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Load Sharing in an Integrated Satellite -Terrestrial Cellular Network

by

Simon Arcand, B.A.Sc.

*A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of*

Master of Engineering

*Ottawa-Carleton Institute for Electrical Engineering
Faculty of Engineering
Department of Systems and Computer Engineering*

*Carleton University
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submitted by Simon Arcand, B.A.Sc.

in partial fulfillment of the requirements for the degree of Master of Engineering

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Abstract

Global Personal Communication Services will incorporate an integrated satellite-terrestrial cellular telecommunications network. The implementation of this network may be done by adding a satellite "extension" to any of the well-developed terrestrial cellular systems which have been in use for many years. The network will provide service to a user population equipped with single mode terminals (SMTs) that have access to the terrestrial cellular system only and dual mode terminals (DMTs) that have access to both components of the network. Two complications arise from this. First, as recommended by many authors, DMTs will use the satellite system as a secondary server for the traffic that cannot be serviced by the terrestrial system. DMTs risk monopolizing the terrestrial system to the detriment of SMTs that cannot choose the system they are connected to. Secondly, any algorithm that reduces this problem must do so over a wide range of SMT-DMT proportion since operating companies will have very little control over that factor.

This thesis examines several algorithms used by DMTs in choosing from which system they are to request service. For each algorithm, the quality of service is computed by employing a hybrid method where the output of a mathematical analysis is used as the input to a Monte Carlo simulation.

This thesis found that an algorithm that uses the satellite as a last resort only offers a good performance if all terminals have dual mode capability. Otherwise its performance is poor.

The thesis also found an algorithm that outperforms all others for any DMT proportion.

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List of Abbreviations and Acronyms

DMT	Dual mode terminal
erl	erlang (unit of traffic load)
GEO	Geo-stationary orbit
LEO	Low Earth Orbit
MAHO	Mobile assisted handoff
MBPS	Measurement-based prioritization scheme
MCHO	Mobile controlled handoff
MSAT	Mobile satellite
MSC	Mobile switching centre
NCHO	Network controlled handoff
OOTC	Out of terrestrial coverage
PCS	Personal communication services
PSTN	Public switched telephone network
SMT	Single mode terminal
SRS	Sub-rating scheme
UMTS	Universal Mobile Telecommunication System

List of Mathematical Symbols and Notation

a	traffic load offered to a queueing system
$B(s,a)$	blocking probability, obtained via the Erlang B formula
G	grade of service
L_c	number of satellite channels available in the footprint
m_s	number of busy satellite channels in the cell of interest
m_t	number of busy terrestrial channels in the cell of interest
m_v	number of terrestrial channels occupied by DMTs in the cell of interest
m_w	number of terrestrial channels occupied by SMTs in the cell of interest
n_n	number of Markov states in the cell of interest
n_p	number of significantly different solutions of the mathematical analysis
n_s	number of satellite channels available in the cell of interest
n_t	number of terrestrial channels available in the cell of interest
N_{Cell}	number of cells covered in the footprint
$P_{m_r, m_s}(t)$	probability of the cell of interest being in state (m_r, m_s) at time t
P_{m_r, m_s}	probability of the cell of interest being in state (m_r, m_s) at steady state
P_b	blocking probability
P_d	call dropping probability
$P_b(SMT)$	SMT blocking probability
$P_b(DMT)$	DMT blocking probability
$P_{m_s}^{(B)}$	SMT blocking probability conditional on m_s

$P_{m_s}^{(D)}$	SMT call dropping probability conditional on m_s
$P(n_t m_s)$	Probability that the cell is occupying n_t terrestrial channels, conditional on using m_s satellite channels
P_{m_s}	Probability that the cell is occupying m_s satellite channels
s	number of servers in a queueing system
R	an intermediate term used in formula 4.1
t	time
α	channel capture rate per cell
θ	degree of mobility
λ	new call arrival rate per cell
λ_{ho}	handoff arrival rate per cell
λ_T	total call arrival rate
$\lambda_{m_t, m_s}^{(s)}$	satellite capture rate in the cell of interest conditional of m_t, m_s
Λ_{m_s}	total satellite capture rate in the cell of interest conditional on m_s, n_s
μ	call servicing rate
μ'	channel release rate
$\mu_{m_t, m_s}^{(s)}$	satellite release rate in the cell of interest conditional of m_t, m_s
M_{m_s}	total satellite release rate in the cell of interest conditional on m_s, n_s
π	constant 3.14159...
ρ	traffic load per cell

CHAPTER 1

INTRODUCTION

1.1 Introduction

The concept of satellite-based personal communication services (PCS) has been discussed for many years. It is seen by many as an essential component of the universal personal telecommunications service whose ultimate goal is to ensure an exchange of information with anyone, anywhere at anytime.[7][15]

Fundamental to all satellite-based PCS is a requirement to interwork with the existing terrestrial fixed networks [32]. The goal is to have access to both satellite and terrestrial cellular systems from one handheld terminal.

Given the advanced development of terrestrial cellular systems, the emphasis will be on their extension with a satellite component, rather than the development of a completely new integrated network. It can be expected that, at first, the overwhelming majority of users will be equipped with single mode terminals (SMTs) that have access to terrestrial systems only. Acquisition of dual mode terminals (DMTs) having access to satellites and terrestrial systems will be gradual, albeit quick. It is doubtful that all SMTs will ever be replaced by DMTs. For PCS operators, customer support must be oriented toward a mixed population of terminals.

1.2 Definition of the Problem

Previous literature on the subject has concentrated on populations where all users have DMTs. In such scenarios, DMTs should request a satellite channel only when all terrestrial channels in the cell are occupied. During the call, they should revert back to the terrestrial system as soon as terrestrial channels become free.

Such algorithms are efficient when all terminals have equal access to the satellite. Saturating the terrestrial system does not present a risk, since any terminal setting up a new call can always try the satellite if all terrestrial channels are occupied. However, if some terminals only have a single mode capability, they face a higher blocking probability when DMTs monopolize the terrestrial system. This reduces the quality of service averaged over the whole subscriber population.

This problem does not appear to have been studied at all. The complexity of the problem is not known; consequently, no solution has been investigated.

1.3 Thesis Objectives

The objectives of this thesis are

- (1) to determine the reduction in quality of service suffered by a mixed SMT-DMT population when the channel allocation algorithm minimizes the use of the satellite system, and
- (2) to investigate other algorithms that would improve the quality of service to a mixed population.

The ultimate goal is to find an algorithm that performs better than any other one, for any DMT proportion.

1.4 Proposed Approach

The main part of this thesis is the development of a method to measure the quality of service for each algorithm. For reasons explained in chapter 3, a grade of service is assumed to consist of a weighted average of blocking probability and call dropping probability. Consequently, the main task in this study is the computation of the two probabilities, with the parameters being the traffic load density and the DMT proportion.

This is done with two scenarios. In the first one, mobile terminals are assumed stationary. This first scenario helps in understanding the basis of the model, without the complexities of calls being dropped when terminals cross cell boundaries. Only the blocking probability is examined.

The second scenario is similar to the first one but is more rigorous and assumes a certain degree of mobility of terminals between cells. Call dropping probability is included in the calculation of the grade of service and is actually given a greater weight than blocking probability. This is explained in details in section 3.5.

With each of these two scenarios, the computation is based on a two-step hybrid method of analysis and simulation. This is required because of the magnitude of the network under study. Mathematical analysis is performed on an individual cell, conditional on the number of satellite channels available to that cell only. The conditional statistics obtained in the analysis are then used in a simulation conducted on a cellular cluster overlaid with one satellite beam. The results of the simulation include the number of satellite channels occupied by each cell. Consequently, the condition imposed previously is eliminated and we have the total probability of blocking and probability of call dropping.

1.5 Thesis Outline

This thesis is organized as follows.

Chapter 2 reviews current literature on the subject. Although much of the material in that chapter is not used in the remainder of the thesis, it helps in appreciating the context of the study.

Chapter 3 describes both components of the network, i.e. the satellite and terrestrial cellular systems. It also describes the traffic model, first with immobile terminals, then with inter-cell movement.

Chapter 4 describes seven algorithms used with immobile terminals and analyzes the performance of each.

Chapter 5 addresses the scenario where mobile terminals travel across cellular boundaries. Only four algorithms are examined. These algorithms are the four most interesting ones taken from chapter 4 and are modified to reduce the probability of call dropping inherent with movement. Again, their performance is analyzed and compared. One algorithm is found to perform extremely well and, in the last section of this chapter, is analyzed with varying external conditions.

Chapter 6 is a conclusion. It offers recommendations for future work on this subject.

