Network and Signalling Aspects of Satellite Personal Communication Networks

by

Cionaith Cullen

Thesis submitted to the University of Surrey
for the degree of Doctor of Philosophy

Dept. of Electronic and Electrical Engineering
University of Surrey, Guildford, England.

© C. Cullen 1995
Abstract

The use of satellites for mobile communication applications has become a global issue. The use of handheld, vehicle mounted and transportable terminals is a key feature of Satellite Personal Communication Networks (S-PCNs). Due to the higher eirp requirements on the Earth's surface and also because of their inherent delay, geostationary (GEO) satellites are not considered suitable for such applications. Instead, constellations of satellites at lower altitudes have been proposed for use in what are termed 2nd generation mobile satellite communication systems.

Low intensity regions in the Earth's surrounding trapped radiation bands, have resulted in two altitude bands of specific interest, resulting in two constellation types - LEO (Low Earth Orbit) constellations at around 1,000 km and MEO (Medium Earth Orbit) constellations at around 10,000 km. A satellite constellation consists of a number of satellites orbiting at the same altitude and inclination and phased in a specific way. The work reported in this thesis proposes a network control architecture for LEO or MEO based S-PCN systems. Air-interface signalling aspects are then considered for mobility management and call setup signalling.

LEO and MEO constellation design aspects and properties are initially considered. Important implications on the control network are drawn based on constellation coverage and connectivity properties. Other system constraints such as terrestrial network interworking considerations as well as user, network operator and regulator requirements are also considered. Finally network and more specifically satellite control signalling is examined before a S-PCN architecture is proposed. The reference architecture results in constellation control being distributed globally with individual satellite control, at any one time, being located at a specific earth station. The use of two earth station types allows network administration to be separated from traffic channel carrying aspects. In order to reduce system setup cost and delay, the reuse of network related standards from the GSM terrestrial mobile communication system is envisaged. An equivalence is made between the S-PCN architecture and the GSM's terrestrial architecture. Network implementation aspects are considered for a 14 satellite MEO constellation. Network implications resulting from the use of LEO and MEO constellations are considered.

After an examination of S-PCN traffic demand on a MEO constellation, mobility management signalling is considered. A new approach is proposed based on the use of a positioning system. The performance of this approach is examined from a system signalling viewpoint for both LEO and MEO constellations and a method to minimise the required amount of signalling is described. The air interface signalling procedure for location update, based on a modified GSM network layer protocol, is simulated from a delay point of view for both LEO and MEO constellations. User-originated, user-terminated and user-to-user call setup signalling were also simulated and their delay performance examined. The importance of random access channel delay and of user cooperation with the link were highlighted as aspects which have a significant influence on the average signalling delay. Finally, the effect of common and dedicated control channel system signalling on satellite power consumption, based on busy hour call setup and mobility management signalling estimates, was examined for a MEO constellation. From this conclusions can be made on the signalling power efficiency of S-PCN systems.
Acknowledgements

Thanks go out to a lot of people who have helped me, either directly or indirectly, in writing this report.

Professor Barry Evans and Rahim Tafazolli were the two who took me on at the start and to whom I am deeply grateful and hold in very high regard. A special mention also goes to my immediate work colleagues, and in particular Tony Sammut, for his continuous cooperation and friendship. I am also grateful to Javier Benedicto for the opportunity of working at ESTEC and for the help he gave me there.

There are others, from beyond these walls, who have helped, distracted and amused me in plenty of interesting ways. Their contribution is not underestimated. Slán and Salut.
# List of Contents

Abstract........................................................................................................................................ii
Acknowledgements....................................................................................................................... iii
List of Contents............................................................................................................................ iv
List of Acronyms............................................................................................................................ ix

## Chapter 1 Introduction.............................................................................................................. 1

1.1 Thesis Motivation .................................................................................................................... 1
   1.1.1 1998/2002 Timescale Developments .............................................................................. 2
   1.1.2 2005/2008 Timescale Developments .............................................................................. 3
1.2 Thesis Structure....................................................................................................................... 3
1.3 Original Achievements .......................................................................................................... 5

## Chapter 2 Satellite Constellations............................................................................................. 8

2.1 Space Segment Requirements ............................................................................................... 8
   2.1.1 Constellation Altitude ..................................................................................................... 10
      2.1.1.1 Constellation Radiation Environment .................................................................... 11
      2.1.1.2 Resonant Altitudes ................................................................................................. 12
      2.2.1.3 Other Aspects ...................................................................................................... 16
2.2 Constellation Design.............................................................................................................. 17
   2.2.1 'Street of Coverage' Approach ..................................................................................... 18
   2.2.2 'Rosette' Approach ....................................................................................................... 20
2.3 S-PCN Constellations ........................................................................................................... 22
   2.3.1 Iridium .......................................................................................................................... 22
   2.3.2 Globalstar ..................................................................................................................... 23
   2.3.3 MAGSS-14 ................................................................................................................... 25
   2.3.4 'Deligo' Constellation ................................................................................................. 28
2.4 Constellation Connectivity .................................................................................................... 29
   2.4.1 Constellation Properties ............................................................................................... 29
2.5 Conclusions......................................................................................................................... 30

## References................................................................................................................................ 31

## Chapter 3 S-PCN Architecture................................................................................................. 34

3.1 The GSM Network Architecture ........................................................................................... 34
3.2 S-PCN / GSM Interoperability ............................................................................................. 36
   3.2.1 S-PCN Requirements ................................................................................................. 38
      3.2.1.1 S-PCN User Requirements .................................................................................. 38
      3.2.1.2 S-PCN Operator Requirements ......................................................................... 39
3.2.1.3 S-PCN Regulator Requirements ................................................................. 40
3.2.2 Quality and Cost considerations ................................................................. 40
3.2.2.1 GSM to S-PCN Traffic Overflow ............................................................. 40
3.2.2.2 GSM to S-PCN Handover .................................................................... 41
3.2.2.3 S-PCN to GSM Handover .................................................................... 42
3.2.2.4 S-PCN Home Location Register ............................................................ 42
3.2.3 Implications of Dynamic Constellations ................................................. 43
3.3 Baseline S-PCN Architecture .................................................................. 43
3.3.1 Spotbeam Control ................................................................................... 43
3.3.2 Satellite Control ....................................................................................... 44
3.3.3 Constellation Control ............................................................................... 45
3.3.4 Competition .............................................................................................. 47
3.4 Conclusions ................................................................................................. 50

References ........................................................................................................ 50

Chapter 4 Network Implementation Aspects .................................................. 51
4.1 S-PCN Ground Segment ............................................................................. 51
4.1.1 MAGSS-14 Ground Segment Layout .................................................... 51
4.1.2 Ground Segment Signalling .................................................................... 55
4.2 S-PCN / GSM Equivalence ......................................................................... 55
4.2.1 S-PCN / BSS Equivalence ........................................................................ 56
4.2.1.1 Traffic Earth Station Transceiver (TEST) .............................................. 57
4.2.1.2 Traffic Earth Station Controller (TESC) ................................................ 57
4.2.1.3 Comparison ......................................................................................... 57
4.2.2 S-PCN / MSC Equivalence .................................................................... 58
4.3 Other S-PCN Aspects .................................................................................. 59
4.3.1 Route Optimisation .................................................................................. 59
4.3.2 Frequency Management .......................................................................... 61
4.3.3 On-Board Network Controller ................................................................. 63
4.3.3.1 Satellite Power Availability ................................................................. 64
4.3.3.2 Common Control Channel Coordination .......................................... 64
4.3.3.3 List of Traffic Channels ...................................................................... 65
4.3.3.4 OBNC Implementation ...................................................................... 65
4.3.3.5 OBNC Review .................................................................................... 65
4.4 S-PCN Operation ......................................................................................... 65
4.4.1 Dual-mode Terminals .............................................................................. 65
4.4.1.1 Terminal Registration ........................................................................ 66
4.4.2 User-Terminated Call Setup ................................................................... 66
4.4.3 User-Originated Call Setup .................................................................... 68
4.5 Conclusions ................................................................................................. 69

References ........................................................................................................ 69

Chapter 5 S-PCN Signalling and Traffic ....................................................... 71
5.1 Common and Dedicated Control Channels .................................................. 71
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGCH/s</td>
<td>Access Grant Channel/satellite</td>
</tr>
<tr>
<td>BCCH/s</td>
<td>Broadcast Control Channel/satellite</td>
</tr>
<tr>
<td>BSS</td>
<td>Base Station System</td>
</tr>
<tr>
<td>BSC</td>
<td>Base Station Controller</td>
</tr>
<tr>
<td>BTS</td>
<td>Base Transceiver Station</td>
</tr>
<tr>
<td>DSC</td>
<td>Dynamic Satellite Constellation</td>
</tr>
<tr>
<td>FPLMTS</td>
<td>Future Public Land Mobile Telecommunications Systems</td>
</tr>
<tr>
<td>GES</td>
<td>Gateway Earth Station</td>
</tr>
<tr>
<td>GEO</td>
<td>Geostationary Earth Orbit</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile communication</td>
</tr>
<tr>
<td>HLR</td>
<td>Home Location Register</td>
</tr>
<tr>
<td>HLR/s</td>
<td>Home Location Register/satellite</td>
</tr>
<tr>
<td>IMEI/s</td>
<td>International Mobile Equipment Identity/satellite</td>
</tr>
<tr>
<td>IMSI/s</td>
<td>International Mobile Subscriber Identity/satellite</td>
</tr>
<tr>
<td>LAPDm</td>
<td>Link Access Protocol on the D channel/modified</td>
</tr>
<tr>
<td>LEO</td>
<td>Low-altitude Earth Orbit</td>
</tr>
<tr>
<td>MEO</td>
<td>Medium-altitude Earth Orbit</td>
</tr>
<tr>
<td>MS</td>
<td>Mobile Station</td>
</tr>
<tr>
<td>MSC</td>
<td>Mobile-services Switcing Center</td>
</tr>
<tr>
<td>OBNC</td>
<td>On-Board Network Controller</td>
</tr>
<tr>
<td>OBP</td>
<td>On-Board Processing</td>
</tr>
<tr>
<td>PCH/s</td>
<td>Paging Channel/satellite</td>
</tr>
<tr>
<td>PLMN</td>
<td>Public Land Mobile Network</td>
</tr>
<tr>
<td>RACE</td>
<td>Research on Advanced Communications in Europe</td>
</tr>
<tr>
<td>RACH/s</td>
<td>Random Access Channel/satellite</td>
</tr>
<tr>
<td>S-PCN</td>
<td>Satellite Personal Communication System/Network</td>
</tr>
<tr>
<td>TES</td>
<td>Traffic Earth Station</td>
</tr>
<tr>
<td>TESC</td>
<td>Traffic Earth Station Controller</td>
</tr>
<tr>
<td>TEST</td>
<td>Traffic Earth Station Transceiver</td>
</tr>
<tr>
<td>TMSI/s</td>
<td>Temporary Mobile Subscriber Identity/satellite</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunication System</td>
</tr>
<tr>
<td>UT</td>
<td>Universal / User Terminal</td>
</tr>
<tr>
<td>VLR</td>
<td>Visitor Location Register</td>
</tr>
<tr>
<td>VLR/s</td>
<td>Visitor Location Register/satellite</td>
</tr>
<tr>
<td>MAP</td>
<td>Mobile Application Part</td>
</tr>
</tbody>
</table>
Chapter 1  Introduction

Mobile satellite communication Services were initially provided by Inmarsat, the International Maritime Satellite Organisation. Their most advanced currently operable service allows users to access the PSTN network using portable (briefcase-size) terminals [Inmarsat-M]. An almost global coverage is provided through the use of a constellation of 4 geostationary (GEO) satellites. This Inmarsat system could be considered as being towards the forefront of 1st generation (although it is a digital system) mobile satellite systems.

With the proposal of Iridium - a 77 satellite constellation of satellites orbiting the Earth at an altitude of 785 km\(^1\) - by Motorola in 1991, the concept of 2nd generation mobile satellite communication systems (S-PCN) was born. The aim is to provide global voice and data services to users with handheld and low power terminals. Iridium is termed a Low-altitude Earth Orbit (LEO) system because its altitude is below the damaging lower belts of trapped-Earth radiation (i.e. below about 2,000 km). Constellations at altitudes above the lower belts of trapped-Earth radiation are termed Medium-altitude Earth Orbit (MEO) systems and are at about 10,000 km.

Following the Iridium proposal, other ‘similar’ proposals of LEO and MEO constellations have followed. The implementation timescale of these systems is, optimistically, around 1998. However, before the end of the millennium seems a more reasonable estimate, considering the magnitude of the developments still required - both technical and otherwise. This thesis is aimed specifically at these near-future, non-GEO mobile satellite communication systems. It is therefore oriented towards systems such as Iridium [Iridium], Globalstar [Globalstar], Odyssey [Odyssey] and Inmarsat-P [Inmarsat-P].

These 2nd generation mobile satellite communication systems (called ‘Big LEOs’ at WARC’92 [WARC’92]\(^2\)) intend to offer services such as low bit rate (e.g. 4.8 kb/s) voice, low rate data messaging, paging and positioning services. These services are to be provided to handheld, low power terminals as well as to vehicle mounted, transportable and even fixed terminals. The target market for these S-PCN systems consists of business (‘international traveler’) users and also maritime, aeronautical and developing country (using fixed terminals to supplement the existing telecommunications structure) users. A basic level of interoperability with terrestrial mobile cellular systems allowing interoperability with terrestrial mobile networks through the use of dual mode terminals and a single subscriber number, is an important S-PCN objective.

1.1 Thesis Motivation

For S-PCN systems, there are many technological challenges involved. Ultimately, providing an economically sufficient number of terrestrial quality channels to system users is their most important objective. S-PCN systems are all aiming at complementing terrestrial network coverage. The Global System for Mobile

---

1 It has since become a 66 satellite constellation at a slightly higher altitude.

2 ‘Little LEOs’ could also be at either LEO or MEO altitudes but they were restricted to non-real time services such as data transmission.
communications (GSM) system [GSM], because of its rapid global acceptance, is the only terrestrial system with which all the above mentioned S-PCN systems aim to be compatible with. The reuse of GSM standards, specifically in terms of protocols (with appropriate modifications) and network nodes, is a very important issue for these systems. It means that less development work is required on those aspects which are reused, reducing system development costs, development time and simplifying interoperability with terrestrial networks. Such an approach, in which current operational systems are modified and enhanced, is an evolutionary approach in that it allows current standards to drive development.

Another approach to system development is termed the revolutionary approach. With this approach, a new system is designed which is completely different from those systems which already exist. An example of the successful application of this approach was the development in Europe of the 2nd generation mobile terrestrial communication system - GSM. The GSM terrestrial mobile communications system has since become the unofficial global standard for terrestrial mobile communications. This system, based on advanced digital transmission and signalling methods, has distinct advantages over first generation analog mobile terrestrial communication systems.

The cost of revolutionary system development can be very high and the development period can be long, due to the new technologies which must be developed. However, as with the GSM system and its rapid global growth, the resulting improvement in system performance can be a big factor. The evolutionary approach usually involves less initial investment. It is also usually more secure in terms of its market since a current market already exists. For S-PCN this current market comes in the form of terrestrial systems which do not provide full coverage.

1.1.1 1998/2002 Timescale Developments

At the WARC'92 conference, 2 x 16.5 MHz of spectrum (at L and S bands) was allocated globally for S-PCN applications (termed 'Big LEO' systems at the conference). No system was allocated specific spectrum at that stage. Recently, the American FCC (Federal Communications Committee) has licensed three of the currently proposed S-PCN systems in the United States [Space News]. This ruling is likely to have global implications, resulting in the 2 x 16.5 MHz of available bandwidth being shared between these systems globally. The most likely allocation scenario, and one which has already been suggested by the FCC, is as follows:

- Allocate 2 x 5.5 MHz to the Iridium 66-satellite, TDMA-based, LEO system. In fact Iridium proposed to use Time Division Duplex/TDMA.
- Grant 2 x 5.5 MHz of the remaining 11 MHz to the Globalstar 48-satellite, CDMA-based, LEO system.
- Allocate the remaining 2 x 5.5 MHz to the Odyssey 12-satellite, CDMA-based, MEO system.

The Inmarsat-P 10-satellite MEO proposal is not included here as no application was made to the American FCC. However, it has already applied for FPLMTS spectrum which should be available by the year 2000. Because being first to the market place is likely to be an important factor determining the economic viability of these systems, all are currently under accelerated and secretive development. Each of these systems
involves the development of new technologies - both on the satellite and on the ground. This thesis concerns research into S-PCN systems from a network architecture and air interface signalling point of view.

A key feature of these systems is their use of non-geostationary orbits to provide basic services to handheld and mobile terminals. Another feature is the high level of interoperability with 2nd generation terrestrial mobile systems envisaged (compared with 1st generation GEO systems). With launch around the year 1998 and a 7 to 10 year constellation lifetime, the initial phase of these systems should be operable until about 2005 / 2008. Further system phases can then build on the services previously offered and improve system quality and efficiency.

1.1.2 2005/2008 Timescale Developments

Work has already started, in ITU and in ETSI, on outlining a framework for 3rd generation mobile communication systems. In Europe the 3rd generation system is termed UMTS [UMTS]. Globally, these systems come under the IMS-2000 (or FPLMTS) umbrella [IMS-2000]. Such systems are planned for introduction in the period 2005/2010 and will include a satellite component, called S-UMTS in Europe.

Three different options are being considered within ETSI- 'evolutionary', 'migratory' or 'revolutionary'. The 'evolutionary' approach, is when the 3rd generation system is developed from current 2nd generation systems. The 'revolutionary' approach involves the development of a completely new 3rd generation system. The 'migratory' approach can be considered as a compromise between the two other approaches. It is a migration from a known starting point (2nd generation systems) to a known finishing point (3rd generation system specifications).

The ETSI approach was initially based on a revolutionary approach, in that a wholly new and more advanced systems are being studied. However, due to the high level of investment in current 2nd generation systems (e.g. the GSM standard took 10 years to develop and is only operable since 1991), there is a reluctance among the mobile communications industry to implement a 3rd generation mobile communication system until the investment made on the 2nd generation GSM system has been justified. A strong preference exists within the European mobile industry towards the reuse of current developed technologies. A study performed for the European Commission [KPMG] shows this clearly. The 'migratory' approach is therefore likely to have a very big influence on the development of future terrestrial and satellite mobile communication systems.

The starting point for such a migration in Europe (and in most of the world), would be the GSM system. The GSM system, in terms of its network architecture and protocols is therefore very important to S-PCN systems. Work in this thesis is directed at the development of a S-PCN architecture and therefore is generally 2nd generation, S-PCN oriented.

1.2 Thesis Structure

This thesis examines the networking of LEO and MEO satellite constellations. It goes on to examine S-PCN mobility management and air-interface common and dedicated control channel signalling, based on the use of a modified GSM LAPDm air-interface protocol. Evaluation is made on a new approach to S-PCN mobility management and
air interface signalling is examined from a signalling delay and user requirement point of view. Finally the effect of common control channel signalling on satellite power consumption is examined.

The structure of this thesis is basically the same as the approach adopted over the research period. Chapters 2, 3 and 4 concern non-geostationary constellation design and the development of a baseline network architecture for S-PCN systems. In chapters 5, 6, 7 and 8, this network architecture is used as a baseline over which network air-interface common control channel signalling aspects are examined. A slightly modified network layer version of the LAPDm GSM protocol messages are simulated in the satellite network. For the S-PCN physical layer, only basic bit-rate assumptions are made with no physical channel mapping or consideration of the multiple access approach. Individual chapters are now reviewed.

After this introduction, chapter 2 examines satellite constellation design techniques. These are the Rider 'Street of Coverage' approach and the Ballard 'Rosette' approach. From this, two constellations - a slightly modified Globalstar and the European Space Agency's proposal - Medium Altitude Global Satellite System [MAGSS14] - are chosen as representative LEO and MEO constellations respectively. These are examined from a signalling point of view in later chapters. Work is presented on constellation properties which are of particular importance for S-PCN networking and connectivity. Orbit resonance was noted as a useful property and a new resonant LEO constellation called Deligo is proposed, which offers a unique set of coverage properties.

In chapter 3, requirements on a S-PCN architecture are examined from the users, the operators and the regulators viewpoints. Integration aspects with the GSM terrestrial mobile communications system are also examined. Considerations from chapter 2 relating to the dynamic properties of these constellations are also input here. Based on these requirements and considerations, a S-PCN architecture is proposed. By using globally distributed network control with full local centralized control of individual satellites, the architecture aims to minimise air-interface signalling overheads while providing effective system control.

Chapter 4 initially proposes a possible ground segment implementation based on the S-PCN architecture described in chapter 3 and the MAGSS-14 MEO constellation. The architecture provides 100% dual control connectivity for each satellite in the constellation. The equivalence between the proposed architecture and the GSM network architecture is compared and contrasted. Important aspects concerning S-PCN implementation such as route optimisation, frequency management and the potential role of an on-board network controller are considered. Finally, basic S-PCN operation is reviewed.

Chapter 5 looks in a general way at space segment common and dedicated control signalling channels, used for mobility management and call setup signalling. Based on the likely propagation link conditions and the excess margin compared with a voice channel, channel bit rates are estimated. Peak traffic signalling rates are estimated for the MAGSS-14 constellation and the throughput requirement on individual signalling channels are indicated. Operation of the random access and paging channels is considered here.
In chapter 6, approaches for S-PCN mobility management are considered. A new approach, based on the use of a positioning system for monitoring the location of user terminals, in combination with a specific network uncertainty radius, is proposed. This approach is seen to minimise air-interface signalling compared to other approaches being currently considered. Using modified LAPDm (the network layer - Layer 3 - air interface signalling protocol used by the GSM system) messages, the location update procedure signalling delay spread for both the LEO and MEO baseline constellations is found by simulation. This allows important conclusions to be drawn on system operation and performance. Finally, the previously proposed mobility management approach is analysed in terms of its air-interface signalling requirement based on a user mobility curve. A trade-off is performed between location updating signalling requirement and paging signalling requirement, allowing an optimum uncertainty radius to be found for both the LEO and MEO constellations considered. The peak power requirement, in equivalent voice channels, of mobility management signalling is estimated for the MAGSS-14 constellation where values on peak signalling rates were available.

Chapter 7 uses the proposed S-PCN architecture to examine call setup signalling aspects. The signalling messages used are based on a modified version of the GSM network layer signalling protocol - LAPDm. User-originated, user-terminated and user-to-user call setup signalling sequences are all simulated according to different operation scenarios. Late assignment of the traffic channel is used in signalling sequences in order to maximize traffic channel usage efficiency. The parameter examined for both the LEO and MEO baseline constellations is the call set-up signalling delay. Based on peak call setup rate estimations for the MAGSS-14 constellation, the equivalent power in terms of voice channels is estimated. From the results obtained, important deductions and comparisons can be made on system operation and performance for both LEO and MEO systems.

Finally, a conclusions and future work section is included in chapter 8. This section reviews the work done and the important contributions made in this thesis as well as highlighting areas where further work needs to be done. Annexes are included which describe the GSM LAPDm protocol message and information element modifications used for S-PCN simulations. The simulation models built to examine the various procedures are described in different annexes.

1.3 Original Achievements

This section lists the original achievements concerning the use of S-PCN systems which are part of this thesis.

1. Orbit and constellation ‘resonance’ was examined and its usefulness was highlighted. A ‘resonant’ LEO constellation providing 100% dual satellite visibility over its full service area was specified and designed.

2. A list of requirements for a S-PCN architecture were specified and a globally distributed architecture was proposed which provided global network control with local individual control of satellites.

3. A global architecture structure was developed for the ‘resonant’ MAGSS-14 constellation and specific S-PCN operational aspects were examined and described.
The equivalence of the proposed architecture with the GSM network architecture is examined.

4. Signalling and traffic channel peak loadings were estimated for the MAGSS-14 MEO constellation. A review of signalling channel requirements and bit rates was also made.

5. A new S-PCN mobility management approach is proposed and compared with other approaches. A trade-off between location update and paging signalling was performed. An estimation of mobility management signalling delay was found through simulation.

6. Delay estimation for different call setup procedures was performed through the simulation of common and dedicated control channel air-interface signalling. LEO and MEO constellation performances were compared under different operating conditions.

7. The peak equivalent voice channel power requirement of common and dedicated control channel signalling for mobility management and call setup signalling was estimated.

A list of different publications resulting from or relating to the work described in this thesis is provided in annex C.

References


Chapter 2 Satellite Constellations

In this chapter the basic requirements for the space segment of a S-PCN system are discussed. This explains why constellations at both MEO and LEO altitudes, about 10,000 km and 1,000 km respectively, rather than higher altitude geostationary Earth orbit (GEO) or elliptical, highly-inclined Earth orbit (HEO) constellations, are preferable for the provision of S-PCN services. Important constellation design parameters such as satellite altitude, minimum elevation angle, path loss, inter-satellite handover frequency and intra-satellite handover frequency are highlighted. Specific work on the constellation property of orbit resonance (resulting in repetitive ground tracks) is described.

The two main constellation design approaches are reviewed. Two new constellations with interesting coverage properties are proposed. Three representative constellations - Iridium (LEO), Globalstar (LEO) and MAGSS-14 (MEO) - are described in some detail, in order to introduce the key aspects of currently proposed constellations. The latter two are used as baseline LEO and MEO constellations for signalling analysis later in this report. Finally, the connectivity properties associated with satellite constellations are specifically examined in order to highlight the problems and implications imposed on S-PCN networks by satellite orbit dynamics.

2.1 Space Segment Requirements

A personal communication network (PCN) is a network that provides personal communication services to users. PCN requirements include:

- Universal service availability (access across multiple networks with wireline or wireless terminals).
- Network mobility management (registration, location management, deregistration).
- Provision of a quality of service similar to fixed networks (this requires suitable availability of traffic channels).
- Customization for individual users (authentication, service profile management, privacy and service flexibility).
- Provision of services to handheld (pocket sized) mobile terminals.

When these terrestrial network requirements are extended to S-PCN, one of the more demanding requirements is to be able to provide users with handheld terminals. Four S-PCN terminal types are envisaged - handheld, portable, vehicle mounted and fixed. Due to their low EIRP and G/T, handheld terminals result in the most extreme system limitations. Handheld terminals are very important in terms of S-PCN market acceptability. Lower satellite orbit altitudes, which result in a reduced free space loss, can offer important advantages to S-PCN systems. GEO (and most HEO) constellations are obviously at a disadvantage here.

Voice is expected to be the prime S-PCN service. Additionally, a real time data service, a low delay data service, a paging service as well as a positioning service are all considered possible for S-PCN implementation. In terms of voice quality, satellite altitude has an important influence. Delays of more than 150 ms require the use of echo cancellers on links. Even with good echo cancellers, the voice service quality is impaired. An upper limit of 400 ms has been recommended by ITU-T for any voice
communication. This recommended delay limit does not exclude any currently considered orbit type - GEO, HEO (e.g. Tundra - 24 hour, Molniya - 12 hour, Archimedes - 8 hour) MEO or LEO. However, LEO and MEO constellations are preferable when the end-to-end delay budget, which includes voice and channel coding delays, is considered.

Another, although less important, disadvantage of GEO satellites is their inability to provide a truly global coverage. Since GEO satellites are 'fixed' relative to the Earth, the coverage quality provided by a satellite (in terms of elevation angle to the satellite) reduces, the further that point is from the sub-satellite point. Due to their orbit inclination of 0° (which keeps them above the equator), GEO satellites provide a reduced service quality to higher latitude regions.

The three main disadvantages of GEO constellations, when considered for the provision of S-PCN services, are now summarized.

- A larger free-space propagation loss, resulting in G/T and power problems for terminals. Also a very large satellite antenna is required to provide sufficient eirp.

- A single-hop propagation delay of about 270 ms is excessive as, with the addition of other system delays, the overall delay can surpass the CCITT's overall delay recommendation of 400 ms.

- An unavoidable coverage disadvantage to regions further from the sub-satellite point.

HEO constellations (which are inclined at a specific angle of about 63° to the equator in order to eliminate a drift in the orbit planes argument of perigee [Wertz]) which use elliptical orbits, result in satellites not being fully active for their full orbit period so coverage ability is reduced. When a satellite reaches apogee, HEO orbits can experience large propagation delays, sometimes even larger than GEO delays, so the first two GEO disadvantages also can apply to HEO constellations, depending on the orbit period being considered.

HEO satellites can provide a global coverage so the third GEO restriction does not apply to them. In [Draim] a HEO constellation of four common period satellites was proposed which provides full earth coverage. This required the four satellites to be active throughout their orbit. In this consideration, the high orbit altitudes and the low coverage elevation angles are not practical for S-PCN applications.

The main advantage of HEO orbits is for regional coverage and considered applications of HEO constellations to date show this - e.g. the Russian use of the Molniya orbit for coverage of its higher latitude regions. The European Space Agency has proposed the 8-hour Archimedes constellation for coverage of three regions (spaced by 120°) on the Earth, while the American S-PCN Ellipso [Ellipso] proposal, which is hoping to obtain an FCC license in 1996) is initially aimed at providing north American coverage.

Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) constellations do not suffer from the above disadvantages. Because of their lower altitudes, lower free space loss and lower propagation delays are inherent properties. Also LEO and MEO constellations can, according to the design specification, provide global or almost global coverage making them both compatible with the S-PCN idea of global / almost-global PCN coverage extension. The coverage geometry and altitude restrictions
which result in both LEO and MEO constellation altitudes are considered in the following section.

2.1.1 Constellation Altitude

Having looked at the reasoning behind the move towards lower orbit altitudes, the specific reasons resulting in the LEO and MEO altitude split are now considered. Specific altitudes within this range are then highlighted. Firstly, the satellite coverage geometry is introduced in figure 2.1, which shows the most relevant parameters relating to a satellites coverage of the Earth. The orbit period and the minimum elevation angle indicated refer to the European Space Agencies 'MAGSS-14' MEO constellation proposal, which is explained later. [Davidoff] is a useful reference for this section.

\[ T = \frac{2\pi h}{v} \]

where $T$ is the orbit period, $v$ is the orbital velocity, and $h$ is the satellite altitude.

These parameters are as follows:
- $r_{\text{earth}}$ is the radius of the Earth, which is about 6,375 km ($R_e$ is used in later formulae)
- $h$ is the satellite altitude,
- $\beta$ is the Earth centered half angle of coverage,
- $\rho$ is the slant path range from the Earth to the satellite,
- $S$ is the curved Earth distance between the sub-satellite point and the point to where $\rho$ is being measured.
- $\varepsilon_{\text{UT(min)}}$ is the minimum elevation angle from a user terminal (UT) to the satellite
- $\varepsilon_{\text{ES}}$ is the minimum elevation angle from an earth station (ES) to the satellite.

![Figure 2.1 Satellite Coverage Geometry](image-url)
The size of a region on the Earth's surface that can be served by a communications satellite depends on the satellite altitude \((h)\) and the minimum elevation angle \((\varepsilon_{\text{min}})\) required for coverage. The choice of the minimum elevation angle depends on a variety of factors such as propagation characteristics of the operation environment, link margin restrictions and constellation coverage diversity (if 2 or more satellites are visible at a point). In general, the higher the minimum elevation angle, the better the propagation channel and the lower the link margin required. The area, \(A\), of a region covered by a satellite is given by:

\[
A = 2\pi R_e^2 \left(1 - \cos \beta\right) \quad (2.1)
\]

with

\[
\cos (\beta + \varepsilon_{\text{min}}) = \cos \varepsilon_{\text{min}} / (1 + h / R_e) \quad (2.2)
\]

Equation (2.2) is used to calculate \(\beta\) when the constellation altitude and minimum elevation angle are known. With \(\beta\) known, the slant path range, \(\rho\), can be calculated by the following formula which is derived from application of the cosine rule:

\[
\rho = \left[\left(\frac{R_e + h}{R_e}\right)^2 - \frac{1}{2}\right]^{1/2} \quad (2.3)
\]

In this case \(\beta\) is the Earth centered angle between the sub-satellite point and the point to where \(\rho\) is being measured. It is calculated as follows (with \(\beta\) in radians):

\[
\beta = S / R_e \quad (2.4)
\]

With these basic satellite coverage equations a lot of satellite and constellation coverage and connectivity properties can be worked out. These can be converted into latitude and longitude points according to the satellites sub-satellite point. Finally, they can be plotted on Earth map projections by using the same projection as used for the map.

Constellation altitude is now considered as this is the most fundamental parameter to be decided. The three basic influences on the choice of LEO and MEO altitudes are the Earth's radiation belt intensities, the one-hop propagation delay and the path loss of the link. The latter two factors are linked and both are to be minimized - lower altitudes are therefore preferred. However, altitudes below about 600 km suffer from excessive atmospheric drag and are not considered suitable. The Earth's radiation belts are therefore the main factors which have determined the LEO or MEO choice for constellation altitudes.

### 2.1.1.1 Constellation Radiation Environment

The Earth's space radiation environment consists of three particular radiation types - Galactic, Solar and trapped-Earth. Of these, the trapped-Earth radiation have the most influence on the choice of satellite orbit altitude [Wertz]. Radiation affects a satellite in a number of different ways. For example, radiation damage to solar panels means that these must be initially oversized so that towards the end of the mission they still provide enough power. The trade-off here concerns satellite lifetime or launch mass. Another space radiation effect is in the form of logical upsets on satellite electronics. Space electronics must therefore be radiation hardened (increasing its total accumulated dose resistance level) in order to extend their lifetime in space and reduce the probability of errors (‘upsets’).
The Earth has two inner belts and one outer belt of trapped radiation. The innermost belt consists of electrons and is at its most intense at an altitude of 2,600 km (0.4 Earth radii or \( L = 1.4 \)). The other inner belt, formed by trapped protons, is centered around an altitude of 4,500 km (or \( L = 1.7 \)). The outer belt of trapped-earth radiation consists of electrons and is centered around an altitude of 40,000 km (or \( L = 6.3 \)). In general, the radiation level (and therefore damage to a satellite) increases rapidly with increasing altitude until it peaks at about 2,600 km. It then drops slowly before increasing again at an altitude of about 13,000 km. Air-drag, rather than a high radiation level, is the limiting factor on the lower end of the LEO orbit altitude range.

The conclusion from this is that altitudes between about 600 km and 2,000 km experience acceptable levels of radiation allowing for a respectable satellite lifetime without significantly increasing satellite costs. Between 2,000 km and about 9,000 km radiation levels are considered particularly high and preferable to avoid. However, one commercial satellite system has been proposed which operates within this altitude range [Ellipso]. Above 9,000 km the levels are again low enough to allow lower cost constellations. Since lower altitudes are needed for S-PCN applications, the radiation levels at higher altitudes are not considered further. The orbit inclination, the angle between the Earth’s equatorial plane and the ascending node of the satellite orbit plane, also influences the radiation level received and so both altitude and inclination effects must be considered. Another important factor is the activity cycle of the Sun, resulting in radiation level peaks approximately every 11 years.

However, two altitude bands have been created through the existence of the high radiation level band and it is this exclusion band which has resulted in the division of constellations by altitude - Medium-altitude Earth Orbit (MEO) constellations and Low-altitude Earth Orbit (LEO) constellation. Constellation altitudes within these two subbands are further considered in the next section.

### 2.1.1.2 Resonant Altitudes

Kepler’s third law relates the orbit period \( (T) \) of a satellite to its semi-major axis \( (a) \):

\[
T^2 = \frac{(4\pi^2)a^3}{\mu_\odot}
\]  

(2.5)

Where:

- \( T \) is the orbit period (s), and
- \( \mu_\odot \) is a physical constant related to the Earth and universal gravity \( (s^2/\text{km}^3) \).

In the constellation design cases considered here, circular orbits are used (orbit eccentricity is 0) so ‘\( a \)’ (the semi-major axis) becomes the addition of the Earth’s radius \( (R_\oplus) \) and the orbit altitude \( (h) \).

A resonant orbit is one whose orbit period is an integer division of a sidereal day\(^2\). Because of this, the orbits ground track over the Earth repeats on a regular basis since

---

1 A recent discovery [Dyer] showed that large solar flares can create long lived trapped-proton radiation belts. This discovery is of particular significance as it affects the lower end of the MEO altitude scale. The belt is at an altitude of around 8,300 km \( (L = 2.3) \).

2 A sidereal day is the time it takes the Earth to rotate exactly 360° and is about 1436 minutes. A solar day, during which the Earth rotates slightly more than 360°, is 24 hours (1440 minutes).
the orbit period is synchronized to be an integer division of the Earth's daily rotation. For a satellite inclined at an inclination of \(i^\circ\), the Earth track consists of a series of identical excursions alternately into the northern and southern hemisphere, each reaching a maximum latitude equal to the orbit inclination (or \(180^\circ - i\) for \(i > 90^\circ\)).

Successive ascending nodes occur at westward (since the Earth rotates from West to East) geographical longitude increments of \(\Omega_r\), where \(\Omega_r\) is the rotation of the Earth relative to the orbit plane in one orbit period, \(T\). \(\Omega_r\) has two components - the dominant component is the Earth's own rotation rate \(\Omega_e\) (360° each 1436 minutes) and the combined sum of various perturbing forces (these are quantified below).

Although the Keplerian orbit provides an excellent reference, other forces do act on the satellite to perturb it away from the nominal orbit. The most important perturbing forces are termed 'secular' variations, the effect of which are continuous rather than periodic. The primary forces which perturb a satellite orbit arise from third bodies such as the Sun, the Moon and the non-spherical mass distribution of the Earth. Atmospheric drag is most significant at LEO altitudes [Wertz]. At these lower altitudes, air-drag (the magnitude of which is closely related to solar activity) is the main reason why regular orbit-maintenance maneuvers are necessary [Rosengren].

The Sun and Moon cause secular variation in both the argument of perigee (\(\omega\)) and in the right ascension of the ascending node (\(\Omega\), RAAN), especially for high altitude orbits. Since circular orbits are being considered, the argument of perigee is not relevant and only the RAAN rotation effect is examined. The approximate RAAN rotation values concerning sun and moon effects are calculated as follows:

**Right ascension of the ascending node (RAAN) perturbation effects:**

\[
\Omega_{\text{MOON}} = -0.00338 \cos i / n \text{ (°/day)} \tag{2.6}
\]

\[
\Omega_{\text{SUN}} = -0.00154 \cos i / n \text{ (°/day)} \tag{2.7}
\]

where: \(i\) is the orbit inclination, and

\(n\) is the number of orbits per day.

Perturbation forces caused by the Earth's bulge can be found using the approximate equation:

\[
\frac{d\Omega_r}{dt} = -9.95 \left(\frac{R_e}{a}\right)^{7/2} \cos i \text{ (°/day)} \tag{2.8}
\]

(only applies to circular orbits, \(e = 0\)).

Of the secular forces mentioned, Earth oblateness perturbations cause the largest magnitude in effect for LEO, MEO and even GEO altitudes. The above orbit perturbations effect similar satellite orbits in an identical fashion - they apply equally to similar orbit types. Ascension node drift and the inclination angle fluctuations are the same for all satellites to a first order of magnitude.

If \(\Omega_r / 2\pi\) is equal to \(M/L\), where \(M\) and \(L\) are integers, then the sub-satellite track is repetitive after the completion of \(L\) orbits in \(M\) sidereal days, having covered \(2\pi\) geographical longitude. This condition is called L:M orbit resonance. When \(M = 1\), then a daily repetition results, which is the shortest possible repetition rate. Having each satellite in the constellation with a repetitive ground track can be very useful to a
S-PCN system. The advantages resonant orbits can offer constellation design are now reviewed:

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.

These specific advantages offered by resonant constellations were highlighted in [Cullen92] in which a resonant LEO constellation was proposed. At about the same time the European Space Agency proposed a resonant MEO constellation at an altitude of 10,354 km [Benedicto]. Soon after this, the altitude of the Odyssey constellation was adjusted upwards from an altitude of 10,200 km [Odyssey91] to the resonant altitude of 10,354 km [Odyssey92]. The following table [Cullen93/1] lists the daily unperturbed resonant orbits in the LEO and MEO altitude range. These altitudes are resonant for orbit inclinations of 90° but require modification for different orbit inclinations in order to compensate for the perturbing forces.

<table>
<thead>
<tr>
<th>L:M</th>
<th>Altitude (km)</th>
<th>δ_10 (°)</th>
<th>p_10 (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:1</td>
<td>877 km</td>
<td>20.1°</td>
<td>1,511 km</td>
</tr>
<tr>
<td>13:1</td>
<td>1,248 km</td>
<td>24.6°</td>
<td>2,071 km</td>
</tr>
<tr>
<td>12:1</td>
<td>1,666 km</td>
<td>28.7°</td>
<td>2,652 km</td>
</tr>
<tr>
<td>11:1</td>
<td>2,146 km</td>
<td>32.5°</td>
<td>3,302 km</td>
</tr>
<tr>
<td>5:1</td>
<td>8,041 km</td>
<td>54.2°</td>
<td>10,147 km</td>
</tr>
<tr>
<td>4:1</td>
<td>10,354 km</td>
<td>58.0°</td>
<td>12,583 km</td>
</tr>
<tr>
<td>3:1</td>
<td>13,892 km</td>
<td>62.0°</td>
<td>16,332 km</td>
</tr>
</tbody>
</table>

*Table 2/1 - Unperturbed Resonant Altitudes*

The δ\_10 column indicates the Earth-centered angle relating to a minimum elevation angle of 10°. The p\_10 column indicates the slant path range down to the 10° elevation point. Link budgets need to take the largest slant range value into account for worst case calculations. This difference, in dBs, is most significant for lower altitude orbits and reduces their free space loss advantage. For example the 14:1 LEO altitude (Iridium-like) has a min / max variation of 2.34 dB [10 log\_10 (1,511 / 880)] while the 4:1 MEO constellation has a variation of only 0.84 dB. The difference between these two figures reduces the relative advantage of the LEO constellation by 1.5 dB.

