a model for the echoes. It has been mentioned that the mean power of the near echoes is exponentially decreasing (A-10), the number of echoes is Poisson distributed (A-12) and the delay distribution of the near echoes follows an exponential distribution (A-13).
Appendix A: Characteristics of satellite link and modelling

\[ S(\tau) = S_0 e^{-\sigma \tau} \]  
(A-10)

\[ S(\tau)[dB] = S_0[dB] - d[dB] \tau \]  
(A-11)

\[ P(N) = \frac{\lambda^N e^{-\lambda}}{N!} \]  
(A-12)

\[ P(\tau_k) = e^{-\alpha \tau_k / b} \]  
(A-13)

Where \( \tau \) is the echo delay, \( N \) is the number of echoes and \( \tau_k \) is the \( k^{th} \) echo delay. \( S_0, d, \lambda \) and \( b \) are echo parameters, can be calculated using the measured data. Sample parameters are given in Appendix F. The full set of parameters for L band and S band can be obtained from [99] and [100] respectively.

A.2.4 Shadowing

It has been shown in [101], that the mean signal variation in a shadowed state is lognormally distributed;

\[ P(P_0) = \frac{10}{\sqrt{2\pi}\sigma_1 \ln10P_0} \exp\left[-\frac{(10\log P_0 - \mu_1)^2}{2\sigma_1^2}\right] \]  
(A-14)

\( \mu_1 \) - Lognormal mean and \( \sigma_1 \) - Lognormal standard deviation

where \( P_0 = 2\lambda^2 \) and \( \sigma \) is standard deviation as in (A-5).

It is important not only to have first order statistics (time-invariant), but also to have second order statistics to simulate the required environment using Lognormal distributions. The first-order statistics of the shadowing have been extensively reported, however the second-order (time-variant) statistics are generally much less known. Correlation statistics of shadow fading is one such statistic, which is not yet widely available for satellite channels. From processing the data collected during measurement campaigns carried out by CCSR, a new negative exponential correlation model for various operational environments has been proposed [102]. Figure A-10 shows an example of the autocovariance of the shadow fading in the heavily wooded and suburban category as reported in [102]. A model for generating the correlated shadowing process is shown in Figure A-11 from [103]. \( \sigma_2 \) is location variability as given by equation (A-15). \( A \) (=5.2 for urban case and =6.6 suburban case) depends on the environment. \( \varepsilon \) is given by equation (A-16). \( v \) is the mobile speed in \( ms^{-1} \), \( T \) is the sampling interval and \( D \) is the shadowing correlation distance taken of the autocorrelation to fall to 0.37 \( (e^{-1}) \). \( D \) also depends on the elevation angle in satellite system (for terrestrial the distance from the base station) and the environment. Normalised autocovariance with distance for the satellite case is given in Figure A-10. The data for the terrestrial case can be found in [104] and [105].
Appendix A: Characteristics of satellite link and modelling

\[ \sigma_L = 0.65(\log f_c)^2 - 1.3\log f_c + A \]  \hspace{1cm} (A-15)

\[ \epsilon = e^{-(|\psi|/D)} \]  \hspace{1cm} (A-16)

Figure A-10: Normalised autocovariance, for wooded and suburban environment at L-band with elevation angles, a) 60°, b) 80°

Figure A-11: Model for generating correlated shadowing process

A.2.5 Azimuth correlation

Satellite diversity can be employed as an effective tool for combating shadowing and hence achieving higher service availability figures. However, in realistic diversity scenarios, some correlation between the shadowing of the diversity satellite channels exists depending on the azimuth separation angle, operational environments, constellation and the elevation angle. In order to be able to represent this accurately, fish-eye pictures of various operational environments have been taken. Figure A-12(a), shows one such picture taken in central London, representing a typical European urban environment. Through the use of edge detection algorithm, shadowing profiles have been extracted as shown in Figure A-12(b).
Appendix A: Characteristics of satellite link and modelling

The autocorrelation of the above shadowing profiles provide the important azimuth correlation coefficient used to determine the shadowing likeliness of the diversity channels. A complete set of azimuth correlation coefficients for all the operational environmental categories have been developed and utilised within the channel model to represent the realistic diversity scenarios. In order to incorporate, the azimuth correlation, the four state model proposed by Lutz [106] was utilised. Full details of the Markov model can be found in this reference. Figure A-13 shows the correlation coefficient of two satellites at $45^\circ$ elevations angle with variation in azimuth angle.

![Figure A-12: Fish-eye picture of urban environment, London](image)

![Figure A-13: Variation of azimuth correlation coefficient](image)

### A.3 Comparison of measured data for satellite links

In the last decade, a number of organisations such as NASA, DLR, ESA and CCSR have carried out propagation measurement and modelling activities for mobile satellite systems. The importance of carrying out real propagation measurements and modelling the satellite link for future system testing is applied by the non availability of real mobile satellite in the frequency band and orbit...
Appendix A: Characteristics of satellite link and modelling

required. Our centre, the Centre for Communication System Research (CCSR), has also completed propagation measurements, using helicopters with different environments. The measured data from CCSR and DLR campaigns [99] is compared for different environments in this section.

Figure A-14: Comparison of measured channel data for urban from CCSR and DLR

Figure A-14 shows urban environment data from CCSR and DLR. Only time-share factor of shadowing from CCSR and DLR shows similarity and other parameters lognormal mean, standard deviation and k-factor show dissimilarities. The reason for this is that, the surrounding environment of the receiver is different in CCSR and DLR measurements since the parameters mentioned above except time share of shadowing depend on vegetarian and building structure surrounding the receiver. Therefore it is difficult to come up with standard channel parameters.