CHAPTER 2

REVIEW OF THE STATE OF THE ART

2.1 Introduction

This chapter presents a review of the literature related to integrated satellite-terrestrial cellular systems. Among the subjects relevant to this thesis, are mobile satellite networks, low earth orbit satellites and layered cellular systems.

2.2 Mobile Satellite Networks

Experimental mobile satellite (MSAT) systems have been deployed for several years and many commercial systems will be operational in various countries well before the end of this decade. Most are based on geostationary satellites orbiting the Earth at an altitude of approximately 36,000 km. Due to the large free space loss encountered over that distance, mobile terminals must be equipped with medium-gain antennas, such as the mechanically steered linear array, the mechanically steered planar array with an electronic sensor to determine the satellite position or an electronically steered phase array [19].

Extension of mobile satellite services to handheld terminals can be done via two approaches: (1) use of multi-beam antennas at the satellite or (2) low earth orbit (LEO) systems which are covered in section 2.3. Both methods can be used jointly.

The advantages of multi-beam antennas include high gain with each beam and possibility of

frequency re-use, hence a large supported traffic load [29][31]. One important distinction between terrestrial cellular systems and multi-beam satellites is the size of the beam footprint and the huge overlap between two adjacent beams, which eliminates the need for inter-beam or inter-satellite hand-off during a call [2], unless the footprint travels on the ground.

The number of channels supported in each beam depends on various factors. Some references suggest 150 [27] and 200 channels per beam [22] or a total satellite capacity of 2500 circuits [23].

2.3 Low Earth Orbit

LEO satellites orbit the earth at an altitude of only a few 100s km. Their circular orbit must be high enough to minimize atmospheric drag but must be kept below the radiation belts surrounding the Earth.

The much shorter distance between the mobile terminal and the satellite translates into a smaller propagation delay (a few ms instead of approximately 270 ms) and a smaller free space loss. If the satellite uses a highly directional antenna, the mobile terminal can communicate with an omnidirectional antenna and a transmission power in the order of 1W in the L-band (1.5/1.6 GHz)[27] [40].

One disadvantage of LEO is the smaller coverage of the satellite on the ground, regardless of the number of beams per satellite. If continuous coverage of the globe is desired, a constellation of many satellites is needed. The size of this constellation depends on the minimum elevation angle

desired at the mobile terminal and the altitude of the circular orbit [31]. The best deployment of this constellation is to distribute the satellites in separate orbit planes with many satellites in each plane.

Table 2.1: Commercial Proposals (from [44])

System	Company	Service	Number of satellites
Iridium	Motorola	Mobile voice, paging, data, fax,	66
Globalstar	LQSS	Mobile voice, data, paging, message	48
Ellipso I & II	Ellipsat	Mobile voice	I: 6; II: 18
Aries	Constellation Comm	Voice, data	48
Gonets	Consortium	Store and forward message	36
Leocom	Italspazio	Store and forward message, real time data	24
Leosat	Leosat Corp	Store and forward message, 2-way data	18
Odyssey	TRW Inc.	Voice, data, message	12
Orbcomm	Orbital Sciences Corp	Message	20
Starsys	Starsys Inc.	2-way message	24
VITA	Volunteers in Technical Assistance Inc.	Store and forward message, broadcast	2
Inmarsat	Inmarsat	Mobile voice, data, paging, message	
MSAT/AMSC	TMI/American Mobile Satellite Corp	Voice, data, paging, message	3
Omni-TRACS	Qualcomm	2-way message	1

Table 2.1 gives an idea of some proposed commercial systems. Some, like Orbcomm, have already started to deploy satellites in orbit. Of all proposed LEO systems, Iridium designed by

Motorola Inc. stands out as the most comprehensive [29]. Iridium will operate a constellation of 66 satellites deployed in six polar orbits. Satellite elevation will always be 10° or more. Each satellite will radiate 37 independent beams, each having a diameter of 670 km on the ground [27].

In LEO systems, connection between two mobile terminals serviced by different satellites can be done with each satellite having a direct link to a ground gateway connected to the PSTN or by inter-satellite links connecting the whole constellation. Many patterned constellations like the Walker delta pattern have been studied, as well as the average message delay incurred, based on the number of links terminated by each satellite [46].

A second disadvantage of LEO is the movement of the satellite as seen from the ground. This phenomenon incurs movement of the footprint on the ground and Doppler effects. Consequences include the degeneration of the propagation medium into a mobile channel and the requirement for long-duration calls to be handed off from beam to beam and from satellite to satellite.

Despite intense design efforts on various satellite-based PCS, their proponents admit that these services will not replace terrestrial systems such as the wired network or cellular telephone because their high cost will make them non-competitive[17][27]. The intent is rather to extend the reach of terrestrial PCS islands by overlaying satellite services [17]. This is justified by the estimation that in 1991, more than 10 million people lived in regions of the United States not covered by cellular networks [29]. Similarly, in Europe, the future public land mobile

telecommunications system (FPLMTS) is expected to include satellites that will extend the coverage of the existing and future generations of cellular mobile service to rural or suburban areas [25] [34].

While satellite services cover remote areas where cellular operators believe that the scarce customer base does not warrant the infrastructure associated with a cellular system, conversely, in a city core with a high density of tall buildings and overpasses, it is likely that satellite services are not reliable due to their typical tight link margin [23][26][30]. This is especially critical since the satellite elevation can be as low as 10° .

In the most developed countries, the overwhelming majority of users resides in huge urban and suburban areas covered by both satellite and terrestrial systems.

2.4 Integration

It can be seen that the surface of the Earth will soon be divided in three zones: one covered by terrestrial cellular systems only, one covered by satellite only and one covered by both. There will not be a sharp boundary between these zones and users will travel freely between them. Integration of both systems seems as an option that offers good quality service to users.

In Europe for instance, the Universal Mobile Telecommunications System (UMTS) is seen as being implemented in urban environments first. In suburban and rural environments, the satellite stands as a cost-effective candidate to extend its reach, provided that its functions are integrated with the more developed terrestrial network [3]. "The full integration between cellular networks

and satellite systems is a very promising issue since it immediately provides areas lacking in terrestrial facilities with the radio services offered by the cellular networks. Satellite systems can be profitably used in order to cope with contingent situations of unavailability of terrestrial carriers (e.g. due to traffic congestion in some cells) and/or in order to shorten the terrestrial tails (a mobile and a fixed user involved in a call can communicate, via satellite, through the base station closest to the fixed user)." [11].

The characteristics of a DMT and the services that it provides are explored in [3], [9] and [12]. When the terminal is covered by both systems, it can choose from which one to draw services. The criteria used to make this choice will depend on the commercial product used. Most likely, an automatic algorithm will make that decision for the user [9]. An override option activated by the user may be provided for purposes of economy, depending on the subscription package [2].

The automatic algorithm selects the system not only for call set up but also for handoffs. This implies that the signals transmitted by both the satellite and the terrestrial base station be continuously monitored by the terminal [26]. The primary factor used for the selection may be the quality of the received signals [25].

Many authors agree that the most common mode of operation will give priority to the terrestrial cellular system with satellite as a backup [2][32]. Some go as far as maintaining that, to conserve scarce satellite channels, a satellite to cellular handoff will ideally occur as soon as the mobile enters or reenters adequate terrestrial cellular coverage [6] [13].

2.5 Multilayer

The best representation of this type of integrated network is to consider it as a cluster of terrestrial cells superimposed with a satellite macrocell. The concept of layered cells is often used to study future PCS with clusters of street microcells overlaid with a few macrocells [14][21][35][38]. More elaborate architectures have been mentioned by various authors. Steele [39] alludes to picocells (few metres), nanocells (up to 10 m), nodalcells (10 to 200 m), microcells (10 to 400 m for pedestrians, 300 m to 2 km for vehicles), minicells (500 m to 3 km), macrocells (up to 5 km), large cells (5 to >35 km), megacells (20 to 100 km) and satellite cells (>500 km).

Some see the different layers assigned to different types of user, such as quasi-stationary subscribers (e.g. pedestrians) served by microcells and more mobile users (e.g. vehicles) served by macrocells [21]. Others see all users having equal access to each layer.

Few attempts have been made at studying the performance of such arrangements, in terms of traffic load sharing. Blocking and forced termination probabilities were examined at [37] by both by analysis and simulation. However, the scope of that study was restricted because it considered compulsory handoff from macrocell to microcell as soon as capacity becomes available in the latter; it assumed that all terminals have dual mode capability; and scrutiny of the analytical formulas used reveals that the study examined only situations where each microcell has complete monopoly over the overlaying macrocell capacity.