Orbit perturbation forces affect the right ascension of the ascending node, resulting in the precession of the orbit plane. For non-polar orbit inclinations, perfect orbit resonance does not occur due to these perturbing scalar forces. Because of this, a repetitive ground track is not achieved and all orbit planes precess at the same rate - this RAAN drift is not specific to resonant orbits only but applies to all orbit types. The magnitude of this drift is now examined for specific unperturbed resonant altitudes.
Equation 2.8 is used to find, to the nearest order, the magnitude of the RAAN drift - the sun and moon contributions are negligible. The 14:1, 13:1, 12:1 and 4:1 altitudes are considered. In order to do this, specific orbit inclination values were chosen. Because of the cosine dependence, inclinations of 90° obviously are negligibly affected while inclinations of 0° are most affected. The results are tabulated in the table 2/2 below. The reasoning behind the inclination values chosen is explained further in section 2.2.

<table>
<thead>
<tr>
<th>LM</th>
<th>Altitude (km)</th>
<th>i(°)</th>
<th>Ω(°/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:1</td>
<td>877 km</td>
<td>99°</td>
<td>0.9856° / day</td>
</tr>
<tr>
<td>13:1</td>
<td>1,248 km</td>
<td>52°</td>
<td>-3.28° / day</td>
</tr>
<tr>
<td>12:1</td>
<td>1,666 km</td>
<td>54°</td>
<td>-2.60° / day</td>
</tr>
<tr>
<td>4:1</td>
<td>10,354 km</td>
<td>56°</td>
<td>0.19° / day</td>
</tr>
</tbody>
</table>

*Table 2/2 - Orbit Perturbation Magnitude*

From the above table, it is clear that the magnitude of RAAN planar precession about the Earth makes perfect resonance unrealistic in non-polar orbits. For non 90° inclinations, RAAN precession shifts the ascending node in an East to West direction (for a negative magnitude) and in a West to East direction (for a positive magnitude). Unless an orbit inclination of 90° is used then a ground track deviation will result. For the LEO altitudes and inclinations indicated, the RAAN drift results in significantly different ground tracks each day. However, through altitude (orbit period) compensation, the ground track can be made to repeat on an almost daily basis, resulting in resonant orbit advantages like those listed earlier. This is specifically considered in section 2.3.4 where such a 'resonant' LEO constellation is proposed. At the MEO altitude, the magnitude of RAAN planar precession is much smaller. This makes the orbit almost, but not quite, resonant. The drift is relatively small and so a MEO constellation constructed from such orbits would benefit from 'resonant' orbit advantages to an almost full extent. The advantages previously listed can therefore be attained almost in full.

Equation (2.8) can also be used to design sun-synchronous orbits. This is where the precession of the orbit plane due to the Earth's oblateness is designed to equal the Earth's rotation rate around the Sun Ωₚ (i.e. Ωₚ = Ωₚ). Since Ωₚ is 360° every 365.24 days, then equation (2.8) should be designed to give 0.9856° every day. Practically, this means that for each satellite altitude, there is a particular inclination which, if used, will result in a sun-synchronous orbit plane. The 14:1 orbit inclined at 99° and included in table 2/2 is a sun-synchronous orbit. Sun-synchronous orbits result in the sun being located in a geometrically constant way relative to the satellite orbit plane. Two interesting properties result with Sun-synchronous orbits:

1. Satellite solar panel pointing requirements are simplified due to the fixed satellite - sun geometry.

---

3 An important current application of sun-synchronous orbits is for Earth observation. Sun-synchronicity means that the sun angle on the point of observation is constant for equivalent orbit passes, so reducing shadow variability. However, this is not relevant to S-PCN systems.
2. Satellite thermal properties become easier to predict and therefore easier to counter [Rosengren].

Sun-synchronous orbits result in a satellite plane being oriented towards the sun in a fixed way. This results in the satellite being visible to regions on the Earth at specific Sun geometry’s. For example, a sun-synchronous satellite which has its orbit plane passing over the illuminated / shaded Earth divide will be visible at both dawn and dusk each day. Such orbits allow satellite design to be optimised and can result in extended orbit lifetime and also in lower satellite construction costs [Rosengren].

However, for traffic oriented systems (such as S-PCN), having satellite always visible to the Earth at specific times can be disadvantageous. This is because traffic levels on the Earth are also related to the sun’s position (the time of day). For example, the plane of satellites pointing directly towards the sun will always pass over Earth at noon and at midnight while the plane of satellites perpendicular to this direction will always pass over the Earth at dawn and at dusk. Clearly, the demand for satellite traffic channels as well as satellite solar panel exposure to the sun, will vary greatly between different planes, possibly resulting in an excess traffic demand on some satellite planes. Because of this traffic loading problem, it may be that sun-synchronous orbits are unsuitable for S-PCN applications although considering the large ocean and even land regions where traffic demand is expected to be very low, this is not clear. In order to find out, different sun-synchronous orbit plane geometry’s in conjunction with an Earth traffic map would have to be considered in terms of the resulting effect on satellite power availability. This aspect has not been specifically considered here.

**2.2.1.3 Other Aspects**

Propagation delay is considered here as the main parameter. However other constellation related aspects such as Doppler shift and sub-satellite point velocity, are also considered [Cullen93/1].

At the GEO altitude of 35,863 km and working down to an elevation angle of 5°, a one-hop (ground to satellite to ground) delay is about 270 ms. At a MEO altitude of 10,355 km and working down to a 10° elevation angle again, a one-hop delay is about 90 ms. At a LEO altitude of 1,414 km and using the same 10° minimum elevation angle, the maximum one-hop delay is about 14 ms. Considering that lower constellation altitudes are preferred (to maximize the power to handheld terminals) the preferred LEO and MEO altitudes would be at the lower end of their scales. The preferred altitude at the lower end of the MEO altitudes is the 4:1 resonant 10,355 km altitude (4 orbits per sidereal day). For LEO altitudes, three resonant altitudes fall into the preferred altitude range. These are 880 km (14 orbits per sidereal day) and 1,248 km (13 orbits per sidereal day) and 1,667 km (12 orbits per sidereal day). The effects of satellite motion are now considered at the unperturbed resonant altitudes already introduced.
The velocity of the sub-satellite point is indicated in the second column of table 2/3 below. This value is important as it affects the frequency of handovers in a constellation. It can be used for estimating both the spotbeam to spotbeam handover rate as well as the satellite to satellite handover rate. In order to estimate the spotbeam to spotbeam handover rate, specific satellite coverage geometry’s need to be used. Clearly, LEO constellations will require a very high amount of inter spotbeam and inter satellite handovers. This will result in very high levels of system signalling compared with MEO constellations. The effects of such rapid satellite and spotbeam connectivity changes in terms of earth station connectivity, mobility management and call setup signalling procedures are highlighted in later chapters. The effects in terms of in call handover signalling requirement is not considered here.

The third column indicates the satellite velocity and is used to calculate the satellite to user terminal Doppler shift (S-band) as well as user terminal to satellite Doppler shift (L-band). An elevation angle of 10° (typical worst case) was used for these Doppler calculations. For LEO constellations, where satellites pass into and out of visibility in a short period of time, the Doppler shift and the rate of change of Doppler shift are clearly much higher than for MEO constellations. This results in more difficult air-interface problems being faced by LEO systems.

### 2.2 Constellation Design

The aim of good constellation design is to minimize the total number of satellites, T, needed to provide the required level of coverage at the constellation design altitude. There are two standard geometrical approaches to satellite constellation design. The ‘street of coverage’ approach [Rider85] and the ‘Rosette’ approach [Ballard]. A third and very different approach to constellation design, and which gives similar results to [Ballard], was proposed in [Mozhaev72] and [Mozhaev73].

A basic property relevant to all three approaches is that all satellites in the constellation have the same orbit altitude (h) and orbit inclination (i). Solutions with fewer restrictions may be more optimal from a coverage point of view but other factors such as satellite design costs, launch costs and link budget similarity also need

<table>
<thead>
<tr>
<th>L:M</th>
<th>(V_{sp} \text{ (km/s)})</th>
<th>(V_{sat} \text{ (km/s)})</th>
<th>Rx. doppler (kHz)</th>
<th>Tx. doppler (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:1</td>
<td>6.5</td>
<td>7.4</td>
<td>± 53.8</td>
<td>± 35.0</td>
</tr>
<tr>
<td>13:1</td>
<td>6.0</td>
<td>7.2</td>
<td>± 50.0</td>
<td>± 32.5</td>
</tr>
<tr>
<td>12:1</td>
<td>5.6</td>
<td>7.0</td>
<td>± 46.1</td>
<td>± 30.0</td>
</tr>
<tr>
<td>11:1</td>
<td>5.1</td>
<td>6.8</td>
<td>± 42.3</td>
<td>± 27.5</td>
</tr>
<tr>
<td>5:1</td>
<td>2.3</td>
<td>5.3</td>
<td>± 19.2</td>
<td>± 12.5</td>
</tr>
<tr>
<td>4:1</td>
<td>1.9</td>
<td>4.9</td>
<td>± 15.4</td>
<td>± 10.0</td>
</tr>
<tr>
<td>3:1</td>
<td>1.4</td>
<td>4.4</td>
<td>± 11.5</td>
<td>± 7.5</td>
</tr>
</tbody>
</table>

*Table 2/3 - Satellite Motion Effects*

---

4 These values do not consider Earth rotation (a maximum of 0.5 km/s at the equator), which has a small modulating effect on the final delivered doppler shift.
to be considered, which make the above restrictions appropriate. Two basic points are
initially made in order to introduce the main parameters relevant to constellation
design. The 'Street of coverage' and the 'Rosette' design approaches are then
described.

- Lower satellite altitudes, for a fixed elevation coverage angle, result in reduced
  satellite coverage areas which in turn results in the need for a higher number of
  satellites in the constellation. This typically increases system costs.
- For a fixed altitude, reducing the system minimum elevation angle increases the
  satellite footprint and reduces the number of satellites required for coverage. But a
  lower minimum elevation angle results in increased propagation channel
  variations and can reduce system service quality.

The following graph in figure 2.2, which is based on statistics taken from [Adams87]
shows this trade of clearly for three different minimum elevation coverage angles.

![Figure 2.2 - Satellite Number Vs Altitude Vs Elevation Angle Trade-off](image)

2.2.1 'Street of Coverage' Approach

The seminal contribution on satellite constellation design was published in 1961 with
a paper from Luders [Luders]. Since then the most important contributions were
[Beste], [Rider 85], [Rider86] and [Adams]. Of these, [Rider85] provides the most
complete theoretical contribution. Luders used a 'street of coverage' technique but
with a sub-optimum phasing between adjacent planes. Beste used optimally phased
polar constellations and approached coverage as a function of latitude. Rider extended
this technique to accommodate non-polar orbits and included optimization procedures
for the orbit inclination. Adams listed a large number of 'optimal' constellations based
on Riders work.
Street of coverage constellations consist of satellites equally divided among and uniformly distributed around circular orbits of common altitude. The orbit planes are equally inclined with respect to the equator and are symmetrically arranged about the polar axis (over one hemisphere) to provide global coverage. By symmetry, the other hemisphere is covered on the second half of a satellites orbit.

Satellite coverage areas are fitted together in individual coverage planes, resulting in the creation of a 'street of coverage' associated with that plane. Within this 'street of coverage' user to satellite visibility is assured at or above the minimum design elevation angle. Further planes, having their own associated 'street of coverage' are added to extend the constellation coverage. These adjacent planes are phased in such a way as to maximize the combined coverage of both planes. The optimum phasing is when satellites in adjacent corotating planes are out of phase by half the angle separating satellites within the same plane. This design approach results in a seam of oppositely rotating satellites where inter-plane phasing is not possible. At this seam, planar separation is reduced to the minimum 'street of coverage' value.

To design a constellation, a latitude, \( \lambda \), is specified above which in the Northern hemisphere (and, by symmetry, below which in the Southern hemisphere) one or more satellites are to be continuously visible above a minimum constellation design angle. The Earth centered angle, \( c \), defines the half-width street of coverage angle provided by \( S \) satellites in a single orbit plane. This is calculated based on the minimum elevation angle \( (\epsilon_{\text{min}}) \) chosen for the system. The angle 'c' is related to a satellites Earth centered coverage angle \( (\beta) \) and the number of satellites in a plane \( (S) \) as follows:

\[
\cos c = \cos \beta / \cos (\pi / S) \tag{2.9}
\]

P such planes, appropriately spaced about the equator, are then used to achieve the required coverage. Optimum satellite phasing is achieved in adjacent co-rotating planes, allowing maximum plane separation. Closer spacing is required between adjacent but oppositely rotating planes. \( T \), the total number of satellites in the constellation, is given by \( S \times P \). Since the constellation can be arranged so that there are \( 2(P - 1) \) corotating interfaces and the minimum of one counter-rotating interface, then the constraint equation of the constellation design takes the following form:

\[
(P - 1) (\beta + c) + 2c = \pi \cos \lambda_{\text{min}} \tag{2.10}
\]

For global coverage, \( \lambda_{\text{min}} \), the minimum latitude for which coverage is to be guaranteed, is \( 0^\circ \) (i.e. the equator). Figure 2.3 shows the design geometry.
By using near-polar orbit inclinations, these constellations can provide a fully global coverage. By using mid-latITUDE inclinations, polar and therefore global coverage can be replaced by improved mid-latitude coverage. The 'street of coverage' approach is found to be most suited to global coverage using LEO constellations [Iridium].

2.2.2 'Rosette' Approach

The original work on this constellation design method was reported in [Walker70] and [Walker77]. A few years later in [Ballard] this work was extended and described in a more complete way. This section explains the Ballard approach to constellation design.

The shorthand notation (T,P,f) is used to specify a constellation. T is the total number of satellites in the constellation and P is the number of planes. S, the number of satellites per plane, is therefore given by \( T/P \). All satellite planes are equally separated by \( 2\pi/P \) radians and satellites in these planes are separated by \( 2\pi/S \) radians. All planes have the same altitude and inclination. To understand the function of the f-parameter (harmonic factor), a 'Pattern Unit', defined as \( 2\pi/T \), is used. Adjacent plane satellite phasing can now be defined as follows - when one satellite is at its ascending node, the next easterly satellite is f 'Pattern Units' above its ascending node\(^5\). The harmonic factor, 'f' is allowed to acquire fractional values. The generalized constellation formulation is as follows:

\(^5\) The ascending node of a satellite in its orbit is that point on the equator which a satellite passes over when it travels from south to north.
\[
\alpha_j = 2\pi \frac{j}{P} \quad (j = 0 \text{ to } P-1) \tag{2.11}
\]
\[
\gamma_j = f\alpha_j \quad (f = 0 \text{ to } (T - 1) / S) \tag{2.12}
\]

where \(\alpha_j\) is the right ascension angle for the \(j^{\text{th}}\) plane and \(\gamma_j\) is the initial phase angle of the \(j^{\text{th}}\) satellite in its orbit plane at \(t = 0\), measured from the point of right ascension. If \(f\) is a simple integer, then a constellation of one satellite in each of \(T\) planes is being referred to. If \(f\) is an unreduced ratio of integers, a constellation of \(S\) satellites in each of \(P\) planes is being referred to, where \(S\) is the denominator of \(f\). The harmonic factor \(f\) is an important descriptor of a rosette constellation. It influences the initial distribution of satellites over the sphere.

The constellations minimum elevation angle, \(\varepsilon_{\text{min}}\), is calculated by finding the largest circumcircle radius of triangles formed by sub-satellite points (and which, for single satellite visibility, contain no other sub-satellite points), during a time period over which the satellite geometry repeats. Based on this radius (measured as an Earth centered half angle - \(\beta\)) and the constellation altitude (\(h\)), \(\varepsilon_{\text{min}}\) can be calculated equation 2.2). Figure 2.4, where \(R_e\) is the radius of the earth, shows the approach used to calculate \(\varepsilon_{\text{min}}\).

Based on this approach, a software tool was developed which allowed constellation coverage patterns to be examined [Pinede], [Sado]. This tool was further extended to allow specific constellation properties to be examined [Sammut93], [Sammut94]. The ‘Rosette’ constellation design method is considered to result in optimum constellations for global coverage when MEO altitudes are chosen. It also results in efficient LEO constellation coverage if the polar coverage is neglected. In such cases, the circumcircle approach to finding \(\varepsilon_{\text{min}}\) should only be applied in the coverage area of interest. The Globalstar [Globalstar], Odyssey [Odyssey], Inmarsat-P [Inmarsat-P] and MAGSS-14 [MAGSS-14] proposals use this approach. In the Globalstar case,
near-global coverage is provided using 48 satellites inclined at 52° and at an altitude of 1,414 km (LEO). In the other three cases (which use 12, 12 and 14 satellites respectively), this design method provides a more efficient global coverage at the 10,354 km altitude chosen (MEO), than the street-of-coverage technique. This altitude is the 4:1 resonant altitude.

2.3 S-PCN Constellations

In this section different constellations are described. The first two constellations are the Iridium [Iridium90] [Iridium92] and Globalstar [Globalstar] constellations which have been allocated operational spectrum by the FCC. Both are intended to become operational by about the year 1998. However, as mentioned in the introduction, these dates are likely to be on the optimistic side. The third constellation, MAGSS-14 [MAGSS-14], is a good representative MEO constellation. It provides improved coverage (at the expense of 2 extra satellites) than the 12 satellite Odyssey constellation (the third constellation to receive an FCC license). Coverage comparisons between MAGSS-14 and the 10 (plus 2 in-orbit spares) satellite Inmarsat-P constellation, which was designed for dual satellite visibility, are not well matched due to the different design constraints.

Finally a new LEO constellations, which was developed during the study period, are described. Named ‘Deligo’, it is a quasi-resonant constellation which provides 100% dual satellite visibility in the target service area. Further work in this thesis concerning S-PCN air-interface signalling requirements specifically uses the Globalstar LEO and MAGSS-14 MEO constellations.

2.3.1 Iridium

The 77 satellite Iridium constellation (named after the 77th atomic element) has been modified since its original proposal. The Iridium constellation, proposed originally by Motorola, now consists of 66 satellites at near-polar inclinations (i = 86°). The Iridium constellation has the lowest altitude of all the proposed S-PCN constellations (h = 785 km) and achieves a worst case, user single satellite visibility at a minimum elevation angle (E_min) of 8.2°. Iridium consists of 6 planes with 11 satellites in each plane.

Because Iridium intends to interconnect satellites through inter-satellite links (ISLs), and because of the very simple and fairly constant geometric relation between satellites in the 'street of coverage' constellation design technique, it is likely that this design approach was favored. Another factor was likely to be the efficient achievability of global coverage at the low Iridium altitude, although polar region traffic is not considered as a big Iridium market. Figure 2.5 shows the 66 satellite Iridium constellation. The closer planar spacing, associated with the 'seam' of oppositely rotating satellite planes, can clearly be seen off the west coast of America and 180° away, off the west coast of India. The convergence of satellites around the polar regions is also clearly indicated in the figure.
The coverage area between Iridium satellites and earth stations are slightly larger than the above satellite to UT contours due to the lower elevation angle used - 5° rather than 8.2°. It can be noticed that many Iridium satellites have their full footprint over ocean regions, many of which are probably without any landmass. For a transparent satellite, this would result in an inability to offer services - since no earth station could connect to the satellite. Iridium overcomes this problem of loss of service area through using satellite On-Board Processing (OBP) and Inter-Satellite Links (ISLs). Such technologies are considered high risk for space applications also make the Iridium system vulnerable to satellite failure. However, it terms of the ground segment control network, it does mean that each satellite is not required to have an earth station within range at all times, thus reducing ground segment complexity.

2.3.2 Globalstar

The Globalstar constellation was originally proposed by Space Systems/Loral and Qualcomm and is intended to provide S-PCN services to a global market before the year 1999. It is a Ballard constellation (48, 8, 1/6) at an inclination of 52° and at an altitude of 1,414 km. Because of this inclination, coverage is optimised for mid-latitudes with polar regions not being covered. The coverage is therefore more specifically market-oriented. In this service region the minimum user elevation angle is 10°. A 100% level of satellite diversity is provided in mid-latitude regions but this drops down to about 60% at the equator. Satellite diversity can be used to reduce link margin requirements and allow a soft-handover capability, resulting in improved system performance. Figure 2.6 shows the 48 satellite Globalstar coverage down to the 10° minimum user elevation angle. The high level of mid-latitude (at about the continental United States level) coverage and the lack of polar coverage are clearly visible from this figure.
The coverage area between satellites and earth stations are slightly larger than the above contours due to the lower elevation angle used - 5° rather than 10°. As with the Iridium constellation, Globalstar satellites can suffer from a lack of ground (segment) connectivity - the south Pacific ocean being a clear problem area. However, this is on a much lower scale than Iridium due to the larger satellite coverage area, also, the above world map does not indicate all land masses. Globalstar satellites are fully transparent so lack of earth station connectivity makes the satellite unusable for the connectionless duration. The effect of this on system ground segment architecture is that the density of earth stations will be much higher for Globalstar, compared to Iridium. It also means that earth stations are required in remote locations if continuous satellite usability is envisaged.

Each of the 48 Globalstar satellites have 16 spotbeams to increase radiated eirp to users. The individual satellite coverage shown in figure 2.7 is a slightly modified version of this coverage. In this case, each satellite has 19 spotbeams associated with its coverage. This geometry was used because no exact geometry for the 16 spotbeam coverage was available and because a 19 spotbeam coverage, based on a two ring hexagonal pattern, is easy to construct and close to the actual coverage geometry. Satellite antenna beamforming is assumed and this is why the spotbeams are equally sized. This spotbeam coverage geometry is used later in chapter 6 in order to obtain paging requirement statistics for user-terminated call setup.
Globalstar intends to offer services such as voice, data, messaging and navigation. Handheld, portable, vehicle mounted and fixed terminal types are envisaged. Such service and terminal types can be considered as general to S-PCN systems.

2.3.3 MAGSS-14

The MAGSS-14 (14, 7, 11/2) satellite constellation is a paper constellation proposed by the European Space Agency and used by them to study different factors pertaining to S-PCN systems. It consists of 14 satellites, excluding spares, orbiting at the 4:1 'resonant' altitude of 10,354 km. The orbit plane is inclined at an angle of 56° to the equatorial plane, providing enhanced satellite visibility to a user terminal (UT) between 30° and 60° latitude, while still ensuring 100% global single satellite visibility at an elevation angle above 28.5°. The satellite altitude, together with the specified minimum elevation angle to a user terminal, gives a user coverage area beneath each satellite with a radius of approximately 4,500 km. The minimum elevation angle considered usable for earth stations is 5°.

Figure 2.8 illustrates a 'snapshot' of the MAGSS-14 user coverage at the 28.5° contour. The complete global coverage provided by the constellation should be noted, as well as the large areas of coverage overlap, which provide a high level of satellite diversity for users. The ground track of one of the satellites over the resonant period is also indicated (dark line) - as indicated earlier a shift of just under 0.2 °/day does actually occur.
Individual satellite coverage to user terminals is divided into 37 spotbeams. The spotbeams provide higher gain to UTs compared with a single global beam, whilst simultaneously enabling a more efficient utilization of the available radio spectrum. Communication to and from a user terminal takes place through one of these beams, and typically through the satellite with the highest elevation angle to the user. The coverage area for 5° minimum elevation angle is indicated in figure 2.9 (outer circle). This coverage is a circular single beam. Figure 2.9 also shows the possible shape of the coverage areas formed by these spotbeams if beam forming at the satellite is not used. Each satellite has a 37-zone multibeam coverage of its user service-area. The resulting spotbeams diverge from the ideal circular shape due to the distortion effects of the curved earth. This has implications for overlap between satellites and thus the diversity offered to users. If beam forming is used on board the satellites then the spotbeam projections are modified so as to create a more ideal coverage pattern - similar to the Globalstar spotbeam coverage but with a third ring and covering a larger area.

Connectivity between MAGSS-14 satellites and earth stations is clearly not a problem, according to the 5° elevation angle contour indicated above. For
MAGSS-14, the satellite to user $e_{\text{max}}$ of 28.5° results in a maximum slant path range ($R_{\text{max}}$) of 12,500 km. This translates into an approximate coverage region which is within a radial distance (along the Earth's surface) of 4,650 km from the sub-satellite point. As indicated above (and even if beam forming is used), satellite coverage zones will naturally extend somewhat beyond this radial distance in order to provide full coverage at the required elevation angle. For an earth station (ES) - envisaged to work down to an elevation angle of 5° - the slant path range is 15,000 km corresponding to a curved-Earth coverage area radius of 6,750 km. Analysis of constellation connectivity statistics indicate that up to 3 satellites may be visible to a UT at a time while up to 5 satellites may be visible to an earth station. These distances and geometric connectivities have an important influence on the eventual S-PCN network architecture in the following ways:

1. Satellites can only link with user terminals (UTs) when the UT is within its respective coverage region (even this does not guarantee connectivity - especially for UTs - as local propagation factors can have a big influence);

2. Transparent satellites without Inter-Satellite Links (ISLs) always require at least one earth station (and possibly more for link redundancy) within its coverage area at all times in order to allow service provision through that satellite.

Figure 2.10 shows satellite to UT diversity statistics for a satellite coverage area defined by the 28.5° contour$^6$ [Sammut93].

---

$^6$ In general, constellation design and therefore satellite connectivity properties are latitude dependent and longitude independent. With resonant constellations (which result in repetitive satellite ground tracks), a small longitude dependence also exists.
This figure indicates the 100% constellation single visibility provided between satellites and UTs above the 28.5 degree minimum elevation angle. The lower curve indicates the level of dual satellite diversity provided at an elevation angle above 28.5°. Although dual-satellite diversity is not guaranteed by this constellation, a high level is provided, especially in mid-latitude regions. The x-axis indicates 0° to 90° only since north-south coverage symmetry exists.

2.3.4 ‘Deligo’ Constellation

Providing user terminals with dual satellite visibility can, through the application of diversity techniques at the terminal, reduce link margin requirements and improve service quality [Globalstar]. As part of work carried out for the SAINT (Satellite Integration into UMTS) project (part of the European RACE II research initiative), the following unique set of constellation specifications were proposed [Meenan]:

1. Use of a LEO altitude to minimise user terminal G/T and transmit power requirements;
2. Use of a quasi - resonant altitude in order to provide an easily predictable and repetitive coverage geometry (resonant orbit like advantages);
3. A coverage area between latitudes of approximately 70° north and south in order to optimize constellation coverage to Earth traffic;
4. 100% dual diversity above ~15° in this coverage area. This elevation angle was chosen based on output from [SaintD1].

Because of the non-global coverage requirement, the Ballard constellation design technique was chosen. In order to minimise the number of satellites required in the constellation, the higher resonant altitude of 1,666 km was used as the baseline ‘unperturbed’ altitude. At this altitude a (64, 8, 1/8) constellation at an inclination angle of 54° was found to provide the best trade-off in terms of optimum coverage and minimum satellite numbers.

However, a precession rate of ~2.6 °/day has been indicated in table 2/2 for such an orbit plane altitude and inclination. The constellation, as described above, does not therefore exhibit resonant properties and provide the associated network advantages. In order to deduce the orbit altitude at which the ground track does repeat, equations 2.5 and 2.8 were solved for ‘a’ (h + R_E) with i = 54° and a total Ω_E of 30°. The solution, h = 1,610 km, is the altitude at which the ground track of each satellite in the constellation repeated after 12 orbits (30° / 360°).

The reduced orbit altitude reduced the orbit period by about 60 seconds per orbit. Since each satellite orbits the Earth 12 times per day, this results in a satellite appearing about 12 minutes earlier than on the previous day. The repetitive ground track property still holds but with an associated time shift. Likewise, the advantages offered by resonant orbits in terms of system frequency and traffic planning also have to be shifted 12 minutes forward each day. The resulting ‘quasi-resonant’ constellation can still offer these important connectivity advantages to the S-PCN control architecture compared with unresonant constellations. The mean elevation statistics for the first two (dual diversity) satellites are shown in figure 2.11.
Such high average elevation angle coverage statistics compare very favorably with other constellation proposals. This results in improved service quality for system users, reduced link margin requirements and should also lead to increased system capacity. The number of satellites required in this constellation is two less than the Iridium proposal and 16 (33%) more than the Globalstar proposal. The satellite numbers cannot be considered excessive. The altitude is higher than the other two LEO constellation proposals. It is 196 km higher than the Globalstar constellation. However, it is still well below the radiation imposed cut-off altitude of about 2,000 km and so should not suffer from excessive radiation levels.

2.4 Constellation Connectivity

Satellite motion results in a varying earth station connection or coverage area. As satellites pass into and out of range, an earth stations coverage area is altered. Because of this motion, it is impossible to associate an exact service area with an earth station. For an earth station to be effectively in control of its 'service area' requires the earth station to have exclusive control over a certain area. This requires the signalling channels of that earth station to be exclusively heard in that region. Even ignoring satellite coverage overlap and network control organisation, satellites moving at 2 km/s (~MEO) or 7 km/s (~LEO) and having spotbeam diameters in the range 500 km to 2,000 km, cannot be associated with an exact coverage boundary. This is significantly different from terrestrial mobile systems and has a fundamental influence on the proposed S-PCN baseline network architecture and on network control aspects such as mobility management and call control.

2.4.1 Constellation Properties

The following list of properties summarizes the key factors associated with S-PCN constellations and highlights the main trade-offs involved.
1. The range of LEO constellation altitudes can be considered to be between about 600 km and 2,000 km.
2. Between about 2,000 km and 8,000 km, electron and proton radiation belts about the Earth are considered too active for long-life satellite missions.
3. The range of MEO constellation altitudes can be considered to be between about 10,000 km and about 20,000 km.
4. A large but unavoidable amount of satellite coverage overlap occurs with both constellation design techniques (comparisons of real constellation satellite numbers with the ideal 'static bound' coverage show this).
5. The regions and amounts of inter-satellite coverage overlap are continuously changing due to satellite motion.
6. As a satellite orbits the Earth, it has a continuously changing coverage area - and hence traffic demand.
7. The inclination (i) of the constellation planes can be adapted, depending on constellation altitude, to optimize coverage of specific latitudes.
8. The 'minimum user elevation angle' $\varepsilon_{\text{min}}$ (user), is the angle above which a user is guaranteed to see a satellite.
9. As $\varepsilon_{\text{min}}$ (user) reduces, the link margin ($L_{\text{bd}}$) required to close the link increases, as the propagation channel quality degrades from 'Ricean' to 'Rayleigh'.
10. The minimum design requirement is single satellite visibility above a certain elevation angle - however, constellation diversity coverage is a useful property.
11. For a given $\varepsilon_{\text{min}}$ (user) and/or satellite diversity requirement, the number of satellites required increases as the constellation altitude decreases.
12. For a given constellation altitude, the number of satellites required increases as the $\varepsilon_{\text{min}}$ and/or satellite diversity requirement increases.

### 2.5 Conclusions

In this chapter, the reasoning behind the used of LEO and MEO constellation altitudes was initially considered. Lower orbit altitudes were favored from delay and free space loss point of view and high radiation belt intensity was seen to split the lower altitudes into two low intensity bands - Medium-altitude and Low-altitude. The satellite orbit properties of sun-synchronisation and resonance were examined in relation to their applicability to S-PCN systems.

Sun-synchronous orbits can simplify satellite design and possibly extend orbit lifetime due to optimised satellite bus design. However, the correlation between satellite passes and Earth time was noted as a possible problem in that traffic rates also vary according to the local Earth time. This may result in some satellites experiencing excessive traffic channel demand levels. Further work could be done on this based on an accurate Earth traffic map and knowledge on the satellite power requirement per satellite.

Resonant orbits were also considered in terms of their suitability for S-PCN systems. Advantages in terms of ground segment to space segment network connectivity
repetition are provided by perfectly resonant orbits, allowing an important simplification in ground segment control. However, non-spherical Earth perturbations were seen to cause RAAN precession of all the orbit planes, and thus removing the resonance property. This RAAN precession affected LEO constellations more than MBO constellations, which experience a very low RAAN drift.

The Iridium, Globalstar and MAGSS-14 constellations were reviewed before a new constellation - 'Deligo' was proposed which provides 100% satellite diversity over its target service area of between 70° north and south. This service area is optimised for expected Earth traffic. The 1,610 km altitude combined with an orbit plane inclination of 54 were specifically chosen to give a quasi-resonant LEO constellation. The ground track is repetitive but with a daily time lag of about 12 minutes. This quasi-resonance still provides the constellation with network advantages in terms of ground segment connectivity and traffic planning.

The final section contrasted S-PCN connectivity with terrestrial mobile communication system connectivity. The space segment dynamics is seen to have an important influence on the network control strategies. A list of constellation characteristics was also provided.

References


[Rosengren]  ‘ERS-1 - An Earth Observer that exactly follows its chosen path’, M. Rosengren. ESA Bulletin 72, pp. 76 - 82.


* using Inclined Circular Orbits


Chapter 3  S-PCN Architecture

This chapter initially reviews the GSM (Global System for Mobile communications) system [GSM]. Because of the global predominance of the GSM terrestrial mobile communications standard [Chambers], integration between S-PCN systems and the GSM system is specifically considered and some general conclusions are drawn. With GSM / S-PCN integration in mind, the requirements on a S-PCN network architecture from a users, operators and regulators point of view are examined. A review of the specific problems presented by satellite motion is made before a baseline S-PCN architecture, which provides full constellation control and operability with a hierarchical two layer approach, is proposed.

3.1 The GSM Network Architecture

The GSM architecture is reviewed briefly in order to clarify the main elements of this mobile communication network [Mouly]. This allows the S-PCN architecture, proposed later, to be more easily understood. The GSM system is a digital based, European-developed mobile cellular radio system. The GSM specification is rapidly becoming a global standard digital mobile communication system. It is termed, after the 1st generation analog mobile communication systems, a 2nd generation digital mobile communication system. Figure 3.1 outlines the core GSM network architecture and identifies the interfaces (lettered A to E) between these nodes.

![GSM Network Architecture Diagram](image)

Figure 3.1 - GSM Network Architecture and Interfaces

The following is a brief description of the main GSM network nodes.

**Mobile services Switching Center (MSC):** The MSC is an exchange which performs all the switching functions for the mobile stations located in a geographical area - the MSC area. The MSC manages the procedures required for location registration and
handover. A gateway MSC (GMSC) is sometimes used as the main interface between the GSM and other networks (e.g. ISDN, PSTN, other PLMNs etc.). Besides its service connection role, an MSC also has a service control role in terms of mobility management and network security, involving signalling links with other network entities. MSCs are linked with other MSCs via the E-interface;

**Home Location Area (HLR):** A HLR is a database in charge of the management of mobile stations. A GSM national network may contain one or more HLRs - depending on the number of mobile stations, the capacity of the equipment and the organisation of the network. All mobile station subscription data is stored here, including permanent subscriber parameters and service features. Additionally, the HLR holds information on the current address of individual mobile stations in order to be able to correctly route mobile terminated calls. The HLR is connected to its associated MSC via the C-interface (an internal MSC interface).

**Visitor Location Register (VLR):** A VLR is a database in charge of data management for mobile stations roaming in an MSC area which is not their home MSC area. It contains information such as mobile station identification, roaming numbers and service parameters. The VLR is connected to its associated MSC via the internal B-interface. A VLR and HLR are linked together by the D-interface.

**Base Station System (BSS):** The BSS manages radio network resources and cell configuration data. It contains one Base Station Controller (BSC) and one or more Base Transceiver Stations (BTS). The BSC works as a bridge between the MSC and the BTSs. The interface between the BSC and BTS is the A_bis-interface and is not fully specified within GSM. The BSC performs radio network and BTS management. It also controls individual mobile station connections. The BSS is linked to the MSC via the A-interface and to mobile stations via the U_a air interface.

**Mobile Station (MS):** The MS is the equipment used by GSM users, providing them with access to a set of services. The provided services are chosen upon registration in the system. Different MS sizes and transmit powers are available. A MS is linked to the BSS (BTS part) over the U_a air interface.

The protocols used on the above GSM interfaces are now listed. In all cases, except over the radio link, signalling messages are sent over 64 kb/s circuits.

- The A-interface is capable of supporting all the services offered to GSM users. In addition it also manages the allocation of suitable radio resources within the PLMN. It uses Signalling System 7 (SS7), Message Transfer Part (MTP), Signalling Connection Control Part (SCCP), Direct Transfer Application Part (DTAP) and Base Station System Mobile Application Part (BSSMAP) protocols.

- On interfaces B, C, D and E, SS7, MTP, SCCP, Transaction Capabilities (TC) and Mobile Application Part (MAP) protocols are used.

- On the U_a air interface, a modified version of the ISDN Link Access Protocol on the D channel (LAPD_{modified}) is used.

The GSM layered signalling protocols used between the MSC and the MS are identified in figure 3.2 [SAINTSD8].
3.2 S-PCN / GSM Interoperability

A S-PCN system is most suitably divided into three segments - Space, Ground and User. Other terrestrial networks (PSTN, ISDN) are considered to be connected to the S-PCN Ground Segment via SS7 interworking. The space segment is the active constellation of satellites in orbit. Its main feature concerns satellite and constellation coverage characteristics, which were discussed in chapter 2. In the derivation of a suitable S-PCN architecture for this report, satellites are considered as transparent transponders. The ground segment includes earth stations which, because of the assumption of a transparent space segment, must provide complete control over space segment resources. If a transparent satellite does not have connectivity with an earth station, then its resources cannot be used and user terminals only within its coverage area do not receive system broadcast channels. The user segment consists of user terminals (UTs) which provide users with access, via satellites, to the ground segment. On the user segment side, it is assumed that forward and return link coverage geometry's are the same for each satellite. This can be effectively achieved through appropriate forward and return link antennae matching. This spotbeam matching is a very important system requirement which simplifies network operation.

Clearly, the interaction between the space segment and both user and ground segments has a big influence on the choice of network architecture. This simple segmentation of the overall system is shown in figure 3.3.

\[\text{Figure 3.2 - GSM network protocols}\]

---

1 Only Iridium, of all the proposed S-PCN systems, is non-transparent, so this assumption is in line with all other S-PCN system proposals.
It can be seen that there are two network connectivity types - those on the user segment and those on the ground segment. On the user side, satellite spotbeams (only one is indicated) provide high eirp levels to users. In the ground segment, a single coverage zone provides connectivity to earth stations within visibility of a satellite. The minimum elevation angle used on the ground segment side of the link can usually be lower than that used on the user segment side of the link. This is indicated in the above diagram by the larger ground segment coverage area.

The service scenario considered for S-PCN systems include [ETSI]:

1. A global roaming capability;
2. The support of handheld, low eirp terminals;
3. The provision of cellular quality voice (the baseline rate used here is 4.8 kb/s which is lower than the current lowest rate of 6.4 kb/s in Inmarsat-M);
4. The provision of low rate data messaging and paging;
5. A positioning / navigational capability;
6. A level of interoperability with Public Land Mobile Networks (e.g. GSM).

Development cost is a key issue for S-PCN systems. By reusing GSM standards, appropriately modified for the S-PCN system, development costs can be reduced. Because both GSM and S-PCN should offer similar services and will require similar control functionality. This means that similar protocols are used (with Inter Working Functions when necessary) in both systems. The use of similar signalling approaches between to the GSM standard will naturally facilitate interoperability between these two systems (point 6) and improve market accessibility of the S-PCN system. This approach is more favorable compared with the alternative option of developing a new set of protocols. Also, the GSM systems global predominance makes it the most suitable system for S-PCN interoperability.
Network level integration is characterized by the sharing of network infrastructure and functionalities that allow mobile roaming between the two networks to be handled transparently. A user has one Mobile Station ISDN (MSISDN) number and can be reached on either network with this number. However, once a call is established, it is treated separately within each system. Call handover between systems is not provided. Ground segment protocols are similar while those used over the air-interface may be quite different. With this approach, common ground segment switching network infrastructure can be used by both systems, reducing costs.

System level integration means that the S-PCN system is viewed as an extension of the terrestrial system with a similar set (subset) of services and using similar (although not identical) protocols in the ground segment as well as over the air-interface. Inter-segment handover can be provided, but does not necessarily have to be provided. Apart from radio frequency and associated hardware, the two networks should mostly use the same components.

Considering the different stages of development between the GSM system (finally standardized in 1991) and currently developing S-PCN systems, system level integration (i.e. the maximum conceivable level of integration between the two networks), is not a realistic option. The next level of interoperability between the S-PCN system and terrestrial mobile networks is a more realistic proposal - network level integration. The key service that could be offered is inter-network call forwarding, allowing users to be reached, via a single number, on whichever network they are currently registered with [ETSI]. This would require database interoperability between the two systems and would offer users the advantage of a more global service. Handover between the GSM and S-PCN networks is considered, from a non-technical point of view, in the next section on system requirements.

3.2.1 S-PCN Requirements

In order to be able to define more precisely the functionality of a network level integration between GSM and S-PCN, a baseline description has to be made of the requirements of both systems. This is now done based on S-PCN user, network operator and regulator requirements. From this, certain directives concerning GSM / S-PCN interworking can be deduced and used to determine a suitable level of interoperability between the systems. This in turn will help in forming a list of S-PCN architecture requirements.

3.2.1.1 S-PCN User Requirements

A list of user requirements, involving both technical and non-technical aspects, for an interworking S-PCN / GSM system is now outlined:

1. Users require a range of suitable terminal types, including handheld terminals.
2. Handheld terminals should be light and low cost.
3. Service cost should be as comparable as possible to current mobile terrestrial systems.
4. Service quality should be as comparable as possible to current mobile terrestrial systems.
5. Service types, when possible, should be comparable to established terrestrial standards.