Figure A-15 shows the measured data from CCSR for three different environments. The trend of the curves is similar. But the values for highway differ considerably from those in urban and suburban environments. It is also interesting to note that the parameters (except time share of shadowing) of all the environments (except open and highway) are close in value. From the above arguments, we can come to the conclusion that the propagation channel in open and highway environments are significantly different from the other environments. Therefore, it is felt that data from open and urban environments is sufficient for modelling the propagation channel at its extremes and for testing purpose even though any individual measurement will be different.
Further analysis of the measured data shows delay spreads of 100ns or less. At higher elevation angles and open environments there are few multipath components. As far as multipath is concerned, low elevation angles in the urban environments have been found to be the most hostile environments. Figure A-8 shows the power-delay profile of one such urban environment at 45°. It can be observed that, even in this environment, all the resolvable echoes arrive very close to the LOS signal. As shown in Figure A-8, no more than 2 major reflections are encountered in this particular case. This has been validated for all the environments using the S-band measurement carried out by CCSR. Furthermore, the average power in the reflected components, are generally about 15-30 dB below the average power of the LOS component. Nevertheless, at lower elevation angles the LOS is significantly attenuated resulting in much higher reflected powers (relative to the LOS).

A.4 Mobile satellite channel modelling

A channel model replicates the actual characteristics of a channel. When a mobile user moves through the considered communication environment, the signal received by the user is blocked from time to time due to obstructions such as trees and buildings around the user. This leads to a large drop in the signal strength known as the shadowing as mention in section A.2.4. Normally,
the shadowed and the non-shadowed case are referred to as bad and good state respectively, in the literature. The bad and good duration are measured in terms of distance for a required environment and the measured values are incorporated within a two state Markov model for a single user-satellite link. Within any given state, there is signal strength variation due to the wideband multipath effect. The wideband multipath characteristics are represented by the tap delay line structure as explained in section A.2.3. The total received signal variation comes from the combination of all the signal variations due to the factors mentioned above. A sample of signal variation is shown in Figure A-16. The signal variation \( \{ r_d(t) \} \) comes only from multipath propagation and is called as multipath fading (A.2.3), fast fading, short term fading or Rayleigh fading [107][108]. The signal fluctuation \( \{ m(t) \} \) coming only from shadowing is called the long term fading or lognormal fading (A.2.4). The total signal variation \( \{ r(t) \} \) is a combination of the above two and is given by equation (A-17).

2\( T \) is the time interval for averaging and it is normally 20 to 40 wavelengths of the signal [107].

\[
r(t) = m(t)x_{r_0}(t) \tag{A-17}
\]

\[
m(t) = \frac{1}{2T} \int_{t=1-T}^{t=1+T} r(t) dt \tag{A-18}
\]

From the discussion in the previous section, the following aspects should be taken into consideration to model the ground segment propagation part of a channel.

- State change statistics.
- Characteristic of the signal in the transition region between the good and the bad states.
- Slow shadowing variations within the bad state mainly caused by obstructions of the \( LOS \) as the \( MT \) moves within a given operational environment. The lognormal shadowing is
characterised by a mean, standard deviation and an effective correlation distance, all
dependant on the operational category.

- Fast variations due to the multipath and the frequency selective propagation channel.
- Effect of noise.
- Effect of interference from other channels.

In [109], it is mentioned that, for very slow variations, correlation distances on the order of the
minimum state length 7m may be used and for the slow variations, correlation distances slightly
smaller than 1m have been observed in the measured data.

**A.4.1 State transition probability**

A two state Markov model has been proposed by Lutz [106] for handling transition states with
one mobile satellite channel and four states Markov model for two mobile satellite channels (e.g.
diversity operation). These are explained below.

![Two state Markov model for one mobile satellite channel](image)

**Figure A-17:** Two state Markov model for one mobile satellite channel

\[ P_{BG} = \frac{u}{(1 - \mathcal{R}B)} \text{ and } P_{GB} = \frac{u}{(1 - \mathcal{R}G)} \]  

(A-19)

\[ u - \text{Velocity of the mobile terminal} \]

\[ D_B - \text{Bad duration in meters} \]

\[ D_G - \text{Good duration in meters} \]

\[ \mathcal{R} - \text{Lutz mentioned as transmission rate} \]

From the measured good and bad duration, the transition probability is calculated as in (A-19).
Using this probability and a random variable generator, the state of the channel is decided. The
next state of the channel depends on the current state of the channel and the transition
probabilities. In this model, the problem is that, the signal level change is sudden when the state
changes from one to another. This is not the case in reality. As mentioned in [110], linear
interpolation can be used to smooth the transition between the states. In [109], it is mentioned
that, in urban areas, transitions from good state to bad state tend to resemble very closely the
knife-edge diffraction loss curves. Another way of overcoming this is to introduce extra states,
which represent intermediate levels of shadowing with smaller Rice K-factors than the line of
sight good state.

The autocorrelation of the above shadowing profile provides the all important azimuth correlation
coefficient (see section A.2.5), used to determine the shadowing likeliness in a two diversity
channel statistics. A complete set of azimuth correlation coefficients for all the operational environmental categories can be developed and utilised within the modelling. In order to incorporate, the azimuth correlation, the four state model (Figure A-18) proposed by Lutz [106] was utilised. Full detail of the Markov model can be found in his reference.

![Four state Markov model for a mobile satellite channels with two satellites](image)

**Figure A-18: Four state Markov model for a mobile satellite channels with two satellites**

### A.4.2 Narrowband channel model

In the latter two sections we have discussed echo modelling and state transition probability. This section addresses how the echo modelling, state transition probabilities and probability distribution functions discussed in section A.2 can be combined together to form an overall Mobile satellite channel model. A so-called narrow band channel model is shown in Figure A-19 from Lutz [96].

![Narrow band channel model for mobile satellite communication systems](image)

**Figure A-19: Narrow band channel model for mobile satellite communication systems**

### A.4.3 Wideband channel model

A more general wideband mobile satellite channel model is shown in Figure A-20. It is considered as more appropriate to represent all the characteristics of the channel.
A.5 Multiple access interference

CDMA systems experience multiple access interference due to the cross correlation among the various spreading sequences. When de-spreading the received signal, the unwanted signals become gaussian noise, since the different signature waveforms are never fully orthogonal. This interference will significantly impact on the link quality. Figure A-21 presents the different sources of interference in the mobile satellite systems. The amount of multiple access interference received from each source will be estimated taking the following information into account.