More comprehensive analyses of multilayer systems have been conducted and a portion of

queueing theory deals with overflow traffic [8] [41]. Unfortunately most of the published work applies to traffic that is directed to a secondary server group after being blocked by only one primary server group, not a cluster of many groups as it is the case here.

A cellular system with a mixed population of analog and digital terminals is analyzed in [24]. Analog subscribers can access analog channels only but digital subscribers can access analog channels if all digital channels are occupied. Here, the secondary group sees traffic coming from two sources: overflow of the primary group (digital terminals) and independent analog subscribers. However, since all traffic sources are confined within one cell again, that paper does not contribute significantly in the study of satellite macrocell overlaying a terrestrial cellular cluster.

2.6 Channel assignment and handoff in a cellular system

In a cellular system, the methods used to assign channels to cells vary over a wide range. Tekinay and Jabbari [42] offer an excellent review of channel assignment strategies and regroup them in fixed, flexible and dynamic. Each has its advantages and disadvantages. Fixed channel assignment is chosen for this complete thesis.

In a scenario with mobile terminals crossing cell boundaries, channel occupancy time is smaller than the call duration. Its distribution is best fitted with a negative exponential [18].

The handoff procedure (also called handover) is reviewed in [42]. While a mobile terminal is connected to the PSTN via a base station, the call may change to a new channel before

termination. Handoffs can be regrouped in three categories. An inter-cell handoff occurs when the mobile terminal crosses a cell boundary and sees the signal quality of the radio link drop below a certain threshold. The handoff connects the mobile terminal to the new cell and disconnects it from the old cell. Intra-cell handoffs occur when a call changes channel within the same cell, possibly to reduce interference. Finally, in an integrated network, inter-system handoffs occur when a call is switched from one channel of one system to a new channel in the other system.

Various procedures exist to implement handoff. Although many different factors may be used to determine whether a handoff is required, the received signal level is the most fundamental handoff initiation criterion [4][10]. To reduce the number of unnecessary handoffs caused by fading signals, a hysteresis must be included in the threshold level and the measurement on the received signal must be averaged over a certain period of time [5][10].

Three handoff procedures are examined in detail in [9] and [28]. The difference among the three lies in the role taken by the terminal in the handoff decision. In mobile controlled handoff (MCHO), the mobile terminal selects the best base station for the next connection, based on the quality of reception of the signals transmitted by the possible candidates. In network controlled handoff (NCHO), the decision is taken solely by the mobile switching centre (MSC) based on the reception of the mobile's signal by the surrounding base stations. Finally, in mobile assisted handoff (MAHO), the selection of the new base station is done by the MSC based partly on information transmitted by the mobile terminal on the quality of its reception of signals from surrounding base stations.

In MAHO and MCHO, handoff initiation is identified via the existing channel (backward handoff) or target channel (forward handoff) [4]. For inter-system handoff, four scenarios apply (satellite to satellite; terrestrial to terrestrial; satellite to terrestrial; terrestrial to satellite). No one protocol is suitable for all handoff scenarios [4] [13].

A fact recognized in most discussions on handoff is the much greater inconvenience caused by the forced termination of an ongoing call than blocking a new call attempt. It is widely accepted that, in the assignment of channels, a handoff must be given a higher priority than a new call in order to ensure a high quality of service. Reference [42] reviews handoff prioritization schemes: “Handover prioritization schemes are channel assignment strategies that allocate channels to handover requests more readily than originating calls. Prioritization schemes provide improved performance at the expense of reduction in the total admitted traffic.”

The same document presents two prioritization schemes. In the “guard channel” concept, a number of channels are reserved exclusively for handoffs. The remaining channels can be shared equally between handoffs and new calls. Note that no channel is specifically identified for handoffs only; it is simply that the cell stops accepting new calls if the number of free channels is below the critical number. “If reducing call drop probability is more important than reducing total call incompletions and if implementation cost is a major concern, then the guard channel is the best option.” [28]

The other scheme is the queueing of handoff requests. It takes into account the interval between

the moment that a handoff is positively recognized as required and the moment that the signal with the old cell is lost. This interval is called “degradation interval” [43]. If the new cell cannot assign a channel to the incoming mobile terminal when the requirement for a handoff is recognized, it keeps the handoff request in a queue and stops accepting new calls. As soon as a channel becomes free, it is assigned to the first terminal in the handoff request queue. If that terminal has not lost the link with its old cell, the handoff is implemented; otherwise the call is dropped.

More than one scheme have been proposed for queueing discipline. First-in-first-out (FIFO) is used in [20]. A more elaborate measurement-based prioritization scheme (MBPS) is examined in [43]. It takes into account the difference in degree of mobility among users and the resulting difference in the duration of the degradation interval. The handoff queue is dynamically reordered according to the received power levels of the terminals awaiting handoff. According to [43], MBPS is clearly more advantageous than FIFO.

Lin *et al* [28] introduce another scheme, called the sub-rating scheme (SRS) which creates a new channel by sub-rating an existing call. This new temporary channel is then assigned to the handoff attempt. Sub-rating means dividing an occupied full-rate channel into two half-rate channels. According to [28], SRS has the smallest call drop probability of all handoff schemes at the expense of extra hardware/software complexity and slight voice quality degradation. These drawbacks are not quantified.

2.7 Mobility models

Among the multitude of studies done on the handoff process, a panoply of mobility models have been used. A few examples follow.

[14] examines a highway scenario with all mobile terminals flowing with the same velocity.

[18] examines a two-dimensional space with all mobiles keeping the same constant speed with random changes in directions at arbitrary places and times. Each change of direction is drawn from a uniform distribution over $[0, 2\pi]$.

[20] assumes that the speed of the terminal remains constant in magnitude and direction while the terminal stays within a cell. As the terminal crosses a cell boundary, the speed and direction change randomly. Both magnitude and direction are uniformly distributed over $[0, V_{\max}]$ and $[0, 2\pi]$ respectively. This model was the subject of criticism in [47].

[28] and [36] use a simpler mobility model: the dwell time of a vehicle in a cell has a negative exponential distribution and so does the call duration. The ratio between both means is fixed.

[43] assumed a normal distribution for the degradation interval with a mean of 10 s and a standard deviation of 2 s.

In [33], handoff rates are examined in environments with varying cell sizes. In urban

environments, the cell size tends to decrease with the increase in traffic load. However the average speed of mobile terminals also tends to decrease with vehicle congestion. "The actual handoff rates do not increase rapidly at high user density (high penetration) due to the decrease in user mobility".

Rappaport [37] discusses the intricacies associated to an accurate mobility model: "Clearly, dwell time depends on many factors such as propagation conditions, the path a mobile platform follows, its velocity profile along the path, and especially the definition of communications range. The dependency is complex and burdensome. Much of the difficulty can be circumvented by characterizing dwell time as a random variable whose distribution function is known but chosen to accommodate empirical data."

Foschini *et al.* [16] suggest a very simple model that bypasses the unnecessary complexities of velocity, direction change, etc. A degree of mobility, θ , ($0 \leq \theta \leq 1$) is defined as the probability that, when a user stops occupying a particular channel in a cell, it is because user motion has forced the user to seek to hand off the call to another cell. Consequently, $(1 - \theta)$ is the probability of relinquishing a channel because the call is completed.

2.8 A requirement for further research

Many studies have been done on GEO mobile satellite service and on stand-alone LEO systems. Many others have dealt with new methods to increase the efficiency of terrestrial cellular systems such as improved channel assignment, handoff schemes and protocols. Significant effort is also devoted to the integration of satellite components with existing cellular systems to

build a global PCS [3][6][7][9][12][13][25][32].

However very little has been done on the connection that a DMT should attempt first when faced with the choice of either system of the integrated satellite-terrestrial network. Most documents reviewed in the research leading to this thesis have assumed that all terminals in such a system have dual mode capability. The reality is that, once the integrated network in place, the user population will be mixed, some equipped with SMTs and some equipped with DMTs.

There is a vacuum in the knowledge base. This thesis intends to fill that void. The contribution to the vast subject of PCS will be mainly appreciated by PCS operating companies, which will be most definitely concerned with the quality of service that they provide to their subscribers. Terminal manufacturers will also be interested in the connection algorithm that needs to be stored in the DMT circuitry.

CHAPTER 3

TERRESTRIAL/SATELLITE TRAFFIC MODEL

3.1 Introduction

This chapter describes the model used throughout the thesis and the methodology to measure the performance of various algorithms. Recall that the aim of this study is to examine algorithms to be used by a DMT for handling connections to either the satellite or the terrestrial system. Acampora and Naghshineh [1] suggest that the main factors in computing the grade of service for a delay-sensitive real-time system are the blocking probability and call dropping probability. Other considerations, such as quality of link, propagation delay, etc., are of lesser importance.