6. The service should be available ‘globally’ with minimum restrictions.

7. Users should be contactable on both terrestrial and satellite segments via a single number.

Provision of small, light and relatively cheap terminals is an obvious user requirement and should help with system acceptability. Considering system cost (point 3), a significant difference in charges between the GSM and S-PCN systems is likely. Initial S-PCN prices are likely to be high while GSM prices by the end of the century are likely to be very good value. Possible system capabilities such as GSM to S-PCN handover (going from low to high cost) as well as the use of S-PCN traffic channels as a GSM capacity backup (again, higher cost to the user) become much less favorable when cost is considered.

In order for system interworking to make real sense, the services offered by the systems need to be similar in both quality and type (points 4 & 5).

S-PCN services should be available in as many environment-types as possible (point 6). The required level of user cooperation is important. Due to link power limitations, very different usage restrictions will apply to S-PCN systems compared to terrestrial systems. A user requirement to obtain ‘a maximum sky visibility’ during a call is almost certain to apply to all S-PCN systems. This needs to be taken into account when deciding the appropriate level of GSM / S-PCN integration. For example GSM to S-PCN handover becomes further complicated since the user needs to be informed of the new link requirement.

Use of a single user contact number (point 7), which is the key interworking requirement, has effects on the network architecture and on switching / routing between systems. The use of similar protocols and therefore network components helps with system interworking as well as reduces development costs. This is key to the importance of GSM on S-PCN development.

3.2.1.2 S-PCN Operator Requirements

Another very important set of system requirements which influences the level of S-PCN / GSM integration, comes from the S-PCN operator. Apart from providing users with a service cost and quality as comparable as possible to terrestrial systems, the S-PCN operator also has the following requirements:

1. To provide a suitable network architecture for the control of a global network.
2. To use S-PCN resources (ground, user and space segment) efficiently.
3. To interwork with terrestrial mobile communication systems while minimizing required modifications to that network.
4. Minimise S-PCN development and setup costs.

An effective network architecture which uses available resources efficiently (points 1 & 2) is clearly a basic requirement. Because S-PCN systems, based on dynamic satellite constellations, involve a whole new set of parameters which need to be prioritized and then optimised, careful examination of the basic S-PCN architecture and control mechanisms is required.
Interworking with terrestrial networks (point 3) is clearly a goal of S-PCN network operators. It provides access to a much broader market and also complements terrestrial coverage. Importantly, the main interworking functions should be implemented by the S-PCN system (GSM operators will want to minimise, if not eliminate, the number of changes to their network).

In order to minimise S-PCN costs (point 4), currently available and successful terrestrial standards should be reused (appropriately modified) as much as possible in system development. This leads to the already stated conclusion - the S-PCN network and protocols are likely to use those of the GSM system as a basis for development.

3.2.1.3 S-PCN Regulator Requirements

The world of telecommunications is becoming more and more competitive. Advanced telecommunications nations are opening their markets to competition, through legislation [EC]. The following requirements are therefore likely to apply to S-PCN systems and operators:
1. Two or more S-PCN systems are likely to exist in order to ensure competition at a technological level.
2. Individual S-PCN systems should allow a competitive structure for use of their resources by service providers.

3.2.2 Quality and Cost considerations

In this section, the implications resulting from the above requirements are examined. Specifically, the aspects of GSM traffic overflow into S-PCN, GSM to S-PCN handover, S-PCN to GSM handover and the control of S-PCN users, are examined.

3.2.2.1 GSM to S-PCN Traffic Overflow

Consider a dual-mode (GSM / S-PCN) UT located in the service area of both systems but currently registered with the GSM system. A user-originated call setup attempt, requesting a service offered by both systems, is blocked by the GSM system due to lack of capacity. The UT might (automatically) attempt to setup the call via the S-PCN system. Such a call is likely to:
1. Cost more than in the GSM system;
2. Provide a poorer service quality than the GSM - in terms of user cooperation requirement rather than BER.

Alternatively, the advantage is that the user was able to attempt S-PCN call setup and so increase their chances of making the call. The question is whether users would appreciate the traffic overflow capability of their dual mode terminals. Most users are likely to be content to wait a little bit longer and reattempt the call setup within the cheaper terrestrial system. Upon registration, users could be offered that choice. The information required for this could be stored in the terminal or at the UT's HLR. Some indication on the terminal would still be required so that the user would know that S-PCN type link cooperation is necessary. However, there is still the problem of S-PCN traffic overload. Traffic diverted to S-PCN from overloaded terrestrial systems, because of the much higher terrestrial traffic magnitude involved, could quickly overload the S-PCN system.
An alternative approach is to allow users to manually switch their terminals onto a particular mode, thus allowing them to change to S-PCN from an overloaded GSM system, depending on the urgency of their call. Considering that both of these possibilities are feasible, and that only a very low percentage of users would opt for this costly alternative, it seems best that dual-mode terminals should provide such an option. The manual option seems preferable as it is easy to implement and provides users with the greatest control flexibility.

For user-terminated calls, GSM to S-PCN traffic overflow is more complex. If dual-mode terminals only monitor one segment at a time (a likely scenario for the first phase of these systems, considering terminal design complexity) then there is a problem in terms of terminal notification. The GSM network would have to signal to the UT to request a change of mode, which might then be done. It may be possible to use the GSM ‘cause’ element to trigger this with the UT then acknowledging the GSM system. Further work is required on this aspect.

3.2.2.2 GSM to S-PCN Handover

Now consider handover from the GSM to S-PCN. A dual-mode user begins a call within the GSM system but then starts to leave GSM coverage. The network could initiate handover to the S-PCN system. According to typical system specifications, this handover should be perceptibly transparent to the user. But such a transparent call handover from the GSM system to the S-PCN system, if possible, is unlikely to be appreciated by all users. The reasons have occurred before, namely:

1. The cost is almost certain to increase;
2. The user link cooperation requirement is likely to become more strict;

Only if cost, quality and link environment did not change appreciably could such a handover be performed in a manner that is actually transparent to the user. It is likely to be necessary to warn the user that if they continue with this call the cost is likely to increase and they may have to find a more suitable location in order to maintain the link (‘maximum amount of visible sky’). Because of the ongoing call, user notification is difficult. A ‘beep’ sound is needed to indicate to a user that the current signal power level is low and to suggest inter-segment handover. The user could then decide whether to go ahead with the handover (and its associated implications).

As with the previous traffic overflow case, only a small percentage of users are likely to avail of such a service, were it available. The reasons already listed would deter most. The user could either terminate the call or complete it at their current location. If they did want to continue the call, in motion and no handover was provided, then the call would have to be terminated and a new channel setup via the S-PCN segment. When these factors are considered, along with the technical complexities and network complications required to provide such a service, the provision of GSM to S-PCN handover is not of high priority. Also, note that the earlier one of these 2nd generation S-PCN system can offer the basic services of voice and data transmission, the more likely they are to gain a market foothold. It is considered that the question of inter-
3.2.2.3 S-PCN to GSM Handover

From the user viewpoint, this kind of handover is much more favorable:

1. The cost is likely to reduce.
2. The user cooperation requirement is likely to relax.

This is the sort of handover which will interest subscribers the most. It offers them the ability to make a call where the GSM service is unavailable with handover to the preferred GSM system when possible. Of course, with this type of handover, the S-PCN operator would lose out in terms of revenue from the handed over part of the call. An indication to the user would still be useful to alert them to the new operation conditions. For a system interworking point of view, this is a service which should be considered. But the complexities still remain and a high level of interworking is needed between the two systems. Considering the timescale involved, this service is more applicable to 2nd phase constellations with the initial constellation aiming at simply offering a set of services at a sufficient quality.

3.2.2.4 S-PCN Home Location Register

In this section, aspects associated with the location of a users HLR are considered. All UTs require a single location at which they are registered. For dual-mode UTs a choice exists - they might use the GSMs HLR or the S-PCNs HLR/satellite (HLR/s). In general, it is preferable that no changes are made to the GSM since it is an already established and operating system. Since the GSM system currently has no mechanism for transferring calls over to S-PCN, use of a HLR for dual-mode UTs, with a VLR/satellite (VLR/s) in the S-PCN system, is not preferred. Interoperable UTs would therefore use a HLR/s, which has the ability to switch a call to a GSMs VLR as required. The interworking requirement is therefore that the HLR/s looks like a HLR to a VLR. Another advantage of this approach is that it gives the S-PCN system full control over S-PCN subscribers.

For 2nd phase S-PCN systems, a more integrated approach might be considered, where only a single HLR is used in the integrated system. In this case, the S-PCN system still requires a VLR/s. When roaming in the S-PCN service area (i.e. anywhere outside its PLMN coverage area) its HLR can store the forwarding address of the appropriate VLR/s. In this case, the S-PCN system becomes a more direct extension of the GSM system.

---

2 The second phase of 2nd generation S-PCN systems is when a second set of satellites is launched to replace the original satellites launched.

3 Due to the dynamically varying network connectivities of S-PCN systems and depending on the mobility management approach adopted (see chapter 6), the idea of a VLR/s always being able to directly contact a UT does not hold. This is an important difference between the GSMs HLR, and VLR pair and the S-PCNs HLR/s and VLR/s pair.
3.2.3 Implications of Dynamic Constellations

There are clearly many differences between terrestrial and space-based mobile communication systems and many terrestrial network features cannot be directly mapped onto a S-PCN system. From the discussion in chapter 2 on the physical aspects of satellite constellations, the following observations were made which relate to the networking of (transparent) S-PCNs:

1. Satellite orbit dynamics result in dynamic network connectivities, with LEO constellations much more variable than MEO constellations;

2. Satellite orbit dynamics results in an earth station to earth station connectivity handover requirement within the controlling ground segment;

3. Satellites and their individual spotbeams experience highly variable traffic levels as they orbit the Earth;

4. The use of orbit resonance in the design of the constellation makes these network connectivities repeat in a repetitive and easily predictable way, simplifying network planning in terms of control and traffic management

5. Due to satellite dynamics and the resulting variations in network connectivity, the concept of each earth station having a clearly defined region of access does not hold.

6. The principles, listed here and in earlier sections, concerning S-PCN systems and their operation are taken into account in the following section in which a new S-PCN control architecture is described.

3.3 Baseline S-PCN Architecture

A baseline S-PCN architecture is proposed in this section [Cullen93/3]. As well as the inputs from the previous section, other aspects looked for include the minimization of space segment signalling, the provision of a flexible control mechanism, the integration requirement with a terrestrial system and compatibility with the implementation of a competitive structure. The network should also have low startup and running costs so minimum control approaches are favored. The influence of the GSM system architecture on S-PCNs is important. These aspects are considered below in choosing an appropriate S-PCN architecture. The use of fully regenerative On-Board Processing (OBP) or Inter-Satellite Links (ISLs) within the space segment is not considered.

3.3.1 Spotbeam Control

As seen in chapter 2, each satellite in a constellation has a coverage zone made up of a number of spotbeams. In order to derive an S-PCN architecture, signalling control channels within these spotbeams are initially considered. This is done in terms of the satellite signalling power requirement and also in terms of control channel monitoring by UTs. In any satellite system, space segment power availability is a most important system parameter. This is due to the limited RF transmit power available to satellites. Because of this, signalling over the air-interface which uses precious space segment resources, should be minimized. Since signalling also requires bandwidth, such an argument is also true for system bandwidth, which is another scarce resource.
From the network management point of view, each spotbeam can be considered as the equivalent of a terrestrial cell. Each spotbeam therefore requires at least one set of network control channels. Although spotbeams with two or more sets of network control channels would allow implementation of a competitive structure (with competing earth stations broadcasting their own individual set), it would also increase the amount of power and bandwidth required for signalling channels. In order to maximize the possible number of subscribers, a maximum amount of satellite transmit power needs to be allocated to traffic channels. Signalling channels, because they require high link margins to guarantee high availability, use relatively high levels of satellite power - typically equivalent to that of a voice channel but at a lower bit rate\(^4\).

The use of two or more sets of signalling channels within each spotbeam results in poor use of satellite resources. Considering this, it is clearly preferable to draw the following conclusion:

**⇒ Each spotbeam in the S-PCN system will have only one set of signalling channels associated with it.**

In this case, all UTs within the same spotbeam hear the same set of control channels, which come from a single network ground segment location.

### 3.3.2 Satellite Control

The next point concerns the choice of earth station(s) to control these spotbeams. It is important to remember that each satellite is a finite unit of resource (power). Each satellite offers a limited number of traffic channels. Satellite capacity is power limited. Another aspect of an S-PCN system based on dynamic satellite constellations is the large variation in traffic demand as the satellite orbits the earth (e.g. within 20 minutes a satellite can pass from a low traffic area - Atlantic ocean coverage - to a high traffic region - European and North African coverage). Large variations in adjacent satellite coverage overlap also occur. This would even be more complex for constellations which provide 100% diversity such as the Inmarsat-P proposal and 'Deligo'. These factors result in each satellite being required to coordinate its resources in a highly dynamic manner. Traffic channels need to be flexibly allocated to spotbeams with high traffic demand while coordination must be done within a satellite's own coverage area as well as with adjacent satellites, in order to ensure that co-channel interference levels are not exceeded. This is done on an individual satellite level as well as between satellites. In terms of resource and frequency management, each satellite spotbeam is likely to require individual coordination which can only be done with due consideration to adjacent spotbeams and satellites. For any particular satellite, especially in a Ballard/Rosette constellation, the identity and region of overlap with adjacent satellites, is highly dynamic.

Considering the above, there is clearly a high level of both inter and intra satellite coordination involved in S-PCN control. For changes in traffic or frequency allocations, all earth stations which have control of satellite resources would need to be consulted. This ensures against exceeding satellite capacity or system interference

\(^4\) Any signalling channel requires a high propagation margin so that UTs can transmit and receive signalling information over a wide range of sub-optimum location types.Propagation margins of 15 dB to 20 dB may be required. Providing such large margins over satellite channels results in either reduced channel bit rates or, if possible, increased transmit power.
limits. By using two or more earth stations to control a satellites resources (each uniquely allocated different sets of spotbeams), intra satellite coordination becomes distributed and terrestrial control signalling required for resource coordination, increases significantly. Using just one earth station per satellite localizes all intra satellite coordination. Inter satellite coordination is always required but with this approach, is all done through a single center, with, at any one time, just one control location per satellite. From this it can be concluded:

⇒ Each satellite in the S-PCN system will, at any single time, be controlled by only one controlling earth station. This controlling earth station is responsible for the signalling channels in each of the satellites coverage zones and for the satellites overall resources.

3.3.3 Constellation Control
The choice of global control architecture now arises. The options are either distributed control - spread around the S-PCN service area - or centralized control - where one single global location coordinates all network resources. The choice depends on which architecture is able to manage network resources in the safest and most efficient manner.

A centralized architecture involves only one global control centre which controls the resources of each satellite in the S-PCN system. This centre would have terrestrial links to earth stations which provide it with continuous (although indirect) access to each satellite in the constellation. Figure 3.4 outlines the concept of a centralized architecture controlling the satellites of the MAGSS-14 constellation (14 satellites are indicated).

Figure 3.4 - Schematic of Centralized Architecture
In a distributed architecture, control of satellites resources is continuously passed around the S-PCN service area between earth stations which are within the satellites coverage region. Each satellite is directly controlled by an earth station with which it has direct connectivity. As the satellite passes out of range, control of that satellites resources is handed over to a different earth station having improved connectivity with that satellite. Figure 3.5 shows the concept of a distributed network controlling the 14 satellites of the MAGSS-14 constellation. Clearly some satellites have connectivity with more than one earth station, however, its resources are only controlled by one of these.

![Figure 3.5 - Schematic of Distributed Architecture](image)

Spotbeam and satellite management have already been considered and it has been found preferable to have these controlled by a single control location. The decision on whether to adopt a centralized or a distributed architecture for the overall control of S-PCN must now be made. To do this, consider a user-terminating call. The call is initially directed towards the users HLR/s.

In a centralized architecture, there is only one HLR/s which holds the exact information concerning how to contact the UT (considering this, a VLR/s is not required). The use of a single global register results in long terrestrial signalling lengths for most calls. Basically, locating the register at only one global location makes it local for that region but remote for most regions. Measuring signalling cost as a function proportional to both bit requirement and distance, and considering also

---

^ From the MAGSS-14 satellite coverage geometry and dynamics, the average connectivity window between a satellite and an earth station is 103 minutes. This results in about 196 (14 x 1440 / 103) earth station to earth station handovers per day. For Globalstar, with an average visibility window of about 18 minutes, then 3,840 (48 x 1440 / 18) earth station to earth station handovers are required per day.
the increased signalling delays that would result from such a setup, a centralized architecture can be seen as inefficient.

In a distributed architecture, each satellite is controlled by an earth station which has direct connectivity with the satellite. Each of these controlling earth stations has an associated HLR/s and VLR/s and can therefore make the proper call control decisions. For the user-terminating call, the call is therefore switched to the appropriate register which is ‘local’ to the users current location. In this case, while the signalling bit requirement should not change significantly, both the distance and delay are reduced. It seems more appropriate to distribute network intelligence and control around the S-PCN network. A distributed network architecture is favored.

The same conclusion is reached with user-originated call setup requests. In order to obtain a channel allocation in either network architecture, the relevant controlling centre of S-PCN resources needs to be interrogated. With a centralized architecture, large signalling lengths are typical. With a distributed architecture, traffic channel allocation can be made with reduced signalling overheads. A distributed network architecture is again favored. When considering system robustness, this is also the case.

Yet there is a cost in keeping satellite control information local to each satellite. For example, since MAGSS-14 satellites orbit the earth every six hours, so also must the relevant satellite control information. This control information must be passed along between the earth stations controlling individual satellites. This adds to the terrestrial signalling cost. The low delay for user-oriented signalling is not affected. From a user satisfaction point of view, call setup delay is an important quality of service parameter. A distributed architecture is favored.

This choice between a distributed and a centralized architecture was also considered in [Araki], where a MAGSS-14 like MEO constellation was used. A distributed architecture was considered optimum as it resulted in a minimization of global system signalling. The favored architecture, found through the simulation of system signalling, provided each earth station with a HLR/s and VLR/s (the main weakness with this approach was that it was assumed that each earth station had direct access to a satellites signalling and traffic channels - this possibility, considered earlier, was found to result in the inefficient use of satellite power and to increase system control complexity). From this it can be concluded:

⇒ *A globally distributed terrestrial control network is favored.*

The amount of distribution required is mainly influenced by the constellation and its service area. For MEO constellations whose satellites have large coverage regions, then only a few (~10) earth stations are needed to provide full constellation connectivity. For a transparent LEO constellation, the smaller satellite coverage area results in more (~40) earth stations being required.

3.3.4 Competition

At this stage a seemingly complete and effective architecture has been reached. Each satellite in the S-PCN system is fully controlled by an earth station which has direct visibility with that satellite. As satellites pass out of the range of these stations, a handover of satellite control to a more suitable earth station takes place. The problem with the above S-PCN architecture is that, until now, the likely requirement for a
competitive internal structure concerning the use of S-PCN resources by service providers has not been adhered to. To introduce a competitive structure a two layered approach is proposed.

Level one earth stations, called Gateway Earth Stations (GESs), are involved in administering satellite traffic channel allocation as well as common and dedicated signalling control channels, as explained in the previous sections. Each satellite in the constellation is controlled, at all times, by separate GESs. The number of GESs required to control a constellation will depend on the constellation altitude and the intended service area. For MEO constellations the number will be much smaller than for LEO constellations. The basic criteria is that operable satellites must always be in view of at least one GES. Because of their role in network control, GESs are associated with both HLR/s and VLR/s databases.

Level two earth stations, called Traffic Earth Stations (TESs), are not involved in non-call related S-PCN control. Traffic channels are routed through these TESs according to the TESs suitability. They might be distributed on a country by country basis - depending on country size, population and traffic competition in that region. There may also be political constraints, requiring traffic associated with a particular country to be routed through a particular TES when possible. For example, S-PCN traffic channels to Mexico may have to use a TES in Mexico when this is possible. This Mexican TES may also be nominated as the preferred TES for other Central American countries. The choice of TES through which a call is routed is chosen during the route optimisation stage of call setup. The use of preferred TESs will reduce the routing choices available and therefore reduce the possible level of route optimisation. TESs are linked with local GESs using a terrestrial-based mesh network.

All initial signalling required to set up a call via a satellite is performed by the GES which is currently controlling that satellite. When a call request arrives at a GES, this information is sent to relevant TESs. These TESs then bid for the call, with the cheapest offer being accepted by the GES6 according to a set of predefined rules. A GES can also act as a TES and so bid for appropriate calls. The choice of TES through which a call is routed depends on a fair appraisal of the optimal route to the call destination in terms of terrestrial distance, satellite loading and ultimately the cost. Factors such as handover possibility (which may result in a new call routing requirement) also need to be taken into account. The final routing decision is taken by the GES.

In a MEO system, the number of TESs is likely to outnumber the number of GESs. In a LEO system, where smaller satellite coverage footprints will result in an increased number of GESs, then the ratio is less clear. The existence of TESs will reflect the needs of the local market. They therefore provide the network with a competitive structure independent of the network operator. TESs also offer improved space segment to ground segment traffic channel connectivity as well as improved inter ground segment connectivity, both of which provide the network with greater routing

---

6 In mobile communication systems most calls are local. To minimise call costs, the length of terrestrial tails (the distance within the terrestrial ISDN/PSTN networks between the S-PCN system and the end user) should be kept short.
flexibility. Figure 3.6 [Cullen93/1] shows the proposed S-PCN architecture. The conclusion here is:

⇒ Through distinguishing between network operators and service providers, a two layered architecture offering a competitive structure can be achieved.

Figure 3.6 - Baseline S-PCN Network Architecture

In this figure, the darker lines between a GES and a satellite indicate GES control of a satellites resources. The lighter shaded lines between UTs and TESs indicate traffic channels (these can also go between GESs and UTs since a GES can act as a TES also). Network control regions are indicated down to the level of satellite spotbeams (Sat x, y). GESs have associated user location registers - H for HLR/s and V for VLR/s. Both GESs and TESs are interconnected by a meshed architecture and both interface with the fixed 'networks'. Specific signalling interfaces exist between the GSM PLMN and the interworking S-PCN system.

An alternative structure is also considered for the S-PCN architecture in terms of location registers. Considering that TESs may be distributed on a almost country by country basis, then is might be appropriate to locate the HLR/s of subscribers from that country, or group of countries, at their 'local' TES. This structure allows individual countries to appear more politically independent within the network and subscribers are also likely to appreciate the more local service offered. In reality, the network operator looses the more centralized control offered by the smaller number of GESs. It also requires TESs to have an extra element of equipment and so increasing their complexity and cost. Locating a VLR/s at a TES is not appropriate as TESs are not involved in common or dedicated control channel signalling. VLR/s databases are
more suitably located at GESs. This possibility is not considered further in this report but only mentioned here as a valid though slightly less efficient alternative.

3.4 Conclusions

In this chapter the S-PCN architecture structure has been examined in detail. Because of its global acceptance, the GSM structure was reviewed. Considering the similarities in terms of a mobile network control structure, it was noted that a functionality similar to the GSM system is required by the S-PCN system. Modifying the GSM network architecture is proposed as a suitable way forward in S-PCN architecture specification. This provides the added advantage of simplifying GSM system interoperability.

The overall system requirements - user, operator and regulator - for the S-PCN system were then considered. From this, conclusions were made on the level of GSM interoperability to be targeted. Dual mode terminals which can switch either automatically or be switched manually between segments are considered. Handover between segments is not suggested as being an initial priority for these systems.

A new S-PCN architecture is proposed which is considered to provide an optimum control structure for transparent LEO and MEO S-PCN constellations. Each satellite is controlled, at any one time, by a single location. This allows a most effective coordination and control structure in the control of individual satellites and their associated spotbeams. Space segment signalling overheads are minimized with this approach. A distributed control architecture was found to be the most appropriate form of global control for such networks. Finally, two levels of earth station types - GESs and TESs - are used which allow network control to be done on a separate level to traffic channel carrying.

References


[Mouly] 'The GSM System for Mobile Communications', M. Mouly, M. Pautet. Published by the Authors, France, 1992

Chapter 4  Network Implementation Aspects

This chapter describes a global structure for the baseline S-PCN architecture described in the previous chapter. This is done for the MAGSS-14 MEO constellation. Ground segment control is analyzed based on a control approach which ensures dual gateway earth station (GES) visibility for each satellite. Ground segment handover frequency resulting from this architecture is also reviewed. An equivalence between GSM and S-PCN networks is proposed. Specific S-PCN aspects such as route optimization, frequency management and a potential role for an on-board controller are examined. Finally, top level descriptions are made of S-PCN call setup signalling procedures within the baseline architecture.

4.1 S-PCN Ground Segment

In this section, the baseline architecture and the MAGSS-14 MEO constellation are brought together and a possible physical implementation is outlined. Practical implications of this structure are then considered. The density of GESs in the network architecture reduces as the constellation altitude increases (ISLs are not considered) since, for a fixed elevation angle, satellite coverage area increases with altitude. The S-PCN architecture proposed in the previous chapter is also applicable to LEO constellations, but because of the higher numbers of satellites and their smaller coverage area, higher numbers of GESs would be necessary.

TESs are not considered as, since GES functionality includes TES functionality, their existence is not necessary for normal constellation operation. The existence of extra TESs should ideally depend on purely outside factors and TES costs would not be part of the network operators costs but be paid for by external investment.

4.1.1 MAGSS-14 Ground Segment Layout

Considering the baseline network architecture proposed in chapter 3, a physical implementation is now applied to the MAGSS-14 constellation. This is done from a network operators point of view that only GESs are considered. Since these must provide full constellation connectivity and since they can also act as TESs, a global functional network results.

GESs are controlled by the S-PCN operator. They must be located to ensure that satellites are controlled by the network throughout each day. When a satellite reaches the end of its period of connectivity with a particular GES, it must already have connectivity with a new GES which takes over control of that satellite. An overlap in connectivity windows allows handover of control from one GES to the next. Gaps in the connectivity window would result in gaps in satellite operation.

Initial work [Sammut93] was done on finding the minimum number of GESs required in order to guarantee satellite-to-GES connectivity at all times. It was found that six globally distributed GESs provided 24 hour ground segment to space segment connectivity.

A follow up study [Sammut94/1] aimed at a higher level of redundancy - one which provided a 100% level of GES-to-satellite connectivity redundancy. This means that even in the event of a GES failure, there is always a backup GES which can assume control and ensure full network connectivity. The full level of redundancy
incorporated into the S-PCN architecture improves network reliability. This can be used, for example, during heavy rain fades or in the event of any failure on the ground. It was found that a worldwide network composed of 11 GESs - shown in figure 4.1 - provided the full level of 100% connectivity backup. In the figure, the contours indicate earth station-to-satellite visibility at an elevation angle of 5°. Each satellite has two or more GESs within its coverage area.

![Figure 4.1 - Possible Gateway Earth Station Layout](image)

The control of a satellite by a GES is decided by the constantly changing physical connectivity between them. As satellites progress about their orbits and the Earth spins, the set of GESs visible to each satellite changes. Because MAGSS-14 is an almost resonant constellation, the satellite to GES connectivity pattern repeats every 24 hours. The RAAN shift of 0.19 °/day, estimated in chapter 2, means that connectivity windows do change but these changes are slow and the task of network control is still much simpler than for a fully non-resonant constellation. Such coverage repetition is clearly useful from a ground network layout and control point of view. The GES which controls any particular satellite is chosen through a combination of parameters such as elevation angle to the satellite, duration of connectivity window and the GESs surrounding communications infrastructure. This optimizes the use of suitably located GESs.

Considering the above physical implementation and approach to GES control allocation, two of the GESs are only ever used as backups for network control (Nairobi and Easter Island). Their remote locations are suitable in ensuring dual visibility while keeping the number of GESs required low, but less suitable from a call routing point of view - little traffic is expected to come from the region of Easter Island, for example. Clearly, each satellite has visibility with a large number of earth stations each day. Each satellite passes 'over' between 13 and 16 earth stations per day.1

---

1 A typical MAGSS-14 satellite will pass 'over' approximately 14 GESs each day - an average of once every 103 minutes. A typical Globalstar satellite might pass 'over' about 72 GESs per day - an average of once every 18 minutes. This results in, respectively, about 196 (14 x 14) and 3,840 (48 x 72) GES-to-GES control handovers per constellation per day. The signalling implications for such handovers need to be further examined.
Figure 4.2 illustrates the control of one of the MAGSS-14 satellites by the ground network over a 24 hour duration. Darker shading is used to indicate satellite connectivity and control, while lighter shading implies connectivity without control. From the four distinct sets of connectivity bands, the four daily orbits of the satellite can be identified. Initial control of this satellite is by a GES in Perth. At this time, the satellite also has visibility with Nairobi and Singapore, which therefore act as additional TESs for this satellite, allowing the possibility of direct call routing to these two continents. After a control period of over two hours, satellite control is handed over to a GES in Hawaii. Further handover of control can be inferred from the diagram. Because of the very small RAAN drift at this MEO altitude, the connectivity pattern repeats each day for each satellite. Changes will occur to this pattern slowly - for example once every month. On a shorter timescale, note how Perth is again in control of the satellite at hour 24. The simplification in network connectivity and control is a distinct and unique advantage offered by these, almost resonant, orbits to S-PCN systems. Non-resonant constellations are likely to require continuous updates concerning network connectivity and network control.

![Figure 4.2 - 24 hour Control and Connectivity for satellite 1](image)

Figure 4.3 indicates the satellite(s) being controlled by one of the Lisbon GES. The satellites are numbered 1 to 14 on the vertical axis. As with figure 4.2, this figure indicates constellation connectivity over a 24 hour period. In order to describe the whole constellation connectivity, a set of 14 figures such as figure 4.2 (one for each satellite), or, a set of 11 figures such as figure 4.3 (one for each GES) would be required. Note that the first rows in figures 4.2 and 4.3 are similar as they refer to the same satellite / GES pair.
For the ‘resonant’ Deligo constellation - proposed in chapter 2 - which has a repetitive ground track, a similar approach could be used in creating its ground segment connectivity pattern. For ‘Deligo’, and due to its orbit period compensation to eliminate the effects of RAAN precession, the connectivity windows would shift forward by twelve minutes each day.

A GES may control more than one satellite simultaneously. Figure 4.4 shows the number of satellites visible to the Lisbon GES together with the number of satellites normally under its control (darker shading only), over a 24 hour period. Considering their backup role in network control, a MAGSS-14 GES must therefore have the ability to manage up to 5 satellites. TESSs, in order to be able to connect to any satellite within range, would also require up to 5 earth station antennas, which increases their cost.

In a LEO constellation such as Globalstar, lower numbers of satellites will be visible to earth stations because of the smaller satellite coverage area overlap. For ‘Deligo’,...
which provides 100% dual diversity, higher numbers can be expected. GES and TBS costs obviously increase since more satellite coverage area overlap occurs.

4.1.2 Ground Segment Signalling

Ground segment signalling is required for S-PCN control. Ground segment connectivity is therefore an important issue. A mesh network connectivity geometry allowing terrestrial routing redundancy was proposed in the baseline architecture. It is also useful as each GES will need to coordinate with 'adjacent' GESs throughout each day and so direct and independent links are preferable. The signalling level at the moment of GES-to-GES handover is likely to be high and of high priority. At this moment, the 'old' GES will pass over all relevant satellite control information to the 'new' GES, allowing the new GES to take subsequent control of the satellite. Even so, a short link discontinuity for system control channels is likely to result for each handover. Other normal signalling exchanges between GESs and TESs include call set up and call handover signalling.

Further work is required in order to estimate the signalling message requirement. To do this, an examination into the full range of signalling procedures is required. S-PCN flow control and signalling sequences are introduced later although specific message content is not proposed.

4.2 S-PCN / GSM Equivalence

The S-PCN network hierarchy parallels that of the GSM architecture [GSM] [Mouly] in many respects. Interworking between GSM and S-PCN is envisaged at the MSC (or Gateway MSC) to GES level. In the GSM system, the BTS, BSC combination is called the BSS. Its S-PCN 'equivalent' is called a Traffic Earth Station (TES). A GES is proposed as the 'equivalent' of a BSS and MSC combination. A GES is therefore like a TES but with an additional network control capability. In the following sections, the equivalents of key GSM network elements - the Base Transceiver Station (BTS), the Base Station Controller (BSC) and the Mobile services Switching Centre (MSC) - are considered in more detail in the S-PCN architecture. Figure 4.5 indicates the S-PCN architecture in a way which mirrors the GSM architecture (figure 3.1). GSM interfaces, modified for S-PCN, are indicated. As already discussed in chapter 3, TESs are not indicated with a location register role even if this is possible within the architecture. This is because the reasons for this are political rather than technical.
Some points concerning this are now made. In all cases, the comma indicates a modified version of the original GSM interface. A distinction has been made between a Full Um’ interface and a Basic Um’ interface. A Full Um’ interface is offered by a GES and is considered the equivalent of the GSM Um interface [Steele]. A Basic Um’ interface is offered by a TES. Only a reduced functionality of the Full Um’ interface is required because TESs are not involved in system management functions. Only traffic channel related functionalities are therefore needed.

Concerning the ground segment, the GES-to-TES interface is likely to contain a subset of the functionality contained in the GES-to-GES interface. As with the air interface, the difference is in terms of system management functions. Where the ‘A’ interface is indicated in the diagram, A_{eq} interface functionalities are also referred to. In order to allow for the handover of control information between GESs (GES-to-GES handover), the GES to GES interface will need to be modified and provided with this additional functionality.

### 4.2.1 S-PCN / BSS Equivalence

The S-PCN equivalent of a BSS is a TES. As with a BSS, a TES is considered to consist of two distinct elements. Paralleling GSM terminology, these are called traffic earth station transceiver (TEST) and traffic earth station controller (TESC). The distribution of TESs may be, depending on regulations and requirements, almost on a country by country basis and possibly more for larger countries. However, since in the network architecture described here TESs are not required, the existence or not of a TES in a country or region depends on investment from that region. Requiring the network operator to invest in TESs for each country in which they wish to offer a service is likely to be excessively expensive.
Considering the small number of GESs required to provide full control to a MEO constellation and the large distances between these GESs, then there is likely to be plenty of scope for the addition of TESs. For a LEO constellation, which requires a much higher number of GESs in order to provide full network control, then there will be less of a need for additional TESs.

4.2.1.1 Traffic Earth Station Transceiver (TEST)
The TEST is concerned with air-interface transmission aspects. It transmits in either C or Ku-band, depending on spectrum availability. If Ku-band is used then specific fade counter measures may be required. This could be done locally by locating a second set of TESTs beyond the required ‘site separation distance’ (usually more than 10 km). However, with TESTs probably requiring up to 5 antennas, this may be an expensive option. A TEST would have the following core tasks:

- Convert the bit streams of individual channels arriving from the TESC into the correct format for S-PCN transmission. This would involve coding and modulation followed by upconversion to an appropriate carrier frequency;
- Transmission of the S-PCN traffic and associated signalling channels to the correct coverage zone of the correct satellite. This is likely to require coordination with other TESTs using the same satellite and coverage zone in terms of transmit power level and timing. The level of connectivity provided depends on the satellite payload structure;
- Ensure the delivery of correct frequencies on the user side of the link through Doppler compensation on the carrier;
- Perform the equivalent procedures on the return link.

4.2.1.2 Traffic Earth Station Controller (TESC)
A TESC is mainly concerned with network issues such as signalling and call routing. It can connect with terrestrial networks but is not involved in route optimisation for calls. A TESC is allocated a traffic channel from a GES. When allocated a traffic channel it is responsible for that traffic channel and its associated signalling channels. The TESC must deal with air-interface network layer problems such as intra and inter satellite handover. The following is a list of the core tasks performed by a TESC:

- Interface with terrestrial networks (PSTN, ISDN and PLMNs);
- Perform network level signalling with the UT to monitor spotbeam connectivity;
- Perform network level signalling with the TEST to monitor satellite connectivity;
- Interface with GESs that control the resources of satellites within range;
- Transmission and correct routing of the bit streams passing through it in both directions.

4.2.1.3 Comparison
The (TEST, TESC) combination is termed a TES. A TES is considered the S-PCN equivalent of a BSS in the GSM system. The differences and similarities are listed below:

Differences.
1. A TES does not have direct control over channel allocation. In the GSM, the BSS does, to a large extent, manage its own set of traffic channels. This difference is a direct consequence of changing constellation connectivities;

2. A TES interfaces directly with other networks. In the GSM, the MSC interfaces with other networks. This difference for S-PCN systems makes sense due to the larger distances between S-PCN earth stations and also from a regulatory point of view;

3. A stand-alone TES is not directly involved in common control channel signalling for call set up or network mobility management signalling. This is due to the proposed S-PCN architecture which aims at minimizing space segment signalling;

4. A TES is involved in the final dedicated control channel handshake before the assignment of a traffic channel. It is also responsible, upon call termination, for channel release signalling.

Similarities.

1. A TES performs all radio interface tasks for active traffic channels and their associated signalling channels;

2. A TES is transparent to higher level network signalling aspects such as database management;

4.2.2 S-PCN / MSC Equivalence

The role of a gateway earth station (GES) is now considered. The basic functionality of a GES includes the functionality of a TES since it is through the air interface capability of a TES that the GES obtains access to the satellites. A GES which is not in control of a satellite can therefore be considered as a TES. A GES currently in control of a satellites resources has network responsibilities allowing it to control satellite resources. Since transparent satellites only are being considered, a GES can only control satellites which are within range. At any one time, a satellite is controlled by only one GES. As a satellite orbits the Earth, control of its resources is handed over between different GESs. Depending on network connectivity - which is a function of constellation design - a GES can have visibility of more than one satellite. Considering this, a GES must have the ability to control a similar number of satellites (the number of antennae associated with a TEST is determined by this). For MAGSS-14 this was shown to be five, with a sixth probably being used as a backup.

In terms of network control the GES has a combined MSC and BSS role. A GES is responsible for database management, including security, mobility management, service, authentication and equipment registers. The interfaces between the GES and these registers can be similar to the GSM approach\(^2\). A GES can interface with the fixed networks (in line with its TES capability) which is a similarity with MSCs. A GES is responsible for call route optimisation.

A satellites GES is associated with a call on that satellite for the duration of the call. This ensures the provision of handover or in-call modification capability. For

\(^2\) This allows reuse of GSM-developed protocols and standards. Modified versions of both LAPDm and MAP are expected to be used in the S-PCN architecture.
handover due to a satellite moving beyond the range of the serving TES, a new earth TES needs to be chosen, which implies a new call routing. The simple option for such cases is to route the call terrestrially from the old earth station to the new earth station and use the already established terrestrial link between the old TES and the call destination.

An important difference with the GSM approach is that a GES, unlike a MSC, has direct and full control over the allocation of satellite traffic channels. In the GSM network, BSSs mainly have this capability with MSCs overlooking traffic channel allocation with the capability of intervening in order to redistribute the traffic load. This difference in functionality is as a result of the improved efficiency gained by centralizing control of individual satellites. A GES has full control of a satellites common control signalling channels and is responsible for initial dedicated control channel signalling. This means that mobility management signalling and all preliminary call setup signalling with a UT is done by the GES. Interworking with the GSM network (call forwarding, mobility management address updating, billing, user profile changes etc.) is an important extra feature for S-PCN systems. It is envisaged on specialized links between GESs and MSCs. The following is a list of similarities and differences between a MSC and a GES:

Differences:

- Air interface route optimization is a more complex function for S-PCN compared with GSM and becomes a specific responsibility of the GES;
- The GES (through its TES capability) is responsible for setting up common and dedicated control channel signalling with UTs;
- A GES has full responsibility for S-PCN channel allocation.

Similarities:

- The GES is responsible for S-PCN database management;
- A GES can interface with the fixed networks.

4.3 Other S-PCN Aspects

In this section the issues of route optimization, frequency management and the use of a satellite on-board network controller are considered. Route optimisation and frequency management are seen to create specific new problems for S-PCN systems. The use of an on-board network controller is proposed as a possible intermediate step between transparent satellites and satellites with full on-board processing (OBP) capability.

4.3.1 Route Optimisation

Because of the fundamental difference in connectivity between terrestrial mobile systems and S-PCN systems based on the use of dynamic satellite constellations, and also because of the longer ground segment distances involved, a new approach to route optimization needs to be devised [Cullen93/3] [Cullen94/2]. On a separate level still, charging is likely to vary depending on satellite / coverage zone loading. It may also vary between developing regions and developed regions. For example the use of 'fixed' terminals as public telephones in developing countries cannot work at
developed country prices. Considering the links from a connectivity only point of view, an S-PCN system link consists of the following two components:

- An air-interface link from a UT up to a satellite and back down to an earth station (TBS or TES/GES);

- A terrestrial link from the earth station to the other end of the call - typically into the ISDN, PSTN or PLMN systems but possibly back to the S-PCN system.

In deciding on the final routing, the combined call path over both of these segments needs to be optimized. Considering possible call routing restrictions, optimization may not be based purely on a minimization of cost.

To optimize the call routing, the two end points of the call are located. The routing options between these points are then considered. Satellite diversity can offer a choice here. If two or more satellites are visible to a UT then a choice can be made between the available satellites. There is also the possibility that the call may be routed to a UT via two satellites (link diversity being used to reduce the required link margin). In this case, only earth stations in visibility of both satellites can be considered. To find this out, the network asks the UT for its satellite and coverage zone diversity. In idle mode, a UT scans system broadcast channels and maintains a list of those which provide a signal of sufficient quality. This approach requires a specific modification to the standard GSM air interface call setup procedure.

Satellite loading is an important factor. If two satellites are available to a UT - one lightly loaded, the second heavily loaded - then it may be preferable for the network operator to use the lightly loaded satellite. By so doing, the problem of call blocking is reduced on the heavily loaded satellite and so overall service quality is less likely to degrade. Terrestrial tail lengths are another very important factor in finding the most appropriate call routing. For a call destined for New York, it is preferable to use an earth station located on the American east coast rather than in Europe or the American west coast. Using an appropriate earth station reduces the terrestrial length of the call and therefore the cost of the terrestrial segment of the call. This trade-off between satellite loading and terrestrial tail lengths is indicated in figure 4.6.