- Satellite constellation
- Mobile terminal position
- Satellite spot beam/antenna pattern
- Mobile Antenna pattern
- Land mobile satellite channel
- Distribution of users

Figure A-21: Sources of interference
A.5.1 Forward and return links implementation differences

The interference calculations are performed following the same approach for both the forward and the return links. However, two differences have to be considered. Firstly, in the forward link, users in the same spotbeam as the user of interest have synchronous transmission. Hence, by using low cross-correlation spreading codes within one beam, the intra-spotbeam interference can be significantly reduced. This is not the case in the return link where the different users transmit independently from one another. Therefore intra-spotbeam interference is considered in the return link and not considered in the forward link. Secondly, in the forward link, the user of interest will see interference from the adjacent satellite as well as satellites in the other constellation. Since there is only one source for the interfering signals (all the signals come together from the satellite), the user of interest will suffer from the interference from all the user traffic carried by the adjacent satellite as well as that of the satellite in the other constellation. However, in the return link, since the interfering sources are spread over different coverage areas and thanks to the directivity of the satellite antenna (high spotbeam isolation), the interference from users (b) and (c) can be ignored.

A.5.2 Interference simulation model

Interference scenarios with different terrestrial landmarks are shown in Figure A-22. Interference levels depend on the type of environment (Urban, suburban etc.). A basic simulation model (Figure A-23) for interference has been developed to represent the environmental obstacles as shown in Figure A-22 with the help of different environmental channel models (Fad_{FLk} & Fad_{RLk}). Equations (A-20), (A-21) and (A-22) represent C/(N_o+I_o) in three noise injection points (Inj=1, 2, 3) shown in Figure A-30. Using the simulation models, the C/(N_o+I_o) is calculated for different constellations (LEO, MEO and GEO). A LEO-48 simulation result is shown in Figure A-24 for equation (A-21) as a function of time. Full details on the interference calculations are available in [111].

![Figure A-22: Channel condition with the signal and interferences](image-url)
A.6 Payload non-linearity

The signals from different users are combined and transmitted through a single high power amplifier (HPA) on the satellite. This HPA can operate its saturation region. This leads to amplitude and phase distortion of the signal transmitted through the HPA (Figure A-25). This is called payload non-linearity effect. HPA's is generally exhibit two kinds of nonlinearities. First, there is a non-linear input against output power (AM/AM) relationship. Secondly, a non-linear output phase against input power (AM/PM) relationship. This effect is larger in CDMA access techniques compared to TDMA or FDMA, since the user signals are added together and
transmitted on the same time-frequency medium. Figure A-26 shows the situation where the operating point of the HPA is pushed into the saturation region.

Appendix A: Characteristics of satellite link and modelling

Figure A-25: HPA Characteristics

![Figure A-25: HPA Characteristics](image)

**A.6.1 Selection of high power amplifier model**

The assessment of the payload nonlinearities on the transmission quality calls for a HPA mathematical models. Due to its simplicity and good accuracy compared to other models [112][113] the Saleh model [114] based on polynomials is selected here in. The input and output signal can be expressed by the equations (A-23) and (A-24) respectively.

\[ x(t) = r(t)\cos(\omega_c t + \psi(t)) \] (A-23)

\[ y(t) = A[r(t)]\cos(\omega_c t + \psi(t) + \phi(r(t))) \] (A-24)

\( \omega_c \) is the carrier frequency and \( r(t) \) and \( \psi(t) \) are the modulated envelope and phase, respectively. \( A(r) \) is an odd function of \( r \), with a linear leading term representing the AM/AM conversion, and \( \phi(r) \) is an even function of \( r \), with a quadratic leading term representing the AM/PM conversion.

The Saleh model represents these two quantities given by the equations (A-25) and (A-26) respectively:

\[ A(r) = \alpha_\phi r/(1 + \beta_\phi r^2) \] (A-25)

\[ \phi(r) = \alpha_\phi r^2/(1 + \beta_\phi r^2) \] (A-26)

Table A-1 presents the parameters of the Saleh model corresponding to the Hughes 261-H tube model.

**Table A-1: Hughes 261-H tube model**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( \alpha_\phi )</th>
<th>( \beta_\phi )</th>
<th>( \alpha_\theta )</th>
<th>( \beta_\theta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>( 1.6623 \times 10^3 )</td>
<td>( 5.52 \times 10^4 )</td>
<td>( 1.533 \times 10^5 )</td>
<td>( 3.456 \times 10^5 )</td>
</tr>
</tbody>
</table>

![Figure A-26: Satellite repeater architecture](image)
Appendix A: Characteristics of satellite link and modelling

A.6.2 Payload non-linearity simulation model

Figure A-27: Payload non-linearity simulation model

Figure A-27 shows the simulation model for the payload non-linearity. The HPA parameters in Table A-1 were used for simulation. In order to see the bit error performance of the payload non-linearity, BER with payload non-linearity for different value of IBOs, without payload non-linearity and theoretical values were calculated. The results are shown in Figure A-28. The simulation model is validated by comparing the simulation result with theoretical results for thermal noise only. The rest of the curves shown in the Figure A-28 are similar to BER performance of the modulation scheme with noise only. This observation leads to the concept of injecting additional noise into the communication signal, in order to introduce the payload non-linearity effect in the satellite link. The additional noise required to represent the payload non-linearity is given by equation (A-27).

\[ N_{\text{amp}}[\text{dBm}] = N_0[\text{dBm}] - (E_i/N_{\text{amp}})_{\text{Payload non-linearity}}(E_i/N_0)_{\text{Noise only}}[\text{dB}] \]  

(A-27)

Figure A-28: Non-linearity performance of QPSK

Using the BER performance of the payload non-linearity (Figure A-28), the second element in the right hand side of the equation (A-27) has been found for different BER and IBO. The result is given in Figure A-29. According to the variation of the number of users in a particular footprint and the payload architecture (Figure A-28), the total signal to the HPA can be calculated assuming that the signals from unblocked users experience only path loss and the signals from blocked users...
experience path loss and lognormal fading. Then the additional noise required for payload non-linearity can be calculated using the data from Figure A-29 and equation (A-27).