The main task in this thesis is the elaboration of a method to compute these two probabilities for each proposed algorithm.

Because of the magnitude of the network, we propose a analysis/simulation hybrid methodology to study the system. The input of the analysis is the traffic load and the DMT proportion. The output of this analysis is then used as the input of the Monte-Carlo simulation whose output is the set of two probabilities originally sought. Section 3.3 describes the mathematical analysis in a scenario where terminals are immobile. Section 3.4 explains the simulation for the same scenario. Finally inter-cell movement is added in the model. Section 3.5 describes how the necessary adaptation of the hybrid method.

3.2 General Description

The network is divided into two integrated systems. Both systems provide circuit switching service to a user population which generates calls with a Poisson arrival process at a call arrival rate per cell λ . Call duration has a negative exponential distribution with mean μ^{-1} . The user population is assumed infinite so the call arrival rate is independent of the number of calls being processed by either system. Blocked calls are cleared.

The terrestrial system is divided into contiguous cells with one base station per cell. There is a clear demarcation between cells: one mobile terminal may not be connected to two base stations simultaneously, except during the handshaking process inherent to handoffs. The size of a cell is inversely proportional with the traffic load density in that cell. Therefore, from an offered traffic point of view, all cells are identical. In order to keep the model as general as possible, no particular size or shape is assumed for the cells. Offered traffic is independent between cells and between users inside a cell. Fixed channel assignment is used. Each cell has n_t channels.

The satellite footprint is divided into beams, and only one beam is examined in this study. This beam of interest is assumed to cover a fixed number N_{Cell} of terrestrial cells and has L_c channels. The beam is immobile; it is radiated by either one geostationary satellite or a LEO satellite with steerable antennas rotating at an angular velocity that matches the apparent velocity of the ground. In the latter option, the footprint is continuously illuminated by a succession of beams from the same satellite or a succession of different satellites. Before a terminal user sees a satellite setting below the horizon, the radio link has been handed off to the

next satellite. A handoff transfers a complete footprint between satellites or beams. Since all calls are handed off simultaneously, there is no risk of dropping a call.

Both terrestrial and satellite systems are connected to the PSTN. Once a terminal has established a link with a base station or the satellite, the call is considered successful. Each call lasts until voluntarily completed by the user or when an unsuccessful handoff causes a forced termination (call dropping).

There is no shadowing or interference. A user covered by one of the two systems, can always establish communications with that system unless channels are not available. It can be assumed that a terminal covered by a system at a call setup stays so covered for the duration of a call.

Each user is equipped with either a SMT that allows connection with the terrestrial system only or a DMT that allows connection with either system. No user is equipped with a "satellite-only" SMT, although some DMT users are outside the coverage of the terrestrial system; in the remainder of this thesis, the traffic that they generate will be designated as the out-of-terrestrial-coverage load (OOTC load). There is no movement of these users to and from the terrestrial coverage. Within terrestrial coverage, the proportion of terminals that have dual mode capability is a parameter which varies between $\gamma = 0$ and $\gamma = 1$. It is fixed among all cells.

Upon call setup, a SMT can establish a connection with only the terrestrial system. If all channels inside the cell are occupied, the call is blocked. Similarly a SMT crossing a cellular boundary during a call must request a channel from the new cell. If all channels are occupied,

the call is dropped.

A DMT can choose from which system it requests a channel. The choice is made solely by the DMT in accordance with a determined algorithm. A number of different algorithms are studied in chapters 4 and 5. These algorithms assume that before call setup (or handoff) the DMT can sense the number of busy channels on each system. This is the only criterion used to make the decision. There is no preferred subscription to either system or commercial carrier. If a channel request made by a DMT for call setup (or handoff) is denied by the system first chosen, the DMT can always request a channel from the other system before the call is declared blocked (or dropped).

Calls may be handed off between the two systems or within cells of the terrestrial system, whether terminals are mobile or not. Intracell handoffs (change of channel within the same system and same cell) are not considered. The overhead, such as signalling load, not considered either, although it would not be negligible in practice.

3.3 Individual cell

Sections 3.3 and 3.4 assume stationary terminals or, equivalently, mobile terminals that do not cross inter-cell boundaries. Since calls cannot be dropped, only the blocking probability is used to determine the grade of service. Calls that are not blocked upon setup are allowed to continue until completed by the user. They can stay assigned to the same channel throughout their duration or, depending on the algorithm, they can be handed off between systems.

3.3.1 Cell states

The blocking probability can be determined by analyzing the channel occupancy in equilibrium. The number of channels occupied by the cell population can be represented by a cell state. Due to the memoryless property of calls, the state evolution of the cell follows a Markov process: system behaviour after time t depends only on the state of the cell at time t , regardless of how and when that state was reached. This system can be solved if the state transition probabilities are known.

The cell is in state (m_t, m_s) when its base station has m_t busy channels and the satellite provides service to m_s users inside that cell (or, equivalently, the user population inside that cell occupies m_s satellite channels). These variables can take any value $0 \leq m_t \leq n_t$, $0 \leq m_s \leq n_s$. Here n_t is the number of terrestrial channels per cell. The number n_s does not correspond to any physical quantity. It is the sum of the number m_s of satellite channels occupied by the cell of interest plus the total number of free satellite channels in the beam. Seen from a different angle, it is the number of channels L_c offered by the beam less the those occupied by users outside the cell of interest. The number of possible states per cell is $n_n = (n_t + 1) \cdot (n_s + 1)$.

3.3.2 State transitions in the two-dimensional model

A cell may increase the number of its busy channels (channel capture) or may decrease it (channel release). These two operations are explained as follows.

The only event that can cause a channel capture is the arrival of a new call. A channel capture is

reflected by a transition from (m_t, m_s) to $(m_t + 1, m_s)$ if the call takes a channel from the terrestrial system or a transition from (m_t, m_s) to $(m_t, m_s + 1)$ if the call takes a satellite channel. The ratio between the two transitions depends on the algorithm used by the terminal. If there is no blocking, the sum of the two transition rates is the call arrival rate λ .

A channel is released when the call is completed voluntarily by the user. The service rate for one call is μ , where μ is the inverse of the mean call duration. The state transition rate from (m_t, m_s) to $(m_t - 1, m_s)$ is $m_t \mu$. The state transition rate from (m_t, m_s) to $(m_t, m_s - 1)$ is $m_s \mu$.

We now have all state transitions rates. A set of algebraic equations detailing all state probabilities and all transition rates can be obtained for each algorithm. For instance, if $P_{m_t, m_s}(t)$ represents the probability that the cell occupies m_t terrestrial channels and m_s satellite channels at instant t , the set of equations applicable to algorithm A (described in section 4.2.1 at page 46) is:

$$\begin{aligned} \frac{d}{dt}P_{m_t, m_s}(t) = & -(\lambda + m_t\mu + m_s\mu) \cdot P_{m_t, m_s}(t) & \text{for } m_t < n_t \\ & + \lambda \cdot P_{m_t-1, m_s}(t) \\ & + (m_t + 1)\mu \cdot P_{m_t+1, m_s}(t) \\ & + (m_s + 1)\mu \cdot P_{m_t, m_s+1}(t) \end{aligned}$$

$$\begin{aligned} \frac{d}{dt}P_{m_t, m_s}(t) = & -(\gamma\lambda + m_t\mu + m_s\mu) \cdot P_{m_t, m_s}(t) & \text{for } m_t = n_t \\ & + \lambda \cdot P_{m_t-1, m_s}(t) & m_s < n_s \\ & + \gamma\lambda \cdot P_{m_t, m_s-1}(t) \\ & + (m_s + 1)\mu \cdot P_{m_t, m_s+1}(t) \end{aligned}$$

$$\begin{aligned} \frac{d}{dt}P_{m_t, m_s}(t) = & -(m_t\mu + m_s\mu) \cdot P_{m_t, m_s}(t) & \text{for } m_t = n_t \\ & + \lambda \cdot P_{m_t-1, m_s}(t) & m_s = n_s \\ & + \gamma\lambda \cdot P_{m_t, m_s-1}(t) \\ & + (m_s + 1)\mu \cdot P_{m_t, m_s+1}(t) \end{aligned}$$

where $P_{m_t, m_s} = 0$ for $m_t < 0$ or $m_s < 0$ or $m_t > n_t$ or $m_s > n_s$

Figure 3.1: State Transition Diagram of a Cell (Sample)

Figure 3.1 illustrates cell states and accompanying cell transitions. A break-down of transition diagrams into two (one for channel captures and one for channel releases) reduces the overall complexity. Figure 3.2 is an example of channel capture rates only of figure 3.1.