---

3 For example, it may be that all calls that enter or leave a country must pass by the official GES or TES nominated by the country.
Another aspect concerns network signalling. It may be that certain satellite / earth station combinations are disadvantaged because connectivity between them is not going to last very long. The GESs choice of satellite and earth station through which a call is routed is summarized in the following list:-

1. International routing restrictions which may be imposed;
2. The availability of traffic channel capacity on the satellite(s) through which the call might be routed;
3. Use of the most suitable earth station in order to minimise the length of the terrestrial tail required by the call;
4. The appropriateness of the use of that satellite / coverage zone from a call continuity / signalling viewpoint.

Considering all these factors, the appropriate call routing can be chosen by the GES involved in call set-up.

### 4.3.2 Frequency Management

This section considers S-PCN frequency management which relates to the optimisation of the frequency reuse factor of the constellation in order to maximize the number of traffic channels offered. It is very closely related to S-PCN resource management which deals with the optimum allocation of network traffic channels in order to ensure that network traffic demand is met. Due to the limited resources available, the S-PCN system must be configured in a way that guarantees the efficient use of system power and bandwidth. Under normal circumstances, many coverage zones will have little traffic demand while others will have a high traffic demand. In those zones of high traffic demand, bandwidth limitation will be a real problem and effective S-PCN frequency management will be required.

With the purpose of S-PCN resource management being to ensure a maximum availability of traffic channels within the network, achieving this is directly related to effective frequency management. Frequency management becomes a complex issue when dynamic satellite constellations are used [Cullen93/3]. Given the shortage of L- and S-band spectrum available to these systems (the FCC allocated 5.5 MHz to each
of Iridium, Globalstar and Odyssey), obtaining a high level of frequency reuse is a key network design issue. The Frequency Reuse Factor (F) is defined as follows:

\[ F = \frac{B_{\text{information}}}{B_{\text{occupied}}} \]  

(4.1)

where \( B_{\text{information}} \) is the number of channels times the channel bandwidth, and \( B_{\text{occupied}} \) is the bandwidth allocated to the system.

The ultimate obtainable level of frequency reuse depends on a number of parameters, the most important of which are listed below:

1. The type of constellation design used (since this effects the level of dynamically changing overlaps of satellite coverage) and how constellation coverage relates to the traffic distribution on the Earth.

2. The number and type of beams generated by the satellite antenna (dictated by link budget G/T requirements).

The basic task is to determine, depending on the multiple access scheme being used, the distance apart two coverage zones can be in order to be allowed to use the same frequency. This is likely to vary depending on the relative geometry between coverage zones location and also on the traffic demand in their region of coverage. Coverage-zone cross-over levels and gain fall-off rates are related parameters. High numbers of coverage zones allow for potentially high levels of frequency reuse. In order to do this the satellite coverage pattern needs to be effectively defined. The network Multiple Access approach - CDMA or TDMA - is important in order to estimate an allowable carrier to interference (C/I) ratio.

The next task involves the incorporation of network traffic statistics. In regions where traffic demand is high, it will be necessary to allocate extra traffic capacity (in the form of extra bandwidth) so that the traffic demand can be met. This should allow an estimate of how much bandwidth re-allocation flexibility is required by the system. Daily and weekly variations in traffic further modulated by satellite motion, result in a high flexibility requirement for the satellite payload. Flexibility in assigning traffic capacity to beams is therefore important. The use of 'floating' bandwidths which can be allocated by the network to satellites and coverage zones which require them is proposed. For example, satellite spotbeams passing over Europe at times of peak traffic demand are likely to be overloaded. However, if additional bandwidth could be allocated in certain coverage zones where the traffic demand would otherwise exceed the available capacity, then service availability can be improved. Individual spotbeams are likely to have the capability to increase their power output to 40% of the satellites total.

Extra signalling and traffic channels can be temporarily allocated if extra traffic capacity is required within a spotbeam. This allocation of spare system bandwidth (through frequency management) could be based on either traffic predictions or on real-time traffic demand. Satellite motion implies dynamically varying regions of satellite coverage overlap, resulting in dynamically varying traffic and inter-satellite interference levels. Due to both satellite and coverage zone overlap, such bandwidths would be specifically used in regions where the traffic demand peaks. In examining traffic loading, the possibility of off-loading traffic to adjacent satellites in regions where satellite spotbeams overlap should also be considered. A frequency
management approach can then be devised for those traffic peaks which remain the most critical.

Frequency management involves the task of reconfiguring the satellite payload to allow it to carry the extra bandwidth without effecting channel quality through increased interference. The requirements on the satellite payload need to be further examined before a configuration is chosen. If sufficient payload flexibility is not incorporated from an early stage, then the ability of the S-PCN system to adopt to regions of high traffic intensity is reduced.

Another aspect of frequency management concerns interference avoidance. Payload reconfiguration of spotbeam operating frequency must also occur if two spotbeams, on separate satellites but using the same frequency subband, approach each other. Within a certain minimum distance, co-channel interference between these spotbeams will result in channel degradation for certain areas within both spotbeams. If CDMA was the access method used, too many overlapping and co-channel spotbeams can result in a high interference noise floor. In such cases, spotbeam operating frequencies must be changed in order to ensure service quality. Such changes must be minimized as they require all channels within the spotbeam to be switched to a new frequency. This requires intra-spotbeam handover which has an associated signalling overhead. Payload reconfigurations of spotbeam operating frequency should therefore be minimized.

Through the use of resonant constellations, the traffic loading of individual satellites becomes predictable on a daily, weekly or yearly basis. Constellation resonance means that specific planning would only need to be done once for each satellite / region combination. For non-resonant constellations, such coordination would be an on-going and complex network task since new combinations result each day. Resonant orbits therefore offer S-PCN systems a key advantage in terms of system resource usage. The near-resonant MEO constellations at 10,354 km will require reoptimization at approximately monthly intervals, due to their low rate of RAAN precession and their resulting almost repetitive ground track. The ‘Deligo’ constellation would also benefit to some extent due to its repetitive orbit ground track - coordination is still required, however, to take the daily time shift into account, since traffic demand will vary with time.

4.3.3 On-Board Network Controller

This section considers a non-transparent option in terms of on-board satellite technology. It is considered more appropriate to 2nd phase S-PCN systems and 3rd generation mobile satellite communication systems [SAINT]. The key purpose of an OBNC is to locate a limited set of functions - those which are most optimally placed there - on board the satellite. An ‘On-Board Network Controller’ (OBNC) is located on each satellite and is given the task of on-board demodulation of network common control channels. Network traffic channels are treated separately and transparently by the satellite. Traffic channels may be channelized and switched, possibly even individually, within the payload but are not demodulated at any stage. Considering that signalling channels are of fundamental importance to the system as a whole, then locating the control of these channels in an OBNC would allow important network control procedures to be performed by the satellite. The next section considers which network control aspects are most suitably located on the satellite.
The main problem concerning a fully ground based approach to network control derives from the dynamically changing set of network connectivities. With all control functions located in the ground segment, all satellite specific information must follow the satellite around in its orbit, increasing the ground segment signalling requirement. As noted already, this is most significant for LEO constellations due to their shorter orbit period. The idea behind the use of an OBNC is to avoid the negative influences of satellite dynamics on the network through placing a minimum amount of network control in the space segment. The aim of an OBNC would be to minimise the amount of ground segment signalling information that must follow a satellite around its orbit and this is done by placing such information on board the satellite.

The use of an OBNC is not a requirement but is an attempt to increase network signalling efficiency. Even if control of satellite parameters such as power loading and traffic channel availability is placed on the satellite, it is likely that a backup mechanism is required in the ground segment. A problem associated with the use of an OBNC is that it adds further to satellite complexity - although not as much as a fully regenerative payload, it would result in a more complex payload than a transparent satellite. The following is a list of the main types of information or procedures considered relevant for OBNC implementation.

1. Monitoring the percentage of satellite power capacity currently being used;
2. Monitoring the percentage of capacity being used within each satellite coverage zone;
3. Managing common control channel signalling procedures;
4. Monitoring the identity of traffic channels which are currently active within each coverage zone;
5. Managing the identity and allocation of traffic channels which are available within each coverage zone;

The aim is to optimize the location within the S-PCN architecture at which control decisions are made. These information types are now considered for their suitability for location on the satellite.

4.3.3.1 Satellite Power Availability

The amount of useful RF power available to a satellite is a key parameter in determining a satellite's ability to provide traffic channels. Such data is generated on the satellite and depends on factors such as current and future RF power availability, current and future RF power consumption rate, solar panel performance and battery performance. Based on these, an OBNC monitors the ability of the payload to transmit more traffic channels. If this information and control function was located on the ground, then each time a handover between GESs is required, these parameters will need to be updated for the new GES. Locating it on a satellite eliminates this requirement.

4.3.3.2 Common Control Channel Coordination

Specific channels of interest for OBNC implementation are the broadcast channel, the paging channel, the random access channel and the access grant channel. These are the four main GSM common control signalling channels [GSM]. The OBNC could be the focal point through which coordination of a satellite's common control channel signalling is done. The transmission delay would be halved because the signalling for
these channels is now directly between the UT and the satellite and does not initially involve a GES. For random access channels, where repeated collision can cause large delays, the reduction in delay is most significant. Also, signalling channel discontinuities, which otherwise occur at each GES to GES handover, would not occur because these channels are demodulated by the OBNC and retransmitted continuously towards the users.

4.3.3.3 List of Traffic Channels
For each satellite coverage zone a list of all currently available and currently active channels is kept. Normally this information would be stored in a GES. With an OBNC, this information can be stored on the satellite. The advantage is that, upon handover between GESs, the exchange of traffic channel information is not necessary. GES to GES handover may no longer be necessary since the information previously needed to be handed over is now permanently located on the satellite. The effect on protocol timers for common control channel signalling would need to be taken into account in protocol development.

4.3.3.4 OBNC Implementation
Dual redundancy can be used for the OBNC processor - the processor and its duplicate running the same algorithms and procedures and their output is compared. If any disagreement arises from the comparison, a recovery procedure can be invoked to resolve the disagreement. If the recovery procedure fails to resolve the situation, a switch-over is initiated to a backup ground segment based solution and normal OBNC operation is interrupted.

4.3.3.5 OBNC Review
The functions that could be optimally performed by an OBNC include coordination of a satellites available power, coordination of a satellites common control channels and coordination of a satellites traffic channels. The use of OBNCs can result in network efficiency gains at the expense of increased satellite complexity. Due to the higher rate of GES-to-GES handovers required, an OBNC is more advantageous to LEO constellations rather than MEO constellations.

4.4 S-PCN Operation
The operation of an S-PCN network is now considered. By describing control flows through the system, this section clarifies network operation. Detail on the mobility management approach is not provided here but a difference in the role of the VLR/s is noticed. The connectivity distances used indicate a MEO constellation. The specific GES locations mentioned refer to the global GES layout proposed earlier in this chapter (section 4.1).

4.4.1 Dual-mode Terminals
A dual-mode terminal is assumed to be capable of monitoring only one system at a time. In idle mode, the terminal monitors only one set of system paging channels in order to detect in-coming calls. When a terminal is turned on it registers with one of the systems available - GSM by default and S-PCN if it is outside GSM coverage. Registration specifies the network a UT is monitoring. Based on this, the network
knows the system over which to page a UT. A deregistration procedure is introduced for terminals which are turned off. In this way, the network can further distinguish between active and inactive terminals, allowing a reduction in redundant paging signalling.

An indicator is used on each terminal which allows the user to deduce their system coverage. For example, if the average signal strength of a system is above a certain cut-off level then a light indicates system availability. For dual-mode terminals, four combinations could exist. A user should have the ability to register with whichever available system they want to - automatic, GSM only or S-PCN only. A terminal indication of which system a user is currently registered with is needed. This allows the user to control the call types made (GSM or S-PCN), which effects aspects such as cost, service availability and link cooperation.

### 4.4.1 Terminal Registration

Assume the user of a dual-mode UT is usually based in Paris. The UT’s HLR/s is associated with the GES in Lisbon. Consider the user is on a trip to Moscow and switches on the UT. The following list describes the sequence of events which follow.

1. The UT searches for GSM broadcast channels but does not find any. The UT indicates this (e.g. no green light). A different light indicates the strength of the S-PCN signal.

2. The user realizes that S-PCN should be used and verifies that the S-PCN signal strength (broadcast channels) is above a certain level. It may be necessary to cooperate with the link.

3. Once a sufficient signal level is available (this typically depends on the satellite to UT elevation angle), the UT searches S-PCN broadcast channels in order to register within the system. These channels come from one or more GESs - depending on constellation coverage diversity and current satellite control.

4. The UT begins a random access signalling procedure to the network.

5. After a successful random access procedure the contacted GES allocates the UT a ‘stand-alone dedicated control channel’ on which it starts location registration.

6. The contacted GES is located in Singapore. Assume it is currently controlling a satellite in orbit over the Indian Ocean and another in orbit over Eastern Europe. The UT provides its identity to the Singapore GES via a specific coverage zone of the ‘Eastern Europe’ satellite.

7. The GES uses the UT’s air interface identity to locate its HLR/s - found to be in Lisbon. Authentication, ciphering and location registration is performed and the signalling channel is released.

8. The Singapore GES becomes the UT’s VLR/s and the UT’s HLR/s is updated. Further calls to the UT are now forwarded from the Lisbon HLR/s to the Singapore VLR/s.

### 4.4.2 User-Terminated Call Setup

With the UT now registered in the S-PCN system, a user-terminated call is considered. In idle mode a UT user must ensure that signal strength is sufficient.
Assume a fixed user in the Paris area phoned the UT. The following list describes the general flow of control upon call setup.

1. The call is switched to the UTs HLR/s in Lisbon. From there it is forwarded to the UTs VLR/s in Singapore.

2. This GES is responsible for locating the UT. Considering constellation dynamics and changing network connectivities, the Singapore GES is not automatically in control of satellites over Moscow (because of this, there is an argument to use the HLR/s at the time of location registration if it is more local to the UTs location).

3. Assume that two satellites currently cover the Moscow region - one controlled by the Lisbon GES, the other by the Singapore GES. It is unclear which of these satellites / coverage zones the UT is currently monitoring. The Singapore GES must arrange to page the UT via both satellites.

4. Upon hearing its identity on the paging channel (Singapore GES) it was monitoring, the UT initiates a random access procedure.

5. A 'stand-alone dedicated control channel' link is established between the UT and the Singapore GES. Information is exchanged concerning UT identity and diversity (for route optimization).

6. Because the call originated in France, it is likely that an earth station (TES) located in France which has connectivity with one of the relevant satellites, will provide the optimum route for such a call.

7. The Singapore GES allocates a channel to the UT (over the air-interface) and the chosen TES (over a terrestrial interface).

8. A final signalling exchange is made between the UT and the TES. The call can now proceed with a ringing tone at the UT.

Figure 4.7 shows the links established for call setup. Initially the call is switched to Lisbon and a link is established to the UT (darker line). The lighter line indicates the actual traffic channel link between the UT and a TES near Paris.
4.4.3 User-Originated Call Setup

For a user-originated call it is assumed that the UT user in Moscow makes a call to a number in Japan. The following list describes the sequence of events.

1. The user dials the number and pressed the ‘send’ button. The UT begins a random access request procedure. The chosen random access channel depends only on the strongest signal that was available to the UT.

2. The Lisbon GES is assumed to be contacted and it establishes a stand alone dedicated control channel link between itself and the UT. The UT provides its identity to the GES which assumes control of the call.

3. As part of call setup signalling, the UT provides the GES with the destination number - a number in Japan. The UT includes its satellite diversity - assume that it reports three visible satellites, two having direct connectivity to the Tokyo GES.

4. The Lisbon GES performs route optimisation and chooses a call routing. The routing is almost certain to include the Tokyo TES since this results in the shortest terrestrial tail.

5. The GES controlling the chosen satellite is contacted (assume the GES is located in Singapore) and a channel in the specified coverage zone is requested. The TES in Tokyo is informed and sets up the terrestrial tail for the call.

6. The Singapore GES specifies a traffic channel to the Lisbon GES which identifies this channel to the UT over the established air interface.
7. The link between the UT in Moscow and the TES in Tokyo begins with a final signalling dedicated control channel exchange between these two entities. The signalling channel between the UT and the Lisbon GES is dropped. The only air-interface link to the UT is via the Tokyo TES.

8. The GES in Singapore remains associated with the Tokyo TES due to it being the controller of that satellite. The GES in Lisbon remains associated with the call since the UT has its HLR/s located there and UT capabilities are held there.

4.5 Conclusions

In this chapter a global layout was proposed for control of the MAGSS-14 MEO constellation. It is based on the S-PCN architecture proposed in chapter 3. Dual connectivity to all satellites in the constellation is achieved through the use of 11 Gateway Earth Stations. The low GES numbers required for MEO constellations leaves room for additional TESs. For LEO constellations, higher GESs are required and so TESs are less prevalent. The usefulness and practicality of resonant orbits in terms of ground segment to space segment connectivity and control was pointed out in terms of the MAGSS-14 and Deligo (LEO) constellations. The connectivity implications resulting from the use of MEO and particularly LEO constellations were highlighted.

A comparison between the architecture and the GSM architecture was done in terms of functionality and interfaces. Similarities and differences in the network control approach were examined but overall functionalities were seen to be equivalent. This equivalence can allow GSM interfaces to be reused, with appropriate modifications, as interfaces within the S-PCN architecture, thereby reducing S-PCN development costs.

S-PCN aspects such as route optimisation, frequency management and the use of an on-board network controller on the satellites were introduced. Route optimisation is seen to require up to date knowledge on the network status and is well suited to being located at the GES. Frequency management in S-PCN systems is seen to be a highly complex issue depending on very dynamic factors such as traffic demand and satellite coverage overlap. It is highlighted as an area requiring detailed examination. A On-Board Network Controller was introduced as a way of improving network efficiency by locating some control functionalities on the satellite.

Finally S-PCN operation was examined and described in order to provide a clearer picture of system functionality. Location registration, user-originated and user-terminated call setup signalling procedures were introduced in a general way. This allowed some of the unique operational features of S-PCN systems, compared with terrestrial systems, to be highlighted.

References


Chapter 5  S-PCN Signalling and Traffic

This chapter introduces S-PCN air-interface signalling, based on the GSM LAPDm protocol [GSM]. The channels considered are the paging channel, the random access channel, the access grant channel and the stand-alone dedicated control channel. After taking into account S-PCN service environment types and necessary link margins, conclusions are drawn on the possible bit rates of these signalling channels. No distinction between LEO and MEO constellations is necessary for this. Estimates on S-PCN traffic levels are also made, allowing common and dedicated control channel throughput requirements to be quantified. Finally, the random access and paging channel performances are considered.

5.1 Common and Dedicated Control Channels

This section examines air interface signalling channels. For initial, 1st phase, S-PCN systems, the use of GSM based protocols on both the network side and over the air interface, is desirable. This reduces protocol development costs and simplifies interworking with other networks. The GSM LAPDm air interface protocol is therefore considered as the basis for S-PCN air interface signalling. Modifications are required in order to adapt it for S-PCN applications - the modified version might be termed LAPDm\textsubscript{satellite}. The air-interface signalling channels considered here which relate to GSM network layer control are now reviewed. Within each spotbeam there are other signalling channels which are not considered here as they operate on the physical rather than the network layer. The common control channels described above are indicated in figure 5.1. The dedicated control channel (SDCCH/s) is also indicated.

![Figure 5.1 - Basic System Signalling Channels](image)
5.1.1 Broadcast Control Channel/ satellite (BCCH/s)

This channel is in the forward link direction only. It is broadcast by the Gateway Earth Station (GES) which is currently in control of the satellites resources. It broadcasts general network information, specific for each satellite spotbeam. User Terminals (UTs) in each coverage zone monitor this channel while in idle mode. UTs obtain the ‘identities’ of the paging, random access and access grant channels from the broadcast control channel. Therefore, the identity of all broadcast channels needs to be held permanently by all UTs. In order to reduce the time required by UTs to search for currently available broadcast channels, the number of BCCH/s channels should be minimised within the system.

5.1.2 Paging Channel/ satellite (PCH/s)

This channel is also in the forward link direction only and is transmitted by the GES which is currently in control of a satellite. UTs in each satellite coverage zone must also monitor this channel while in idle mode - a level of coordination with the BCCH/s channel is therefore required. On this channel, the air-interface identities of UTs are transmitted by the GES as a first step in contacting a UT for a user-terminated call setup. Upon hearing their identity, UTs make a random access request to the network for allocation of a stand-alone dedicated control channel.

5.1.3 Random Access Channel/ satellite (RACH/s)

This channel is in the return link direction - from a UT to a GES. When a UT has to contact the network (after being paged, for mobility management related signalling or for user-originated call setup) it accesses the network on this channel. This channel is therefore required to provide a high throughput and low delay. A slotted - aloha channel is considered most appropriate for this [Abramson]. It is a key network channel and one whose performance has an important influence on the signalling delay performance of S-PCN air interface signalling. This will become more evident in chapters 6 and 7 where air interface signalling procedure delay performance is examined by simulation.

5.1.4 Access Grant Channel/ satellite (AGCH/s)

This channel is in the forward link direction only - from a GES to a UT. It is used by the GES to reply to UTs which have made a successful request on the random access channel. The access grant channel allocates a stand-alone dedicated control channel to a UT.

5.1.5 Stand-alone Dedicated Control Channel/ satellite (SDCCH/s)

This is a bi-directional signalling channel allocated by a GES via the access grant channel. It allows for direct signalling between a GES and a UT. If this signalling is for location registration or update, then it is completed on this channel and the channel is released. If the signalling is for either user-originated or user-terminated call setup, then (if call setup is successful) the signalling results in the setup of a traffic channel.
and its associated control channels\textsuperscript{1} between the UT and an appropriate satellite / TBS combination.

5.1.6 S-PCN Operation Review

In chapters 6 and 7, these channels are used to perform the different signalling procedures - location registration / update, user-originated call setup and user-terminated call setup. A review of the current S-PCN operation scenario is now provided for clarification. To do this, reference is made to the MAGSS-14 constellation.

- There are 14 active satellites in orbit, directly controlled by about 10 GESs;
- Each satellite has 37 spotbeams which are the basic units of network control;
- Each spotbeam has an associated set of traffic and signalling channels;
- Depending on constellation diversity, each UT might have more than one spotbeam available to it;
- A UT in idle mode monitors both satellite broadcast and satellite paging channels;
- As the satellites orbit, the Earth rotates and UT users move, different paging and broadcast channels are monitored by the UT;
- A GES may not know the exact paging channel being monitored by a UT at a particular time.

5.2 Space Segment Signalling Aspects

In this section aspects relevant to the space segment air-interface are described. Signalling channel bit rates are estimated from a voice channel relative link margin point of view. In order to do this, a description is required of the intended operating environments for S-PCN. Propagation margin requirements can then be estimated which will indicate the sort of bit rates that can be used. These are used for simulations in the next chapters in obtaining the delay distribution of different air interface signalling procedures.

5.2.1 S-PCN Link

S-PCN services should be available to users in the following environment types - 'open', 'rural', 'semi-wooded', 'suburban' and 'urban'. However, the following qualifier is usually added - 'users should seek a maximum amount of sky for active communication' [ETSI]. This reduces the required margin for voice channels. Figure 5.2 below shows a UT and a 'Pager' terminal in possible operating environments.

\textsuperscript{1} In the GSM system, each traffic channel (TCH) has two associated channels - a fast associated control channel (FACCH) and a slow associated control channel (SACCH).
In certain circumstances, signalling channels will need to operate without user cooperation. For example, during mobility management location update or user-terminated call setup signalling procedures user cooperation cannot be assumed since users are not aware of the ongoing signalling. In such cases, ‘maximum sky visibility’ does not automatically apply. Even for links where user cooperation can be assumed, satellites at low elevation angles will still be shadowed and link power is reduced.

The main concern of the payload designer is how to get enough power for the forward downlink (satellite-to-UT), which is the single largest power consumer in the payload. In fact, forward link amplification is considered to consume twice the amount of power as return link amplification. This is because of the low UT G/T compared with the G/T of an earth station on the return link. The occurrence of shadowing and blockage on such links, can, to some extent, be offset by link power control. Individual channel power levels can be controlled either at the earth station or, for fully channelized digital processing payloads, on the satellite. However, for high levels of shadowing and blockage, then this capability will not suffice. Moreover, for CDMA based systems, which suffer from near-far effects [Dixon], power differences between different channels should be minimised so increasing the power level for individual channels requires increasing the power level for all channels.

The implications of this restriction on system design are important. Certain environment types are clearly disadvantaged. Providing users with dual satellite visibility is being considered as a way of improving service quality while reducing the link margin required. In this technique, calls might be transmitted from the GES to the UT via two different satellites. The forward downlink path - from satellite to the UT is the hardest link to close for the system link budget. Through using link diversity it is sent via two different paths (satellites), both paths arriving at the UT at the same time. This allows diversity combining at the UT resulting in an improved service quality. The UT can transmit the return channel to the GES via whichever link is the strongest (since forward and return link paths are closely correlated). The return link would therefore use a form of switched diversity. Such an approach requires extra air-interface and network signalling but can improve service quality and reduce the required system link margin. Both Globalstar and Inmarsat-P propose using link diversity techniques [Globalstar] [Inmarsat-P]. The ‘Deligo’ constellation, introduced
in Chapter 2, is a constellation specifically designed with, among other things, the provision of 100% link diversity in mind.

Applying such diversity techniques to system traffic channels is a feasible proposition, especially in the light of the benefits it offers. However, using these for common control and dedicated channel signalling, i.e. those channels mentioned above and which are specifically considered in this report, is not feasible. The first problem is that link diversity information is not initially available - the UT must first report its diversity to the GES. Another problem is that extra signalling is required to maintain such links and too much signaling can be generated from this compared to the amount of data that needs to be transmitted.

Consider the 'maximum amount of sky' qualification. During the active phase of a call the user is well aware of this requirement. But when signalling is ongoing without the user's knowledge - location update and user-terminated call setup - link cooperation cannot be expected. In such cases, the required signalling link margin is much higher than usual.

All common control channels require a high propagation margin so that UTs can transmit and receive signalling information over a wide range of location types. Specifically, indoor and non line-of-sight locations offer the greatest difficulty. Propagation margins of between 10 and 17 dB are used in order to provide good indoor signal penetration [Matra]. Providing such large margins over satellite channels is not an easy task. The system can either increase the link power or reduce the channel bit rate in order to provide the required margin. Because of the large margin that is required, use of the satellite payload to provide extra power is not a practical option from the satellite payload point of view - payloads will not have the ability to amplify individual channels by the required amount.

A practical option is to reduce the signalling channel bit rate while maintaining the power level and using the extra Eb/N0 margin as a buffer against link shadowing. The baseline traffic channel voice rate is 4.8 kb/s. These channels already include a basic link margin capability (perhaps a maximum satellite power variation of 5 dB can be provided). The link margin requirement for signalling channels is in addition to this. This results in a range of common control channel bit rates from 480 b/s down to 152 b/s (10 dB and 15 dB below 4.8 kb/s respectively). A value of 240 b/s is chosen here as a suitable medium and this bit rate is used in later simulations as the common control signalling channel bit rate. If link cooperation is assumed, or if Automatic Repeat Request (ARQ) is used for error recovery, then a higher bit rate can be considered. A lower propagation margin can be used for these cases. A margin of 6 dBs over the baseline 4.8 kb/s voice channel is chosen as the signalling channel margin in these cases, resulting in a maximum signalling channel bit rate of 1.2 kb/s.

This rate is used for simulations involving dedicated control channel signalling. For common control channel signalling where link cooperation can be assumed, or for SDCCCH/s channel signalling where no link cooperation is likely, bit rates of 1.2 kb/s and 240 b/s are also considered. The channel rates used are shown in table 5/1:

---

2 For location registration, location deregistration and user-originated call setup and since the user started the procedure, link cooperation can be assumed.
Table 5/1 - Signalling Channel Rate Options

<table>
<thead>
<tr>
<th></th>
<th>Voice Rate</th>
<th>No Cooperation (Common)</th>
<th>Cooperation (Common)</th>
<th>No Cooperation (Dedicated)</th>
<th>Cooperation (Dedicated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit Rate</td>
<td>4.8 kb/s</td>
<td>240 b/s</td>
<td>1.2 kb/s</td>
<td>240 b/s</td>
<td>1200 b/s</td>
</tr>
<tr>
<td>Margin</td>
<td>&quot;basic&quot;</td>
<td>&quot;basic + 13 dB&quot;</td>
<td>&quot;basic + 6 dB&quot;</td>
<td>&quot;basic + 13 dB&quot;</td>
<td>&quot;basic + 6 dB&quot;</td>
</tr>
</tbody>
</table>

Depending on the system and the circumstances under consideration, signalling channels may be left uncoded, they may be coded for error detection capability only or they may be coded with a forward error correction capability. For example, power control signalling is very delay sensitive and is transmitted uncoded in order to minimise the delay [Ariyavisitakul]. In the Inmarsat-M system, only error detection is applied [Inmarsat-M]. In the GSM system, common and dedicated control channels are coded with both block and convolutional codes. In the GSM broadcast, paging, access grant and stand-alone dedicated channels, initial 184 bit message blocks are encoded by a (224, 184) block code and then by a R = 1/2, K = 5 convolutional code, resulting in an output of 456 encoded bits. For the GSM random access channel, the initial eight information bits used (these are explained at the start of Annex A.1) become 36 encoded bits at the output. In the GSM system, synchronisation bits are transmitted during the 26 bit midamble within each transmitted slot. 16 of these bits are for channel synchronisation.

For the S-PCN baseline, precise coding implementations are not available. The following assumptions, which are in line with the GSM approach and with the approaches of S-PCN systems, were made on the coding and synchronisation of S-PCN signalling channels:

- The overall coding rate is equivalent to the application of a half rate code (R = 1/2).
- Synchronisation is achieved through a 24 bit (3 octet) synchronisation word.

In chapters 6 and 7, this coding and synchronisation approach is used for analysis of S-PCN common and dedicated control channel message transmission. The signalling channel bit rates used are based on the rates indicated in table 5/1 and on whether link cooperation can be assumed or not.

5.3 S-PCN Traffic

Traffic variation within an individual spotbeam of a satellite is now considered. More specifically, peak values for the following list are estimated:

1. Total number of system subscribers
2. The busy hour number of call setup attempts per spotbeam per second.

The total number of system subscribers can be estimated based on offered system traffic and on traffic per user rate estimations. Account must be taken of the high level of user (and therefore system traffic) distribution. Telecommunications weekday traffic levels vary according to a daily pattern which results in traffic peaks at around 11.00 and 15.00. The higher peak is usually in the morning during the busy hour.
Based on the rates of the different signalling procedures, the loading of individual signalling channels can be calculated. These loadings for individual common and dedicated control channels are used in order to correctly dimension signalling channel throughput.

Only the MAGSS-14 constellation is considered. This is because specific traffic data has been obtained which has been directly applied to MAGSS-14 [Cullen93/3]. Because MAGSS-14 is a paper constellation and is not intended for commercial application, such data was more easily obtained. Other constellations have more restrictive commercial considerations and so less information is available.

5.3.1 MAGSS-14 Traffic Assumptions

Assumptions on S-PCN terminal types are initially described. Four types are envisaged - handheld (H), vehicular (V), transportable (T) and fixed (F). Their typical characteristics are summarized in table 5/2 [Rastrilla]:

<table>
<thead>
<tr>
<th>Size</th>
<th>H</th>
<th>T</th>
<th>V, F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pocket</td>
<td>0 ≤ 3</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Gain (dBi)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF Tx. power (W)</td>
<td>0.5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>EIRP (dBW)</td>
<td></td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>G/T (dB/K)</td>
<td>-24 ≤ -21</td>
<td>-17</td>
<td>-20</td>
</tr>
</tbody>
</table>

*Table 5/2 - User Terminal Specifications*

Handheld terminal eirp ranges between -3 and 0 dBW while the other terminal types can produce eirps of 7 dBW. For low eirp handheld terminals, a large amount of satellite transmit power is required while higher eirp terminals, because of their higher antenna gain, require less satellite power. Therefore, S-PCN system capacity varies according to the terminal types being used. Higher eirp terminals can provide additional services (at higher bit rates). Based on these figures, satellite power estimation and the calculations shown [Rastrilla], satellite capacity to handheld terminals was estimated as 1000 voice (4.8 kb/s) circuits. In table 5/3, maximum and minimum values of satellite traffic channel capacity are indicated for the MAGSS-14 constellation.

<table>
<thead>
<tr>
<th>Traffic channels / satellite</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1000 (handheld only)</td>
<td>2000 (handheld, portable, vehicle mounted, fixed)</td>
</tr>
</tbody>
</table>

*Table 5/3 - Satellite Channel Capacity Range*

In table 5/4, assumptions on traffic channel usage are provided. Where relevant, minimum and maximum estimates are given. These values are standard values used in traffic estimations [Matra].
Table 5/4 - Satellite Channel Assumptions

<table>
<thead>
<tr>
<th></th>
<th>Minimum value</th>
<th>Maximum value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Busy hour user traffic</td>
<td>5 mErlangs</td>
<td>10 mErlangs</td>
</tr>
<tr>
<td>Call duration (Tc)</td>
<td>180 s</td>
<td>240 s</td>
</tr>
</tbody>
</table>

Call duration, assumed to have a negative exponential distribution, is important for estimating the peak number of call setups per spotbeam per second. The average active time spent on the system per user per day is taken as 540 seconds. Based on the minimum call duration of 180 seconds above, and considering that 50% of calls are taken to be user-originated, this results in an average of 1.5 user-originated calls per subscriber per day and 1.5 user-terminated calls per subscriber per day. These values are based on S-PCN traffic estimates taken from [Cullen93/3], [Matra] and [Saint3200].

For S-PCN systems, traffic demand will not be evenly distributed between coverage zones. It is necessary that coverage zones have the capability to reduce / increase their traffic carrying capability according to the demand. This is one of the reasons why frequency and resource management are so important to S-PCN systems. Spotbeams are likely to be designed with a capability of carrying (transmitting) up to 40% of the satellites total traffic (power). The limitation is due to amplification and transmit power limits. The more feeds that are used per beam (each fed by a high power amplifier), the higher the percentage of total traffic that can be carried.

5.3.2 MAGSS-14 Traffic Estimation

S-PCN system traffic assumptions based on satellite capacity, average call duration, call-type distribution and user Erlang rates were described above. Because only a small percentage of users make call attempts at the same time, the number of channels available is much lower than the number of potential users. It can be assumed that the number of UTs in a satellite coverage zone is much larger than N, the number of available traffic channels in that coverage zone. In order to convert available traffic channels and user traffic requirements into an estimate of user numbers, the Erlang-B formula (Erlangs first formula) can be used\(^3\). This formula is derived on the basis that no queuing occurs, so that if all N channels are busy the call is blocked and the user must try again. For the busy hour peak traffic rates, a network design blocking probability of 2% is typically targeted [Lee]. For simplicity, the requirement of having spare channels for handover is not considered here. This is justified since, on average, the number of channels ‘lost’ through handover is about the same as the number of channels ‘gained’ through handover. The probability, B, of a call attempt being blocked is given by:

\[
B = \frac{A^N / N!}{\sum_{i=0}^{N} A^i / i!}
\]

where

\(^3\) If a finite population is assumed, then the Engset formula should be used.
A is the offered traffic within a particular satellite spotbeam and
N is the number of channels available in a satellite spotbeam.

'\(A\)' can be found from either of the following equations:

\[ A = \frac{\lambda}{\mu} = \lambda T_c \]  \hspace{1cm} (5.2)

where

\(\lambda\) is the mean call arrival rate within a satellite spotbeam,
\(\mu\) is the mean rate at which calls are terminated and
\(T_c\) is the mean call duration or the mean channel holding time.

The blocked traffic is \([A \times B]\) while the traffic carried by the network is given by \([A \times (1-B)]\). N, the number of traffic channels considered available in a coverage zone, is taken as 64\(^4\). With 64 channels available per satellite coverage zone and for a blocking probability of 2\% then, from Erlang-B tables, each coverage zone can provide 53 Erlangs ('\(A\)'). For a user traffic rate of 5 or 10 mErlangs per user, then either 10,600 or 5,300 users can be served in each satellite coverage zone during the busy hour. With 37 coverage zones per MAGSS-14 satellite, each satellite can therefore serve either 392,000 users or 196,000 users. This theoretically allows either 14 x 392,000 users (5,488,000) or 14 x 196,000 users (2,744,000) for the 14 satellite MAGSS-14 constellation. From a more practical viewpoint, lower totals might be expected due to the unevenness of the traffic distribution. These results are tabulated for MAGSS-14 in table 5/5 [Cullen93/3].

<table>
<thead>
<tr>
<th>P(B) = 2%</th>
<th>Peak User Traffic = 10 mE</th>
<th>Peak User Traffic = 5 mE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Users per Spotbeam</td>
<td>5,300 users</td>
<td>10,600 users</td>
</tr>
<tr>
<td>Users per Satellite</td>
<td>196,000 users</td>
<td>392,000 users</td>
</tr>
<tr>
<td>Total Users</td>
<td>2,744,000 users</td>
<td>5,488,000 users</td>
</tr>
</tbody>
</table>

Table 5/5 - MAGSS-14 Traffic Estimates

The next step involves estimating the user call setup rate. For this, call durations are considered. Table 5/4 indicates two \(T_c\) values - either 3 minutes or 5 minutes. For \(T_c = 3\) minutes and \(A = 53\) Erlangs then \(\lambda = 53/3\) or about 18 call arrivals per coverage zone per minute. For a \(T_c = 5\) minutes then the call arrival rate reduces to about 11 call arrivals per coverage zone per minute. These are now split up into user-originated calls and user-terminated calls, where a 1:1 ratio is used.

Traffic unevenness must also be considered since users are not spread evenly around the globe. Considering most users are land or near-land based then there is an increase of the traffic rates over land with traffic from ocean regions being negligible. A multiplication factor of 2 is used to take this into account.

\(^4\) With 37 coverage zones and 64 channels per zone this might imply a satellite capacity of 2,368 channels, which is above the maximum value indicated earlier. However, 64 channels per zone is reasonable since all coverage zones are extremely unlikely to be used to capacity at the same time and also, a different terminal mix can result in an increased capacity.
Widely varying traffic demands from different regions on the Earth also need to be considered. This can, partly at least, be averaged through the use of satellite diversity which exists to some extent in all constellations. When regions are covered by two satellites then the traffic can be shared between both satellites. Another averaging factor is that the traffic involves the whole region covered by the satellite spotbeam and so the average traffic in the spotbeam area, not the peak within the area, is important. A final reason, and one which depends on the effectiveness of frequency planning within the S-PCN and on satellite spotbeam power flexibility, is that it should be possible to allocate extra transmit power and bandwidth (and therefore capacity), to a satellite spotbeam as it passes over regions of peak traffic, thus increasing the traffic carrying capability in that region.

Since only marketing studies are currently available concerning a global traffic map, no set figure can be used here with certainty. However, from an examination of results from a study available to the European Space Agency, 2 is used as a global average relating to potential traffic concentration over land in the region covered by a satellite spotbeam. From this discussion, a traffic variation factor of 4 (2 x 2) is used. The calculated rates, based on the above discussion, are tabulated in table 5/6.

<table>
<thead>
<tr>
<th>Number of users</th>
<th>2,744,000 users</th>
<th>5,488,000 users</th>
</tr>
</thead>
<tbody>
<tr>
<td>Call arrival rate</td>
<td>18 calls per minute</td>
<td>11 calls per minute</td>
</tr>
<tr>
<td>Traffic variation factor</td>
<td>x 4</td>
<td>x 4</td>
</tr>
<tr>
<td>UT-orig. calls</td>
<td>0.6 calls per zone per second</td>
<td>0.365 calls per zone per second</td>
</tr>
<tr>
<td>UT-term. calls</td>
<td>0.6 calls per zone per second</td>
<td>0.365 calls per zone per second</td>
</tr>
</tbody>
</table>

Table 5/6 - Peak Spotbeam Loading

Peak signalling procedure rates for MAGSS-14 satellite spotbeam loading are thus obtained. These are useful in estimating the likely loading for system common and dedicated control signalling channels and, when combined with message requirement and channel bit rate, to dimension the throughput of these channels correctly.

5.4 Channel Operation

Both the BCCH/s and AGCH/s channels are simple broadcast channels controlled by a GES and transmitted to individual spotbeams. The operation of the RACH/s and PCH/s channels are more complex and the network signalling approach adopted for these channels have important influences on the overall network performance. These two channels are therefore examined further in the following two subsections.

5.4.1 The Random Access Channel

The slotted ALOHA protocol is used on the random access channel to allow UTs to concurrently access a GES in an uncoordinated fashion [Abramson]. This approach is used in GSM [GSM], Inmarsat-M [Inmarsat-M] and most other mobile communication systems. If two UTs attempt to access the same channel at the same time, then collision will typically result. In some cases, and especially in Rayleigh channel fading conditions, one message may succeed due to the other message experiencing a deep fade. This is known as the capture effect [Zorzi]. Typically, however, both messages will fail and the UTs will attempt retransmission. In order to
reduce the probability of a subsequent collision, a random delay (backoff) occurs before retransmission is attempted. The random statistics of throughput and delay are the figures of merit that characterize slotted aloha channel performance [Tobagi]. A slotted aloha random access channel typically has low throughput and high delay characteristics. Channel performance can be estimated based on the analysis of a Poisson process. The probability of \( n \) packets colliding in the same slot is given by:

\[
P(n) = G^n e^{-G} / n!
\]  

(5.3)

where \( G \) is the mean channel load expressed in number of packets per slot (including new and retransmitted packets).