A.7 Emulation of the satellite link

Figure A-30 shows the block diagram of the satellite link emulator (SLE) hardware platform. The SLE has two parts, satellite channel emulator (SCE) and noise controller. SCE represents the hardware platform required for emulation of the wideband channel model explained in section A.4 and the noise controller represents the hardware platform for emulation of multiple access interference model explained in section A.5 and payload nonlinearity model explained in section A.6. The channel, multiple access interference and payload nonlinearity models sit in the controller PC.

The emulation process of the satellite channel is shown in Figure A-31. The constellation model calculates the elevation angle, Doppler, delay and path loss. Using the elevation angle and the channel data bank, which can be prepared from the measured channel data given in section A.3 or in Appendix F, the rest of the parameters can be calculated considering all the factors mentioned in section A.4 and using the corresponding theoretical models explained in section A.2.

The process of emulating multiple access interference and the payload non-linearity is explained in Figure A-32. With the system parameters shown in Figure A-32, the interference simulation
model finds the addition of interference and noise \( (I_0^1, I_0^2 + N_0, I_0^3 + N_0) \) at the three noise injection points \( (Inj=1,2,3) \) and the payload non-linearity simulation model computes the noise contribution \( N_{amp} \) from the payload at two noise injection points \( (Inj=2,3) \). It has been assumed that traffic load is equal through forward and backward HPAs. Combination of interference contribution, payload contribution and thermal noise gives the total noise required at each noise injection points in the SLE. These noise values are finally converted into control digital signals of the noise controller. The noise controller is controlled by a controller PC.

The following system parameters are considered for calculating the total noise at each injection point:

- Satellite constellation
- Spotbeam configuration
- Distribution of users
- Environment parameters
- Number of Users
- Bit Rate
- Digital modulation type
- TWTA model parameters \( (\alpha_0, \beta_0, \alpha_1, \beta_1) \)
- Type of spreading code
- Thermal noise level
- Distribution of users
- Environment parameters
- Thermal noise level

The noise controller is controlled by a controller PC.

**System parameters**

**Multiple access interference & Payload non-linearity Emulation model**

When the model is used for experiments, the communication signal power at each noise injection point \( (Inj=1,2,3) \) has to be measured using a power meter or spectrum analyser (say \( C_1, C_2, C_3 \)). Using these measured values and equations \( (A-20), (A-21) \) and \( (A-22) \) the actual noise required at three noise injection points \( (N_1, N_2, N_3) \) can be calculated. The values are given in equations \( (A-28), (A-29) \) and \( (A-30) \). Where “\( \omega \)” is communication signal bandwidth.

\[
N_1 = \omega(I_0^1) \tag{A-28}
\]

\[
N_2 = \omega(I_0^2 + N_0 + N_{amp}) \tag{A-29}
\]

\[
N_3 = \omega(I_0^3 + N_0 + N_{amp}) \tag{A-30}
\]

### A.8 Implementation and usage of the emulator

So far, the theory and design aspects of the satellite channel emulation have been explained. This subsection details the full arrangement of the satellite channel emulator and its applications.

There are a few hardware platforms capable for real-time satellite link emulation, but their capability is largely constrained by the absence of a comprehensive software which generates the
Appendix A: Characteristics of satellite link and modelling

emulation sample points for any given desired real life scenario. The available hardware platforms can be categorised into two main families,

- **Real-time DSP-based emulation:** generates fast phase, amplitude, frequency changes internally based on a pre-defined set of statistical distributions.
- **Real-time playback emulation:** create the desired impairments by pre-loading the fading sample points and FIR filtering of the input signal.

The former is the preferred platform as pre-loading the sample points would require large amounts of on-board memory, which imposes limited run-time. Based on this the NoiseCom emulation platform was selected, since it combines characteristic of both families.

The selected hardware consists of one NoiseCom Satellite Link Emulator (SLE-250) capable of emulating 2 full-duplex paths and two multipath fading emulators (MP-2700) each capable of emulating one full duplex link as shown in Figure A-34. The SLE-250 is capable of generating varying Doppler shift, propagation delay, path loss, and slow fading. Each half-duplex MP-2700 link emulates direct path component and two echoes with Ricean and Rayleigh fading statistic respectively. The complete unit is hence capable of emulating two full duplex channels, which represent the radio link between two satellites/spotbeams and the mobile.

In order to be able to realistically emulate the relative characteristics of the two links within a given constellation, all the hardware units have been externally synchronised by the emulator controller unit. The precision noise generator units in Figure A-34, enable introduction of dynamic interference and thermal noise during a run according to the configured scenario. The considered configuration is currently capable of coping with a maximum 10MHz input bandwidth.

The **SCE** software consists of three main sections, the dynamic satellite constellation generator, the wideband channel model for all the environments and the elevation/azimuth angles followed by the interference generator module. The relationship between different sections was already shown in Figure A-31 and Figure A-32. Through the use of a graphic user interface (GUI) as shown in Figure A-34, the user can define the desired set of parameters.

The dynamic constellation generator provides a series of relevant information such as the elevation angle of the two highest satellites/spotbeams, the azimuth separation angles, Doppler and delay (compensated or uncompensated), etc. to other software modules of the **SCE** controller. The **SCE** controller would then produce the necessary files for a given set of parameters. These files also include other relevant information required by various hardware platform units to reflect the dynamic nature of constellation dependant changes in real-time. The format of the
environment dependant parameters is that of a dynamic link library (DLL). By selection of the appropriate DLL (via the GUI), different operational environments can be emulated. This ensures complete flexibility for user defined environmental DLLs to be simply plugged into the software if deemed necessary.