Figure 3.2: State Transition Diagram of a Cell (Channel Capture Only)

This two-dimensional representation of occupied channels is sufficient for the analysis of algorithms that do not involve inter-system handoffs. When inter-systems handoffs are included, a more elaborate representation is required, as explained in section 3.3.3.

At statistical equilibrium, the rate of occurrence of the transition into a state equals the rate of occurrence of the transition out of that state [8]. By replacing $\frac{d}{dt}P_{m_r, m_s}(t)$ by 0 and by dividing by μ , we get a new set of equations for algorithm A:

$$\begin{aligned} 0 = & -(\rho + m_t + m_s) \cdot P_{m_r, m_s} \quad \text{for } m_t < n_t \\ & + \rho \cdot P_{m_t-1, m_s} \\ & + (m_t + 1) \cdot P_{m_t+1, m_s} \\ & + (m_s + 1) \cdot P_{m_r, m_s+1} \end{aligned}$$

$$\begin{aligned} 0 = & -(\gamma\rho + m_t + m_s) \cdot P_{m_r, m_s} \quad \text{for } m_t = n_t \\ & + \rho \cdot P_{m_t-1, m_s} \quad m_s < n_s \\ & + \gamma\rho \cdot P_{m_r, m_s-1} \\ & + (m_s + 1) P_{m_r, m_s+1} \end{aligned}$$

$$\begin{aligned} 0 = & -(m_t + m_s) \cdot P_{m_r, m_s} \quad \text{for } m_t = n_t \\ & + \rho \cdot P_{m_t-1, m_s} \quad m_s = n_s \\ & + \gamma\rho \cdot P_{m_r, m_s-1} \\ & + (m_s + 1) P_{m_r, m_s+1} \end{aligned}$$

where $P_{m_r, m_s} = \lim_{t \rightarrow \infty} P_{m_r, m_s}(t)$ and $P_{m_r, m_s} = 0$ for $m_t < 0$ or $m_s < 0$ or $m_t > n_t$ or $m_s > n_s$

and where $\rho = \frac{\lambda}{\mu}$ is the offered load per cell, measured in erlangs (erl).

In the two-dimensional model, for set values of n_t and n_s , we have a system of $n_n = (n_t + 1) \cdot (n_s + 1)$ equations with n_n unknown quantities, each one being a state probability at statistical equilibrium. The resulting matrix is singular but is solved with the additional knowledge that the sum of all state probabilities equals unity.

The solution for one value of n_s gives a complete set of probabilities P_{m_i, m_j} , for $0 \leq m_i \leq n_i$, $0 \leq m_j \leq n_j$.

The value of n_s takes all possible values $0 \leq n_s \leq L_c$, where L_c is the total number of satellite channels available to the beam footprint. Using different values for $n_s = 0, 1, 2 \dots L_c$, results in an equal number of matrices to be solved independently. In the practical cases of interest, there exists a number n_p such that the solutions for $n_p \leq n_s \leq L_c$ are practically equal. Therefore only a set of $(n_p + 1)$ solutions needs to be retained for the simulation. The solution for $n_s = n_p$ can be used for all situations where $n_s = n_p \dots L_c$.

The first step in the computation of the blocking probability is almost complete. Since the terrestrial system is partitioned into equal cells, the analysis of one individual cell gives all the statistics required to determine the behaviour of the whole terrestrial system. The simulation portion will examine how the N_{Cell} cells share the L_c satellite channels and determine the overall blocking probability without the condition on n_s , imposed in the analysis.

Before proceeding with the simulation, only essential information needs to be retained from the analysis. Specific information is required about (1) total satellite channel transition rates and (2) blocking probability. All other information about terrestrial channel utilization may be discarded.

The total satellite channel transition rates are the probabilities that a cell, occupying m_s satellite channels, capture (or release) a satellite channel in a time unit, regardless of the number of

terrestrial channels it is using. The total satellite channel capture rate Λ_{m_i} is obtained by the following formula:

$$\Lambda_{m_i} = \sum_{m_s=0}^{n_s} P_{m_i, m_s} \cdot \lambda_{m_i, m_s}^{(s)}$$

where $\lambda_{m_i, m_s}^{(s)}$ is the satellite channel capture rate when the cell is in state (m_i, m_s) . For instance, in figure 3.1,

$$\lambda_{m_i, m_s}^{(s)} = \begin{cases} 0, & m_i < n_i \text{ or } m_s = n_s \\ \gamma\lambda, & m_i = n_i \text{ and } m_s < n_s \end{cases}$$

Similarly, the total satellite channel release rate M_{m_i} is obtained by the following formula:

$$M_{m_i} = \sum_{m_s=0}^{n_s} P_{m_i, m_s} \cdot \mu_{m_i, m_s}^{(s)}$$

where $\mu_{m_i, m_s}^{(s)}$ is the satellite channel release rate when the cell is in state (m_i, m_s) .

The second set of data required for the simulation portion is the blocking probability. The blocking probability must be differentiated in two quantities: the probability that a SMT call is blocked (SMT blocking probability) and the probability that a DMT call is blocked (DMT blocking probability).

Since offered calls follow a Poisson process, the SMT blocking probability is the proportion of time that all terrestrial channels in a cell are occupied. For a set value of n_i , it is easily

computed conditional on m_s :

$$P_{m_s}^{(B)} = P(n_t | m_s) = \frac{P_{n_t, m_s}}{P_{m_s}} .$$

where

$$P_{m_s} = \sum_{m_t=0}^{n_t} P_{m_t, m_s} .$$

The DMT blocking probability is the proportion of time that all terrestrial channels and all satellite channels are occupied. It is the SMT blocking probability conditional on $m_s = n_s$. This data is readily available from the analysis.

3.3.3 Inter-system handoffs

As explained above, the two-dimensional state representation is not sufficient when inter-system handoffs are involved in the algorithm. An inter-system handoff consists in a DMT call being transferred from the satellite to the terrestrial system or vice-versa without necessitating movement across cellular boundaries. It is important to note that a call can be handed off from the terrestrial system to the satellite only if at least one of the m_t occupied terrestrial channels is used by a DMT. Therefore, the two-dimensional diagram in figure 3.1 or 3.2 cannot represent such a transition because the state component m_t does not include any information about the distribution of occupied terrestrial channels between SMTs and DMTs. This is alleviated by differentiating the m_t occupied terrestrial channels into m_v channels occupied by DMTs and m_w occupied by SMTs, as illustrated in figure 3.3. Each former state (m_t, m_s) must now be considered as a superstate broken down into m_t different states (m_v, m_w, m_s) , such that

Figure 3.3: Break-down of terrestrial channel utilization by terminal user

$$m_v + m_w = m_t .$$

With algorithms that support inter-system handoffs, a channel may be captured via one of two mechanisms: (1) arrival of a new call or (2) a call being handed off from the other system. A channel may be released via one of two mechanisms: the call may be (1) completed voluntarily

Figure 3.4: Three-dimensional diagram of channel captures

by the user or (2) handed off to the other system.

The breakdown of superstates is illustrated in figure 3.3. State transitions (call capture only) are shown in figure 3.4. Figure 3.5 shows an example of intersystem handoff and an example of a

Figure 3.5: Two examples of inter-system handoffs

terrestrial channel capture immediately followed by a handoff of a DMT call from terrestrial to satellite. As with the two-dimensional representation, all transitions are known. The difference is that we have a system of n_n equations with n_n unknown quantities, where

$$n_n = \frac{(n_t + 1) \cdot n_t}{2} \cdot (n_s + 1)$$

3.4 Cluster of cells within one footprint

Section 3.3 described the method used to determine the channel occupancy probability for an individual cell, given the offered traffic load, the DMT proportion and an assumed number n_s of satellite channels available to that cell. This section elaborates on the simulation, which determines how users located in the cluster of N_{Cell} cells and the OOTC users share the limited number of satellite channels available. The number of free satellite channels in the cluster can be deduced and so can the number n_s of free satellite channels per cell which was assumed in the analysis. With this condition removed, the actual blocking probability is obtained.

The choice of simulation is justified by the complexity of any rigorous mathematical analysis of the network. Even with a small system, it would be difficult to model the call arrival process which the satellite is subjected to. This process is not a Poisson process because DMT users attempt to access the satellite only when the terrestrial system is saturated (or when it approaches saturation, depending on the algorithm used by DMTs). When a cell is under-saturated, it does not offer any call to the satellite. Since the terrestrial system is expected to handle the complete load most of the time, each cell may be seen by the satellite as idle for long periods of time.

On the other hand, a solution of this problem relying purely on simulation rather than a hybrid analysis/simulation methodology would be impractical. The large number of terrestrial cells in

the satellite beam multiplied by the number of terrestrial channels per cell would make the problem too large to handle by a common computer.