The slotted aloha channel throughput, \( S \), is given by:

\[
S = G e^{-G}
\]  

(5.4)

Disregarding the possible effects of capture, a successful access happens only if one access occurs during a slot. The maximum slotted ALOHA throughput of \( 1/e \) or about 0.368 occurs when the channel loading is 1 access per slot. This rate is clearly a critical point from a channel throughput point of view. At access rates above this, the throughput and delay performance of the channel degrade markedly. So channel loading should never be allowed to go above this level. The general slotted ALOHA throughput and delay performance curves are shown in [Maral].

From a signalling delay point of view, the performance of the channel degrades more as the channel loading increases and, correspondingly, the delay performance improves as the channel loading drops. In the extreme case, if only one access is made during a day, then the channel throughput is very low while, since no collisions occurred, the delay performance is very good (one round trip delay). In dimensioning a random access channel, a loading below 1 access per slot must be ensured to achieve efficient channel throughput. If delay is considered more critical, then a much lower loading should be used. The access delay of a successful transmission on a slotted aloha channel with retransmission can be calculated by [Saint4160]:

\[
D_{RA} = T_r + L_R + N \cdot D_e
\]  

(5.5a)

\[
D_e = 2T_r + L_R + L_{AG} + L_R \cdot \delta
\]  

(5.5b)

Where

- \( N \) is the number of retransmission times,
- \( T_r \) is the round trip propagation delay,
- \( L_R \) is the packet slot duration,
- \( L_{AG} \) is the duration it takes to detect an incoming access grant packet and
- \( \delta \) is a randomly chosen integer number between 1 and \( n \).

After collision is deduced, the UT delays retransmission by a randomly selected duration \( L_R + \delta \). \( \delta \) might be uniformly or exponentially distributed. In the simulations performed in chapters 6 and 7, the random access is modeled with a uniformly distributed \( \delta \) between 1 and 10 (see Annex A.2). In the simulations performed, slotted ALOHA channel performance is based on two different channel loadings. These are
chosen to mark the two possible extremes of the slotted aloha random access channel operation.

The first loading modeled represents a channel loading just below the maximum allowed loading of 1 access per slot. In this case, channel throughput is at close to its maximum while channel delay increases due to each packet experiencing more collisions. The second loading modeled represents a much lower channel loading. This means that channel throughput is very low but channel delay performance is improved. Exact random access channel modelling is not simulated - this is very difficult to implement due to the numbers of UTs involved. Instead, an access success probability is used which can be varied according to a simulation input file parameter in order to emulate different slotted ALOHA channel performance characteristics. In order to model the higher loading, an access success probability of 30% is used. To simulate the lower loading, an access success probability of 60% is used. A slotlength is automatically generated in the simulation based on the message duration plus additional guard bands for delay compensation.

The probability of success, P(s), of an individual message (packet) is given by the probability that no collisions occur over the packet transmission time. This is calculated according to a Poisson process arrival rate, as mentioned earlier. If k attempts are authorised, the summed probability of random access success P(S)_k is:

\[ P(S)_k = 1 - [1 - P(s)]^k \]  

(5.6)

and the average number of attempts required (R_{eff}), which indicates the average efficiency of the random access channel, is:

\[ R_{eff} = \frac{P(S)_k}{P(s)} \]  

(5.7)

Figure 5.3, P(S) is plotted against k for the two different P(s) values used in the simulations. For a P(S) requirement of greater than 0.99, k can be calculated and so R_{eff} for both curves can be deduced - for P(s) = 0.3 then k = 13 and R_{eff} = 3.3, for P(s) = 0.6 then k = 3 and R_{eff} = 1.65.
5.4.2 The Paging Channel

The paging signal is now examined. The two parameters of specific concern are the paging channel efficiency \( (P_{\text{eff}}) \) and paging channel delay. Paging channel efficiency is specifically discussed in chapter 6 where a detailed examination is performed for both the Globalstar and MAGSS-14 constellations based on different mobility management approaches. Therefore only paging delay is considered here.

A UT might be paged either in parallel (via a set of satellite spotbeams at the same time) or in serial (over a similar set of satellite spotbeams sequentially) until a reply is heard from a UT over the random access channel. However, a UT only monitors one PCH/s at a time. If paged in parallel, redundant signalling occurs. The advantage is that the UT is contacted within a minimum delay. If it is paged in serial then signalling efficiency is improved (especially with an optimised approach) since typically only half the zones are paged before the UT is contacted. The problem with serial paging is that the call set-up delay is increased since a minimum waiting period must be spent at each paged zone waiting for the UT to respond on the RACH/s channel. And as seen above, the RACH/s response delay can vary considerably depending on the channel success probability.

Suppose the network knows a UT to be covered by one of 9 spotbeams. In order to contact the UT, it needs to pages the UT in these zones. If it pages all zones in parallel then the paging efficiency is 11.1% \( (1/9) \) but the UT is contacted with a minimum of delay. If the 9 zones are paged serially then the UT is, on average, contacted on either the 4th or 5th zone to be paged. The paging efficiency is increased to 22.2% \( (1/4.5) \). However in this case there is a larger delay before the UT is paged - possibly up to 8 times longer than with parallel paging. Since call set-up signalling should be performed as fast and efficiently as possible parallel paging is necessarily used for the
simulations performed. The paging efficiency is examined in more detail for both the Globalstar and MAGSS-14 constellations, in chapter 6.

5.5 Basic Signalling Procedures

Initial common control channel signalling procedures are now examined in terms of the signalling channels used.

5.5.1 Mobility Management Signalling

The common control channel signalling sequence for a UT location registration / update / deregistration are now considered. UT registration or deregistration are both a direct consequence of the user either turning on or off the UT. For both of these procedures, user cooperation with the link can therefore be assumed. For example, when a user either turns on or off their terminal, they wait for a 'beep' sound to indicate that the associated signalling exchange has been completed. The UT can then be used or put away. If cooperation is not requested for UT deregistration, then it may not be possible to perform S-PCN deregistration effectively - the UT may be placed in a location from where the completion of location deregistration signalling is not possible (e.g. a briefcase in a car boot!). The initial signalling messages are shown in figure 5.4. More than one random access messages indicate the possible retransmission requirement due to random access channel collisions.

![Figure 5.4 - Preliminary Mobility Management Signalling](image)

Two common control channel types are used here - the RACH/s and the AGCH/s. The UT contacts the network (always a gateway earth station) on a random access channel and provides a random reference. After receiving a successful random request, the network replies on the access grant channel, allocating the UT an appropriate stand-alone dedicated control channel on which the subsequent mobility management signalling will continue.

In the previous section, different numbers of active users within the system were estimated. By combining user numbers with different possible rates for mobility management related signalling, the resulting loading on the above network signalling channels can be found. Estimates are provided based on the mobility management approach and simulation trade-off results which are explained and examined in detail in chapter 6.
5.5.2 Call Setup Signalling

Both call types are considered - user-originated and user-terminated. For both cases the UT is initially in stand-by mode, monitoring both broadcast and paging channels. The signalling considered is up to the point of dedicated control channel allocation.

5.5.2.1 User-Originated Call Setup

From the broadcast channel the UT knows the identity of the random access channel associated with a spotbeam. Only when the user has fully dialed the number and has pressed a ‘send’ button does the UT begin its channel request procedure - this reduces the average signalling channel holding time although is can result in longer call setup delays from the user viewpoint. The signalling procedure for UT-originated calls is similar to that for mobility management signalling shown in figure 5.3.

In section 5.3, different rates of UT-originated call setups per coverage zone per second were estimated. Taking the larger estimates, the resulting peak loadings on the common control signalling channels are shown in table 5/7. R_eff indicates the random access channel throughput efficiency.

<table>
<thead>
<tr>
<th>RACH/s</th>
<th>R_eff x 0.6 / coverage zone / second</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGCH/s</td>
<td>0.6 / coverage zone / second</td>
</tr>
</tbody>
</table>

Table 5/7 - User-Originated Call Signalling Requirement (MAGSS-14)

5.5.2.2 User-Terminated Call Setup

The UT is assumed to be in idle mode and holding its available satellite / coverage-zone connectivity (diversity) in memory. It is tuned to and monitoring a strong paging channel. When the number of a UT is dialed, the call is routed to the UT's HLR/s. If necessary the call is forwarded to the UTs VLR/s. From this the network obtains the latest location associated with that UT and its air-interface identity. The GES then pages the UT via the appropriate spotbeam or set of spotbeams.

When the UT hears its identity on the paging channel it uses the random access channel to request a dedicated control channel. After a successful random access, the network responds with a message on the access grant channel, providing the identity of the dedicated control channel on which subsequent signalling can continue. The LAPDm signalling sequence used for UT-terminated calls is shown in figure 5.5.
In section 5.3, different rates of user-terminated call setups per coverage zone per second were estimated. Based on the maximum estimates, the peak loadings on the common control signalling channels are given in Table 5/8. $P_{\text{eff}}$ is the paging efficiency. This value was estimated in chapter 6 for both LEO and MEO constellations.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Rate</th>
<th>$P_{\text{eff}} \times 0.6$</th>
<th>Spotbeam</th>
<th>Second</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCH/s</td>
<td></td>
<td>$P_{\text{eff}} \times 0.6$</td>
<td>Spotbeam</td>
<td>Second</td>
</tr>
<tr>
<td>RACH/s</td>
<td></td>
<td>$R_{\text{eff}} \times 0.6$</td>
<td>Spotbeam</td>
<td>Second</td>
</tr>
<tr>
<td>AGCH/s</td>
<td></td>
<td>0.6</td>
<td>Spotbeam</td>
<td>Second</td>
</tr>
</tbody>
</table>

Table 5/8 - User-Originated Call Signalling (MAGSS-14)

5.6 Conclusions

In this chapter, the common and dedicated control channels used for S-PCN air interface signalling were introduced. These channels were directly based on GSM LAPDm network signalling channel equivalents. Because of the lower S-PCN power availability, and hence the tighter link budgets, a closer look at space segment operating environments was made. The magnitude in power differences between scenarios involving link cooperation and link shadowing were seen to result in important S-PCN service restrictions. Due to the lack of satellite flexibility in terms of individual channel amplification, and considering the margins which needed to be provided, lower signalling channel bit rates were chosen in order to provide the required margin for these channels. Power levels similar to those used on voice channels were assumed.

The MAGSS-14 traffic capability was then analysed and peak rates for mobility management and call setup signalling were estimated based on various traffic data statistics. Subscriber numbers and individual channel loading peaks could be calculated, based on traffic distribution estimates. The performance of both the random access and paging channels were considered. For the random access channel, the channel operation and delay performance were considered. The probability of success for individual slots is used to model channel delay performance. It was noted that in order to minimise signalling delay, the RACH/s channel may have to operate well below peak throughput. For the paging channel, the use of parallel paging, rather than serial paging, is used. This reduces the paging channel efficiency but also reduces the paging channel associated delay.

Finally, the common control signalling channel signalling procedure for mobility management and call setup signalling were reviewed. Common control channel loading due to mobility management signalling will be estimated in chapter 6 after S-PCN approaches to user mobility management are considered. Common control channel loading was estimated for call setup signalling based on user-originated and user-terminated call setup rates indicated earlier in the chapter. These figures will be used in chapter 7 to dimension common control channel throughput.

References


Chapter 6  S-PCN Mobility Management

In this chapter, S-PCN mobility management is specifically examined. Different approaches are initially considered before a preferred option, based on the use of a positioning system, is chosen. The air interface bit requirement for mobility management signalling is then estimated, based on the GSM LAPDm network layer. The LAPDm signalling sequence is modified to take the S-PCN architecture into account. Air interface mobility management related signalling is simulated using models built with the network simulation tool 'BONes Designer'. From this, delay distributions relating to mobility management signalling are obtained for both LEO and MEO constellations and for different random access channel performances. With signalling bit requirements estimated, a user mobility model is used to examine the performance of the selected mobility management approach in terms of the overall air interface signalling level. Again, this is done for both the LEO and MEO selected constellations. Finally, the implications of this signalling in terms of satellite power consumption are considered.

6.1 Mobility Management Approaches

The aim of mobility management is to provide the S-PCN system with a means of contacting any user terminal (UT) in an efficient and effective manner. Due to S-PCN constellation dynamics, combined with user mobility, the network may not have precise knowledge on how to contact a UT. Four situations can be envisaged in which S-PCN location registration, location updating or location deregistration procedures are used:

1. A UT, just switched on, registers with the S-PCN system.
2. A dual-mode UT, previously registered within its PLMN, leaves this coverage and registers within the S-PCN system.
3. The UT performs a location update within the S-PCN system.
4. The UT is switched off and so deregisters from the S-PCN system.

The signalling procedures for the first three of these procedures are all of a similar structure and different information content. User authentication and the setting up of a link cipher are not used for location deregistration. Location registration and deregistration procedures are triggered by very definite terminal operational changes. The location update procedure is different. In the GSM system, mobile stations move through static cells, each cell (or group of cells) having its (their) own locally unique broadcast address. Location update is triggered when a mobile station recognises a new broadcast address. Location update is therefore a result of the mobile stations motion through static terrestrial cells.

In a S-PCN system where dynamic satellite constellations are used, relative motion between UTs and satellite spotbeams (the S-PCN equivalent of cells) is dominated by the satellite orbit velocity. With satellite orbit velocities in the range of 7 km/s and 2 km/s (LEO and MEO respectively), UT motion is negligible. The effect of this is that the UT has an equivalent constant motion through the S-PCN system. The S-PCN location update algorithm needs to be reconsidered in the light of this [Cullen93/1]. Another problem concerns dual-mode terminal registration instability. For dual-mode terminals, a mobility management location update instability can occur if a UT passes
through islands of terrestrial coverage in the 'sea' of S-PCN coverage. This would require registration and deregistration onto and from the different segments. The level of system mobility management might increase significantly because of this effect. In order to minimise the effects of this instability, it is best to combine location registration from the old system with location registration to the new system, with the network (according to the UTs HLR/s) performing the appropriate network oriented location deregistration.

The purpose of holding user location information is to allow the network to contact individual UTs for user-terminated call setup. Considering S-PCN systems only, three different approaches concerning S-PCN mobility management are now considered.

6.1.1 'Direct Connection' Approach

In its most precise form, this approach is similar to the terrestrial approach in that the UT always registers itself within the spotbeam it is currently monitoring. The network knows the exact GES, satellite and spotbeam combination through which a UT can be contacted. According to the S-PCN architecture proposed in chapter 3, each spotbeam is the equivalent of a terrestrial cell in terms of network control. All the spotbeams of a satellite are controlled, at a specific time, by just one GES. To avoid interference, overlapping spotbeams (whether from the same satellite or overlapping satellites) need to avoid using the same system control and traffic channels. Therefore each spotbeam has a locally unique set of signalling channels through which all the UTs in its coverage can interface with the network. This is standard to all mobile communication systems and is provided by the S-PCN architecture proposed in chapter 3.

In order for the network to know the exact GES, satellite and spotbeam triplet through which to contact a UT, it needs to receive continuously updated information from the UT. In order to assess the likely magnitude required to perform such signalling, constellation connectivities can be examined. For the Globalstar LEO constellation [Globalstar] with a satellite-to-user visibility of about 20 minutes and 16 (two rings) spotbeams per satellite (a maximum thickness of 5), then updates are required about 5 times every 20 minutes. This results in a location update requirement of about 15 per hour, when the terminal is in active mode. For the MAGSS-14 MEO constellation [Benedicto], with a satellite-to-user visibility of about 90 minutes and 37 (three rings) spotbeams (a thickness of 7), then updates are required about 7 times every 90 minutes, resulting in a location update requirement of 4.67 updates each hour while the terminal is active.

Clearly, in order to provide the network with a precise mechanism for contacting a UT, a very high price is paid in terms of location update signalling when this approach is used. In section 6.2, location update is seen to involve a high level of signalling. Such high levels of signalling frequency would require a significant proportion of system bandwidth and satellite transmit power, resulting in the inefficient use of system resources. For LEO constellations, the location update requirement would be far in excess of the expected call set-up rates. Even for MEO constellations, where the location update rate is lower, the level of network signalling required for such 'housekeeping' (rather than revenue earning) tasks, is still excessive.

If, instead of obtaining the GES / satellite / spotbeam triplet, the network only held the identity of the GES / satellite couplet through which a UT could be contacted, then the
rates at which updates were required would drop markedly. For the Globalstar LEO system, the update rate would become at best once every 20 minutes, or three times per hour. For the MAGSS-14 MEO constellation, the update rate would reduce to, at best, about once every 90 minutes, or 0.67 times per hour. Both of these levels are much more respectable that when spotbeam identity was required.

But there is a problem with network paging due to the reduced level of information available. If only GES and satellite information was available, then in order to contact a UT, each satellite coverage zone would need to be paged. For the Globalstar LEO constellation, this would mean paging 16 spotbeams in order to contact a UT which is tuned to only one of these. The resulting paging efficiency is a low 6.25% (1 in 16). For the MAGSS-14 MEO constellation, with 37 spotbeams per satellite, the paging efficiency is even lower, at 2.7% (1 in 37). From chapter 5, the busy hour paging requirement (based on user-terminated calls) for MAGSS-14 was estimated as 0.48 calls per spotbeam per second. At such a low paging channel efficiency, a MAGSS-14 paging channel would require a peak throughput of 17.76 pagings per second. Also, considering an active day of 12 hours per UT, then at least 8 mobility management related signalling procedures would be required each day.

It is clear that with either of these approaches, signalling inefficiencies result, depending on the type of information that is used. As different satellites pass overhead and the Earth rotates, attempting to link each UT to a specific satellite spotbeam, or even a specific satellite, results in signalling inefficiencies. This approach to S-PCN mobility management is seen to be unsuited to S-PCN systems which use dynamic satellite constellations - it is seen to be inefficient to locate UTs according to space segment connectivity.

6.1.2 ‘GES Registration’ Approach

From the previous discussion, it is clearly preferable to perform S-PCN mobility management with respect to a fixed point on the Earth, rather than a dynamic spotbeam and/or satellite identity. In this alternative approach, each UT is registered with a specific GES. When a UT is switched on, it searches for a satellite broadcast control channel. This may be associated with a specific GES or it may be the strongest available channel. The UT then registers with the selected GES. As long as the UT can still receive a broadcast channel from that GES, then it is contactable by the network. If not, then a location update is performed to a new GES.

In order to contact a UT, the GES must page the UT. According to the baseline architecture, a GES might typically control more than one satellite (up to three for the MAGSS-14 constellation - figure 4.4). However, in general, the GES can note the location of the UT when it registers and so certain satellites and spotbeams might be eliminated from being paged. Although this approach seems to reduce the number of location updates required, paging efficiency is still quite low. Also, user mobility is not fully taken care of with this approach if spotbeams are selectively paged according to the assumed UT location.

There is also a potential instability with this approach which is a consequence of satellite dynamics. Consider a UT tuned to the broadcast channel of a GES which is controlling a specific satellite. At a certain time, control of the satellite (the only one
visible to the UT) is handed over to a new GES, resulting in a change of BCCH/s channel\(^1\). Since the GES identity has changed, the UT is required to perform a location update procedure due to constellation dynamics rather than due to its own motion. The same can happen if the satellite controlled by the GES and with which the UT is registered, moves out of range of the UT. The GES may not be controlling the satellite which is visible to the UT, so, the UT is again obliged to perform a location update. Since such occurrences - which are termed 'flip-flop' here - are normal consequences of dynamic satellite constellation connectivity, then certain UTs will have to perform an excessively high amount of location update signalling [Cullen93/1].

Also, the space segment common control channel signalling structure proposed in the S-PCN architecture of chapter 3, would need to be modified. To allow each GES, in visibility of a satellite, to broadcast its BCCH/s channel over all, or at least a subset of a satellites spotbeams would result in a less efficient usage of space segment resources.

### 6.1.3 'UT Position' Approach

With this approach [Cullen93/2], [Cullen93/3], the geographic coordinates (latitude, longitude) of individual UTs are used as the address with which to locate them. Each UT therefore has its own unique network address. A positioning system must be used and each UT needs to have the ability to measure its own position. With navigation and positioning services already mentioned as very probable S-PCN services, then this requirement is not really an extra burden for these systems. Considering that the smallest satellite coverage zone radii might be around 300 km [Iridium], high levels of positional accuracy are not necessary - accuracy to within 10s of km should be sufficient. The GPS or GLONASS systems easily meet such an accuracy requirement while even an approach using S-PCN satellites (signalling delay combined with doppler shift) can provide a high enough level of accuracy for this purpose. Having first measured its 'UT position', the UT contacts a GES via the random access channel provided on the strongest available broadcast channel\(^2\). The UT provides the GES with its identity and 'UT position'. From the UTs identity its HLR/s can be deduced, contacted and updated with its latest 'UT position'. If necessary, a VLR/s is selected by the contacted GES and forwarded the appropriate location information.

Associated with the users position is an 'uncertainty radius' - \(R_u\). This can be a constant for all the users in the constellation, or, as seen in section 6.3, it can be optimised according to individual UT motion. Each UT therefore has an address which consists of the following three parameters - latitude, longitude and uncertainty radius (\(\lambda, \phi, R_u\)) which define the 'uncertainty area' of that UT. The network can easily identify the uncertainty area within which the UT is located. To page it over that region the GES must just page the UT on those coverage zones which overlap the uncertainty area. If some of these zones are controlled by a different GES, then the

---

\(^1\) As seen in chapter 2, it is impossible to maintain an exact pairing between satellite broadcast channels and geographical regions, due to constellation dynamics.

\(^2\) There is an option of giving the UT the intelligence to initially attempt to select a specific GES - the one where its HLR/s is located.
UTs reply will reach this different GES rather than the GES which was originally controlling the call.

The uncertainty radius, $R_u$, is the distance UTs refer to in order to determine whether or not they need to perform a location update. Since each UT knows its network position (the latest $\lambda$, $l$ it provided the network), can calculate its current position and knows its associated uncertainty radius, then performing a location update is straightforward. The UT calculates the distance between its actual 'UT position' and the 'UT position' known to the network and compares the magnitude against $R_u$. If the distance is greater than $R_u$ then it has moved beyond its uncertainty area and a location update is necessary. Some error margin must be included here - to compensate for both positional error and the delay between position checks. For example, a UT might measure its distance from its network 'UT position' as ($R_u - 20$) km and make no update. At its next position check (perhaps one hour later), it measures its distance as ($R_u + 100$) km. The area over which the network pages the UT must take this uncertainty into account. With this approach, location update is fully automatic within the network and only occurs when necessary. Figure 6.1 provides a 3-step overview of this approach.

![Figure 6.1 - 'UT Position' Mobility Management Approach](image)

Figure 6.1 - 'UT Position' Mobility Management Approach
The smaller \( R_u \), the more accurately the position of the UT is known to the network and thus, fewer pagings are necessary. As \( R_u \) is increased, fewer UTs will require a location update. However, a smaller uncertainty radius requires the UT to monitor its 'UT position' at a higher rate (a passive operation in terms of system signalling) and, more significantly from a network signalling point of view, to perform location updates more frequently. Alternatively, as \( R_u \) increases, the area over which a UT has to be paged increases. All spotbeams which, at the time of paging, overlap with a UTs uncertainty area must be paged. The average number of zones that are paged depends on constellation and satellite coverage. It varies between LEO and MEO constellations according to spotbeam sizes. It also increases with constellation coverage diversity and is therefore a function of latitude - due to certain constellation design techniques favoring coverage at certain latitudes.

There is therefore a clear trade-off between the level of location updates and the system paging efficiency. This is considered in section 6.3 where appropriate values for \( R_u \) are found through estimation of the total signalling traffic produced for different uncertainty radii based on a UT mobility profile. For a certain level of user mobility, an uncertainty radius exists at which the signalling magnitude is minimised.

With this approach, a location update is only required when a UT has moved beyond the uncertainty radius. The approach is completely independent of constellation dynamics and the subsequent network connectivity changes (the problem with the first and second approaches). The performance of both of the other approaches were seen to be degraded by constellation dynamics. Of the three approaches to S-PCN mobility management described, this method is favored due to its independence from constellation dynamics and because it can reduce the overhead of system mobility management signalling. This method was proposed to the SAINT project and is being considered for S-UMTS mobility management [Saint].

### 6.2 LAPDm MM-Part

The LAPDm protocol, with specific modifications suggested for S-PCN functionality, is now examined for mobility management signalling. The mobility management approach adopted is based on the 'UT position' approach described above. Location registration is specifically examined but the signalling sequence is similar for both location update and location deregistration. The bit requirement estimates are applied to both the Globalstar and MAGSS-14 constellations. The overall procedure is then simulated over models built on the network design tool 'BONEs Designer' and results on S-PCN mobility management signalling delay are obtained.

#### 6.2.1 Mobility Management Signalling Sequence

This section describes an S-PCN modified LAPDm location updating procedure on the radio interface [LAPDm]. It consists of specific combinations of elementary messages. Location registration, update or deregistration is always initiated by the UT. S-PCN location registration is considered to involve the same signalling sequence as location updating while user authentication and cipher establishment are not included in location deregistration. Figure 6.2 indicates the air interface location update (registration) signalling sequence. Note how only the GES and UT are involved in the signalling. According to the proposed S-PCN architecture TESs are not involved in database management.
Figure 6.2 - Location update signalling sequence

Location updating is initiated by a UT when it finds it has moved beyond its associated ‘uncertainty area’. This means that, after passively measuring its location, it realises it has moved more than R_u km from its previously registered location. Realising this, the UT sends a CHANNEL REQUEST message to a GES on the random access channel (RACH/s). The two random access channel types as described in chapter 5 are used. In order to obtain worst case estimates, results are mainly provided for the more heavily loaded random access channel which has a success probability of 0.3. After the sending of each RACH/s message, the UT monitors the satellite access grant channel (AGCH/s) to find out whether it has been allocated a dedicated signalling control channel - IMMEDIATE ASSIGNMENT message reply. Because no recovery procedure can operate with both these common control signalling channels, high link margins are necessary to avoid signalling errors. At this stage an RR-connection is established.

Once a stand-alone dedicated control channel (SDCCH/s) has been allocated, then ARQ (Automatic Repeat Request) can be used for error recovery. In this case, it may be reasonable to increase the bit rate so that even if errors do occur, those messages not acknowledged within the protocol time-out period can be repeated. The main signalling for UT location update occurs over the SDCCH/s channel.

The UT sends a LOCATION UPDATING REQUEST message to the GES. Before the GES accepts this message, UT authentication and the establishment of a cipher over the SDCCH/s channel is performed. The network returns a LOCATION UPDATING ACCEPTED message which includes the UTs new temporary Mobile subscriber

---

94

3 If no channel is available then an IMMEDIATE ASSIGNMENT REJECT message is sent by the GES to the UT. However, only successful signalling procedures are considered here.
identity (TMSI). A TMSI REALLOCATION COMPLETE message is sent by the UT to the GES to acknowledge this. If no further transactions are scheduled, the GES initiates channel shutdown with a CHANNEL RELEASE message, releasing the RR-connection. Each of these messages is broken into its constituent information elements and further analysed in [LAPDm].

6.2.2 Bit Estimation

The messages used in the S-PCN mobility management signalling sequence (see figure 6.2) are now examined. These messages are based on the LAPDm air interface protocol with S-PCN specific modifications proposed. Further detail (based on the GSM message) within each of these network layer messages is provided in Annex A.1 where estimates are made on the S-PCN message composition and length. Half rate coding is applied to all these network layer messages. A further three octets are added for channel synchronisation. From this, the final bit requirement for each message was estimated and is indicated in table 6/1 below.

<table>
<thead>
<tr>
<th>Message</th>
<th>S-PCN Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Request</td>
<td>40 bits</td>
</tr>
<tr>
<td>Immediate Assignment</td>
<td>120 bits</td>
</tr>
<tr>
<td>Location Updating Request</td>
<td>216 bits</td>
</tr>
<tr>
<td>Authentication Request</td>
<td>152 bits</td>
</tr>
<tr>
<td>Authentication Response</td>
<td>120 bits</td>
</tr>
<tr>
<td>Ciphering Mode Command</td>
<td>72 bits</td>
</tr>
<tr>
<td>Ciphering Mode Complete</td>
<td>56 bits</td>
</tr>
<tr>
<td>Location Updating Accept</td>
<td>200 bits</td>
</tr>
<tr>
<td>TMSI Reallocation Complete</td>
<td>56 bits</td>
</tr>
<tr>
<td>Channel release</td>
<td>72 bits</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1,104 bits</td>
</tr>
</tbody>
</table>

Table 6/1 - Location Update Bit Requirement

The above modified LAPDm signalling sequence was simulated using the network simulation tool 'BOnES Designer'. Detail on the simulation model built is included in Annex A.2. User cooperation can be expected at times of UT registration and deregistration since the user initiates both of these procedures. User cooperation cannot be assumed for location update related signalling, since the user is unaware of it happening. Because of this, large signalling channel margins are likely to be required for a successful location update. The bit rates used - 240 b/s and 1.2 kb/s - result in margins of 13 dB and 6 dB, respectively, over the baseline 4.8 kb/s voice channel. Two channel rate combinations were simulated. The first was at 240 b/s for each of the three channels involved - RACH/s, AGCH/s and SDCCH/s. This is indicated as 240/./. with LEO/MM or MEO/MM before this to indicate a LEO or MEO constellation and mobility management signalling. This rate combination can be considered as a likely candidate for location update signalling due to the high channel margin provided. The second combination is 240/./1200 which indicates 240 b/s for
the first two channels, increasing to 1.2 kb/s for SDCCH/s channel signalling. This rate combination is more appropriate to location registration / deregistration since lower SDCCH/s channel margin is provided. Simulations were performed for the Globalstar (LEO) and MAGSS-14 (MEO) constellations.

Only successful signalling sequences were simulated and ARQ use over the SDCCH/s channel was not considered. The high link margins used and the use of half-rate forward error correction (FEC) coding makes this a reasonable assumption. As channel BER performance is quantified more precisely, the message error rate can be derived allowing message errors and ARQ to be included in the simulation. The RACH/s performance, based on a message success probability and on channel backoff, was considered in chapter 5.

As well as random access channel delay, each simulation recorded the propagation delay between the UT and the GES (uniformly distributed between maximum and minimum delay values), the message duration delay according to the message sent and the relevant channel bit rate and, finally, a processing delay chosen from a uniform distribution between 25 ms and 250 ms and included at the transmitting end. This delay is considered to include receiver-end signal acquisition delay. A total of 50,000 location update procedures were simulated for each scenario - LEO or MEO and the different bit-rate combinations considered for these.

6.2.3.1 LEO Simulation Results

The Globalstar constellation, at its minimum elevation angle of 10°, has a maximum single hop (GES-to-satellite-to-UT) propagation delay of about 14.7 ms. Its minimum single hop propagation delay (90° elevation angle) is about 9.5 ms. The propagation delay value chosen for each transaction simulated was within this range. The random access channel success probability for the first two simulation runs was 0.3. The results, showing the delay distribution for 99% of cases, are shown in figures 6.3. Note the differences in scale between the two graphs, due to the different channel rates simulated. In the results presented, completed signalling procedures are tabulated for half-second slots.

---

4 In the INMARSAT-M system (GEO) the initial acquisition time for carrier and clock synchronization is 20 ms with a ±10 kHz carrier frequency offset and a received data clock error of ±3.5×10⁻⁷.
The average signalling duration of the distribution indicated in figure 6.3 (a) is 8.5 seconds. In figure 6.3 (b), where the SDCCH/s channel rate was increased to 1.2 kb/s, the average signalling duration dropped to 6 seconds. Such signalling durations are clearly non-negligible. Both distributions are similar in shape, with the lower bit rate combination having a higher delay. The dominant factor contributing to the shape of both distributions is the RACH/s channel delay. In figure 6.3 (b), the throughput peak in the 2.5 s -> 3 s interval indicates the bulk of those RACH/s channel requests which were successful on their first attempt - approximately 30% of requests. Subsequent peaks are less pronounced. The second (in the 4.5 s -> 5 s interval) and third are just visible and clearly indicate lower throughput - about 20% and 15% respectively. This dilution in channel throughput is typical for the slotted aloha channel with backoff and for the different propagation delays for each transaction. With a slotted aloha...
channel throughput probability of 0.3, the probability of 13 failures is just less than 1% \([(0.7)^{13}]\). This results in an average number of 3.3 \((0.99/0.3)\) random access attempts per successful access. Successive failure on the random access channel is clearly a major contributor to the wide range of system signalling delays.

For the LEO/240/., simulation, a signalling duration of up to 21 seconds is indicated. For the Globalstar constellation, a satellite passes overhead in less than 20 minutes. Five different spotbeams make up such a pass and so a spotbeam is typically visible for less than 4 minutes. The average visibility duration of the first spotbeam is therefore about 2 minutes or 120 seconds. For a signalling duration of up to 21 seconds, the probability of the spotbeam passing beyond UT range, is 17.5% \((21/120)\). For the same simulation the average signalling duration was found to be 8.5 s, such a connectivity change is a real possibility 7% \((8.5/120)\). For the 240/./1200 b/s channel rate combination with an average delay of 6 seconds, the possibility of a connectivity change reduces to 5% \((6/120)\).

Because of its complexity, handover of signalling channels is not an option so those signalling procedures which terminate due to loss of spotbeam connectivity, are considered to have failed and the UT must make another attempt. This effect has not been previously considered. Its effect in the Iridium constellation - considering the same average signalling duration and where the first coverage zone is visible for approximately 52 seconds - is even more significant due to the higher satellite velocity and the smaller satellite spotbeams. In this case, the probability of connectivity loss is just over 16% \((8.5/52)\). Signalling rate estimates for LEO mobility management will clearly increase due to this effect. This has important implications on overall signalling channel throughput dimensioning. For the higher rate signalling rate combination, with a 6 second average delay, the probability of connectivity loss is still a high 11.5% \((6/52)\).

Because location registration and deregistration involve the user making a specific action, link cooperation can be assumed and the higher rate SDCCH/s channel rate is appropriate. For location update, the choice between the two bit rates is less clear since user cooperation cannot be assumed. However, with a dedicated signalling channel between the UT and the GES, ARQ can be used for messages, or message elements, received in error. For this reason, the faster 240/./1200 b/s channel rate combination obviously the preferred rate combination and is considered as a suitable combination for general mobility management signalling.

While the above simulations examine system signalling performance at a high level of random access channel throughput (still stable operation) loading, results were also obtained for low loading levels. The random access channel success probability for the following simulation is 0.6. This implies very low random access channel throughput but also low random access channel delay. This is indicated in the figure by the word ‘fast’ in the header. The simulation delay distribution for the preferred 240/./1200 b/s channel rate combination is shown in figure 6.4.
Clearly, the delay performance for the mobility management signalling procedure is greatly improved due to the lower blocking probability of the random access channel. The average for the above simulation, for 99% of procedures, is 3.5 seconds. This is compared to an average delay of 6 seconds for the same channel bit rates but with the random access channel operating at both higher throughput but also higher delay. The average number of random access channel requests required is 1.65 (0.99/0.6) requests per successful access. The importance of random access channel performance on system signalling delay performance is clear from this comparison. The use of lowly loaded random access channels can be an important technique in minimising S-PCN system signalling delays. The drawback is their low throughput performance - resulting in poor use of system spectrum. A more realistic approach may be to only allocate extra RACHs channels when overall signalling channel loading goes above a certain figure. For this lower delay signalling performance, the probability of connectivity loss with an Iridium satellite is just under 7% (3.5/52) which is still a significant contribution on signalling loading.

6.2.3.2 MEO Simulation Results

For the MAGSS-14 constellation, the maximum and minimum single hop delays are 92 ms and 67 ms respectively and the individual delay used in each simulated procedure is chosen uniformly from within this range. The results in figures 6.5 indicate the location update delay distribution for 99% of cases for a random access channel operating at a success rate of 0.3. Differences in scale between the graphs should again be noted.

Figure 6.4 - LEO Location Update Signalling Delay Distributions (240/.1/1200 - fast)
Figure 6.5 (a) - MEO Location Update Signalling
Delay Distributions (240/1/)

Figure 6.5 (b) - MEO Location Update Signalling
Delay Distributions (240/1/1200)

The average signalling duration of the distribution indicated in figure 6.5 (a) is 10 seconds, an increase of about 1.5 seconds over the LEO equivalent. This is expected since there are on average 12 ‘hops’ involved in the signalling procedure with each of these being longer than the LEO equivalent. Also, the hop delay has an effect on the response waiting delay used in the slotted ALOHA implementation model. In figure 6.5 (b), where the SDCCH/s channel rate was increased to 1.2 kb/s, the average signalling duration dropped to 7.5 seconds. As in the LEO case, this latter bit rate combination is considered more suited to situations which involve link cooperation. The long signalling durations are again significant. The distribution shape is, as with the LEO case, dominated by the random access channel performance and the first two
throughput peaks are noticeable. Beyond this, the larger propagation delay variation causes a flattening effect on the throughput peaks.

For the MEO/240./. simulation, a signalling duration of between 5.5 and 24 seconds was found. For the MAGSS-14 MEO constellation, a satellite passes overhead in about 90 minutes. Seven different spotbeams make up such a pass and so a spotbeam is typically visible for about 13 minutes - with an average of about 6 minutes. Average MEO spotbeam visibility duration is therefore much higher than the equivalent LEO duration and so the probability of a spotbeam passing beyond UT range during a signalling procedure is much lower than in the LEO case and can be considered negligible. This longer visibility duration is therefore an important advantage of MEO systems over LEO systems.

As in the LEO case, MEO signalling delay performance was also examined for a lower level of random access channel loading and so at an improved delay performance. The range of delays experienced by 99% of UTs for the preferred 240/1200 b/s signalling channel rate combination with a random access success probability of 0.6, is shown in figure 6.6.

The average delay of the above distribution is 4.5 seconds. The performance is clearly better than the previous MEO distributions and would result in a much higher level of user satisfaction. The cost is the same as in the LEO case in that random access channels are operated at very low throughput levels, with implications on spectrum usage efficiency. Considering the likely differences in spotbeam sizes between LEO and MEO satellites, this results in different loading requirements between the two systems.

6.3 Mobility Management Signalling Trade-off

The mobility management signalling trade-off between paging signalling and location registration / update / deregistration signalling is now done. As explained in section 6.1.3, the requirement for a UT having to perform a location update within the system depends on the user moving further than some predetermined distance, $R_m$, from its
previous location update location coordinates. The frequency of location update will logically decrease with an increase in the uncertainty radius. In chapter 5, the paging rate was estimated from the rate of user-terminated calls, which were considered as 50% of all S-PCN calls. Average paging efficiency can be estimated for both the Globalstar and MAGSS-14 constellations from this section.

6.3.1 User Update Probability

Before the trade-off could be made, a curve indicating S-PCN user mobility (fixed UTs are neglected) is required. From this, a curve of user location update rate against distance from a central point could be estimated. However, no such curve was found [Saint3200]. The following model is proposed and used here as an attempt to describe the decreasing probability of a UT having to make a location update as the uncertainty radius, $R_u$, is increased. In this model, the decrease is assumed to be exponential, based on the half-life curve $[e^{-0.6937d}]$. This seems to be a realistic model and reflects the fact that most users will remain fairly local to their initial point of registration throughout a day. A range of uncertainty radius values between 50 km and 1,000 km are used. $P(u)$, the probability of mobility management signalling being required is modeled as:

$$P(u) = 2 + N_u [e^{-0.693 \frac{d}{D_h}}]$$  \hspace{1cm} (6.1)$$

where $D_h$ is the distance where the rate of location updates drops by half,

$N_u$ is a constant ‘determining’ the maximum number of updates per user per day, and

$d$ is the distance a user has traveled from their current ‘UT Position’. In this analysis, this is equivalent to the uncertainty radius, $R_u$.

This model is considered to apply to a typical UT activity cycle - i.e. from UT registration to UT deregistration. The value of $D_h$ (the distance beyond which only half the original user population travel) is taken as 250 km and the value of $N_u$ is taken as 3. The number 2 accounts for the daily user registration and deregistration.

The shape of the $P(u)$ distribution has an important effect on the $R_u$ magnitude chosen in the signalling trade-off which follows. Changes in the shape of this distribution influence the value of the optimum uncertainty radius which is chosen. The model is plotted in figure 6.7. Note that values for $d < 50$ km are not plotted as the use of an uncertainty radius of that magnitude would result in excessively high location update requirement (much higher than $N_u$). Note also that the curve is a user oriented curve. It is constellation independent and so this same curve is applied to both the LEO and MBO constellations considered.
Mobility Management Signalling Frequency

![Graph showing Mobility Management Signalling Frequency](image)

Figure 6.7 - User Location Update Rate v Distance

For low uncertainty radius values, the number of mobility management procedures per day is seen to be high - almost 5 per day. As $R_u$ is increased the number drops off and approaches 2 - location registration and location deregistration. Such a range of distribution values does seem to offer a realistic model of the average daily user mobility management signalling procedure requirement over the range of uncertainty radii used. Fixed terminal types are not relevant to this analysis but can still be given a (latitude, longitude) coordinate and a very small $R_u$, which applies to them as long as they are not installed elsewhere. These values seem realistic.

6.3.2 User Paging Efficiency

Average LEO and MBO paging efficiency can be found through constellation simulation [Sammut94/2]. If 10 spotbeams must be paged (a paging requirement of 10) in order to contact a UT, then the paging efficiency is 10%. For a paging requirement of 12 spotbeams, the efficiency reduces to 8.33%. Paging efficiency is seen to be a function of the following two factors:

1. Uncertainty radius ($R_u$). As $R_u$ is increased, the paging requirement increases since more spotbeams must be paged (and the paging efficiency reduces).