The emulation features of the SCE are as follows;

- Satellite Link variation due to satellite movement
  - Doppler, Delay and Path loss variation
  - K-factor variation due to change of elevation angle with satellite position change
  - Change of shadowed state and non-shadowed states (Azimuth correlation incorporated with the help of Fish-eye picture)
- Multipath propagation
- Interference
  - Extra-System interference
    Other satellite system like LEO, MEO and GEO
  - Intra-System interference
    - Intra-Spotbeam interference
    - Inter-Spotbeam interference
    - Inter-satellite interference
- Payload non-linearity
- Thermal noise

Figure A-33 shows an example of a satellite handover scenario. As it can be seen, the power in link-a (solid line) starts deteriorating almost halfway through the run. On the other hand, the upcoming satellite of link-b (dashed line) appears to be increasingly received at a higher level until the crossover point, when handover should take place. Note that both the links experience uncorrelated shadowing in this environment.
Figure A.33: A typical handover scenario

Fading and normalised pathloss/(dB)
wrt centre of footprint

| Time(s) | 8.4  | 16.8 | 25.2 | 33.6 | 42  | 50.4 | 58.8 | 67.2 | 75.6 | 84  | 92.4 | 100.8 | 109.2 | 117.6 | 126  | 134.4 | 142.8 | 151.2 | 159.6 | 168  | 176.4 | 184.8 | 193.2 | 201.6 | 210  | 218.4 | 226.8 | 235.2 | 243.6 | 252  | 260.4 | 268.8 | 277.2 | 285.6 | 294  | 302.4 | 310.8 | 319.2 | 327.6 | 336  | 344.4 | 352.8 | 361.2 | 369.6 | 378  | 386.4 | 394.8 |
|---------|------|------|------|------|-----|------|------|------|------|------|------|-------|-------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|
PAGES MISSING IN ORIGINAL
Appendix A: Characteristics of satellite link and modelling

A.9 Summary

Satellite link characteristics and modelling has been discussed in depth and the importance of having realistic satellite link models has been highlighted. The process involved in real time satellite link emulation has been outlined. Aspects of path loss, Doppler shift, delay, multipath propagation, shadowing has been explained and models given. Channel data from different field trials have been analysed and the possibility of having a generalised database for the satellite channel has been investigated. It has been shown that it would be very difficult to have a common database for satellite channel parameters except for the sharing factor. It has also been found that the characteristic of the satellite channel in the shadowed state for different environments is similar. Therefore it is not very important to have different field trials for different environments in a shadowed condition.

A combined overall satellite mobile link model has been produced together with models for interference from other satellites in LEO/MEO constellations and effects on onboard satellite non-linearity. The software to emulate of these models into a hardware/software link emulator has been produced as part of this work. The emulator was calibrated and tested and shown to be capable of regenerating real satellite conditions. The emulator was used in EU projects SINUS and SUMO to regenerate the satellite element in user trials. It has since been modified for use on other projects and condition to produce on spin off product is in hand.
Appendix B: Satellite constellation design methods

The design of constellations can be categorised into two main methods, *street of coverage method* and *spherical triangle method*, which are explained below. The literature suggests that the street of coverage method is suitable for polar orbits and the spherical triangle method is suitable for inclined orbits. Therefore the ‘street of coverage’ method and ‘spherical triangle’ method are considered for polar orbit and inclined orbits respectively. The aim of the constellation design is to select the optimal number of satellites \( N_T \) for required coverage. The main factors influencing the selection, are altitude of the satellite \( h \) and the minimum elevation angle \( \sigma \). Variables are orbit inclination \( \beta \), number of orbit \( N_0 \) and number of satellites per orbits \( N_S \).

\[
N_T = N_0 \times N_S
\]  
(B-1)

### B.1 Street of coverage method

The foundations to the street of coverage method, was first given by Vargo [30]. This method was then continued by Luder [33] for a general case with full analytical solutions. But he did not consider the spacing between counter rotating orbits. This problem was first discussed by Gobetz [34] and continued by Ullock and Schoen [35] for a fully optimised global coverage. It has been well analysed by Adam and Rider [36] who extended the situation to multi-coverage.

In polar orbit constellation arrangements, the polar regions enjoy the maximum coverage and regions closer to the equator experience the minimum coverage due to the intersection point of all the orbits at the pole. Therefore all the analytical solutions have been derived as a function of latitude \( \phi \) (shown in Figure B-1(c)) above which one or more satellite are visible.

#### B.1.1. Single satellite coverage

![Figure B-1: Spacing arrangement between co-rotating and counter rotating orbits](image)

Figure B-1: Spacing arrangement between co-rotating and counter rotating orbits
Referring to Figure B-1 the inter orbit distances $\Delta_1$ (co-rotating) and $\Delta_2$ (counter rotating) are given by (B-2) and (B-3) respectively. The relationship between $\Delta_1$, $\Delta_2$ and $N_o$ is given by equation (B-4).

$$\Delta_1 = \sin^{-1} \left\{ \frac{\left[ 1 - \frac{\cos^2 \theta / \cos^2 (\pi N_o / N_T) \pi / 2} \right]}{\cos \phi} \right\} + \sin^{-1} \frac{\sin \theta}{\cos \phi} \tag{B-2}$$

$$\Delta_2 = 2 \sin^{-1} \left\{ \frac{\left[ 1 - \frac{\cos^2 \theta / \cos^2 (\pi N_o / N_T) \pi / 2} \right]}{\cos \phi} \right\} \tag{B-3}$$

$$\pi = \Delta_2 + (N_o - 1) \Delta_1 \tag{B-4}$$

For global coverage, $\phi = 0$ and $\varepsilon$ & $\theta$ overlap the equator and the following simplified equations can be used.

$$\varepsilon = \cos^{-1} \left\{ \frac{\cos \theta / \cos (\pi N_o / N_T)}{\cos \phi} \right\} \tag{B-5}$$

$$\Delta_1 = \varepsilon + \theta \tag{B-6}$$

$$\Delta_2 = 2 \varepsilon \tag{B-7}$$

Using equations (B-5), (B-6) and (B-7) the minimum number of satellites required for global coverage was found for different numbers of planes ($N_o$) and the results are presented in Figure B-2. As the altitude increases, the number of planes and total number of satellites for global coverage decrease. It is important to note that optimum number of satellites in terms of global coverage does not necessarily mean optimal for other aspects such as cost and other technical aspects of telecommunications. Some of these aspects have already been discussed in sections 2.1, to 2.3, and the cost will be dealt with in section 2.5.1.