In the remainder of this section, we will refer to satellite channels only, unless specified otherwise.

As shown in section 3.3, the rate at which the cell captures additional channels is known, as well as the rate at which it releases channels. These two rates are conditional on the number of channels now occupied by the cell and the total number of channels available to that cell.

The simulation is an event-based one, where an event is the capture or the release of a channel by a cell. The simulation begins with all cells occupying $m_s = 0$ channels. As illustrated in figure 3.6, a random number is drawn to determine which cell is subject to the first event. Except for the very first event which is inevitably the capture of a channel, this random number also determines whether this event is a capture or a release, based on the number of channels now occupied by the cell and the two corresponding rates computed at the end of the analysis phase. The same procedure is repeated until a satisfactory number of events has been generated.

During this simulation, measurements are taken on the cells at regular intervals. These measurements are taken when steady state is reached. A measurement examines all $N_{Cell} = 1024$ cells one by one and looks at the number of occupied channels m_s and the number of channels available n_s and gets the two blocking probabilities (SMT and DMT) calculated during the analysis. If, during that measurement, no satellite channel is free, then both types of terminal are

Figure 3.6: Simulation flowchart

in a blocking position: a new call, originating from either terminal, would be blocked. The sum of SMT blocking probability and DMT blocking probability is retained. If, on the other hand, at least one satellite channel is free, then only SMTs are in a blocking position. Only the SMT blocking probability is retained.

Averaging over all N_{Cell} cells gives the mean blocking probability for the whole terminal population within terrestrial coverage at that time. Finally, a series of measurements are taken during a large period. The interval between consecutive measurements is kept large enough to avoid any correlation between successive measurements. The final result of the simulation is P_b , the blocking probability for any terminal located within coverage of the terrestrial system.

Seven different algorithms are tested with this procedure. Results are in chapter 4.

3.5 Mobile scenario

This section examines the performance of various algorithms when terminals roam between cells. Only movement between terrestrial cells is considered. Movement of a terminal in or out of the satellite footprint is negligible because it pertains only to mobile terminals near the perimeter of the footprint and the beam does not have a sharp boundary. Because of the sheer size of the footprint and the relatively short distance travelled by a mobile terminal during a call, the received power level does not vary enough to trigger a handoff request.

The mobility model suggested by Foschini *et al.* [16] is used.

In our network model, a handoff request is either accepted or blocked. Handoff requests are not queued at the MSC. A guard channel is reserved for handoffs.

With movement of terminals across cellular boundaries, our methodology to determine the grade of service must be modified in two ways. First, a call may drop before completion if the inter-cell handoff request is denied in the new cell. Service quality is consequently reduced and a new grade of service must account for the probability of dropped calls. Second, state transitions are more complex. A channel may now be captured via one of three mechanisms:

- (1) arrival of a new call,
- (2) a call being handed off from one system to the other or
- (3) a mobile user entering the cell while handling a call.

A channel may be released via one of four mechanisms: the call may be

- (1) completed voluntarily by the user,
- (2) handed off from one system to the other,
- (3) handed off from one cell to another (inter-cell movement) or
- (4) dropped after a failed handoff.

Because of these additional mechanisms, both channel capture rate and release rate are increased.

3.5.1 Grade of service

The new grade of service must measure the probability that an attempted call fails before voluntary completion. Failure include two possibilities: (1) call blocking which refers to a new

call that fails to capture a channel upon setup and (2) forced termination which refers to a call that is suddenly dropped before voluntary completion. In our scenario, this can be caused by channel unavailability only.

Because forced termination of a call is much more disruptive than blocking, the grade of service, G , is defined as

$$G = 0.9 \cdot P_d + 0.1 \cdot P_b \quad (3.1)$$

where P_d is the call dropping probability (or forced termination) and P_b is the blocking probability. Since P_b and P_d vary between 0 and 1, so does G . This simple formula has its limitations in that these two probabilities always have the same weights, regardless of the probability of single or multiple handoffs in a call. This is done on purpose in order to keep the model as general as possible. Any attempt to determine the exact weights to be given to each probability, would necessitate an analysis of the mean number of handoffs per call. This depends heavily on the size of the cell, velocity of mobiles, etc.

3.5.2 Influence of movement on channel capture and release rates

Mobility affects occupancy of terrestrial channels only, since a mobile crossing a cell boundary while connected to the satellite does not demand a channel in the new cell nor does it relieve a channel in the old cell. In the following analysis, calls refer to terrestrial calls only.

Mobiles crossing cell boundaries during calls raise the channel request rate. For each cell, the channel request rate is the sum of the new call arrival rate and the handoff arrival rate (the sum of the rate at which mobiles connected to the terrestrial system enter the cell and the rate at which terminals are handed off from the satellite to the terrestrial system). The following analysis is required to determine the channel request rate.

Let λ : new call arrival rate per cell (includes blocked calls)
 λ_{ho} : handoff arrival rate per cell (includes dropped calls)
 θ : proportion of channel releases that were caused by the mobile terminal exiting the cell of interest
 α : channel capture rate per cell.

In one time unit, α channels are captured in the cell. This quantity is the sum of the number of channels captured by new calls that are not blocked and the number of incoming terminals that do not have their calls dropped:

$$\alpha = \lambda_{ho} \cdot (1 - P_d) + \lambda \cdot (1 - P_b) \quad (3.2)$$

After α calls have successfully captured one channel each, $\alpha\theta$ of them will attempt to continue into a new cell before completion. These calls will request a channel when the terminals enter a new cell. Therefore,

$$\lambda_{ho} = \alpha\theta \quad (3.3)$$

By substituting (3.3) into (3.2), we get

$$\alpha = \frac{\lambda \cdot (1 - P_b)}{1 - [\theta \cdot (1 - P_d)]}$$

Consequently,

$$\lambda_{ho} = \frac{\theta \cdot \lambda \cdot (1 - P_b)}{1 - [\theta \cdot (1 - P_d)]}$$

We now have the two call arrival rates, which can be used in the state transition rates. Since P_b and P_d are not known at the outset, an iterative approach is necessary to find their exact value. A good initial assumption is $P_b = P_d = 0$.

Movement also affects the channel release rate. Foschini *et al.* [16] prove that the new channel release rate is increased to

$$\mu' = \frac{\mu}{1 - \theta}$$

We now have all channel release rates; as mentioned, channel capture rates are determined on an iterative process. The remainder of the analysis is done in a similar fashion to the one explained in section 3.3 . Before proceeding with the simulation, extraction of the essential information is done again, but differently than when there is no movement for two reasons.

First, because of the guard channel, the SMT blocking probability is the probability that one or less terrestrial channel is free:

$$P_{m_s}^{(B)} = P(n_t | m_s) + P(n_t - 1 | m_s) = \frac{P_{n_t, m_s} + P_{m_t - 1, m_s}}{P_{m_s}}$$

The DMT blocking probability is the proportion of time that one or less terrestrial channel is free and all satellite channels are occupied. It is the SMT blocking probability conditional on $m_s = n_s$.

Second, not only the blocking probability must be computed, but the call dropping probability is also required. A call handoff request from a SMT is denied when all terrestrial channels are busy. Therefore the SMT call dropping probability is the proportion of time that $m_t = n_t$:

$$P_{m_s}^{(D)} = P(n_t | m_s) = \frac{P_{n_t, m_s}}{P_{m_s}}$$

The DMT call dropping probability is the proportion of time that all terrestrial channels and all satellite channel are occupied. It is the SMT call dropping probability conditional on $m_s = n_s$.

With all probabilities known, the grade of service G is now attainable via (3.1). Four different algorithms are evaluated with this procedure. Results are in chapter 5.

CHAPTER 4

ALGORITHMS FOR A STATIONARY TERMINAL SCENARIO

4.1 Introduction

In this chapter, a restricted model is used where terminals are presumed stationary. This constitutes a stepping stone before the full mobility model is used in chapter 5. The user population is mixed; the proportion of terminals with dual mode capability ranges between $\gamma = 0$ and $\gamma = 1$. DMTs use an algorithm to determine which system a channel is assigned to them. All DMTs use the same algorithm.

Throughout this thesis, each cell has $n_t = 10$ channels in each of the uplink and downlink. This number is kept low to help reduce the computing load and is consistent with other studies on this subject [14][28]. The satellite beam covers $N_{Cell} = 1024$, which corresponds roughly to a beam diameter of 600 km (Iridium) and a terrestrial cell diameter of 20 km. This beams has $L_c = 350$ channels; this can be implemented with a transponder bandwidth of 1.75 MHz and a channel bandwidth of 5 kHz for compressed voice.