2. Constellation coverage geometry. The paging requirement increases as constellation diversity increases (and the paging efficiency reduces).

Greatest constellation diversity for the MAGSS-14 and Globalstar constellations considered here occurs in the mid-latitudes, since they are inclined at 56° and 52° degrees respectively. Average paging requirement statistics are shown below in figures 6.8 and 6.9. The paging requirement is indicated at two latitudes - 0° and 45°. For both of the constellations modeled, a high level of diversity exists in mid-
latitudes. This is why the paging requirement is higher at $\lambda = 45^\circ$ compared with at $\lambda = 0^\circ$. Since constellation coverage is longitude independent, so also is the paging requirement.

\begin{figure}[ht]
\centering
\includegraphics[width=0.7\textwidth]{figure6.8.png}
\caption{User Paging Requirement (LEO) v Uncertainty Radius}
\end{figure}

A 19 spotbeam per satellite Globalstar-like constellation is modeled here to as the satellite coverage geometry - based on the hexagonal coverage pattern - could be used. For the 16 spotbeam per satellite Globalstar constellation, a slight reduction in the paging requirement should result, due to the lower number of spotbeams. The higher and increasing paging requirement at a $45^\circ$ latitude is also clearly evident. Each point indicates an average real value. Each of these points has an integer distribution associated with it.
For MAGSS-14, the proposed three-ringed, hexagon-based 37 spotbeams per satellite coverage pattern was used. The number of channels that must be paged is clearly seen to rise with increasing uncertainty radius. Consequently, paging channel efficiency decreases with increasing Ru. As with the ‘Globalstar’ results, the variation with latitude is again clearly visible, as is the effect of the increased mid-latitude diversity. The 19 spotbeam ‘Globalstar’ constellation is seen to result in a higher paging requirement with respect to the MAGSS-14 constellation. This is due to the smaller size of the ‘Globalstar’ spotbeams when projected on the Earth. The Inmarsat-P MEO constellation, which proposed at least 121 spotbeams per satellite [Space News], would have a much higher paging requirement than the 37 spotbeam MAGSS-14 constellation.

6.3.3 Mobility Management Signalling Trade-off

The minimum bit requirement for a full location update signalling procedure can be calculated from table 6/1 as being 1,104 bits. From equations 5.5 and 5.6 the random access channel, operating at a success probability of 0.3, and with a maximum of 13 (k) attempts, then the average number of RACHs channel attempts per successful access is 3.3. With 40 bits required for a ‘Channel Request’ message this increases the previous bit requirement by 92 bits (2.3 x 40 bits), resulting in an average bit requirement of 1,196 bits. In order to trade-off location update signalling against paging signalling, the bit requirement for network paging is also necessary. This is estimated in annex B.3 for user-terminating call setup. For location deregistration, where authentication and cipher procedures are not used and where the UTs identity is not included, the S-PCN bit requirement is estimated as being 480 bits fewer that the
other mobility management signalling procedures. The bit requirements from these procedures are tabulated below in table 6/2.

<table>
<thead>
<tr>
<th>Task</th>
<th>Bit Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Location Registration / Update Bit Requirement</td>
<td>1,196 bits</td>
</tr>
<tr>
<td>Average Location Deregistration Bit Requirement</td>
<td>716 bits</td>
</tr>
<tr>
<td>Paging Message Bit Requirement</td>
<td>152 bits</td>
</tr>
</tbody>
</table>

Table 6/2 - Location Update and Paging Bit Requirements

Based on the above signalling bit estimates and the user mobility management signalling probability curve, a trade-off between location update related signalling and network paging signalling was made. Paging signalling requirement is multiplied by the estimated number of user-terminated calls per day. For MAGSS-14, this was estimated as 1.5 user-terminated calls / user / day. The same rate is used for the Globalstar constellation. Figure 6.10 plots the bit requirement per mobile user per day against $R_u$ for the 19 spotbeams per satellite (rather than 16) Globalstar constellation.

Figure 6.10 - Location Update Vs Paging (LEO): Active Period Bit Requirement

The curve of paging bit requirement is seen to rise steadily with increasing uncertainty radius. Each point is calculated by multiplying the PAGING MESSAGE bit requirement by the average paging requirement at that uncertainty radius and finally by 1.5 (i.e. the estimated number of user-terminated calls per day). The location management bit requirement curve follows a similar form as the $P(u)$ distribution - reducing to almost the location registration / deregistration bit requirement for high $R_u$ values. The third curve is a summation of the earlier two curves and shows the active
period total bit requirement. This curve clearly reaches a minimum for an $R_u$ value of about 400 km. Below 400 km, location update related signalling increases the signalling bit requirement while above 400 km, reduced paging channel efficiency increases the total required bit rate.

Figure 6.11 shows the equivalent results for the 37-spotbeam MAGSS-14 MEO constellation. The same user update probability curve is used but the paging requirement statistics are specific to MAGSS-14 constellation coverage.

![MEO Mobility Management Signalling Trade-off](image)

**Figure 6.11 - Location Update Vs Paging (MEO): Active Period Bit Requirement**

From this graph, the optimum radius for the minimisation of S-PCN mobility management signalling (registration / update / deregistration and paging) can be read. The curve of paging bit requirement is seen to rise steadily with increasing uncertainty radius. Due to the lower MAGSS-14 paging requirement compared to the smaller spotbeam LEO constellation, the level of paging signalling required is lower than in the LEO case. The location management bit requirement is similar to the LEO case. The highest curve is a summation of these two curves and shows the active period total bit requirement. This curve clearly reaches a minimum for an $R_u$ value of about 600 km. The final LEO paging efficiency and mobility management signalling rates are provided in table 6/3 below. The estimated rates for the alternative mobility management procedures discussed in section 6.1 are also tabulated for comparison. An active daily duration of 12 hours is assumed.
In table 6/4, the mobility management approach comparison is made between the different approaches but for the MAGSS-14 constellation.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Procedure Frequency</th>
<th>Paging Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>GES / Satellite / Spotbeam (6.1.1)</td>
<td>~ 180 times per day</td>
<td>100 %</td>
</tr>
<tr>
<td>GES / Satellite (6.1.1)</td>
<td>~ 36 times per day</td>
<td>6.25 %</td>
</tr>
<tr>
<td>GES Registration (6.1.2)</td>
<td>~ 36 times per day</td>
<td>6.25 %</td>
</tr>
<tr>
<td>UT Position (6.1.3)</td>
<td>~ 3 times per day</td>
<td>10 %</td>
</tr>
</tbody>
</table>

Table 6/4 - Mobility Management Approach Comparison (MAGSS-14)

In both the LEO and MEO cases, the performance of the proposed mobility management approach is seen to be much lower than the estimated equivalent rates for the other mobility management procedures described in section 6.1. The values indicated for the UT position approach are based on the optimum R_u found in the above trade-off, referred back to the relevant curve from either 6.7, 6.8 or 6.9. In fact, even when not operating anywhere near its optimum uncertainty radius, the UT position approach is still seen to outperform the other two approaches. Since each constellation has its own specific paging statistics, each constellation also has an optimum uncertainty radius, at which, with this approach to mobility management, the overall signalling requirement is minimised. The shape of the P(u) distribution curve is seen to have an important influence on the value of the optimum R_u and so specific work should be done in order to estimate this distribution in greater detail.

### 6.4 MAGSS-14 Power Requirement

The effect of mobility management signalling from a satellite power consumption point of view is examined here, based on the bit requirements indicated in section 6.2 and the signalling rate requirement indicated in section 6.3. This examination is done at a spotbeam level. The number of users per MAGSS-14 spotbeam (incorporating the traffic variation factor of 4) was estimated as between 21,200 and 42,400. According to the mobility management approach adopted, the number of mobility management related signalling procedures per user per day is taken from table 6/4.

These values are now converted into average mobility management signalings per spotbeam per second by assuming an average distribution, for the first three approaches, of signalling throughout the day. This is reasonable due to the high level of location updates. For the fourth approach, based on the use of a positioning system, peak rates associated with morning location registration (assumed to be spread over two hours) are used. Table 6/5 indicates the resulting peak mobility management
signalling rates per spotbeam per second. The maximum number of 42,400 users is assumed in these calculations and a day is considered as an active duration of 16 hours. For example, with the first approach 56 signalings per user per day becomes 3.5 signalings per user per hour which becomes 148,400 signalings per spotbeam per hour. This is the equivalent of 41 signalings per spotbeam per second.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Peak Signalling Frequency / Spotbeam / Second</th>
</tr>
</thead>
<tbody>
<tr>
<td>GES / Satellite / Spotbeam (6.1.1)</td>
<td>~ 41 signalings per spotbeam per second</td>
</tr>
<tr>
<td>GES / Satellite (6.1.1)</td>
<td>~ 6 signalings per spotbeam per second</td>
</tr>
<tr>
<td>GES Registration (6.1.2)</td>
<td>~ 6 signalings per spotbeam per second</td>
</tr>
<tr>
<td>UT Position (6.1.3)</td>
<td>~ 1.8 signalings per spotbeam per second</td>
</tr>
</tbody>
</table>

Table 6/5 - Mobility Management Signalling Rates (MAGSS-14)

The UT position approach clearly results in a lower signalling requirement. The savings offered to the network are in terms of signalling bandwidth and satellite transmit power. The equivalent power requirement in terms of voice channels is now calculated, based on the location registration / update signalling bit requirement estimated in annex A.1 and shown in the first row of table 6/2 (the slightly lower location deregistration bit requirement is not considered here as peak values are of interest). Depending on whether channel cooperation exists or not and according to the terminal type, signalling channel bit rate assumptions were made for each of the procedures considered.

- Handheld terminals transmit at 240 b/s for all common control channel signalling. Handheld terminals transmit at 240 b/s for SDCCH/s channel signalling when user-cooperation cannot be assumed and at 1.2 kb/s when user cooperation can be assumed.

- Other terminal types transmit at 240 b/s for all common control channel signalling. They transmit at 1.2 kb/s for all SDCCH/s channel signalling.

Another important factor concerns the mix of terminals which might be used within the system. Terminal types include handheld (H), vehicle mounted (V), transportable (T) and fixed (F). For this study, these terminal types are divided into two groups - handheld and otherwise. In this split the signalling channel rate assumptions indicated above are used. The assumed mix of terminal types is given in table 6/6.

<table>
<thead>
<tr>
<th>Terminal Type</th>
<th>Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>50%</td>
</tr>
<tr>
<td>T</td>
<td>17%</td>
</tr>
<tr>
<td>V</td>
<td>17%</td>
</tr>
<tr>
<td>F</td>
<td>16%</td>
</tr>
</tbody>
</table>

Table 6/6 - S-PCN Terminal Type Mix

Based on this, a handheld signalling requires the equivalent of 4.72 seconds (1,132 bits @ 240 b/s) of voice channel equivalent satellite transmit power. The higher G/T
terminal types, which use a higher SDCCH/s channel bit rate for location update signalling require 1.78 seconds (252 bits @ 240 b/s + 880 bits @ 1.2 kb/s) of voice equivalent satellite transmit power. Because of the 50:50 terminal mix assumed, the equivalent power requirement per mobility management signalling procedure is 3.25 seconds. This figure can now be used with the mobility management signalling procedure frequency estimations shown in table 6/5. These figures are per second and should be multiplied by the above signalling duration in order to give the actual signalling channel requirement. Each of these signalling channels uses the same amount of satellite transmit power as is used by a voice channel and so uses satellite and spotbeam transmit power in a way other than for traffic channel transmission. The results are indicated in table 6/7.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Peak Signalling Channel Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>GES / Satellite / Spotbeam (6.1.1)</td>
<td>133.25 signalling channels per spotbeam</td>
</tr>
<tr>
<td>GES / Satellite (6.1.1)</td>
<td>19.5 signalling channels per spotbeam</td>
</tr>
<tr>
<td>GES Registration (6.1.2)</td>
<td>19.5 signalling channels per spotbeam</td>
</tr>
<tr>
<td>UT Position (6.1.3)</td>
<td>5.85 signalling channels per spotbeam</td>
</tr>
</tbody>
</table>

*Table 6/7 - Peak Voice Equivalent Power Requirement (MAGSS-14)*

The numbers indicate the peak voice equivalent power requirement for system mobility management signalling. With the first mobility management approach, where UTs update their network location each time a new spotbeam passes overhead, the signalling requirement within a spotbeam can reach the equivalent of 133 voice channels. This approach to S-PCN mobility management is clearly unsuitable. The other approaches perform much better but still require a significant proportion of satellite spotbeam transmit power. Voice channels must be provided in addition to this signalling.

LEO constellations will suffer from a similar mobility management signalling loading effect. The numbers will be different due to the smaller satellite coverage areas and the different numbers of spotbeams per satellite. The final figure will also need to include those signalling procedures which needed to be repeated due to the loss of connectivity with the satellite spotbeam. Based on the signalling delays estimated earlier, this effect was noted to result in an increase of 16% for the Iridium constellation and of 7% for the Globalstar constellation. These will further increase the satellite power overhead requirement for signalling.

The most effective approach is clearly the one based on the use of a positioning system. Even in this case it is important to note that mobility management signalling results in an important contribution in terms of satellite power consumption as well as system bandwidth. Finally, the very high peak loading mobility management signalling rate is likely to require a suitably large portion of system bandwidth (channels). Since signalling delay performance is a very important system parameter then channel throughput is likely to be kept quite low - further increasing the random access channel bandwidth requirement. Control over random access channel performance will play an important role in overall system performance.
6.5 Conclusions

Three different S-PCN mobility management approaches were described and examined from a signalling efficiency point of view. Constellation dynamics was seen to reduce the performance of the first two approaches considered. The third approach, which was proposed in order to overcome this problem, is based on the use of a positioning system by each UT. It is seen to improve network mobility management performance. Before this approach was examined in further detail, the signalling message bit requirement was examined.

From this examination of the LAPDm network layer protocol messages, S-PCN message information element content was proposed, allowing the equivalent S-PCN message lengths to be deduced. Based on the LAPDm signalling sequence, a simulation model was built in 'BONE'S Designer' and the procedure was simulated for both LEO and MEO constellations for different channel rate combinations. The resulting delay distributions obtained showed clearly the significance of the RACH's channel performance on system delay performance. Propagation delays were not found to be a very important factor in the delay. The use of low delay and very low throughput slotted ALOHA channels was seen to improve system delay performance markedly. In fact, random access channels are seen to play a key role in the overall system performance. Ensuring their stability and low delay performance while not using excessive amounts of system bandwidth will be an important task.

For LEO constellations, the combination of low spotbeam connectivity duration with a relatively high average signalling duration was seen to result in a fairly high percentage of signalling procedures being incomplete, since signalling channel handover is not provided. This effect will be at its most severe for the Iridium constellation where spotbeam connectivity duration is the lowest. The percentage of signalling procedures which are incomplete depends on the average signalling duration and therefore on the signalling channel bit rate combination. This results in a similar increase in the overall mobility management signalling channel loading, which is important when signalling channels are being dimensioned.

The performance of the 'UT position' based mobility management approach was examined in specific detail, with a trade-off between network paging signalling and UT location update signalling being performed. The paging bit requirement was calculated, based on the specific constellation paging requirement and the PAGING MESSAGE bit requirement. Location related signalling bit requirement was taken from a proposed user mobility model. The resulting trade-off allowed an optimum uncertainty radius to be estimated for the specific constellations considered. The resulting performance was seen to be much better than the other approaches considered.

The equivalent voice channel power resulting from mobility management related signalling was finally considered, based on the signalling rates required by different S-PCN mobility management approaches. Only the MAGSS-14 constellation is considered here because of the traffic data available. The requirement, in terms of system bandwidth and power, for this non-revenue earning network signalling was seen to vary greatly according to the approach used. The newly proposed UT position approach to mobility management resulted in the lowest, although still not negligible, overhead of all the approaches considered.
References


[Sammut94/2] ‘Mobility Management Related Signalling for a MAGSS-14 based Satellite Personal Communications Network (S-PCN)’, C. Cullen, A. Sammut, R. Tafazolli, B. Evans. COST 227, (TD) 94 ....


Chapter 7  S-PCN Call Control

The three different types of S-PCN call setup procedures are now examined - user-originated, user-terminated and user-to-user. A version of the LAPDm protocol [LAPDm], [Mouly], [Steele], modified at the network layer level in terms of message content, is used. Changes are made to the message information element content and a new signalling sequence is proposed which takes the baseline S-PCN architecture into account. Each call setup type is simulated from a signalling delay point of view for different signalling channel rate combinations and random access channel success probability. Call setup delay distributions for these different cases are then obtained. Signalling channel bit rate combinations are chosen according to the level of user cooperation envisaged. Important conclusions on S-PCN operation scenarios and the role of the user can be made, based on the results obtained. In each case, simulation results are indicated for the Globalstar [Globalstar] and MAGSS-14 [Benedicto] constellations.

7.1 User-Originated Call Setup

Two channel assignment techniques are provided for within the LAPDm protocol - early assignment and late assignment. Both are initially considered before one is chosen for simulation. The preferred signalling flow was then built and simulated on the 'BONeS Designer’ network simulator for various system operation scenarios. From this, signalling procedure delay distributions are obtained and analysis can be done on the significance of call setup delay.

7.1.1 User-Originated Call Setup Procedure

This section describes the modified LAPDm user-originated call setup air interface signalling procedure. The procedure consists of a sequence of elementary messages transmitted on network common and dedicated control channels - RACH/s, AGCH/s and SDCCCH/s. The signalling procedure and its relation to the S-PCN architecture is now examined and a suitable mapping is made. Initial signalling, as with mobility management signalling, is between the UT and the contacted GES. The contacted GES may be related to the strongest signal received by a UT or it may be a preferred GES identity held in the UTs memory. Signalling between the UT and GES must progress until at least the stage where the GES has the available information to perform route optimisation and can allocate the UT a traffic channel. Once a traffic channel has been allocated, signalling can be switched to between the UT and the chosen TES. This occurs towards the end of the signalling procedure.

The GSM system provides for two different channel assignment techniques - early or late assignment. Late assignment means that the traffic channel is allocated after the called user has been alerted and has unhooked the receiver (i.e. the phone was ringing - ‘Alerting’ message - and was just answered - ‘Connect’ message). In this case, the ringing tone must be generated locally in the UT. Late assignment results in a more efficient use of system resources since no traffic channels are allocated until they are required. Figure 7.1 shows the late assignment signalling procedure.
Figure 7.1 - User Originated Call Signalling - Late Assignment

From the above signalling flow diagram, signalling between the UT and the GES is seen to proceed up to and just beyond the point where the destination number has been alerted and has answered the call. At that point the GES allocated the UT a traffic channel over the air interface. The same traffic channel was already allocated to the chosen TES via S-PCN ground segment signalling and the TES should already have a link to the destination number. The UT replies to the TES which responds with the 'Connect' message - to indicate that the traffic channel has been fully connected.

The other channel assignment technique, early assignment, the traffic channel is allocated before the 'Alerting' signal is sent by the called terminal (i.e. before the called users terminal begins to ring). The 'Alerting' signal indicates to the UT that the called terminal is 'ringing'. Both signalling procedures are similar up to the point of transmission of the 'Call Proceeding' message. Early assignment is indicated in figure 7.2.
This approach to call setup is initially the same as with the late assignment approach. The UT starts by sending a request to a GES on the RACH/s channel. Once a successful request is received, the GES replies with a AGCH/s channel message, allocating the UT a SDCCH/s link with the GES. The UT then sends a ‘Connection Management Service Request’ message to the GES, indicating the type of service requested (e.g. voice service). UT authentication and channel ciphering are then performed followed by the UT sending the ‘Setup’ message to the GES, indicating the dialed number to the GES. The GES acknowledges this with a ‘Call Proceeding’ message.

It is at this point that the two approaches become different. For early assignment, an appropriate traffic channel is chosen and immediately allocated by the GES to the UT (figure 7.2). This channel is allocated between the UT and the chosen TES which is allocated the channel by S-PCN ground segment signalling. The TES then connects the call through to the destination while the UT confirms the allocated traffic channel with its first message to the TES. The TES completes the end-to-end traffic channel which generates the actual ringing tone at the UT end. When the dialed number begins to ring, the ‘Alerting’ message is sent and forwarded by the TES to the UT. At this point the UT user can hear the destination number ringing. The ‘Connect’ message is sent from the dialed number only when (if) the call is answered. If there is a delay in answering the call or if it is not answered, then the already allocated traffic channel is
wasted for that duration. It is this inefficiency that late assignment attempts to overcome.

In the GSM system and irrespective of the channel assignment technique used, the same air-interface is used throughout the whole call setup procedure and is continued over into the call. For S-PCN, as already explained, GESs are involved in call setup and network control but TESs are involved in the carrying of traffic channels. This is an important difference with respect to the GSM signalling. It is a consequence of the new approach required for S-PCN call routing, as described in chapter 4.

The implications of the use of both these methods are now considered. Early assignment is clearly less efficient than late assignment in terms of traffic channel usage. However, with late assignment there is always a delay between receipt of the ‘Alerting’ message and the allocation of a traffic channel. Because user cooperation can be assumed for a user-originated call, a SDCCH/s channel rate of 1.2 kb/s between the UT and the TES is realistic. Adding on the four propagation delay hops and the four processing delays to the message delay (the bit requirement of the four messages is indicated in the next section) the resulting delay can vary between 1.0 and 1.9 seconds (the average delay was found to be 1.52 seconds), for a MEO constellation. For a LEO constellation the delay range reduces to between 0.732 and 1.532 seconds (the average delay is 1.248 seconds). This is based on appropriate propagation delay ranges, a message delay according to a 1.2 kb/s channel rate and a processing delay range, at both the TES and the UT, of between 25 ms and 250 ms.

Such a delay is likely to cause initial inconvenience on most S-PCN calls. The time it takes a phone user to unhook a phone and reply can be expected to be less than the above mean delays. The early assignment alternative means that a traffic channel is allocated for the call duration plus the ringing duration at the called terminal. This results in the inefficient use of traffic channels resulting in a reduction in system capacity. Therefore, although there is an initial 'silent' period of about half a second, late assignment is still considered acceptable for user-originated calls. The signalling flow shown in figure 7.1 was therefore chosen as the signalling sequence which was simulated.

However, there needs to be the possibility for the network to perform early assignment of the traffic channel. This is in the case where there is a risk of loss of connectivity between the UT and the satellite spotbeam through which the signalling is being performed. If this occurs while the called user's phone is ringing then the call cannot be put through. The network is required to estimate the UTs location relative to the edge of the spotbeam and estimate the remainder of connectivity time a UT has with that spotbeam. This might be done through doppler shift or timing advance measurements. Alternatively if the UT uses a positioning system, then it could report its coordinates to the network. The network can then estimate the connectivity time between the UT and that spotbeam. If this connectivity time is low then the signalling link might be lost before the called user answers the call. In such a case, by the time the called user answers the phone, the link to the UT is lost.

---

1 Between 0.5 and 1.0 seconds seems a reasonable range for the delay between when the phone is unhooked and when the called user begins to speak.
If this possibility is detected in advance, then the traffic channel (with its associated signalling channel / channels) can be allocated to the UT, which switches to the new spotbeam and channel. In such cases, a signalling channel associated with the traffic channels could be used for further contact between the GES and UT - the ‘Alerting’, ‘Connect’ and ‘Connect Acknowledge’ messages. Because user cooperation exists this should not pose a problem in terms of the required link margin.

7.1.2 Bit Estimation

The S-PCN modified LAPDm messages used for a successful user-originated call setup signalling procedure are now listed. The detail within the new messages introduced is provided in Annex B.1, where elementary messages not already described (in annex A.1) are broken into their constituent information elements and the proposed S-PCN modifications are indicated. Annex B.2 describes the simulation model built for user-originating call setup. Half rate coding is applied to these messages and a further 3 octets is added to each for synchronisation. The final estimated bit requirements are indicated in table 7/1.

<table>
<thead>
<tr>
<th>Message</th>
<th>S-PCN Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Request</td>
<td>40 bits</td>
</tr>
<tr>
<td>Immediate Assignment</td>
<td>120 bits</td>
</tr>
<tr>
<td>CM Service Request</td>
<td>136 bits</td>
</tr>
<tr>
<td>Authentication Request</td>
<td>152 bits</td>
</tr>
<tr>
<td>Authentication Response</td>
<td>120 bits</td>
</tr>
<tr>
<td>Ciphering Mode Command</td>
<td>72 bits</td>
</tr>
<tr>
<td>Ciphering Mode Complete</td>
<td>56 bits</td>
</tr>
<tr>
<td>Setup (UT-origin)</td>
<td>760 bits</td>
</tr>
<tr>
<td>Call Proceeding</td>
<td>72 bits</td>
</tr>
<tr>
<td>Alerting</td>
<td>200 bits</td>
</tr>
<tr>
<td>Assignment Command</td>
<td>312 bits</td>
</tr>
<tr>
<td>Assignment complete</td>
<td>72 bits</td>
</tr>
<tr>
<td>Connect</td>
<td>200 bits</td>
</tr>
<tr>
<td>Connect Acknowledge</td>
<td>56 bits</td>
</tr>
</tbody>
</table>

*Table 7/1 - User-Originated Call Setup Bit Requirement*

The user-originated call setup procedure with late assignment, indicated in figure 7.1, was simulated for both LEO and MEO baseline constellations using models built in BOnES Designer. Because late assignment was simulated, the point of signalling termination is when the UT receives the ‘Alerting’ message from the GES. After this point, no further messages are transmitted until the called phone is unhooked. The bit requirements used in the simulations is indicated in table 7/1.
Because user link cooperation can be assumed for user originated calls, the higher signalling channel rate combinations were used for the signalling procedure simulations. The first combination simulated assumed RACH/s and AGCH/s channel rates of 240 b/s and a SDCCH/s channel rate of 1.2 kb/s. This is indicated as 240/./1200 on the resulting delay distribution diagram. The other combination simulated assumed all channels operating at a rate of 1.2 kb/s. This is indicated as 1200/./. in the delay distribution diagram. LEO/MO is used to indicate the Globalstar constellation with mobile originated call setup while MEO/MO indicated the equivalent MAGSS-14 constellation simulations. Between message transmissions, a uniformly distributed processing delay of between 25 ms and 250 ms, at either the GES, TES or UT, were included. 50,000 signalling sequences were simulated in order to obtain each delay distribution shown.

Two different random access channel failure probabilities are simulated. Both model random access channel performance under stable channel loading levels. The first case is where the RACH/s channel operates near peak throughput. For this, an access failure probability of 0.7 was used, resulting in a low channel throughput but in a low channel delay performance. The second model is of a much lower random access channel loading where the channel throughput is well below 36%. Channel delay performance is much better in this case than for the heavier loaded channel. For this, an access failure probability of 0.4 was used.

7.1.3 Simulation Results

The LEO and MEO user originated call setup with late assignment simulation results are presented and discussed in the following two sections. Similar results were presented in [Cullen94/2]. In these call setup delay simulations, the terrestrial segment call setup delay (starts at the time when the GES receives the 'Setup' message) is assumed to be less than the actual S-PCN delay. With late assignment this is especially valid since the 'Alerting' signal does not signify the actual destination number ringing.

7.1.3.1 LEO Results

Each signalling sequence modeled had a propagation delay uniformly chosen from between 9.5 ms and 14.7 ms in order to model Globalstar delays. Differences in scale between the two graphs should be noted. The results indicate 99% of cases. The x-axis indicates the delay in seconds and is subdivided into 0.5 second intervals. The y-axis ('Throughput') indicates the percentage of signalling procedures which are completed in the time interval indicated. As explained already, signalling completion for late assignment means up to the point of the UT receiving the 'Alerting' message. The Globalstar simulation results are shown in figures 7.3 (a) and 7.3 (b) for the heavily loaded RACH/s channel case and two different bit rate combinations.
For the initial signalling rate combination of 240/1200 (7.3(a)), the average user-originated call setup delay was found to be about 7 seconds. The delay range for 99% of calls was between 3 and 19 seconds. When the higher channel rate combination of 1200/1 was used (permitted due to the expected high level of user cooperation), the average delay reduced to 5 seconds with 99% of calls requiring between 2.5 and 12.5 seconds to be setup to the point where the destination number is ringing. The use of a high bit rate RACH/s channel has clearly improved the overall call setup performance.

---

2 If early assignment is used, then the average and upper limit delay values for the above simulations increase by about 1 second.
As in the mobility management signalling case, the signalling delay required for user-originated call setup is a non-negligible percentage of the actual mean connectivity time between a UT and a LEO satellite spotbeam. The further complication added in the case of call setup with late assignment is that the 'delay' duration is further increased by ringing duration. This added ringing duration may result in the use of call setup with late assignment being unsuitable. However, as considered in section 7.1.1, knowledge of the UT position by the GES can allow it to decide whether to perform early or late channel assignment. Also, if early traffic channel assignment was performed, then the associated signalling channels could be used for the final signalling exchange. The disadvantage of this is that it would require more significant LAPDm protocol modifications.

In chapter 6 the mean connectivity time with an Iridium satellite spotbeam was estimated as about 52 seconds. For Globalstar, with fewer spotbeams and higher altitude satellites, the average connectivity duration with the first spotbeam is about 120 seconds. With an average signalling delay duration of 5 seconds (the faster channel rates are used since user cooperation can be assumed at all stages) the probability of a signalling failure approaches 9.6% (5/52) and 4.2% (5/120) for Iridium and Globalstar respectively. In such cases, the call setup procedure will need to restart via a different spotbeam. On average, the connectivity duration with this second spotbeam is longer since it is probably at the start of its connectivity period with the UT. The resulting increase in call setup delay is likely to reduce the level of user satisfaction. However, since it is due to a combination of unavoidable space segment dynamics coupled with the slightly extended signalling durations, the only way to reduce this effect is to reduce the average signalling duration. It should also be noted that the called user ringing duration has not yet been considered. If an average ringing duration of 5 seconds is assumed, then, the actual total 'holding delay' becomes 10 seconds. The loss of connectivity probability increases to 19.2% (10/52) for Iridium and 8.3% (10/120) for Globalstar. The trade-off between early or late assignment of the traffic channel is seen to be fairly dependent on the actual ringing duration. Also, the Iridium constellation is seen to be much more affected by this loss of connectivity than the Globalstar constellation. It may be that it is preferable to use early channel assignment with the Iridium constellation.

The above bit rate combination also suggests a new approach to system signalling channels. For signalling where user cooperation can be assumed, then high rate signalling channel combinations can be used, thus reducing the delay. Where cooperation cannot be assumed, then lower rate channel combinations may need to be used. This results in the requirement to have all channels paired - a low rate channel (240 b/s) and a high rate channel (1.2 kb/s). All of the above considered channels would be paired in this way.

Figure 7.4 shows the delay distribution for a low throughput and low delay random access channel. The RACH/s throughput is very low due to the low number of requests being made. Consequently, the channel delay - which is a key parameter of interest to S-PCN subscribers - is significantly reduced compared to the previous delay distributions shown. A 240/1200 channel bit rate combination was simulated.
Figure 7.4 - User-Originated Call Setup Delay Distribution (LEO) - fast

The average delay from this distribution is about 5 seconds. The average delay is the same as the distribution shown in figure 7.3 (b). The delay range is also equivalent to that shown in figure 7.3 (b). There is an improvement of 2 seconds over the signalling delay distribution for the equivalent signalling channel bit rates - indicated in figure 7.3 (a).

With the appropriate dimensioning of system random access channels, the call setup delay distribution can be reduced to the delay levels indicated in the figure 7.4 distribution. The cost is that, with random access channels operating at such low throughput levels, then a larger proportion of system bandwidth needs to be allocated to these channels, thus reducing the bandwidth available for traffic channels. However, call setup delay distributions of the order indicated in figure 7.3 (a) are unlikely to be satisfactory to system users. A final point to recall concerns the brief 'pause' that will occur between the called user picking up the phone and the traffic channel being allocated. By accepting this inconvenience, overall system capacity is increased by eliminating the 'dead time' associated with the allocation of a traffic channel. Work on reducing this 'pause' delay through modifying the LAPDm signalling procedure sequence needs to be considered in order to minimise the 'pause' duration.

7.1.3.2 MEO Results

The same call setup procedure was considered for the MAGSS-14 constellation. As before, the simulation was run up to the point of reception by the UT of the 'Alerting' message - when the dialed number begins to ring. The 'Assignment Command', 'Assignment Complete', 'Connect' and 'Connect Acknowledge' messages follow only when the called user responds. Figures 7.5 indicate the simulation results for a random access failure probability of 0.7 (i.e. a random access channel working just under optimum loading point). The range of propagation delays used in the simulation was between 67 ms and 92 ms - the delay range associated with MAGSS-14.
For the 240/./1200 rate combination, the average call setup delay, to the point of destination number ringing, is about 8 seconds. The delay spread for 99% of the calls is seen to be between 3.5 and 19 seconds. The extra delay relative to a LEO constellation is, as expected, about 1 second. For the 1200/./ channel rate combination, the average call setup duration is about 6.5 seconds. The 99% delay spread is between 3 and 14 seconds which, again, is slightly longer than the equivalent Globalstar delay spread. Larger MEO delays are expected due to the longer distances involved. However, it can be noted that with 14 messages transmitted, the propagation delay contribution ranges between 1.132 seconds and 0.824 seconds (12.3 x 92 ms and 12.3 x 67 ms). It should be noted from this that in terms of the overall delay, the actual propagation delay component, even for the MEO altitude, is
quite low compared with other contributions (e.g. processing delay, message packet delay and random access delay). The faster RACH/s and AGCH/s channel rates result in a different shaped delay distribution curve - compare figures 7.5 (a) and (b). As in the LEO case, the use of early channel assignment will increase the average delay and upper delay spread limit by about 1 second.

With an initial average spotbeam connectivity duration of about 6 minutes to a MAGSS-14 spotbeam the probability of signalling termination due to loss of spotbeam connectivity is low - 2% (8/360) for the 240/1200 signalling channel rate combination with P(s) = 0.3. However as the spotbeam numbers increase and their sizes decrease, then the average connectivity duration with a spotbeam will reduce accordingly. For constellations like Inmarsat-P, which propose to use 121 spotbeams, then the percentage of signalling failures will increase. With an average spotbeam connectivity duration of about 5 minutes then the failure probability for the same channel type increases to about 2.6% (8/300). By including a 5 second ringing delay, this increases to 4.3% (13/300). MEO constellations are clearly less affected by this connectivity instability than LEO constellations and this means that the use of late channel assignment at times of peak traffic loading, is more suited to MEO constellations.

Since user cooperation can be assumed, then it may be reasonable to use the higher signalling rates. This is similar to UT location registration and deregistration where the user can cooperate with the link, but different from the location update case which occurs independently of the user. Figure 7.6 shows the user-originated call setup procedure for the random access channel operating in the low delay region - P(s) = 0.6.

![Figure 7.6 - User-Originated Call Setup Delay Distribution (MEO) - fast](image)

The average user-originated call setup delay has reduced from about 8 seconds to about 6 seconds. The delay spread range is also reduced. This performance improvement will clearly result in a higher level of user-satisfaction. Again, the use of over-dimensional random access channel seems to be a requirement on the network from a user satisfaction point of view. The shape of the delay distribution is similar to
the equivalent LEO distribution, with the one second difference due to the extra MEO propagation delay.

### 7.1.4 Discussion

An important aspect to be drawn from this examination of call setup signalling delay concerns the relative importance of the different contributions to S-PCN call setup delay. The random access channel delay performance and the signalling channel rates were seen to have important effects. For LEO constellations, signalling terminations were seen as the probable consequence of the short satellite spotbeam connectivity coupled with the extended signalling duration. For MEO constellations this possibility is less, although not negligible, due to the longer spotbeam connectivity period.

Another main point concerns the use of paired rate common and dedicated control channels. These channels would be used according to the link type expected - 240 b/s when user cooperation is not expected and 1.2 kb/s when user cooperation is expected. These two sets of control channels should exist within each spotbeam and they should be dimensioned according to expected signalling throughput. This approach improves system delay performance where possible and reduces the required amount of satellite power and system bandwidth.

The choice between the use of early or late traffic channel assignment is seen to be influenced by quite a few factors. Late assignment, although it results in an initial silent period immediately after the call was answered, is preferable due to the lower blocking probability (or alternatively, increased system capacity) it offers at times of peak traffic loading. However, call setup delay and the additional ringing time at the called end, can result in a loss of signalling channel connectivity due to the space segment dynamics. The trade-off is further influenced by the connectivity differences between LEO and MEO constellations.

### 7.2 User-Terminated Call Setup

The LAPDm protocol user-terminated call setup signalling procedure is now described. The option of whether to use early or late channel assignment is again considered. The lack of user cooperation for user-terminated calls has an important influence on the choice of channel rates used and this in turn influences the channel assignment technique used. However, since users are not supposed to answer the call until they have sufficient link cooperation, higher signalling channel rates can be assumed for the final call signalings. Therefore the choice between early and late assignment of the traffic channel is not affected by initial lack of link cooperation. The chosen signalling procedure is built and simulated on the 'BONeS Designer' network simulator and signalling procedure delay distributions are obtained for both LEO and MEO constellations under various scenarios.

#### 7.2.1 User-Terminated Call Setup Procedure

This section describes the modified LAPDm user-terminated call setup air interface signalling procedure. A successful signalling procedure is considered. The procedure consists of a sequence of elementary messages transmitted on network common and dedicated control channels - PCH/s, RACH/s, AGCH/s and SDCCH/s. Initially these messages are between a GBS and the called UT. An appropriate TES is eventually chosen, through which the call is routed.
Early or late assignment of the traffic channel is again possible. Early assignment means allocating the traffic channel before the UT starts ringing while late assignment means assigning the channel after the UT user has ‘unhooked’ the UT. Late assignment results in a more efficient use of system resources since a traffic channel is allocated later and so for a shorter duration. The problem, as already mentioned in the previous section, is that the SDCCH/s channel holding time is increased by the ‘ringing’ duration. This results in an increase in the probability of spotbeam connectivity loss due to satellite motion. LEO constellations are typically more effected by this. Figure 7.7 shows the early assignment signalling procedure.

<table>
<thead>
<tr>
<th>UT</th>
<th>GES</th>
<th>TES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paging request</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel request</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Immediate assignment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paging response</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Authentication request</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Authentication response</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ciphering mode command</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ciphering mode complete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Setup - t</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Call confirmed - t</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assignment command</td>
<td>Assignment complete</td>
<td></td>
</tr>
<tr>
<td>Alerting - t</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Connect</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Connect acknowledge</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 7.7 - User-Terminating Call Signalling Sequence - Early Assignment*

As indicated in figure 7.7, the channel is assigned by the network - the ‘Assignment Command’ message - before the UT starts ringing - the ‘Alerting’ message. Before the called UT user can reply, they must ensure sufficient signal strength. An immediate reply is therefore less likely and system traffic channel usage efficiency is reduced. In times of low channel usage this is not very important but at times of peak traffic demand, this can have an important effect on the system blocking probability as it increases the call holding time.

The late assignment signalling sequence for a user-terminated call is shown in figure 7.8. Both procedures are equivalent up to the point where the UT sends a ‘Call
Confirmed’ message to the GES. In the late assignment case, a traffic channel is not assigned until after the ‘Connect’ message has been received (i.e. after the UT user has ‘unhooked’ the UT).

<table>
<thead>
<tr>
<th>UT</th>
<th>GES</th>
<th>TES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Paging request</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Channel request</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Immediate assignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Paging response</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Authentication request</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Authentication response</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ciphering mode command</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ciphering mode complete</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Setup – t</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Call confirmed – t</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alerting – t</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Connect</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Assignment command</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Assignment complete</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Connect acknowledge</td>
<td></td>
</tr>
</tbody>
</table>

*Figure 7.8 - User-Terminating Call Signalling Sequence - Late Assignment*

The decision between which assignment approach is used for the simulation is quite a complex one and depends on quite a few variables. The signalling channel under consideration is the SDCCH/s channel. With both approaches and because it is a user-terminating call, the user does not know of the ongoing signalling until the ‘Alerting’ message is sent by the UT. After this point, the UT starts ringing and so the user can be expected to answer the call and therefore cooperate with the link. The SDCCH/s channel bit-rate up to the point of user cooperation could be either 240 b/s or 1.2 kb/s. Once user-cooperation is established, the 1.2 kb/s bit rate can be assumed. With late assignment, there is always a delay between receipt of the ‘Alerting’ message and the allocation of a traffic channel.

In fact, only after the UT has been unhooked (i.e. when the ‘Connect’ message has been sent) does the GES assign the UT a traffic channel. The UT then sends an ‘Assignment Complete’ message to the allocated TES which acknowledges the connection. The call can then begin. The channel rate can be considered as 1.2 kb/s for these messages, resulting in a signalling delay variation (three propagation delay
hops, three processing delays and the message delays) of between 1.4 and 0.64 seconds for the MAGSS-14 constellation and between 1.17 and 0.46 seconds for the Globalstar constellation. Although these delays seem quite small, it must be remembered that the UT user has already ‘unhooked’ the UT (the ‘Connect’ message has already been sent). A silent ‘pause’ of about 0.5 seconds will occur between when the UT is unhooked and when the traffic channel is actually being established. As in the user-originating call setup case, a ‘pause’ will be noticed by the call participants immediately at the start of the call. This is a clear disadvantage related to the use of late traffic channel assignment.

Another disadvantage of late assignment is that the longer SDCCH/s channel holding time increases the probability of loss of spotbeam connectivity. This effect will be most severe with LEO constellations with large numbers of spotbeams (i.e. Iridium and to a lesser effect, Globalstar). For MEO constellations, the effect is much smaller.

The early assignment alternative is to allocate the traffic channel before the ‘Alerting’ message is sent by the UT (i.e. before the UT starts ringing). In this case, the user has no idea of the incoming call so signalling is likely to have to proceed without a high level of link cooperation and therefore possibly at the lower 240 b/s rate. When the user is alerted, they are unlikely to be in a position to answer the call immediately – they will need to search for a suitable location first. Early assignment of the traffic channel will therefore result in the traffic channel being allocated for a longer duration than the call itself. If the call is not answered then the traffic channel allocation is wasted for the full ringing duration. Also, the UT user may decide not to answer the call and so the traffic channel is wasted.