Figure B-2: Number of satellites versus altitude for street of coverage method
B.1.2 Multiple satellite coverage

Footprint arrangements for multi level of coverage is shown in Figure B-3. The redundancy \( N_{RT} \) above latitude \( \phi \) can be defined as follows;

Number of redundant coverage in each orbit \( = N_{RO} \)

Number of street coverage at and above the specified latitude \( = N_{RS} \)

\[
N_{RT} = N_{RO} \times N_{RS} \tag{B-8}
\]

The street width for \( j \)- fold redundant coverage within each orbit is given by equation (B-9).

\[
C_j = \cos^{-1} \left( \frac{\cos \theta}{\cos(j \pi / N_o)} \right) \tag{B-9}
\]

The optimal satellite constellation arrangement can be selected from different combinations of \( N_{RO} \) and \( N_{RS} \) values using the equations (B-8) and (B-9) as explained for single satellite coverage.

Further analysis of multiple satellite coverage and inclined orbits can be found in [37] and [32] respectively. They identify that inclined orbits with odd numbers of planes are better than orbits with even number of planes.

B.2. Spherical triangle method

In this method, the earth's surface is divided into a number of spherical triangles by lines joining each sub satellite point to adjacent sub satellite points. Within each triangle formed by three adjacent sub satellite points, the point furthest from any sub satellite point is the centre of the circumcircle of the triangle. Over the whole earth surface, the point furthest from any sub satellite point is the centre of the largest of such circumcircles, the radius of which will reach its maximum value at a given satellite phasing. For single coverage, the circumcircle, which does not include
Appendix B: Satellite Constellation Design

any other sub satellite points have to be considered. For double coverage, the spherical triangle whose circumcircle encloses one other sub satellite point need to be considered.

This method was first partially discussed by Gobetz [34] in the form of orbits parallel to the face of the regular polyhedra in which he identified that the maximum satellite separation occurs when each satellite is midway between two intersection points and consequently is the position to determine the proper altitude for global coverage. The inclinations of the orbits are not equal in his method, which leads to perturbation. It is to be noticed that the coverage of the earth varies with time. A more general analysis on this method was performed by Walker [38] with double coverage. Walker’s work on constellation design [28] clearly defined the selection method for suitable orbits. It first defines two different constellation types, one has orbits whose reference plane coincides with the equator plane and the other has orbits whose reference does not coincide with the equator plane. One example of the second case is the star pattern constellation originally defined by Vargo [30].

Walker identified delta patterns using a three integer code reference $TIPF$ where $T$ is the number of satellites ($N_T$), $P$ is number of orbit planes ($N_O$) between which they are evenly divided, and $F$ is a non dimensional measure of the relative phasing of satellites in different orbital planes (It may be between 0 and $(P - 1)PU$s where $PU$-Pattern unit = $360/T$). In the selection process of proper delta patterns, he first found the possible number of delta pattern for a given number of satellites. This is equal to the sum of all the factors of $T$ (E.g.: For $T=6$, Number of patterns 1+2+3+6 = 12). He used further algorithm to eliminate some of them that did not provide whole earth coverage. He identified the pattern repetitive interval ($PRI$) for each pattern and the coverage analysis was performed only for that period. He showed that $PRI$ is half the phase angle range between successive nodal crossings (ascending and descending) by different satellites in the pattern. If $N_A$ satellites are at ascending and/or descending nodes simultaneously, the $PRI$ will be $N_A/4$ PU$s. It can be noticed that the pattern has $N_A$ identical sections if $N_A$ satellites cross the nodal simultaneously. More obvious patterns, which do not provide whole earth coverage, are given below.

- Single plane configuration
- All satellites pass through the reference simultaneously.
  1. Pattern $T/T/0$
  2. Pattern $T/T/1/2T$
- All satellites lie in two parallel planes, when number of satellites is relatively large (>=12). Two examples are;
  1. Pattern $T/T/4T$ or $T/T/4T$ and $T/4T/0$
2. Pattern $T/T^{1}/T$ or $T/T^{2}/T$ and $T^{1}/T^{0}$

- Single figure 8 pattern: A pattern whose code reference is of the form $T/T/(T-1)$ for inclination angle less than 90 degrees. It is important to notice that patterns, which are mirror images of one another will have identical characteristics. Particularly, a pattern $T/P/F$ at an inclination $\delta$ to the reference plane will have identical characteristics to the pattern $T/P/P\cdot F$ at an inclination of $180-\delta$ to the reference plane.

- Pattern has even number for $P$ and $(S-F)$ where $S=T/P$.

In order to explain the effect of earth rotation and precession of the orbit Walker used earth track plot on the earth. He derived the equations for the number of distinct repetitive earth tracks ($E_{LM}$) which is given by equation (B-10).

$$E_{LM} = T/K$$  \hspace{1cm} (B-10)

Where $K = \text{HCF}^* [G,PxJ]$, $G = S\times L + F \times M$, and $J = \text{HCF}[S,M]$, $L$ - number of orbit travel, $M$ - Sidereal days.