Seven algorithms are examined. The first four (A to D), do not support inter-system handoff: a connection with one system lasts from call setup to call completion. With algorithms E, F and G, the initiation or completion of a call may cause the inter-system handoff of a different call that is being processed within the same cell. Algorithm E supports such handoffs at call completion

only, F at call setup only, and G at call setup and call completion.

Each section in this chapter examines one algorithm and is divided in two parts: description of the algorithm and performance analysis. The sets of algebraic equations describing the algorithms have not been included to reduce the volume of text.

4.2 Algorithm A

4.2.1 Description

A DMT tries to set up a new call with the terrestrial system first. If all terrestrial channels are occupied ($m_t = n_t$), the DMT tries to connect with the satellite. If all satellite channels are occupied too, the call is blocked. There is no inter-system handoff.

Algorithm A is illustrated by two markovian state diagrams: one for the channel capture process (figure 4.1) and one for the channel release process (figure 4.2).

4.2.2 Performance Analysis

The blocking probability is computed for 13 different traffic loads and 11 different DMT proportions. The resulting blocking probability is illustrated in figure 4.3.

As seen in figure 4.3, the blocking probability increases monotonically with the offered load and decreases monotonically with the DMT proportion. While the first observation was expected, the second one was not obvious. Intuitively, for a given traffic load, an increase in the DMT

Figure 4.1. Channel capture process for algorithm A.

proportion translates into an increased flexibility of the network: there is a greater probability that the next call will originate from a DMT and, therefore, can be sent to the satellite if the terrestrial system is saturated. However it also translates into a greater demand for satellite channels. If a particular cell or group of cells momentarily generates a large demand for satellite channels because of its large DMT proportion, it will reduce the availability of such channels to other cells and increase the average blocking probability inside the beam. Of these two contradicting intuitive arguments, our experiments show that the first one is correct.

Figure 4.2. Channel release process for algorithm A.

Another observation from figure 4.3 is the smoothness of the surface at the edge closest to the reader. For $\gamma = 0$, cells do not use any satellite channel. Since the blocking probability can be computed by analysis only, the curve does not display any of the discontinuities typical of a Monte Carlo simulation.

Since we are looking for the algorithm that offers the best performance to subscribers, we can look at each algorithm by determining at which offered load the users suffer a given blocking

Figure 4.3. Blocking probability versus traffic load and DMT proportion for algorithm A.

probability, for a given DMT proportion. In this chapter, this offered load is termed “supported load”. It is defined as the traffic load per cell for which the blocking probability equals 0.01.

Before analyzing the variations of the supported load versus the DMT proportion, a qualitative analysis of the overall blocking probability is warranted. The average blocking probability within the terrestrial coverage of the beam, P_b , can be broken down into two components: $P_b(SMT)$ and $P_b(DMT)$ which are the blocking probabilities affecting SMTs and DMTs respectively. P_b is the weighted average of these two components:

$$P_b = (1 - \gamma) P_b(SMT) + \gamma P_b(DMT)$$

Although these two new quantities could be evaluated easily, they are introduced only to help make qualitative judgements in the interpretation of the results of the simulation.

Figure 4.4 shows the traffic load supported by algorithm A for a DMT proportion varying

Figure 4.4. Supported load, at which the blocking probability equals 0.01 for algorithm A.

between $\gamma = 0$ and $\gamma = 1$. For $\gamma = 0$, all terminals are SMTs; the terrestrial system does not share the load with the satellite. This is equivalent to a purely terrestrial cellular system with

independent cells. The blocking probability can be computed via the analysis methodology described in chapter 3, or even faster with the Erlang B formula, denoted in the United States by $B(s,a)$ and in Europe by $E_{1,s}(a)$ [8]:

$$P_b = B(s, a) = \frac{a^s / s!}{\sum_{k=0}^s a^k / k!}$$

where s : number of servers,

a : traffic load.

For 10 servers and 4.461177 erlangs per cell, the blocking probability is $P_b = B(10, 4.461177) = 0.01$.

As γ increases but stays small, the demand for satellite channels is well below the number L_c available for the complete beam. The blocking probability for DMTs is negligible and only SMTs suffer from blocking.

When γ approaches unity, there is a higher probability that all satellite channels are occupied; the DMT blocking probability is no longer negligible and has a greater weight in the overall blocking probability P_b . Therefore it becomes the limiting factor in the determination of the supporting load. This explains the reflex point around $\gamma = 0.8$ and the smaller slope for $\gamma > 0.8$.

All values for this supporting load were obtained for an OOTC load of 70 erlangs, which is approximately 1% of the total offered load in the beam. Figure 4.5 shows results with OOTC

Figure 4.5. Algorithm A: supported load for OOTC load = 0, 70, 140 and 350 erlangs.

loads of 0, 70, 140 and 350 erlangs. Three interesting observations are worthy of comment.

When the OOTC load is reduced from 70 erlangs to 0, the supported load per cell for $\gamma = 1$ improves by approximately 3.0%. Similarly, an increase of this load from 70 to 140 erl reduces the supported load per cell by 3.0%.

For an OOTC load equal to the total number of satellite channels (350 erl), the supported load still increases significantly with γ . It can be concluded that a large OOTC load does not significantly reduce the quality of service to DMTs inside terrestrial coverage.

Finally, an integrated system with DMTs only ($\gamma = 1$), all within terrestrial coverage (OOTC load = 0), supports a load of 6.79 erl/cell. In a purely terrestrial system, more than 13 channels per cell are required to support a load of 6.79 erl (from Erlang B formula). It can be concluded that the addition of an overlaying satellite beam of 350 channels gives more additional capacity than the addition of 3 terrestrial channels per cell for each of the $N_{Cell} = 1024$ cells.

4.3 Algorithm B

4.3.1 Description

With algorithm B, the concept of "soft guard channel" is introduced. A soft guard channel is a channel reserved **mainly** for new calls originated from SMTs. It is comparable to the guard channel reserved for inter-cell handoffs in a mobile terminal scenario as described in section 2.6 above. If only this guard channel is free and $(n_t - 1)$ out of n_t terrestrial channels are busy and a SMT sets up a new call, it will connect to this soft guard channel. However, a DMT setting up a new call will connect to a satellite channel. If all satellite channels are occupied, the DMT will be allowed to connect to the soft guard (terrestrial) channel rather than being blocked, hence the qualitative "soft". The objective is to reduce the SMT blocking probability by "diverting" DMTs to the satellite before the terrestrial system becomes saturated.

In algorithm B, the channel release process is the same as with algorithm A.

The diagrams of figures 4.6 (channel capture) and 4.2 (channel release) illustrate this algorithm.

Figure 4.6. Channel capture process for algorithm B.

4.3.2 Performance Analysis

Figure 4.7 shows the traffic load supported by algorithm B. For $\gamma = 0$ the supported load is the same as with algorithm A, since SMTs do not use either algorithm. As γ increases, the supported load increases again, but faster than with algorithm A. This is explained by the effort made by

Figure 4.7. Supported loads, at which the blocking probability equals 0.01, for algorithms A, B, C and D.

algorithm B to keep the last terrestrial free for a future SMT call, therefore reducing the blocking probability for SMTs. For $\gamma > 0.6$, the probability that all satellite channels are busy becomes important. Since the DMT blocking probability has a larger contribution in the overall blocking probability for those values of γ , the supported load reaches a plateau at approximately 6.2 erl/cell.

As γ approaches unity, algorithm B supports a lower traffic load than algorithm A. Cells are

more likely to use satellite channels, even if they have some terrestrial channels free. The greater demand on satellite channels increases the probability that all channels (both terrestrial and satellite) in a particular cell are occupied. Consequently these cells deny service to other cells that are already using all their terrestrial channels.

4.4 Algorithm C

4.4.1 Description

Algorithm C is similar to algorithm B, except that there are two soft guard channels; DMT calls start to be directed to the satellite if there are two or less free terrestrial channels instead of only one. Call release is as per algorithm A. Diagrams illustrate algorithm C at figures 4.8 and 4.2.

4.4.2 Performance Analysis

Figure 4.7 shows that algorithm C performs even better than algorithm B for low DMT proportions. However the improvement from algorithm B to C is not as marked as from A to B. Also the plateau is lower at approximately 5.8 erl/cell because of the greater demand for satellite channels.

4.5 Algorithm D

4.5.1 Description

A DMT tries to set up a new call via the satellite with a probability equal to $\frac{m_t}{n_t}$. For instance, if $n_t = 10$ and 4 terrestrial channels are occupied, the DMT tries to set up a new call with the satellite with a probability of 0.4 and the terrestrial system with a probability of 0.6. This is

Figure 4.8. Channel capture process for algorithm C

illustrated in figure 4.9. Inter-system handoffs are not supported and the channel release diagram of figure 4.2 applies here too.