Considering this, it seems preferable to use, as with user-originated calls, the late assignment procedure, even considering the initial silent period experienced by both parties to the call. The choice can be further considered once the loss of connectivity probabilities have been calculated.

### 7.2.2 Bit Requirement

The S-PCN modified LAPDm messages used for a successful user-terminated call setup procedure are now reviewed. The detail within the extra and altered messages used here is provided in Annex B.3. Annex B.4 describes the simulation model built. Half rate coding is applied and a further three octets is added to each message for synchronisation. The final estimated bit rates are indicated in table 7/2 below.
### Table 7/2 - User-Originated Call Setup Bit Requirement

<table>
<thead>
<tr>
<th>Message</th>
<th>S-PCN Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paging Request</td>
<td>120 bits</td>
</tr>
<tr>
<td>Channel Request</td>
<td>40 bits</td>
</tr>
<tr>
<td>Immediate Assignment</td>
<td>120 bits</td>
</tr>
<tr>
<td>CM Service Request</td>
<td>136 bits</td>
</tr>
<tr>
<td>Authentication Request</td>
<td>152 bits</td>
</tr>
<tr>
<td>Authentication Response</td>
<td>120 bits</td>
</tr>
<tr>
<td>Ciphering Mode Command</td>
<td>72 bits</td>
</tr>
<tr>
<td>Ciphering Mode Complete</td>
<td>56 bits</td>
</tr>
<tr>
<td>Setup (UT-term.)</td>
<td>760 bits</td>
</tr>
<tr>
<td>Call Proceeding</td>
<td>72 bits</td>
</tr>
<tr>
<td>Alerting</td>
<td>200 bits</td>
</tr>
<tr>
<td>Connect</td>
<td>200 bits</td>
</tr>
<tr>
<td>Assignment Command</td>
<td>312 bits</td>
</tr>
<tr>
<td>Assignment Complete</td>
<td>72 bits</td>
</tr>
<tr>
<td>Connect Acknowledge</td>
<td>56 bits</td>
</tr>
</tbody>
</table>

The user-terminated call setup procedure with late assignment, indicated in figure 7.6, was simulated for both constellations using models built in BONEs Designer. The bit requirements used in the simulation can be read from table 7/2. Because user link cooperation cannot be assumed for user-terminated call setup signalling, lower channel bit rate combinations were considered. The first combination was for all four channels - paging, random access, access grant and dedicated - to be working at 240 b/s. This is indicated as 240/./. on the delay distribution diagram. The second combination simulated assumed PCH/s, RACH/s and AGCH/s channel rates of 240 b/s and a SDCCH/s channel rate of 1.2 kb/s. This is indicated as 240/.//1200 on the resulting delay distribution diagram. LEO/MT indicates the Globalstar constellation with mobile terminated call setup while MEO/MT implies the MAGSS-14 constellation for mobile terminated calls. 50,000 signalling sequences were simulated to achieve the delay distributions shown.

### 7.2.3 Simulation Results

Simulation results for user-terminated call setup with late assignment of the traffic channel are now presented for both the LEO and MEO constellations examined. Similar results were presented in [Cullen94/2]. The terrestrial network (ISDN or PSTN, for example) call setup delay is not included in the following delay estimations. The total end-to-end delay is therefore the sum of the two individual delays.
7.2.3.1 LEO Results

The Globalstar simulation results are shown in figures 7.9 and 7.10 for different signalling channel rate combinations and random access channel delay characteristics. As before, the delay distribution for 99% of cases is indicated.

For the 240/././ channel rate combination, the average delay to the point of UT ringing was found to be 14.5 seconds. 99% of the signalling was completed between 10 and 28 seconds after the call entered into the S-PCN ground segment. When a 1.2 kb/s SDCCH/s channel is used, then the average delay before the UT begins to ring, is about 8.5 seconds, which is a significant improvement over the first average and
purely the result of the increased SDCCH/s channel rate. The range of delays within which 99% of procedures are completed is between 4 seconds and 21 seconds.

If the 1.2 kb/s bit rate for the SDCCH/s channel proves too high for a link where users are not expected to cooperate, then all channels may need to be at 240 b/s. The delay implications on user satisfaction need to be further considered in such a case. Aspects like users being alerted at an early stage in the signalling (once the SDCCH/s channel has been allocated, for example) so that they can cooperate with the link during call setup signalling might be considered.

Figure 7.10 shows the user-terminated call setup delay distribution for a random access channel operating at very low throughput levels but at correspondingly low delay levels. The higher rate SDCCH/s channel is also used.

![Figure 7.10 - User-Terminated Call Setup Delay Distribution (LEO) - fast](image)

The average call setup delay for this case, where the SDCCH/s channel bit rate is 1.2 kb/s, is about 6 seconds. This compares with a delay of 8.5 seconds when the random access channel had a higher throughput (and hence blocking probability and delay performance). The user-terminating call setup delay is, because of the extra paging signalling involved, higher than the equivalent signalling channel bit rate user originated call setup delay.

The same problems in terms of loss of spotbeam connectivity will occur to an even greater extent for user-terminated call setup. This is directly a result of the longer call setup durations. At its worst case, the average delay was about 14.5 seconds. If a ringing duration of 5 seconds is used then the probability of loss of spotbeam connectivity for Globalstar is about 16.25% (19.5/120). For Iridium this increases to 37.5% (19.5/52). This would seem to suggest that unless the call setup delay can be reduced to become more comparable to user-originated delays, then it may be necessary to always use early assignment with such constellation types. However, use of a positioning system which allows a UT to report its location to the network could provide a solution. In this case the GES can decide, depending on its estimate of UT / spotbeam connectivity, whether early or late traffic channel assignment should be used.
7.2.3.2 MEO Results

The MEO simulation results for user terminated call setup are presented below in figures 7.11 and 7.12. Two different random access performances are again modeled.

Figure 7.11 (a) - User-Terminated Call Setup Delay Distribution (MEO)

Figure 7.11 (b) - User-Terminated Call Setup Delay Distribution (MEO)

The MEO results for user-terminated call setup, with all channels at 240 b/s, give an average of 15.5 seconds. 99% of signalling was completed between 10.5 seconds and 32 seconds after the call arrived in the S-PCN segment. This is quite a slow call setup delay. It means that a typical fixed user who dials a S-PCN user, would have to wait an average of about 15.5 seconds before they hear a ringing tone. When the SDCCH/s bit rate is increased to 1.2 kb/s, then the average delay reduces to 9 seconds with 99% of signalling being completed between 4.5 and 22.5 seconds after the call entered the
S-PCN segment. Such delay figures are more acceptable. However, the ultimate delay will obviously depend very much on the bit rate that can be used over the SDCCH/s channel. Results for a lower delay random access channel are shown in figure 7.12.

![Figure 7.12 - User-Terminated Call Setup Delay Distribution (MEO) - fast](image)

The average delay for a MEO constellation user-terminated call setup delay is about 7 seconds - an increase of 1 second over the equivalent LEO simulation (figure 7.10). A big improvement over the higher throughput but higher delay random access used in the simulation results shown in figure 7.11 (b) is evident. The improvement is about 2 seconds on average while the range of delay spreads is also reduced.

The main implication of these long call setup delays for MEO constellations is in terms of user satisfaction. Delays of 15.5 seconds are likely to be unacceptable (especially considering the initial pause). Maintaining a low throughput, low delay random access channel is obviously important. The loss of connectivity problem effects MEO constellations less than LEO constellations, but cannot be neglected. For example, the 121 spotbeams per satellite Inmarsat-P constellation will have an average connectivity duration to a satellite of about 10 minutes. Since call setup can begin at any time, this results in an average remaining connectivity duration of about 5 minutes. With a signalling delay of 15.5 seconds plus a further 5 second ringing duration, the probability of connectivity loss is 6.8% (20.5/300). For a 7 second call setup delay this reduces to 4% (12/300).

### 7.2.4 Discussion

The problems of S-PCN call setup delays as well as questions hanging over whether late traffic channel assignment can be used are the main points of discussion resulting from the above analysis. The topics discussed in relation to user-originating call setup, in section 7.1.4, are all seen to be relevant again after this consideration of user-terminated call setup. However, they are even more pressing than in the user-originated call setup case due to the longer delays which result with user-terminated call setup signalling.
7.3 User-to-User Call Setup

These calls are not expected to make up a large percentage of S-PCN traffic. In terrestrial systems [Matra], a maximum of 4% is typical. For S-PCN systems a value of less than 2% seems a reasonable assumption. However, the call setup performance still has to be considered. Based on the long delays found from previous simulations, the average delay and the range of delay variation for these call setup types are likely to be quite large.

7.3.1 Signalling Procedure

UT-to-UT calls are only expected to make up a very small proportion of S-PCN calls. The question of early or late channel assignment does not arise here as it has already been considered for user-originated and user-terminated calls - in both cases, late assignment was preferred. Figure 7.13 below shows the signalling sequence which will be simulated.

![Signalling Sequence Diagram](image)

*Figure 7.13 - UT-to-UT Call Setup Signalling Sequence - Late Assignment*

7.3.2 Bit Requirement

The bit requirement for this signalling has all been reviewed already in sections 7.1 and 7.2 and also in Annex B.1 and B.2. Questions concerning user cooperation channel bit rates have also been considered in earlier sections. Three different combinations of bit rates are considered here. A clear distinction is made between the originating side of the call and the terminating side. This results in 7 different channels needing to be considered. The originating and terminating sides are distinguished by a double slash (//). UT-to-UT calls are indicated in the header by M2M (Mobile 2 Mobile).
7.3.3 Simulation Results

The user-to-user call setup procedure with late assignment, indicated in figure 7.13, was simulated for both constellations using simulation models built in BONeS Designer. In both LEO and MEO cases, the channel rates used on the originating side are 240 b/s for the RACH/s and AGCH/s channels and 1.2 kb/s for the SDCCH/s channel. On the user-terminating side, the same bit rates were used along with a PCH/s bit rate of 240 b/s. This is indicated as 240/.//1200//240/.//1200. The double slash ‘//’ separates the user-originating side from the user-terminating side. M2M implies a mobile to mobile call.

7.3.3.1 LEO Results

Only one bit rate combination was simulated for this call setup type. Two different random access channel performances were considered. The simulation results for the higher delay random access channel operation (P(s) = 0.3) are shown in figure 7.14. The bit rates used for the simulation results indicated are considered one of the more likely rate combinations. With this approach a distinction is made between common and dedicated control channels. An alternative combination would be the 1200/.//240/./, where the distinction is in terms of user link cooperation.

![Figure 7.14 - UT-to-UT Call Setup Delay Distribution (LEO)](image)

The shape of this curve is seen to be markedly different than curves previously indicated. This is mainly because of the combination of two random access channels with the associated backoff delay if a collision occurs. The random propagation delays also contribute to this effect. The average signalling delay, to the point of the called terminal beginning to ring, is 13 seconds. The delay spread for 99% of the calls is between 7 and 31 seconds. These delays are seen to be substantial. Considering that average visibility duration to a Globalstar satellite spotbeam is about 4 minutes, and that the average remaining connectivity is half this, then the problem of a loss of connectivity occurring at the originating end of the call becomes a real possibility. Since the user-termination end of the call only gets involved a bit after half way then the probability of a loss of connectivity at that end of the call is lower. The use of late traffic channel assignment is again called into question when these figures are
considered. The delay performance for a user-to-user call when the random access channel is operating with a lower delay performance is shown in figure 7.15.

For this improved random access channel performance, the average delay is reduced to 10 seconds (compared to 13 seconds). The delay spread 99% maximum is reduced from 31 seconds to 17.5 seconds, which is a lot better. Even with this improved performance, call setup delays are still longer than users are accustomed too, so users may need to be made aware of this fact on subscription (otherwise they are likely to discontinue to call attempt). Apart from loss of spotbeam connectivity, the actual delay required in order to setup these calls is of specific concern. However, considering the low percentage of such call that are likely, this may be acceptable due to its infrequent occurrence.

7.3.3.2 MEO Results
The MEO simulation results for user-to-user call setup are presented below in figure 7.16.
The shape of the distribution is similar to the LEO case and is again the result of the two random access channels acting in serial. The average delay for the above distribution is about 15 seconds. This is in line with the LEO results due to the larger propagation delays which are involved at both ends of the simulation. Because of the longer visibility period between a UT and a spotbeam of a MEO satellite, the probability of a connectivity change occurring during such a signalling procedure is much lower than for a LEO constellation. This problem can be ignored for MEO constellations. Figure 7.17 below indicates the delay distribution for 99% of calls when the lower delay random access channel is used in the simulation.
In this case, the average delay for call setup has reduced to about 10.5 seconds. This is an improvement of about 4.5 seconds compared with the simulation results indicated in figure 7.16 where a higher delay random access channel was simulated.

7.4 MAGSS-14 Power Requirement

Similarly to what was done in chapter 6 concerning the peak power requirement of mobility management signalling, the peak power requirement of call setup signalling is considered in this section. The peak MAGSS-14 call setup rate was estimated as 0.6 calls per spotbeam per second (chapter 5). The call setup bit requirement, based on tables 7/1 and 7/2 are 2460 (user-orig,) and 2580 (user-term.) bits. 50% of calls are assumed to be user-originated and handheld terminals are assumed to make up half of the terminals. Based on this, table 7/3 indicates the breakdown in terms of satellite transmit power required.

<table>
<thead>
<tr>
<th>Type</th>
<th>Channel Rates</th>
<th>Voice Equivalent Power Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handheld, User-orig.</td>
<td>240/.1200</td>
<td>1.05 + 1.84 seconds</td>
</tr>
<tr>
<td>Other, User-orig.</td>
<td>1200/.</td>
<td>0.21 + 1.84 seconds</td>
</tr>
<tr>
<td>Handheld, User-term.</td>
<td>240/.</td>
<td>10.75 seconds</td>
</tr>
<tr>
<td>Other, User-term.</td>
<td>240/.1200</td>
<td>1.55 + 1.84 seconds</td>
</tr>
</tbody>
</table>

*Table 7/3 - MAGSS-14 Peak Call Setup Rates*

The average duration relating to satellite power consumption is the average of the above voice equivalent power requirement totals multiplied by the actual call rate. User originated calls require 4.94 equivalent transmit power seconds but occur at a rate of 0.3 calls per spotbeam per second. This results in a voice equivalent power requirement of 1,482 channels. For user-terminated calls the voice equivalent power requirement is 4,242 channels. The combined total is 5,724 channels. This means that at peak call setup rates, the satellite spotbeam power used for signalling channels is the equivalent of almost 6 voice channels. This total is increased further due to the percentage of calls that are unduly terminated due to spotbeam connectivity loss. This increase is, predictably, most significant for LEO constellations.

Since it is possible for both call setup and mobility management signalling to peak at the same time, then the combined total should be considered. Even with the optimum mobility management approach based on the use of a positioning system, the total power required in the spotbeam is the equivalent of 11.574 (5.85 + 5.724) voice channels. This total should also be increased by approximately the same percentage as signalling procedures that have failed.
7.5 Conclusions

For each call type considered and based on LAPDm messages and signalling sequences specially modified for S-PCN compatibility, the average call setup delay and the call setup delay distribution were found by simulation. Different channel rates and random access channel success probabilities were compared.

The main conclusion that can be drawn from the simulation results obtained concerns the long call setup delays which occur. Of the two main call types, user-terminated call setup is seen to be most severely affected - due to the low bit rates which are used. The possibility of the system providing two different signalling bit rates for common and dedicated control channels would be a distinct advantage. Terminals could then choose the higher rate when possible and the lower rate otherwise. This would help reduce signalling delay which is of specific importance here due to its direct influence on user satisfaction with the system. Another very important factor which is very relevant here concerns the random access channel delay performance. These channels need to be operated at low throughput and low delay. S-PCN systems will probably need to offer multiple random access channels per spotbeam in order to ensure this low delay performance.

A consequence of the long signalling duration was particularly noticeable for LEO constellations. The probability of a connectivity change during a signalling procedure was found to be high for the Globalstar constellation. This results in a signalling break since SDCCH/s channel handover between spotbeams is not provided. For the lower altitude Iridium constellation with higher spotbeam numbers per satellite, this problem is even more noticeable. Another factor which increases the likelihood of a signalling connection loss is the additional link waiting time due to the ‘ringing’ delay of the destination terminal. This is not relevant to mobility management signalling.

All signalling procedures blocked in this way need to initiate a new procedure in the spotbeam to which they have ‘moved’. The probability of this occurring depends on the average signalling procedure duration and the average initial connectivity duration between a UT and a spotbeam. The direct consequence of such an occurrence would be an increase in the average signalling delay as perceived by system users. Since the original signalling procedures is deemed to have failed, a new procedure must be initiated. This results in an increase in the network signalling loading which is directly proportional to the probability of a signalling procedure failure. This results in an approximately equivalent percentage increase in the actual power required by system signalling channels.

A final consideration concerns the approach to call setup and whether early or late channel assignment should be used. Both suffer from the above problem of signalling connectivity loss. For early traffic channel assignment, the dropping probability is reduced since the traffic channel could be handed over to a preferred satellite spotbeam at any stage after it was allocated. In this case the extra ‘ringing’ delay is not relevant. With late channel assignment, overall system efficiency is improved due to the reduced channel holding time. This improvement is uniquely relevant at times of peak traffic channel demand - at low traffic levels the loss in efficiency is not important as spare capacity still exists. The inconvenience of late assignment is in the form of the initial silent period of around 0.5 seconds after the call has been answered. The final choice involves more than just technical considerations.
Overall, MEO constellations suffer from fewer signalling channel difficulties than LEO constellations, a pure consequence of satellite dynamics and system connectivities. On a less positive note, the average MEO signalling delay is unavoidably longer than the average LEO delay by about 1 second - due to the higher propagation delay.

References


[Mouly] 'The GSM System for Mobile Communications', M. Mouly, M. Pautet. Published by the Authors, France, 1992


Chapter 8  Conclusions and Future Work

The work in this thesis has examined many aspects concerning the operation of satellite personal communication networks. The idea for S-PCN systems was first proposed in 1991, with the Iridium proposal. At least three S-PCN networks are likely to be offering world-wide mobile communication services to users of handheld mobile (and probably fixed!) terminals before the end of this decade. These systems are currently at the definition and specification stage. Now that spectrum has been allocated to three different systems (January 1995), development work is likely to progress at a rapid pace. The conclusions and observations resulting from the work presented in this thesis are considered very relevant to these and future systems.

The fundamental properties and the design of LEO and MEO satellite constellations were initially considered. This was followed by a proposal concerning a control architecture and operational review for these systems, which took into account the peculiarities introduced by satellite dynamics. Mobility management and call setup air-interface signalling aspects were then examined and simulation models were built of the signalling flows, allowing the signalling delay to be estimated for different procedures and under different operating circumstances. A new mobility management approach was proposed and is seen to compare very favourably with other approaches considered. Important implications on the call setup approach were noticed from the signalling delay results obtained. Finally, the implications of signalling channels in terms of satellite power requirement were examined.

The main aspects resulting from this work are now reviewed. At the same time, consideration is also given to areas which require further specific work. The review is broken into two parts. The first concerns constellation and architecture aspects, the second part considers air-interface signalling implications.

8.1 Constellations and Architecture

The type of constellation used is seen to have an important influence on the overall system. Both air-interface and network control aspects are affected. Clearly, all three aspects need to be optimised together, rather than individually, in order to produce a coherent proposal. Questions concerning satellite and constellation coverage, constellation service area and space segment to ground segment connectivity are all relevant to the choice of S-PCN architecture ground segment. Aspects such as Doppler shift, propagation delay variation, minimum coverage elevation angle and whether to provide satellite link diversity are fundamental to the design of the air-interface. The air-interface approach adopted also affects the S-PCN architecture - for example earth station visibility requirements if satellite diversity is to be used. Many other factors are also relevant in the trade-off. In all cases, the final output requirement is the capability to provide sufficiently high numbers of high quality voice and data communication channels.

Since its initial proposal, the Iridium constellation was updated but it still provides global coverage (with best coverage in the polar regions). Globalstar provides dual satellite diversity in the 30° to 60° mid-latitude region. In lower latitudes dual diversity is not provided and so service quality may drop in these regions. Both LEO constellations operate down to user elevation angles of around 10° which means that worst case link impairments are likely to be quite severe. The low altitudes used
reduce the link power requirement but larger numbers of satellites need to be built and launched.

The Odyssey constellation switched from its original non-resonant altitude to the 10,354 km ‘resonant’ altitude, without effecting its 19° minimum (single satellite visibility) elevation angle to users. MAGSS-14, originally proposed at the resonant altitude, uses 2 extra satellites and provides single satellite visibility above 28.5°. The Inmarsat-P proposal uses a constellation of 10 satellites to provide dual satellite visibility to users down to an elevation angle of about 10°. All three MEO constellations are inclined in order to offer improved mid-latitude coverage. Fewer satellite numbers are needed and higher elevation angles can be offered but free space loss is almost 10 dBs more than for LEO constellations.

The above range of constellation types indicates the fact that optimum constellations are only optimum according to the goals set. In fact, results in this thesis do not propose one constellation type as being favourable over the other. In this light, constellation designs may further evolve as both air interface and ground segment functionality is clarified in greater detail. It might even be suggested that, following a more detailed look at S-PCN air interface and architectural aspects, a modified set of goals should be used, resulting in a new constellation definition. With this in mind, a new 64 satellite LEO constellation, called Deligo, was specified and designed with a unique combination of coverage properties. Satellite ground tracks are repetitive but with a period slightly less than a day. This still provides the constellation with resonant-like ground segment to space segment connectivity advantages. Its coverage is concentrated in the regions where traffic demand is expected to be highest and at least two satellites are visible to users within the whole service region.

Constellation dynamics is seen to result in important differences between satellite and terrestrial mobile communication networks - unlike terrestrial systems, connectivity between network control nodes is a variable factor for S-PCN systems. The use of resonant orbits reduces the variation in constellation connectivity by providing each satellite with a repetitive ground track. This results in network advantages in terms of simplified planning for network control and traffic management.

Before a S-PCN architecture was proposed all these constellation connectivity aspects needed to be considered. With the proposed architecture, individual satellites are fully controlled at any one time, by an individual Gateway Earth Station. This results in the centralised control of individual satellites. Network control is distributed globally among these GESs, which are responsible for overall network resource management. A second type of earth station - Traffic Earth Stations - were also proposed. These carry traffic channels but have no network management role. Control structures for other S-PCN proposals have probably been devised but have not been publicly released. The above architecture is applicable to other S-PCN proposals (although less so for the Iridium constellation, which uses OBP and ISLs).

Depending on whether LEO or MEO constellations are used, the ratio between GES and TES earth stations changes markedly. For a transparent MEO constellation, between 10 and 15 GESs are sufficient in order to provide a fully redundant level of network control. TESs can be introduced as necessary in order to improve network connectivity in certain regions. For a transparent LEO constellation, a much higher number of GESs are required due to the smaller satellite coverage area. For Globalstar, about 50 GESs would be needed to provide a basic level of network
connectivity. Considering this, LEO ground segment costs are likely to be higher than for MEO constellations. Because of the higher GES density, fewer TES are likely to be required.

Another aspect concerning the ground segment relates to the protocols which might be used between the different nodes. GSM protocols were proposed as the baseline because they provide a similar set of functionalities. These protocols were mapped onto the equivalent interface in the S-PCN system. In some cases, this mapping is straightforward. However, because of the different network control structure of the S-PCN architecture, the S-PCN equivalents of the A and E interfaces (the A' and E' interfaces) were found to require different functionalities and so more substantial modifications are needed here. It was noted that a combination of A, Aсл and E interface functionalities were appropriate for GES-to-GES interfaces. An extra functionality is required in order to provide for GES to GES satellite control handover. For the GES-to-TES interface, a subset of A and Aсл capabilities are necessary in order to provide the required call management and traffic allocation capability.

Further aspects of the proposed architecture were not considered in this thesis. This is clearly an area in which further work is required before a final set of S-PCN modified, MAP protocol functionality is proposed. The final functionality must be made compatible with the envisaged air interface. Network functionality can then be simulated and verified through the construction of an overall network model.

Specific S-PCN differences were highlighted in the areas of frequency management and route optimisation. Of these, frequency management presents the most difficult and pressing set of problems. Further work in this area is essential in order to initially define the problem in a complete way and, according to the different possible scenarios, to look at optimum solutions to these problems. Providing S-PCN coverage flexibility while ensuring a maximum level of coverage continuity is fundamental to the efficient working of S-PCN systems.

8.2 Air Interface Signalling

Mobility management and call setup air interface signalling aspects are reviewed in this section. The new mobility management approach proposed was seen to compare very favourably with other options being considered in terms of the signalling requirement. The need for each UT to be able to measure its location is a requirement but it also allows positional and navigational services to be offered. A disadvantage is that the UT cost and bulk will increase due to the extra functionality which must be provided.

The LAPDm messages sent on these common and dedicated control channels were examined and possible S-PCN equivalents were proposed - down to the level of individual message information elements. As constellation functionality is further defined and specified, then information elements will have to be defined down to the bit level. Actual, rather than estimated, message lengths can then be used. Although it may be too early at this stage, constellation specific work will need to be done in this area in the near future.

Another aspect which affected simulations concerned the channel bit rates and the channel coding approach used. The channel rate assumptions of 240 b/s and 1.2 kb/s
are due to the increased margin required for these signalling channels. The low rates used are seen to result in an important contribution to signalling procedure delays. Although higher channel rates are clearly desirable, an alternative where channel margins are insufficient to provide effective service access cannot be allowed. The problem of a lack of user link co-operation and the lack of available space segment power has a very big influence on the channel rates used. When the access method, the level of user co-operation and the required link margin are fully specified, then the bit rates of the channels can be deduced according to the link budget.

Another point here concerns the trade-off between the allowable channel bit error rate and the use of ARQ over the SDCCH/s channels. This specific question is one which needs to be evaluated. The trade-off concerns the channel BER, the propagation delay, the message length and orthogonality and the expected processing time at both ends of the air-interface. Based on the results, the channel link margin and coding approach can be optimised. The big performance difference between channels with or without link co-operation is likely to result in two sets of signalling channel rates. Because of this it will be necessary to optimise the ARQ approach for both channel types.

Based on ground segment performance estimations, the processing delays used in the simulation at the GES can be modified. In cases where the relevant databases are local to the GES then reductions in the delay should be achievable. In other cases where the contacted GES is not local to the UTs databases, the delay range and distribution may need to be modified upwards. TES and UT processing delays are also likely to be known more accurately as their operation is further specified.

Average signalling delay durations, based on the simulation results and the system operation assumptions made, were found to be high. The random access channel was seen to be the most important single contribution to system delay performance. Even for stable random access channels operating near peak throughput, the resulting delay performance for call setup signalling is likely to be unsatisfactory to some users. It is clearly preferable and probably even necessary to use a high number of low throughput random access channels in order to improve system delay performance. This effects the amount of bandwidth required by the system for signalling channels and may in turn reduce the number of available traffic channels.

A clear difference was noticed between LEO and MEO constellations in terms of signalling performance. The short connectivity duration between LEO spotbeams and UTs, combined with the relatively long average duration - for both mobility management and, especially, call setup signalling - is seen to result in a fairly high proportion of signalling procedure failures due to link loss. This applies to both mobility management and call setup signalling but is a more serious problem in the latter case because of the extra link holding time which results from the destination number 'ringing' delay.

The two types of traffic channel assignment were examined and some difficulties were highlighted with each approach. Late assignment offered network efficiency gains but the problems with signalling procedure failures were increased. Two approaches might be used to overcome this problem - providing for SDCCH/s channel inter spotbeam handover or allowing the GES to measure the UTs location and, depending on the connectivity time left with the spotbeam, to allocate the traffic channel immediately and then allowing traffic channel handover to occur normally. Early assignment, which reduced the efficiency of traffic channel usage, is also
affected by this problem but the call could probably continue since the traffic channel could be handed over to a new spotbeam. However, the SDCCH/s channel protocol handshake is not completed via the original spotbeam. It may be preferable to provide the traffic channel associated signalling channels with the capability of completing the handshake, via a TES. Specific LAPDm and MAP protocol modifications would be required in this case.

For MEO constellations, the higher average spotbeam connectivity duration resulted in a much lower signalling procedure termination probability. However, it is still a problem for MEO systems. The effect of dropped signalling channels is to increase the average signalling duration and also to increase the actual signalling procedure arrival rate since failed procedures will obviously need to be reattempted. The signalling channel power requirement also increases accordingly. In general MEO constellations were less affected by space segment dynamics than LEO constellations.
Annex A - S-PCN Mobility Management Signalling

This annex describes the messages and message content used for mobility management signalling over the radio interface. It is based on the GSM's LAPDM network layer (ISO Layer 3) protocol message content. The main function of the MM-sublayer (Mobility Management) is to support the mobility of UTs and provide user confidentiality. All the MM-procedures in this section are performed after a RR-connection (Radio Resource) has been established between the UT and the network. The MM-sublayer provides connection management services to the different entities of the upper CM (Connection Management) sublayer (GSM 04.07).

Before the specific messages are described, an introduction to the general format of LAPDM messages is provided. LAPDM messages are made up of four types of information elements. Information elements are classified by their length and on whether they are mandatory or optional. These elements are distinguished as follows and their order of appearance within a message is as listed:

MF. A mandatory information element with fixed length. Its length is determined by the protocol discriminator and message type of that message.

MV. A mandatory information element with variable length. Its length is determined by the Length Indicator (LI) which is the first octet of the information element.

OF. An optional information element with fixed length. Its presence is included in the Information Element Identifier (IEI) which is in the first part of the information element.

OV. An optional information element with variable length. Its presence is included in the IEI (usually the first octet) and its length indicated in the LI (usually the second octet).

Annex A.1 S-PCN Mobility Management Message Content

The individual messages involved in LAPDM based S-PCN mobility management signalling are now considered. GSM messages are examined down to the level of individual information elements. Based on this, equivalent S-PCN information elements are proposed, allowing the length of the specific messages to be estimated. Message differences between the two systems are not on a large scale. However, differences in message elements will exist due to system differences. Considering mobility management specifically, such differences are in terms of signalling channel identity and mobility management implementation. These differences are highlighted in the specific message and information element analysis that follows. The successful mobility management signalling procedure has been described in Chapter 6. The UT is initially considered to be in idle mode where it listens to the BCCH/s and the PCH/s channel. The UT also measures BCCH/s channel strengths in adjacent spotbeams.

\[1\] BCCH/s channel information consists of the following - GES identity, spotbeam identity, information on cell selection for handover, a description of current control channel structure, information controlling RACH/s utilisation and information defining different options within the cell. The GES is required to send valid layer 3 messages continuously on the PCH/s.
A.1.1 Channel Request (RACH/s)

This message [GSM 04.08 / 9.1.8] is sent on the RACH/s channel from the UT to the GES. Its GSM equivalent is only one octet long. The following table compares the GSM message content with the proposed S-PCN content. As indicated in the table, a similar message length of 1 octet is considered for S-PCN use.

<table>
<thead>
<tr>
<th>Information Element</th>
<th>GSM Length</th>
<th>S-PCN Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random Reference</td>
<td>Bits 1 to 5</td>
<td>Bits 1 to 5</td>
</tr>
<tr>
<td>Establishment Cause</td>
<td>Bits 6 to 8</td>
<td>Bits 6 to 8</td>
</tr>
</tbody>
</table>

Table A/1 - Channel Request Bit Requirement

A.1.2 Immediate Assignment (AGCH/s)

This message [GSM 04.08 / 9.1.17] is sent on the AGCH/s channel from the GES to the UT. Its GSM equivalent is between 19 and 27 octets long. The following table compares the GSM message content with the proposed S-PCN content. S-PCN modifications are indicated with an ‘*’ symbol.

<table>
<thead>
<tr>
<th>Information Element</th>
<th>GSM Length</th>
<th>S-PCN Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Transaction Identifier / Message Type (MF)</td>
<td>1 + 1</td>
<td>1</td>
</tr>
<tr>
<td>Page Mode (MF)</td>
<td>1 + 3</td>
<td>1 + 1*</td>
</tr>
<tr>
<td>Channel Description (MF)</td>
<td>1 + 3</td>
<td>1*</td>
</tr>
<tr>
<td>Request Reference (MF)</td>
<td>1 + 1</td>
<td>0*</td>
</tr>
<tr>
<td>Mobile Allocation (MF)</td>
<td>1 + 1.. 9</td>
<td>0*</td>
</tr>
<tr>
<td>Starting Time (OF)</td>
<td>1 + 3</td>
<td>0*</td>
</tr>
</tbody>
</table>

Table A/2 - Immediate Assignment Bit Requirement

The S-PCN bit requirement is estimated as 6 octets, resulting in the transmission of 120 bits after half-rate coding and the addition of 24 synchronisation bits. Those information elements for which changes have been indicated are now further examined.

Channel Description. This information element provides a description of the allocated channel - see GSM 04.08 / 10.5.2.5. For S-PCN it is considered that signalling channels are directly associated with the BCCH/s. Therefore, a 2 octet message should suffice in order to identify the SDCCH/s channel to be used.

Request Reference. This information element references the original information contained in the UTs Channel Request message as well as the channel on which it was received - see GSM 04.08 / 10.5.2.18. For S-PCN, it is proposed to have specific RACH/s channels for specific purposes in order to reduce RACH/s delay. In this case, the 'cause' element of the 1 octet Channel Request message should suffice.

Timing Advance. This information element provides the timing advance for use of the SDCCH/s channel - see GSM 04.08 / 10.5.2.18. For S-PCN, the need for a timing
advance depends on whether TDMA or CDMA is used. For MAGSS-14 and Globalstar, CDMA is used so a standard value can be used for all cases.

**Mobile Allocation.** This information element specifically provides the hopping sequence of the allocated channel. With fixed frequency allocation this element is empty, otherwise see GSM 04.08 / 10.5.2.12 for the GSM bit definition. For S-PCN the element is considered empty since frequency hopping would not be used for these CDMA based systems.

**Starting Time.** This information element only appears if a frequency change is in progress. It is used to provide the start TDMA frame number - see GSM 04.08 / 10.5.2.20 for the GSM bit definition. For the CDMA systems considered here it is not considered necessary.

### A.1.3 Location Updating Request

This message [GSM 04.08 / 9.2.13] is sent by the UT to the GES on the newly allocated SDCCH/s channel. Its GSM equivalent is between 13 and 19 octets long. The following table compares the GSM message content with the proposed S-PCN content. S-PCN modifications are indicated with an "*" symbol.

<table>
<thead>
<tr>
<th>Information Element</th>
<th>GSM Length</th>
<th>S-PCN Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Transaction Identifier / Message Type (MF)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Location Updating Type (MF)</td>
<td>1/2 + 1/2</td>
<td>0*</td>
</tr>
<tr>
<td>Ciphering Key Sequence Number (MF)</td>
<td>1/2 + 1/2</td>
<td>0*</td>
</tr>
<tr>
<td>Location Area Identification (MF)</td>
<td>1 + 5</td>
<td>4*</td>
</tr>
<tr>
<td>Mobile Station Classmark 1 (MF)</td>
<td>1 + 1</td>
<td>1/2 + 1/2*</td>
</tr>
<tr>
<td>Mobile Identity (MV)</td>
<td>1 + 1...9</td>
<td>1 + 4*</td>
</tr>
</tbody>
</table>

*Table A/3 - Location Updating Request Bit Requirement*

The S-PCN bit requirement is estimated as 12 octets, resulting in the transmission of 216 bits after half-rate coding and the addition of 24 synchronisation bits. Those Information elements for which changes have been indicated are now examined.

**Location Updating Type.** This information element indicates to the GES the type of location update being performed - see GSM 04.08 / 10.5.3.5. For S-PCN location updating no distinction is required so no bits are used.

**Ciphering Key Sequence Number.** This information element allows exchange of the ciphering key, Kc, without the need for authentication - see GSM 04.08 / 10.5.1.2. For the S-PCN signalling exchange being considered here, authentication is used so this information element is used in a later message.

**Location Area Identification.** This information element provides an unambiguous identification of a UT's location area - see GSM 04.08 / 10.5.1.3. According to the S-PCN mobility management approach chosen in chapter 6, this is in the form of the
UTs latitude and longitude co-ordinates. Considering that a positional accuracy in the range of 10s of km is sufficiently accurate for uncertainty radii in the order of 100s of km, then eight significant figures can specify the UTs address. To provide its location with this accuracy requires a bit message of length 32 bits.

**Mobile Station Classmark 1.** This information element informs the network on high priority UT operational parameters - see GSM 04.08 / 10.5.1.5. For S-PCN only the RF power capability is assumed to be transmitted at this stage, resulting in a total requirement of 1 octet.

**Mobile Identity.** This information element provides the network with one of three possible UT identities: IMSI/s, TMSI/s or IMEI/s - see GSM 04.08 / 10.5.1.4. For S-PCN the shorter (4 octets) TMSI/s identity rather than the IMSI/s identity (15 digits) is proposed, resulting in a final requirement of 5 octets.

**A.1.4 Authentication Request (SDCCH/s)**

This message [GSM 04.08 / 9.2.2] is sent on the SDCCH/s channel from the GES to the UT to initiate authentication of the UTs identity. Its GSM equivalent is 20 octets long. The following table compares the GSM message content with the proposed S-PCN content. S-PCN modifications are indicated with an ‘*’ symbol.

<table>
<thead>
<tr>
<th>Information Element</th>
<th>GSM Length</th>
<th>S-PCN Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Message Type (MF)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Ciphering Key Sequence Number (MF)</td>
<td>1/2 + 1/2</td>
<td>1/2 + 1/2*</td>
</tr>
<tr>
<td>Authentication Parameter RAND (MF)</td>
<td>1 + 16</td>
<td>1 + 4*</td>
</tr>
</tbody>
</table>

Table A/4 - Authentication Request Bit Requirement

The S-PCN bit requirement is estimated as 8 octets, resulting in the final transmission of 152 bits. As indicated in the table, the following changes are proposed for S-PCN use.

**Ciphering Key Sequence Number.** This information element allows exchange of the Ciphering key, Kc - see GSM 04.08 / 10.5.1.2. For the S-PCN signalling sequence described it is included here and requires 1 octet.

**Authentication Parameter RAND.** This information element provides the UT with a non-predictable number (challenge) to be used by the UT to calculate the Authentication Response signature ‘SRES’ and the ciphering key ‘Kc’ - see GSM 04.08 / 10.5.3.1. For S-PCN the length of the RAND parameter is reduced from 128

---

2 One nautical mile is defined as one minute of one degree along the equator. This distance is equivalent to 1.85 km. For a positional accuracy in the order of 10s of km only the first decimal point is necessary. The following format is used: [latitude, longitude] with 0.0 < latitude < 180.0 and 0.0 < longitude < 360.0.
bits (16 octets) to 32 bits (4 octets). This is considered allowable once the RAND ⇔ SRES algorithm is modified.

A.1.5 Authentication Response

This message [GSM 04.08 / 9.2.3] is sent on the SDCCH/s channel from the UT to the GES to deliver a calculated response to the Authentication Request message. Its GSM equivalent is 7 octets long. The following table compares the GSM message content with the proposed S-PCN content. S-PCN modifications are indicated with an "***" symbol.

<table>
<thead>
<tr>
<th>Information Element</th>
<th>GSM Length</th>
<th>S-PCN Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Transaction Identifier / Message Type (MF)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Authentication Parameter SRES (MF)</td>
<td>1 + 4</td>
<td>1 + 3***</td>
</tr>
</tbody>
</table>

*Table A/5 - Authentication Response Bit Requirement*

The S-PCN bit requirement is estimated as 6 octets, resulting in the final transmission of 120 bits. The following changes are proposed for S-PCN use.

Authentication Parameter SRES. This information element provides the GES with a calculated authentication response signature - see GSM 04.08 / 10.5.3.2. For S-PCN the length of the SRES parameter is reduced from 32 bits (4 octets) to 24 bits (3 octets). This change must be incorporated into the modified RAND ⇔ SRES algorithm.

A.1.6 Ciphering Mode Command

This message [GSM 04.08 / 9.1.9] is sent on the SDCCH/s channel from the GES to the UT to indicate to the network that the GES has started deciphering and that enciphering and deciphering should be started in the UT, or to indicate that ciphering will not be performed. Its GSM equivalent is 3 octets long. The following table compares the GSM message content with the proposed S-PCN content. No S-PCN modifications are proposed here.

<table>
<thead>
<tr>
<th>Information Element</th>
<th>GSM Length</th>
<th>S-PCN Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Transaction Identifier / Message Type (MF)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Cipher Mode Setting (MF)</td>
<td>1/2 + 1/2</td>
<td>1/2 + 1/2</td>
</tr>
</tbody>
</table>

*Table A/6 - Ciphering Mode Command Bit Requirement*

A.1.7 Ciphering Mode Complete

This message [GSM 04.08 / 9.1.10] is sent on the SDCCH/s channel from the UT to the GES to indicate that the enciphering and deciphering has been started in the UT, or to acknowledge it is not being used. Its GSM equivalent is 2 octets long. The
following table compares the GSM message content with the proposed S-PCN content. No S-PCN modifications are proposed here.

<table>
<thead>
<tr>
<th>Information Element</th>
<th>GSM Length</th>
<th>S-PCN Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Transaction Identifier / Message Type</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

*Table A/7 - Ciphering Mode Complete Bit Requirement*

**A.1.8 Location Updating Accept**

This message [GSM 04.08 / 9.2.11] is sent on the SDCCH/s channel from the GES to the UT to indicate that updating or IMSI attach in the network has been completed. Its GSM equivalent length is between 11 and 21 octets. The following table compares the GSM message content with the proposed S-PCN content. S-PCN modifications are indicated with an '*' symbol.