This spherical method was continued by Ballard [39] with full mathematical derivations. He coined the name Rosette constellations. He also defined the standard notation for a rosette as $(T, P, M)$ where $T$ is the total number of satellites ($N_T$), $P$ is the number of orbit planes ($N_O$) and $m$ is the harmonic factor which is defined below:

Referring to Figure 2-13,

$$\alpha_i = 2\pi i / P, \; i = 0 \; \text{to} \; T-1$$  \hspace{1cm} (B-11)

$$\gamma = m\alpha_i = mS(2\pi i / T)$$  \hspace{1cm} (B-12)

$$m = (0 \; \text{to} \; T-1) / S$$  \hspace{1cm} (B-13)

---

* HCF-Highest common factor
Using equations (B-14), and the steps explained above, the optimal number of satellites can be selected for the required coverage and altitude.
Appendix C: Coordinates calculation of MS positions on the earth surface

The distance (measured along the surface) between two points on the surface of the earth is $D$, the first one coordinates are $Lat_1$ and $Lon_1$ and the azimuth angle of the second point with respect to first point is $\phi$. Then the suspended angle ($\beta$) at the centre is given by the equation (C-1) and the radius ($r$) of the cross cut circle is given by (C-2)

$$\beta = \frac{D R_e}{r}$$  \hspace{1cm} (C-1)
$$r = R_e \sin(\beta)$$  \hspace{1cm} (C-2)

The second point coordinates ($Lat_2$, $Lon_2$) can be given by (C-3) and (C-4) respectively.

$$Lat_2 = \theta_2$$  \hspace{1cm} (C-3)
$$Lon_2 = Lon_1 + \alpha$$  \hspace{1cm} (C-4)

$\theta_2$ and $\alpha$ can be given by (C-8) and (C-12) respectively

Referring to Figure C-1 (a), the following equation can be derived.

$$h_2 = R_e \cos(\beta) \sin(\theta_1)$$  \hspace{1cm} (C-5)
$$ll = rsin(\phi) = R_e \sin(\beta) \sin(\phi)$$  \hspace{1cm} (C-6)
$$hl = ll \cos(\theta_1) = R_e \sin(\beta) \sin(\phi) \cos(\theta_1)$$  \hspace{1cm} (C-7)
Appendix C. Coordinates calculations on earth surface

\[ \sin(\theta_2) = \frac{(h_1 + h_2)}{R_e} = \sin(\beta) \sin(\phi) \cos(\theta_1) + \cos(\beta) \sin(\theta_1) \]  \hspace{1cm} (C-8)

Referring to Figure C-1 (b), the following equation can be derived.

\[ l4 = 2R_e \sin(\beta/2) \]  \hspace{1cm} (C-9)

\[ h_3 = h_4 - R_e \sin(\theta_2) = R_e \{ \sin(\theta_2) - \sin(\theta_1) \} \]  \hspace{1cm} (C-10)

\[ d l^2 = l4^2 - h_3^2 = 4R_e^2 \sin^2(\beta/2) - R_e^2 \{ \sin(\theta_2) - \sin(\theta_1) \}^2 \]  \hspace{1cm} (C-11)

\[ \cos(\alpha) = \frac{(l2^2 + l3^2 - d l^2)}{2 \ l2 \times l3} = \frac{(\cos(\beta) - \sin(\theta_1) \sin(\theta_2))}{\cos(\theta_1) \cos(\theta_2)} \]  \hspace{1cm} (C-12)
Appendix D: Mobility model

Assumptions

- The maximum direction change is 90° and depends on the speed. Velocity of movement is considered from 50km/h (car) to 2200km/h (Concord flight). Possible change of direction (θ) for different speed is shown in Figure D-1 (b). For example, considering Figure D-1 (a), direction of the terminal from points 1-2 is θ and from points 2-3 is θ+α.

- The terminal can move in the same direction or change direction after certain distance (Called correlation distance). Probability of moving in the same direction, after travelled correlation distance, is 0.2 and probability of changing direction is 0.8.

- It is assumed that the movement of mobile with speed of less than 100km/h is restricted to the countries and the mobile with speed of above 100km/h can move among collection of countries. The mobile with speed above 500km/h can move anywhere on the earth, over ground or sea. The distribution of mobiles with speed is given in Table D-1.

Table D-1: Mobile population distribution with speed

<table>
<thead>
<tr>
<th>Speed/ (km/h)</th>
<th>Around (pedestrian)</th>
<th>Around (car)</th>
<th>Around (High speed train)</th>
<th>Around (plane)</th>
<th>Around (concord)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>20</td>
<td>58</td>
<td>10</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>50</td>
<td>800</td>
<td>250</td>
<td>800</td>
<td>2200</td>
<td></td>
</tr>
</tbody>
</table>

The maximum possible number of mobiles in the MSS system is assumed as 2million based on the statistic in [89]. Position calculation can be found in Appendix C.
Appendix E: Selection of overlapping spotbeams or footprints with ‘LatLongFLA’

Case I: Footprint/spotbeam smaller than LA and centre inside the LA

Case II: Footprint/spotbeam smaller than LA and centre outside the LA

Case III: LA smaller than footprint/spotbeam and centre inside the footprint/spotbeam

Case IV: LA smaller than footprint/spotbeam and centre outside the footprint/spotbeam

Figure E-1: Overlap layout of LatLongFLA with footprints/spotbeams

Four possible different cases of spotbeam or footprint overlap with LatLongFLA are shown in Figure E-1 and the procedure for selecting the spotbeams or footprints, which are overlapping with the LatLongFLA is explained below.

Case I. Check whether center of the circle is inside latitudes $Lat_1$ and $Lat_2$. Yes, check whether center of the circle is inside longitude $Lon_1$ and $Lon_2$, else go check case II

Case II. Check whether the circle cuts longitudes $Lon_1$ or $Lon_2$ by verifying the existence of solution for the equations.

$$\cos(CLon-Lon_2)\times\cos(CLon)\cos(Lat) + \sin(CLon)\sin(Lat) = \sin(FHAng)$$

$$\cos(CLon-Lon_1)\times\cos(CLon)\cos(Lat) + \sin(CLon)\sin(Lat) = \sin(FHAng)$$
Appendix E. Selection of spotbeams overlapping with LatLongFLA

If these two equations don't have solution, then go to case III

Case III. Check whether center of the Trapezium is inside the circle or not ($\beta<\text{FHAng}$). If not go to case IV.