<table>
<thead>
<tr>
<th>Information Element</th>
<th>GSM Length</th>
<th>S-PCN Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Transaction Identifier / Message Type</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Location Area Identification</td>
<td>1 + 5</td>
<td>4*</td>
</tr>
<tr>
<td>Mobile Identity</td>
<td>1 + 2 .. 10</td>
<td>1 + 4*</td>
</tr>
</tbody>
</table>

*Table A/8 - Location Updating Accept Bit Requirement*

The S-PCN bit requirement is estimated as 11 octets, resulting in the transmission of 200 bits after half-rate coding and the addition of 24 synchronisation bits.

**Location Area Identification.** See annex A.1.3.

**Mobile Identity.** See annex A.1.3.

**A.1.9 TMSI Reallocation Complete**

This message [GSM 04.08 / 9.2.15] is sent on the SDCCH/s channel from the UT to the GES to indicate that reallocation of the IMSI/s has been completed. Its GSM equivalent is 2 octets long. The following table compares the GSM message content with the proposed S-PCN content. No S-PCN modifications are proposed here.

<table>
<thead>
<tr>
<th>Information Element</th>
<th>GSM Length</th>
<th>S-PCN Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Transaction Identifier / Message Type</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

*Table A/9 - TMSI Reallocation Complete Bit Requirement*

**A.1.10 Channel Release**

This message [GSM 04.08 / 9.1.7] is sent on the SDCCH/s channel from the GES to the UT to initiate deactivation of the SDCCH/s channel used. Its GSM length is 4 octets long. The following table compares the GSM message content with the proposed S-PCN content.
<table>
<thead>
<tr>
<th>Information Element</th>
<th>GSM Length</th>
<th>S-PCN Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Transaction Identifier / Message Type</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>RR Cause</td>
<td>1 + 1</td>
<td>1/2 + 1/2</td>
</tr>
</tbody>
</table>

*Table A/10 - Channel Release Bit Requirement*

The S-PCN bit requirement is estimated as 3 octets, resulting in the final transmission of 120 bits. The following change is proposed for S-PCN use.

**RR Cause.** This information element provides the reason for channel release - see GSM 04.08 / 10.5.2.10. Since only 13 causes are used, then it should be possible to reduce the bit requirement here to just 1 octet.
A.2 Mobility Management BONeS Simulation Model

The simulation model built for analysis of the S-PCN mobility management signalling delay performance is explained here. The model was built on the BONeS Designer network simulation tool - Comdisco Systems Inc, Foster City, California. The mobility management signalling sequence described in chapter 6 was built using a modular approach. In each of the modules, parameters were created to provide the system with flexibility so that changes to simulation parameters could be done via the input file. To distinguish between LEO and MEO simulations a pair of constants - maximum propagation delay and minimum propagation delay - need to be set within the first system sub-module. Figure A.1 below indicates the overall simulation model used and the parameters associated with the mobility management simulation.

![Figure A.1 - Mobility Management Simulation Model](image)

The sub-module components are now explained.

2 rach part. This sub-module simulates the performance of the S-PCN random access channel through the parameter ‘P (success)’ - the success probability of a random access request. The ‘P mean interarrival time’ parameter is used in conjunction with the standard internal simulation parameter ‘TSTOP’ and allows the number of procedures simulated to be controlled.

The next four parameters in the first module - ‘P rach bits’, ‘P bit duration (s) rach’, ‘P agch bits’ and ‘P bit duration (s) agch’ - concern either the message bit requirement or a signalling channel rate. All parameters indicated by the ‘P’ symbol are passed to the simulation through an input file at the start of simulation providing a high level of system flexibility.

The final parameter indicated in the first module is a memory based parameter - ‘QM one hop’. This concerns the propagation delay used for the UT-to-satellite-to-GES hop in individual simulated procedures. At the start of each simulated procedure, the hop delay is randomly chosen from within a specific delay range and remains constant through that signalling transaction. The delay ranges involved are set through specific constants (set according to the constellation type being modelled) within the first module. Figure A.2 indicates a further level of design detail within the ‘2 rach part’ block indicated in figure A.1.
The sub-module shown in figure A.2 is now explained. Each procedure simulated originates from the sub-module ‘1 traffic and hop’. The data packet which is transmitted is created in this sub-module - it is given a field in which the time delay it has experienced so far within the system is stored. Other fields for monitoring the number of random access attempts and the paging channel requirement were also created. The simulation parameter ‘P mean interarrival time’ is created to provide control over the number of procedures simulated. This parameter is incremented for each data packet sent (i.e. each procedure simulated). When it reaches the global simulation parameter ‘TSTOP’ (part of the input file) no further procedures are transmitted and the simulation is complete. The internal memory parameter ‘M one hop’ is also calculated in this sub-module, based on the maximum and minimum propagation delays of the constellation being modelled. Figure A.3 shows the internal detail within sub-module ‘1 traffic and hop’.

The data packet is then forwarded to the ‘2 rach channel’ sub-module. This sub-module, in conjunction with the ‘3 fail delay’ sub-module, is where the random access channel is modelled. The ‘P (success)’ parameter, the probability that a random access request is successful, is read from the simulation input file. Successful data packets are delayed (in the subsequent ‘4. succ delay’ module) by an appropriate amount, which depends on the packet delay (‘P rach bits’ and ‘P bit duration (s) rach’ parameters) and on the propagation delay between the UT and the GES. This propagation delay was written to memory in the ‘M one hop’ parameter of the
previous sub-module and so, when used in the future, must be read from memory. No processing delay is included at this stage as the start time is considered to be the moment the first bit is transmitted. Figure A.4 shows the internal detail within sub-module '2 rach channel'.

Data packets which fail over the random access channel are delayed in the '3 fail delay' sub-module. The delay is the addition of the maximum response delay and (once the UT realises that no GES response is forthcoming) a random, uniformly distributed, backoff delay. Since a slotted ALOHA channel is assumed, the backoff delay is an integer number (between 1 and 10) of random access channel slot durations. The slot duration depends on the message packet delay (the 'TP rach bits' and 'TP bit duration (s) rach' parameters) and the extra guard time delay within each slot. For the MEO constellation a value of 4 ms is required while for the LEO constellation, a value of 2 ms is sufficient. The increment in the number of RACH/s channel iterations is also done in this sub-module. After being so delayed, the data packet is passed again to the '2 rach channel' sub-module. Figure A.5 shows the internal detail within sub-module '3 fail delay'.

After successfully completing the random access channel (and being delayed by a random amount), the data packet is passed to the '4. succ delay' sub-module. Here the GESs AGCH/s channel reply is modelled. The delay is comprised of three components - the GES processing delay (before it starts to reply to the UT), the propagation delay between the GES and the UT and the message packet delay. The message packet delay depends on the two parameters indicated - 'TP agch bits' (the number of bits in the access grant channel message) and 'TP bit duration (s) agch'.
(the AGCH/s channel bit rate). The data packet is then passed on to the '3.1 loc upd req ut->n’ module indicated in figure A.1. Figure A.6 shows the first level of internal detail within sub-module ‘4. succ delay’. Further detail on Sub-module ‘4.2.1 slotlength’ is not shown.

**Figure A.6 - '4. succ delay' Sub-module Detail**

**3.1 loc upd req ut->n**. This module delays the data packet in the three different ways already described - processing delay, packet delay and propagation delay (in that order). The inside detail of this module is indicated in figure A.7 below.

**Figure A.7 - '3.1 loc upd req ut->n' Sub-module**

The processing delay is chosen from a uniform distribution between 25 ms and 250 ms and is then added to the time stamp field of the 'data packet'. Then the input file parameters 'TP loc upd req' and 'TP bit duration (s) sdcch' are used to calculate the packet duration. Finally, the one hop propagation delay, previously written to memory, is now recalled and added to the time stamp field of the 'data packet'.

**3.2 auth et ciph, 3.3 loc upd acc n->ut, 4.1 TMSI realloc and 4.2 chan rel n->ut**. These four sub-models all act in a similar way to the above sub-module but according to the specific input file parameters associated with them. The main parameter for each of these sub-modules is the 'TP bit duration (s) sdcch' which determines the channel bit rate used in the simulation. The other input file parameters - 'TP loc upd req', 'TP auth req', 'TP auth res', 'TP ciph mod cmd', 'TP ciph mod com', 'TP loc upd acc', 'TP TMSI re-al comp' and 'TP chan rel' - determine the number of bits in the relevant message that is transmitted. The values used for this S-PCN simulation have been deduced and indicated in Annex A.1.

Further detail on the simulation model is not provided here. However, the main models and the simulation mechanism have been explained so that the signalling flow...
is understood. Further detail can be found by directly examining the simulation model in the BONeS environment.

**Results.** Simulation results are obtained through using specific data collecting probes at the simulation output. These probes are set to read and compare specific fields within the simulation data packet. Based on these, the average signalling delay could be obtained as a simulation output with the appropriate probe. The results provided are rounded up into integer values. Similarly, a histogram could be obtained of the procedures completed. For this simulation only the delay field is specifically considered. Simulation delay results for mobility management location registration / update / deregistration signalling with late assignment are indicated in chapter 6.

---

3 As the simulation model is further enhanced, then extra fields could be added to the data packet to allow further evaluation of network performance. The 'iteration number' field which can be used when examining the RACH/s channel performance, is an example of such a field. When more complex models of the RACH/s channel are obtained, where the success probability varies to a greater degree, then its performance can be found through examination of this parameter. Another field could be created to examine the performance of ARQ over the air-interface.
Annex B - S-PCN Call Setup Signalling

This annex describes successful messages and message content used for call setup signalling over the air-interface. The procedures are described from the S-PCN point of view rather than the GSM point of view. The simulation models built for user-originated, user-terminated and user-to-user call setup types are examined in annexes B.2, B.4 and B.5. Differences between GSM and S-PCN messages and information element requirements will clearly exist due to system differences. Considering call setup specifically, such differences are in terms of traffic channel identity, service range availability, network addressing, interworking capability and call modifications. Those messages not already explained in Annex A.1 are examined below where a S-PCN specific message content is proposed and differences with respect to the GSM approach are highlighted in annexes B.1 and B.3.

Annex B.1 S-PCN User-Originated Call Setup Message Content

The individual messages involved in LAPDm based S-PCN user-originated call setup are now considered. The GSM messages are examined down to the level of individual information elements. Based on this, equivalent S-PCN information elements can be proposed, thus allowing the length of equivalent S-PCN messages to be estimated. The UT is considered to be in idle mode, listening to the BCCH/s and to the PCH/s. It also measures other BCCH/s channel strengths in order to monitor spotbeam connection. The signalling sequence for user-originated call setup with late assignment has already been described in chapter 7. Only those messages which differ from those already described in Annex A.1 are examined here.

B.1.1 CM Service Request

This message [GSM 04.08 / 9.2.7] is sent by the UT to the GES to request a service for the connection management (CM) sublayer entities e.g. a circuit switched connection establishment, short message transfer or supplementary service activation. The following table compares the GSM message content with the proposed S-PCN content. S-PCN modifications are indicated with an "*" symbol.

<table>
<thead>
<tr>
<th>Information Element</th>
<th>GSM Length</th>
<th>S-PCN Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Transaction Identifier / Message Type (MF)</td>
<td>2 octets</td>
<td>2 octets</td>
</tr>
<tr>
<td>CM Service Type (MF)</td>
<td>1/2 + 1/2 octets</td>
<td>1/2 + 1/2 octets*</td>
</tr>
<tr>
<td>Ciphering Key Sequence Number (MF)</td>
<td>1/2 + 1/2 octets</td>
<td>0 octets*</td>
</tr>
<tr>
<td>Mobile Station Classmark 2 (MV)</td>
<td>1 + 1 .. 4 octets</td>
<td>1/2 + 1/2 octets*</td>
</tr>
<tr>
<td>Mobile Identity (MV)</td>
<td>1 + 1 .. 9 octets</td>
<td>1 + 4 octets*</td>
</tr>
</tbody>
</table>

Table B/1 - Connection Management Service Request

The S-PCN bit requirement is estimated as 9 octets, resulting in the final transmission of 168 bits. Only the information elements for which changes have been indicated (with an "*"') are now further examined.
**Ciphering Key Sequencing Number.** This information element indicates to the GBS which service is requested from the network - see GSM 04.08 / 10.5.1.2. Since authentication also does this, no S-PCN information element is required here.

**Mobile Station Classmark 2.** This information element provides the network with information concerning aspects of both high and low priority of the UT equipment operation - see GSM 04.08 / 10.5.1.6. For S-PCN only the RF power level is considered to be transmitted at this stage so only 1 octet is used.

**Mobile Identity.** This provides the network with one of three possible UT identities: IMSI/s, TMSI/s or IMEI/s - see GSM 04.08 / 10.5.1.4. For S-PCN the shorter (4 octets) TMSI identity rather than the IMSI (15 digits) is proposed.

**B.1.2 Setup**

For user-originated call setup this message [GSM 04.08 / 9.3.16] is sent from the UT to the GES to initiate call establishment. After the network receives this message it can begin route optimisation. Its GSM equivalent can vary between 50 and 131 octets long. Suggested S-PCN information element modifications are indicated with an '*' symbol.

<table>
<thead>
<tr>
<th>Element</th>
<th>GSM Length</th>
<th>S-PCN estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Transaction Identifier / Message Type (MF)</td>
<td>2 octets</td>
<td>2 octets</td>
</tr>
<tr>
<td>Repeat indicator (OF)</td>
<td>1/2 + 1/2 octets</td>
<td>1/2 + 1/2 octets</td>
</tr>
<tr>
<td>Bearer Capabilities (OV)</td>
<td>1 + 3 .. 11 octets</td>
<td>1 + 4 octets*</td>
</tr>
<tr>
<td>Mobile Identity (OV)</td>
<td>1 + 2 .. 10 octets</td>
<td>0 octets*</td>
</tr>
<tr>
<td>Facility (OV)</td>
<td>1 + 2 .. ? octets</td>
<td>1 + 2 octets</td>
</tr>
<tr>
<td>Progress Indicator (OV)</td>
<td>1 + 3 octets</td>
<td>0 octets*</td>
</tr>
<tr>
<td>Signal (OF)</td>
<td>2 octets</td>
<td>0 octets*</td>
</tr>
<tr>
<td>Called Party BCD Number (MV)</td>
<td>1 + 2 .. 13 octets</td>
<td>1 + 13 octets*</td>
</tr>
<tr>
<td>Called Party Sub-address (OV)</td>
<td>1 + 2 .. 23 octets</td>
<td>1 + 1 octets*</td>
</tr>
<tr>
<td>Repeat Indicator (OF)</td>
<td>1/2 + 1/2 octets</td>
<td>1/2 + 1/2 octets*</td>
</tr>
<tr>
<td>Low Layer Compatibility</td>
<td>3 .. 15 octets</td>
<td>1 + 7 octets*</td>
</tr>
<tr>
<td>Repeat Indicator</td>
<td>1/2 + 1/2 octets</td>
<td>1/2 + 1/2 octets*</td>
</tr>
<tr>
<td>High Layer Compatibility</td>
<td>1 + 4 .. 5 octets</td>
<td>1 + 4 octets*</td>
</tr>
<tr>
<td>User-User</td>
<td>2 .. 35 octets</td>
<td>1 + 2 octets*</td>
</tr>
</tbody>
</table>

Table B/2 - Setup Bit Requirement

The S-PCN bit requirement is estimated as 44 octets, resulting in the transmission of 728 bits. Those information elements for which changes are indicated are now examined. Note that PLMN / ISDN networks are seen as the same environment. Interworking therefore refers to another network type.
Bearer capabilities. In the UT to GES direction at least one bearer capability element must always be sent. This information element indicates a requested bearer service to be provided by the network - see GSM 04.08 / 10.5.4.4. For S-PCN a narrower range of capabilities are likely to apply for the UT since fewer services are likely to be available. Therefore, for S-PCN a total of 5 octets are used.

Mobile Identity. See A.1.4. No octets are required here since this information is already known to the GES.

Progress Indicator. This information element [GSM 04.08 / 10.5.4.15] describes an event (or events) which occur during a call. For S-PCN it is not considered so 0 octets are used.

Signal. This message allows the network to convey optional information to a user regarding tones and alerting signals - see GSM 04.08 / 10.5.4.17. It is not considered here for S-PCN so 0 octets are used.

Called Party BCD Number. This information element is always included in the UT to GES direction and indicates the identity of the called party to the GES - see GSM 04.08 / 10.5.4.6. For S-PCN, the same requirement as with the GSM system is required so the full 13 octets are used.

Calling Party Sub-address. This information element is included in the UT to network direction when the calling user wants to indicate its subaddress to the called user - see GSM 04.08 / 10.5.4.7a. For S-PCN this facility can be sent in a much shorter coded form to the GES which can forward the full UT subaddress to the called party. Therefore 2 octets is considered sufficient here.

Repeat Indicator. This information element indicates whether either low layer or high layer in-call modification procedures are used. It is only included when the in-call modification procedure is used - see GSM 04.08 / 10.5.4.16. No S-PCN changes are necessary so only 1 octet is required.

Low Layer Compatibility. This information element is included in the UT to GES direction when the UT wants to pass low layer compatibility information to the called user. It provides a means for lower layer compatibility checking - see GSM 04.08 / 10.5.4.12. For S-PCN a value of 8 octets is assumed.

High Layer Compatibility. This information element is included in the UT to GES direction when the calling UT wants to pass a higher layer compatibility information to the called user. It provides a means for higher layer remote user compatibility checking - see GSM 04.08 / 10.5.4.10. For S-PCN the lower requirement - 1 + 4 octets - is used.

User-user. This information element is included in the calling UT to GES direction when the calling UT wants to pass user information to the called remote user - see GSM 04.08 / 10.5.4.18. For S-PCN a much shorter and simplified 3 octet information element is considered.

---

4 Bearer capability, Low layer compatibility and High layer compatibility information elements may be used to describe a CCITT telecommunication service, if appropriate. They may be repeated if in-call modification is used.
B.1.3 Call Proceeding

This message [GSM 04.08 / 9.3.3] is sent on the SDCCH/s channel by the contacted GES to the calling UT to indicate that the requested call establishment information has been received and no more call establishment information will be accepted. The following table compares the GSM information elements with the proposed S-PCN information elements. S-PCN modifications are indicated with an "**" symbol.

<table>
<thead>
<tr>
<th>Information Element</th>
<th>GSM length</th>
<th>S-PCN estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Transaction Identifier / Message Type (MF)</td>
<td>2 octets</td>
<td>2 octets</td>
</tr>
<tr>
<td>Repeat Indicator (OF)</td>
<td>1/2 + 1/2 octets</td>
<td>0 octets *</td>
</tr>
<tr>
<td>Bearer Capabilities (OV)</td>
<td>1 + 3 .. 11 octets</td>
<td>0 octets *</td>
</tr>
<tr>
<td>Progress Indicator (OV)</td>
<td>1 + 3 octets</td>
<td>1 octet *</td>
</tr>
</tbody>
</table>

Table B/3 - Call Proceeding Bit Requirement

**Repeat Capability.** This is as in B.1.2. For S-PCN it is considered to have been performed fully as part of the Setup message and so 0 octets are required here.

**Bearer Capabilities.** This is as in B.1.2. For S-PCN it is considered to have been performed fully as part of the Setup message and so 0 octets are required here.

**Progress Indicator.** This is as in B.1.2. For S-PCN a minimal length of 1 octet is considered sufficient at this stage of the late assignment call setup procedure as a simple acknowledgement of call progress.

B.1.4 Alerting

This message [GSM 04.08 / 9.3.1] is sent on the SDCCH/s channel by the GES to the calling UT to indicate that called user alerting has been initiated (phone begins to ring). Its GSM equivalent is between 10 and 43 octets long. The message is constructed as follows with S-PCN modifications indicated with an "**".

<table>
<thead>
<tr>
<th>Element</th>
<th>GSM Length</th>
<th>S-PCN Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Transaction Identifier / Message Type (MF)</td>
<td>2 octets</td>
<td>2 octets</td>
</tr>
<tr>
<td>Facility (OV)</td>
<td>2 octets</td>
<td>2 octets</td>
</tr>
<tr>
<td>Progress indicator (OV)</td>
<td>1 + 3 octets</td>
<td>1 + 3 octets</td>
</tr>
<tr>
<td>User-user (OV)</td>
<td>1 + 2 .. 35 octets</td>
<td>1 + 2 octets *</td>
</tr>
</tbody>
</table>

Table B/4 - Alerting Bit Requirement

The S-PCN system is considered to require 11 octets. For the User-user information element explanation see B.1.2.

B.1.5 Assignment Command

This message [GSM 04.08 / 9.1.2] is sent on the SDCCH/s channel by the GES to the UT to change the channel configuration to a traffic channel configuration. The message is constructed as follows with S-PCN modifications indicated with an "**".

---

* With late traffic channel assignment this and subsequent messages are only sent after the called user has actually answered the phone. Because this may involve a long holding delay, UTs risk loosing
The S-PCN system is considered to require 18 octets. Those messages which differ for the S-PCN system are now considered in more detail.

**Channel Description.** This message describes generally the allocated traffic channel along with its associated signalling channels - see GSM 04.08 / 10.5.2.5. For S-PCN the bit content would be changed as very different and fewer physical resources are on offer. However the same 4 octet requirement is assumed.

**Cell Channel Description.** This information element provides the absolute radio frequency channel to be used for the call - see GSM 04.08 / 10.5.2.1. For S-PCN and because of the more limited resources that are available compared with the GSM system, a lower requirement of 9 octets is assumed here.

**Channel Mode.** This information element is included if the channel mode is changed for the channel defined in the mandatory part of the message - see GSM 04.08 / 10.5.2.6. For S-PCN this option is not considered here so 0 octets are used.

**Channel Description.** This information element appears a second time in the case of a so-called intracell handover - see GSM 04.08 / 10.5.2.5. For S-PCN this is not considered so 0 octets are used.

**Channel Mode 2.** This information element is included as an optional channel description element - see GSM 04.08 / 10.5.2.6a. It is not considered for S-PCN allocation so 0 octets are used.

**Mobile Allocation.** This information element is for the case of channel allocation with frequency hopping - see GSM 04.08 / 10.5.2.12. It is not considered for S-PCN so 0 octets are used.

---

**Table B/5 - Assignment Command Bit Requirement**

<table>
<thead>
<tr>
<th>Element</th>
<th>GSM Length</th>
<th>S-PCN Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator /</td>
<td>2 octets</td>
<td>2 octets</td>
</tr>
<tr>
<td>Transaction Identifier /</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Message Type (MF)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel Description (MF)</td>
<td>1 + 3 octets</td>
<td>1 + 3* octets</td>
</tr>
<tr>
<td>Power Command (MF)</td>
<td>1 + 1 octets</td>
<td>1 + 1 octets</td>
</tr>
<tr>
<td>Cell Channel Description (OF)</td>
<td>1 + 17 octets</td>
<td>1 + 9 octets*</td>
</tr>
<tr>
<td>Channel Mode (OF)</td>
<td>1 + 1 octets</td>
<td>0 octets*</td>
</tr>
<tr>
<td>Channel Description (OF)</td>
<td>1 + 3 octets</td>
<td>0 octets*</td>
</tr>
<tr>
<td>Channel Mode 2 (OF)</td>
<td>1 + 1 octets</td>
<td>0 octets*</td>
</tr>
<tr>
<td>Mobile Allocation (OV)</td>
<td>2 .. 10 octets</td>
<td>0 octets*</td>
</tr>
<tr>
<td>Starting Time (OF)</td>
<td>3 octets</td>
<td>0 octets</td>
</tr>
</tbody>
</table>

connectivity with a satellite spotbeam, particularly for LEO constellations with high numbers of spotbeams per satellite. Early assignment could be used to avoid this, with this and subsequent messages being transmitted on signalling channels associated with the traffic channel, requiring specific protocol changes. The alternative is to use early traffic channel assignment only to provide for the possibility of SDCCH/s channel handover. This also applies to user-terminated calls.
Starting Time. This information element is usually included when a frequency change is in progress. In GSM it provides the start TDMA frame number - see GSM 04.08 / 10.5.2.20. For S-PCN it is not considered so 0 octets are used here.

B.1.6 Assignment Complete

This message [GSM 04.08 / 9.1.3] is sent on the SDCCH/s channel from the UT to the GES to indicate that the UT has established the identity of the main signalling link successfully. By removing spare bits in the GSM approach the S-PCN message length can be reduced to 3 octets. The message is constructed as follows:

<table>
<thead>
<tr>
<th>Information Element</th>
<th>GSM Length</th>
<th>S-PCN Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Transaction Identifier / Message Type (MF)</td>
<td>2 octets</td>
<td>2 octets</td>
</tr>
<tr>
<td>RR cause (MF)</td>
<td>1 + 1 octets</td>
<td>1/2 + 1/2 octets*</td>
</tr>
</tbody>
</table>

*Table B/6 - Assignment Complete Bit Requirement*

RR Cause. See A.1.10.

B.1.7 Connect

This message [GSM 04.08 / 9.3.5] is sent by the GES to the calling UT to indicate call accept by the called user. Its GSM equivalent message is between 10 and 43 octets long. The message is constructed as follows:

<table>
<thead>
<tr>
<th>Element</th>
<th>GSM Length</th>
<th>S-PCN Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Transaction Identifier / Message Type</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Facility (OV)</td>
<td>2 octets</td>
<td>2 octets</td>
</tr>
<tr>
<td>Progress Indicator (OV)</td>
<td>4 octets</td>
<td>4 octets</td>
</tr>
<tr>
<td>User-User (OV)</td>
<td>1 + 2..35 octets</td>
<td>1 + 2 octets*</td>
</tr>
</tbody>
</table>

*Table B/7 - Connect Bit Requirement*

The S-PCN system is considered to require 11 octets.

User-user. See B.1.2.

B.1.8 Connect Acknowledge

This message is sent by the network to the called UT or by the calling UT to the network to indicate that the UT has been awarded the call. The message is constructed as follows. No S-PCN changes are indicated.

<table>
<thead>
<tr>
<th>Element</th>
<th>GSM Length</th>
<th>S-PCN Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Transaction Identifier / Message Type</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

*Table B/8 - Connect Acknowledge Bit Requirement*
Annex B.2 User-Originated Call Setup BONeS Simulation Model

The simulation model built for analysis of the S-PCN user-originated call setup procedure is explained here. The model was built on the BONeS Designer network simulation tool. The late assignment signalling sequence described in chapter 7 and which was simulated, is built in a modular approach. In each of these modules, parameters were created to provide the system with flexibility. To distinguish between LEO and MEO simulations the maximum and minimum propagation delays need to be set within the first system sub-module. Figure B.1 below indicates the simulation model used and the input file and memory parameters associated with the simulation.

Figure B.1 - User-Originated Call Setup Simulation Model (Late Assignment)

Only two blocks are indicated in the first level hierarchy of this simulation module. The first is the same as the '2 rach part' module explained in annex A.2. All the input file parameters indicated are also similar so reference is made to annex A.2.

The second module models the SDCCH/s channel call setup signalling sequence with late assignment - it therefore includes all messages up to the 'P alert' message. These sub-components are indicated in figure B.2.
Looking inside the 'SD/comp' module, it consists of a separate sub-module for each of the messages that are transmitted. The data packet is passed along each of these sub-modules, with each component adding its own delay onto the data packets delay field. The delay added comes from the three standard contributions - the processing delay before transmission starts, the propagation delay which is a constant for individual procedures and the packet delay. The packet delay depends on the bit requirement of the relevant message and the SDCCH/s channel bit rate, which is controlled by the 'P bit duration (s) sdcch' parameter. The SDCCH/s channel message bit requirements are contained in the following parameters - 'P CM serv req', 'P auth req', 'P auth res', 'P ciph mod cmd', 'P ciph mod com', 'P setup', 'P call proc' and 'P alerting'. All these parameters are passed to the simulation via the input file.

Detail within the '1 CM serv req (ut -> n)' sub-module is indicated in figure B.3. The functions of the different parts are then explained.

The input comes from the Rcomp and is named 'success' since it arrives due to the completion of a successful random access request. The first delay to be added is the processing delay at the UT - called 'UT proc delay'. This is chosen from a uniform
distribution between 25 ms and 250 ms. The selected value is then added to the time stamp field of the data parameter. As more precise data is gained on the ground segment signalling requirement, then a more precise range of GES and UT processing delays can be included, according to the messages that are to be transmitted.

The second delay contribution indicated comes from the multiplication of two input file parameters - 'TP CM serv req' and 'TP bit duration (s) sdcch'. The resulting delay is added to the delay field of the simulation data packet. The third delay contribution is the propagation delay of the UT-to-satellite-to-GES hop (or vice versa). It is read from internal simulation memory and then added to the simulation data packet delay field.

Results. Simulation results are obtained through using specific data collecting probes at the simulation output. The use of different probes at the simulation output allowed different result formats to be obtained. For this simulation only the delay field is specifically considered with the average delay, rounded up to seconds being used. Simulation delay results for user-originated call setup signalling with late assignment are indicated in chapter 7.
Annex B.3 - S-PCN User-Terminated Call Setup Message Content

The individual messages involved in LAPDm based S-PCN user-terminated call setup are now considered. The GSM messages are examined down to the level of individual information elements. Based on this, equivalent S-PCN information elements can be proposed, allowing the length of the specific messages to be estimated. A UT is initially considered to be in idle mode where it listens to the BCCH/s and to the PCH/s. It also measures surrounding BCCH/s channel strength to monitor adjacent spotbeam connection. The signalling sequence for user-terminated call setup with late assignment has already been described in chapter 7. Only those messages which differ from those already described in Annex A.1 and B.1 are considered here.

B.3.1 Paging Request Type 1

This message [GSM 04.08 / 9.1.21] is sent on the PCH/s channel by the GES to a UT to trigger a channel access attempt by the paged UT. In the GSM system two MSs, identified by their TMSI or IMSI, can be paged and the message is between 4.5 and 21.5 octets long. The message is constructed as follows with S-PCN modifications indicated with an "*":

<table>
<thead>
<tr>
<th>Element</th>
<th>GSM length</th>
<th>S-PCN estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator /</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Transaction Identifier /</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Message Type (MF)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Page Mode (MF)</td>
<td>1/2 + 1/2</td>
<td>1/2 + 1/2</td>
</tr>
<tr>
<td>Mobile Identity (MV)</td>
<td>1 .. 9</td>
<td>1 + 4*</td>
</tr>
<tr>
<td>Mobile Identity (MV)</td>
<td>2 .. 10</td>
<td>0*</td>
</tr>
</tbody>
</table>

Table B/9 - Paging Request Type 1 Bit Requirement

The S-PCN requirement is estimated as 8 octets. The information elements which have been modified are discussed below.

Mobile Identity. This information element provides either the users IMSI/s or TMSI/s, the field cannot refer to the IMEI/s - see GSM 04.08 / 10.5.1.4. For S-PCN the 4 octet long TMSI/s identity is used, resulting in a message length of 5 octets.

Mobile identity. Only one UT is considered to be paged at a time so 0 octets are used here.

B.3.2 Paging Response

This message [GSM 04.08 / 9.1.24] is sent on the SDCCH/s channel by the UT to the GES in connection with establishing a main signalling link as a response to a paging request message just received. The GSM message varies between 5 and 17 octets. The following table compares the GSM message content with the proposed S-PCN content. S-PCN modifications are indicated with an "*" symbol.
<table>
<thead>
<tr>
<th>Information Element</th>
<th>GSM Length</th>
<th>S-PCN Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Transaction Identifier / Message Type (MF)</td>
<td>2 octets</td>
<td>2 octets</td>
</tr>
<tr>
<td>Ciphering Key Sequence Number (MF)</td>
<td>1/2 + 1/2 octets</td>
<td>0 octets*</td>
</tr>
<tr>
<td>Mobile Station Classmark 2 (MV)</td>
<td>1 + 1 .. 4 octets</td>
<td>1/2 + 1/2 octets*</td>
</tr>
<tr>
<td>Mobile Identity (MV)</td>
<td>1 .. 9 octets</td>
<td>1 + 4 octets*</td>
</tr>
</tbody>
</table>

**Table B/10 - Paging Response Bit Requirement**

The S-PCN requirement is estimated as 8 octets. Those information elements which are changed are examined in more detail in the following:

*Ciphering key sequence number.* See A.1.3.

*Mobile station classmark 2.* See B.1.1.

*Mobile Identity.* See A.1.3.

### B.3.3 Setup

For a user-terminating call setup procedure, this message [GSM 04.08 / 9.3.16] is sent from the GES to the UT to initiate call establishment. Its GSM equivalent can vary between 36 and 130 octets long. Differences compared with the user-originating call setup procedure are explained in the following. S-PCN modifications are indicated with an "*" symbol.

<table>
<thead>
<tr>
<th>Element</th>
<th>GSM Length</th>
<th>S-PCN estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Transaction Identifier / Message Type (MF)</td>
<td>2 octets</td>
<td>2 octets</td>
</tr>
<tr>
<td>Repeat indicator (OF)</td>
<td>1/2 + 1/2 octets</td>
<td>1/2 + 1/2 octets</td>
</tr>
<tr>
<td>Bearer Capabilities (OV)</td>
<td>1 + 3 .. 11 octets</td>
<td>0 octets*</td>
</tr>
<tr>
<td>Mobile Identity (OV)</td>
<td>1 + 2 .. 10 octets</td>
<td>0 octets*</td>
</tr>
<tr>
<td>Facility (OV)</td>
<td>1 + 2 .. 7 octets</td>
<td>1 + 2 octets*</td>
</tr>
<tr>
<td>Progress Indicator (OV)</td>
<td>1 + 3 octets</td>
<td>0 octets*</td>
</tr>
<tr>
<td>Signal (OF)</td>
<td>2 octets</td>
<td>0 octets*</td>
</tr>
<tr>
<td>Calling Party BCD Number (OV)</td>
<td>1 + 2 .. 13 octets</td>
<td>1 + 13 octets*</td>
</tr>
<tr>
<td>Calling Party Sub-address (OV)</td>
<td>1 + 2 .. 23 octets</td>
<td>1 + 6 octets*</td>
</tr>
<tr>
<td>Repeat Indicator (OF)</td>
<td>1/2 + 1/2 octets</td>
<td>1/2 + 1/2 octets</td>
</tr>
<tr>
<td>Low Layer Compatibility (OV)</td>
<td>3 - 15 octets</td>
<td>1 + 7 octets*</td>
</tr>
<tr>
<td>Repeater Indicator (OF)</td>
<td>1 octets</td>
<td>0 octets*</td>
</tr>
<tr>
<td>High Layer Compatibility (OV)</td>
<td>4 .. 5 octets</td>
<td>1 + 4 octets*</td>
</tr>
<tr>
<td>User-User (OV)</td>
<td>2 - 35 octets</td>
<td>1 + 2 octets*</td>
</tr>
</tbody>
</table>

**Table B/11 - Setup Bit Requirement**

The S-PCN bit requirement is estimated as 44 octets, resulting in the ultimate transmission of 728 bits. Those information elements for which changes are indicated
are now examined. Note that PLMN/ISDN networks are seen as the same environment. Interworking therefore refers to another network type.

**Bearer capabilities.** In the GES to UT direction, this element may be omitted in the case where the UT is allocated only one directory number for all services. This information element indicates a requested bearer service to be provided by the network - see GSM 04.08 / 10.5.4.4. No octets are used for S-PCN.

**Mobile Identity.** See A.1.4.

**Facility.** See B.1.2.

**Progress Indicator.** See B.1.2.

**Signal.** See B.1.2.

**Calling Party BCD Number.** This information element may be included by the GES to identify the calling user to the UT user - see GSM 04.08 / 10.5.4.6. For S-PCN, the same requirement as with the GSM system is considered so a full 14 octets are used.

**Calling Party Sub-address.** This information element is included in the GES to UT direction if the calling user includes a calling party sub-address information element in the Setup message - see GSM 04.08 / 10.5.4.7a. For S-PCN a basic requirement of 7 octets is allocated for this. If no octets are required here then extra octets can be allocated to other information elements as required.

**Low Layer Compatibility.** This information element is included in the GES to UT direction if the calling party included a low layer compatibility information element in their Setup message - see GSM 04.08 / 10.5.4.12. For S-PCN and since a reduced service set should result in a reduced compatibility checking requirement, 8 octets are used.

**High Layer Compatibility.** This message is included in the GES to UT direction if the calling party included a high layer compatibility information element in the Setup message - see GSM 04.08 / 10.5.4.10. For S-PCN, the basic 5 octet message is assumed to be transmitted.

**User-user.** See B.1.2.

**B.3.4 Call Confirmed**

This message [GSM 04.08 / 9.3.2] is sent on the SDCCH/s channel by the called UT to the GES to confirm an incoming call request. The message is constructed as follows:

<table>
<thead>
<tr>
<th>Element</th>
<th>GSM length</th>
<th>S-PCN estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Discriminator / Transaction Identifier / Message Type (MF)</td>
<td>2 octets</td>
<td>2 octets</td>
</tr>
<tr>
<td>Repeat Indicator (OF)</td>
<td>1/2 + 1/2 octets</td>
<td>0 octets*</td>
</tr>
<tr>
<td>Bearer capabilities (OF)</td>
<td>1 + 3 .. 11 octets</td>
<td>0 octets*</td>
</tr>
<tr>
<td>Cause (OF)</td>
<td>1 + 4 .. 32 octets</td>
<td>1 + 4 octets*</td>
</tr>
</tbody>
</table>

*Table B/12 - Call Confirmed Bit Requirement*

For S-PCN 7 octets are estimated to be required here. The differences with the GSM requirement are now examined.
**Repeat Indicator.** This information element is related to the inclusion of a Bearer Capabilities information element and is omitted since Bearer Capabilities is also omitted.

**Bearer capabilities.** Included only if the UT needs to change the Bearer Capabilities information element that it received in the *Setup* message - see GSM 04.08 / 10.5.4.4. For S-PCN no modifications should be necessary (the UTs HLR/s can know a UTs capabilities from within the fixed network) so 0 octets are used.

**Cause.** This information element is included if the UT is compatible for the call but the user is busy - see 10.5.4.8. The basic message, without diagnostics, is assumed here resulting in a requirement of 5 octets.
Annex B.4 User-Terminated Call Setup BONeS Simulation Model

The simulation model built for analysis of the S-PCN user-terminated call setup is explained here. The model was built on the BONeS Designer network simulation tool. The late assignment signalling sequence described in chapter 7 was simulated. Input file parameters were created to provide the system with flexibility. To distinguish between LEO and MEO simulations the maximum and minimum propagation delays need to be set within the first system module - in this case the ‘P/comp’ or paging component module. Figure B.1 below indicates the simulation model used and the input file and memory parameters associated with the simulation.

![User-Terminated Call Setup Simulation Model](image)

Three blocks are indicated in the first level hierarchy of this simulation module. The second and third modules are quite similar to those modules discussed in annexes A.2 and B.2 already. The first module is ‘P/comp’ which simulates the delay involved for a GES to page a UT. This module is explained in more detail here. Figure B.5 indicates the first level of design detail within this ‘P/comp’ module.

![‘P/comp’ Sub-modules](image)

1 TS. The first of these three sub-modules is similar to the ‘1 traffic and hop’ sub-module explained in annex A.2. It creates data packets with the required fields and passes them on to the next module. The parameter ‘P mean interarrival time’ is passed to the simulation in the input file and allows the number of procedures simulated to be controlled.

2 Paging Delays. In the second module, the delay resulting from a GES paging a UT is found and added onto the delay field of the data packet. The design detail within this sub-module is indicated in figure B.6.
Functionality within this sub-module is similar to that explained in annex A.2 for the '3.1 loc upd req ut->n' sub-module. This involves the addition of the processing delay, the packet delay and the propagation delay onto the time stamp field of the data packet. The detail within the '3 PES/c to UT paging' sub-module is shown in figure B.7 below.

Results. Simulation results are obtained through using specific data collecting probes at the simulation output. These probes are set to read and compare specific fields within the simulation data packet. Simulation delay results for user-terminated call setup signalling with late assignment as indicated in chapter 7.
Annex B.5 User-to-User Call Setup BONEs Simulation Model

The bit content for the messages used here have already been indicated in annexes A.1, B.1 and B.3 and are not repeated here. The simulation model used is shown in figure B.8 below.

![Diagram of User-to-User Call Setup Simulation Module]

Figure B.8 - User-to-User Call Setup Simulation Module

Some of the 'IP' parameters indicated apply to both modules indicated. All the 'IP ... bit duration (s) ...' parameters refer to one or the other module. This is because different signalling channel bit rates were simulated for the same channel type but at different ends of the call - user-originating side or user-terminating side. Also the 'CM' memory parameters refer to the different ends of the call, the 'CM 2nd hop' memory parameter referring to the user-terminating side of the call. Otherwise, both modules are equivalent to modules already described.

The 'Upart1/comp' is similar to the user-originated call setup module described in annex B.2. However, message delays are only added up to the point of 'Setup' message reception at the GES. At this point, the user-terminated side of the call is initiated and so signalling on this side proceeds in parallel with the 'call proceeding' message on the user-originating side.

The 'Upart2/comp' is similar to the user-terminated call setup module described in annex B.4. The simulation is performed up to the point of the user-originating side receiving the 'alerting' message (indicated at 'IP alert' above).
Annex C Publications

Publications are now listed. They are split into three subsections according to type. Annex C.1 indicates conference publications, annex C.2 indicates contributions which were published in a journal, as part of a European Space Agency Working Paper and in a workshop book compilation, respectively. Finally annex C.3 indicates technical contributions which were made to the RACE II - SAINT (Satellite Integration in future mobile communication systems).

Annex C.1 Conference Publications


Annex C.3 SAINT RACE II Project Submissions