Case IV. Check whether circle cuts Lat1 or Lat2 ($\text{LatDiff1}<\text{FHAng}$ or $\text{LatDiff2}<\text{FHAng}$). If yes, check whether one of the cutting point is in between $\text{Lon1}$ and $\text{Lon2}$, else spotbeam or footprint not overlap with the LA.
Appendix F: Sample satellite channel data

Here the data for the S band is given. The data for the rest of the environment can be found in [99] (L band) and [100] (S band).

Table F-1: Urban direct path parameters

<table>
<thead>
<tr>
<th>Elevation angle</th>
<th>Time Share of shadowing</th>
<th>Good and bad duration</th>
<th>Rice Factor</th>
<th>Shadowed Raleigh/Lognormal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dg/(m)</td>
<td>Db/(m)</td>
<td>μ (dB)</td>
</tr>
<tr>
<td>30</td>
<td>0.2653</td>
<td>9.6301</td>
<td>3.4781</td>
<td>6.3031</td>
</tr>
<tr>
<td>45</td>
<td>0.6211</td>
<td>5.5217</td>
<td>9.0514</td>
<td>3.5162</td>
</tr>
<tr>
<td>60</td>
<td>0.1676</td>
<td>10.6736</td>
<td>2.1491</td>
<td>11.9791</td>
</tr>
<tr>
<td>80</td>
<td>0.0786</td>
<td>19.8078</td>
<td>1.6902</td>
<td>11.7973</td>
</tr>
</tbody>
</table>

Table F-2: Urban environment near echo parameters

<table>
<thead>
<tr>
<th>Echo Parameter</th>
<th>N\textsuperscript{(a)} Poisson</th>
<th>Max. Delay ( \tau_c \text{(nsec)} )</th>
<th>Delay ( \Delta\tau^{(n)} \text{exp.} )</th>
<th>S((\tau))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation angle</td>
<td>(\lambda)</td>
<td>(\tau_c) (nsec)</td>
<td>b ((\mu)sec)</td>
<td>S0 (dB)</td>
</tr>
<tr>
<td>30</td>
<td>1.1811</td>
<td>80.2891</td>
<td>0.0335</td>
<td>-18.8222</td>
</tr>
<tr>
<td>45</td>
<td>0.9841</td>
<td>67.8061</td>
<td>0.0289</td>
<td>-18.2478</td>
</tr>
<tr>
<td>60</td>
<td>1.5013</td>
<td>95.3197</td>
<td>0.0422</td>
<td>-21.4119</td>
</tr>
<tr>
<td>80</td>
<td>1.6395</td>
<td>98.691</td>
<td>0.0441</td>
<td>-21.9008</td>
</tr>
</tbody>
</table>
Appendix G: Satellite constellation parameters

Table G-1: Satellite constellation parameters

<table>
<thead>
<tr>
<th>Descriptions</th>
<th>LEO-66 (Iridium)</th>
<th>LEO-48 (Globalstar)</th>
<th>MEO-10 (ICO)</th>
<th>GEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of satellites</td>
<td>66</td>
<td>48</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Number of planes</td>
<td>6</td>
<td>8</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Inclination of the plane (Deg)</td>
<td>86.4</td>
<td>52</td>
<td>44.4</td>
<td>0</td>
</tr>
<tr>
<td>Orbit period (min)</td>
<td>100.45</td>
<td>114.09</td>
<td>359.13</td>
<td>1436.07</td>
</tr>
<tr>
<td>RAAN (Deg)</td>
<td>30.0</td>
<td>45.0</td>
<td>180</td>
<td>0</td>
</tr>
<tr>
<td>Anomaly (Deg)</td>
<td>16.364</td>
<td>7.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Number of Tiers (N_Tier)</td>
<td>4</td>
<td>2</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Minimum elevation angle (Deg)</td>
<td>8.0</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Further details on satellite constellation parameters can be found in [27].

Number of spotbeam in a footprint ($N_{\text{spot/foot}}$) is given by equation (G-1) and the ratio between footprint half angle and spotbeam half angle ($R_{FHASHA}$) is given by equations (G-2) and (G-3).

$$N_{\text{spot/foot}} = 1 + 3N_{\text{Tier}}(N_{\text{Tier}} + 1)$$  \hspace{1cm} (G-1)

$$R_{FHASHA} = \sqrt{(0.5 + 1.5N_{\text{Tier}})^2 + 0.75} \quad \rightarrow \text{for } N_{\text{Tier}} \text{ even}$$ \hspace{1cm} (G-2)

$$R_{FHASHA} = (0.5 + 1.5N_{\text{Tier}}) \quad \rightarrow \text{for } N_{\text{Tier}} \text{ odd}$$ \hspace{1cm} (G-3)
Appendix H: Signalling network parameters

Table H-1: Link, database access and switching cost

<table>
<thead>
<tr>
<th>Databases, junctions and switches</th>
<th>$C_{VLR}$</th>
<th>$C_{HLR}$</th>
<th>$C_{LSTP}$</th>
<th>$C_{RSTP}$</th>
<th>$C_{RMSC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>1</td>
<td>1.2</td>
<td>1.5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Links</th>
<th>$C_{A-Link}$</th>
<th>$C_{C-Link}$</th>
<th>$C_{D-Link}$</th>
<th>$C_{RA-Link}$</th>
<th>$C_{RE-Link}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.9</td>
<td>0.7</td>
<td>1.0</td>
<td>1.6</td>
<td></td>
</tr>
</tbody>
</table>

The data in Table H-2 are decided based on the data from literature [91][92][115] and the network architecture defined in this chapter 6.

Table H-2: Processing time of network entities

<table>
<thead>
<tr>
<th>Processing time/(ms)</th>
<th>VLR</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LSTP</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>RSTP</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>HLR</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Message length /(bytes)</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link capacity /(kb/s)</td>
<td>64</td>
</tr>
</tbody>
</table>