4.5.2 Performance Analysis

As could have been expected and as shown in figure 4.7, algorithm D takes advantage of the satellite capacity at very low DMT proportions, but the probability that all satellite channels are occupied is higher than with the other three algorithms and the supported load reaches a plateau

Figure 4.9. Channel capture process for algorithm D

at only 5.3 erl/cell.

4.5.3 Comparison of algorithms A, B, C and D

A quick comparison of the four algorithms studied so far reveals that each one performs best for a given range of γ .

For $0 \leq \gamma < 0.2$, algorithm D performs best;

for $0.2 \leq \gamma < 0.5$, algorithm C performs best;

for $0.5 \leq \gamma < 0.8$, algorithm B performs best; and

for $0.8 \leq \gamma \leq 1$, algorithm A performs best.

The complete range for γ is divided in four approximately equal portions and no single algorithm offers a performance clearly superior to the others. Although the presence of DMTs in the population increases the flexibility of the network, these DMTs either (1) compete with SMTs for the terrestrial system or (2) with DMTs from other cells for the satellite. The complications come from the fact that limiting the competition in one area increases the competition in the other. Smarter algorithms might skillfully resolve this complex situation.

4.6 Algorithm E

4.6.1 Introduction

Algorithms A to D studied up to now do not support inter-system handoffs: once a call has captured a channel at setup, it continues utilizing this channel until completion. Algorithms E, F and G use inter-system handoffs during calls to better balance the load of each system as it evolves in time. Handoffs of DMT calls may occur when idle SMTs set up new calls or when other terminals free up channels by completing their calls.

4.6.2 Description

Algorithm E is one method of implementing the "satellite avoidance" measure advocated in the literature where all terminals have dual mode capability (see section 2.4 above). It is based on algorithm A: DMTs set up calls with the terrestrial system unless all terrestrial channels are occupied. The difference is in the channel release process: a DMT occupying a satellite channel

is handed off to a terrestrial channel as soon as one such channel becomes free.

Channel capture is the same as with algorithm A and is illustrated in figure 4.1. Channel release

Figure 4.10. Channel release process for algorithm E.

is shown by the markovian diagram of figure 4.10. Each dotted arrow represents a terrestrial channel release, immediately followed by a handoff of a DMT call from a satellite channel to the terrestrial channel that has just been released.

4.6.3 Performance Analysis

As shown in figure 4.11, algorithm E supports a very large load when the DMT proportion is

Figure 4.11. Supported loads, at which the blocking probability equals 0.01, for algorithms A to G.

close to unity. However, for a DMT proportion lower than 0.75, it offers the worst performance of all algorithms. Actually, if the DMT proportion is equal to the SMT proportion (if $\gamma = 0.5$), the supported load is only 9% better than if there were no DMT ($\gamma = 0$).

4.7 Algorithm F

4.7.1 Description

Algorithm F is based on algorithm B: a DMT tries to set up a new call with the satellite if there is one free terrestrial channel or less. The difference lies in the procedure occurring when a SMT sets up a call via the last free terrestrial channel. If this happens when at least one of the other ($n_t - 1$) terrestrial channels is used by a DMT, this DMT is immediately handed off to the satellite. In a more formal description of the process, if one SMT sets up a call while the following three conditions are met

- (1) $m_v + m_w = n_t - 1$ (i.e. there is only one free terrestrial channel),
- (2) $m_v > 0$ (i.e. at least one terrestrial channel is used by a DMT) and
- (3) $m_s < n_s$ (at least one satellite channel is free),

then the SMT takes the last terrestrial channel and one DMT is immediately handed off from the terrestrial system to the satellite. During this procedure, the last terrestrial (soft guard) channel is assigned to the SMT and momentarily raises the blocking probability of following SMT call setups, but as soon as the handoff is completed, another terrestrial channel assumes the role of soft guard, therefore reduces the blocking probability. The channel captured by the SMT occurs before the handoff of the DMT call. Even if the handoff protocol is lengthy (several handshakes exchanged between the SMT, the DMT and the MSC over a satellite link), the SMT call setup is not unnecessarily delayed.

The channel capture process for algorithm F is illustrated in figure 4.12. The peculiarity of algorithm F is identified by the thin arrow ($\longrightarrow$). The channel release process is the same as in algorithm A (figure 4.2).

Figure 4.12. Channel capture process for algorithm F

Note that if all terrestrial and all satellite channels are occupied, and one satellite channel becomes free at the completion of a call, there is no automatic handoff of another call from the terrestrial system to the satellite.

4.7.2 Performance Analysis

Figure 4.11 shows the marked improvement for small DMT proportions. Two important observations are the steep slope for $\gamma < 0.2$ and the fact that the supported load is the same as with algorithm B when γ approaches unity. They are explained as follows.

For a small γ , DMTs offer a very small load to the satellite. Consequently the probability that all satellite channels are occupied is negligible. The satellite is undersaturated and DMTs are almost guaranteed to be assigned a free satellite channel when required. Therefore, the joint probability that all n_t terrestrial channel are occupied and one of the n_t terminals is a DMT is also negligible. SMTs have virtually the whole terrestrial system to themselves. The SMT blocking probability $P_b(\text{SMT})$ can be computed with Erlang B formula based on the load offered by SMTs only (i.e. $(1 - \gamma) \rho$) as follows:

$$P_b(\text{SMT}) = B(n_t, (1 - \gamma) \rho).$$

The combined blocking probability is

$$P_b = (1 - \gamma) P_b(\text{SMT}) + \gamma P_b(\text{DMT})$$

Now $P_b(\text{DMT}) \cong 0$ for $\gamma \ll 1$. Therefore

$$P_b \approx (1 - \gamma) P_b(\text{SMT})$$

$$P_b \approx (1 - \gamma) B(n_t, (1 - \gamma) \rho)$$

The slope b of the curve (supported load versus DMT proportion) can be computed by applying

the two derivatives $\frac{\partial P_b}{\partial \gamma}$ and $\frac{\partial P_b}{\partial \rho}$ and dividing:

$$b = -\frac{\frac{\partial P_b}{\partial \gamma}}{\frac{\partial P_b}{\partial \rho}} = \frac{\rho}{1-\gamma} \cdot \frac{(n_i + 1)R - \rho(1-\gamma)R + \rho^{n_i+1}(1-\gamma)^{n_i+1}/n_i!}{n_i R - \rho(1-\gamma)R + \rho^{n_i+1}(1-\gamma)^{n_i+1}/n_i!}, \quad (4.1)$$

$$\text{where } R = \sum_{k=0}^{n_i} ((1-\gamma)\rho)^k / k!.$$

By substituting P_b with its actual value in the locus of the curve in figure 4.11 ($P_b = 0.01$) and γ with 0, we get a slope $b = 5.26$. The results of the simulation give a slope of $0.0537/0.01 = 5.37$ between $\gamma = 0$ and $\gamma = 0.01$.

The second observation in need of explanation pertains to the coincidence of algorithms B and F for high DMT proportions. For $\gamma > 0.8$, satellite channels are in high demand from the many DMTs and there is a high probability that they are all occupied. If $m_s = n_s$, one essential condition for inter-system handoff is lacking. Algorithm F without this handoff process is like algorithm B. This explains why the supported loads for algorithms B and F are equal for high DMT proportions.

4.8 Algorithm G

4.8.1 Description

Algorithm G is similar to algorithm F (i.e. inclusion of the soft guard channel, plus one inter-system handoff on an on going call as triggered by the initiation of an independent call) with

two additional handoffs triggered by the completion of independent calls. One of these occurs at the release of a terrestrial channel if the following two conditions are met: (1) one terrestrial channel was already free before this channel release ($m_t < n_t$) and (2) the cell is using at least one satellite channel ($m_s > 0$). The DMT using this satellite channel is then automatically

Figure 4.13. Channel release process for algorithm G.

handed off to the newly released terrestrial channel. This process aims at reducing the demand for satellite channels. The second one is a handoff of a DMT call from the terrestrial system to the satellite and occurs at the release of a satellite channel if all terrestrial channels are occupied. This process is another effort to protect the soft guard channel, in other words, reserve it for future use by SMTs.

4.8.2 Performance Analysis

Algorithm G shows a marked improvement over most other algorithms. For 0.95 of the complete DMT proportion range, algorithm G performs at least as well as any other algorithm. For $0.4 < \gamma < 0.9$, the improvement in supported load exceeds 1 erl/cell over the second best algorithm. The same steep slope for small values of γ as with algorithm F is present and it continues well after algorithm F reaches its plateau. Only for $\gamma > 0.95$, does algorithm E offer a better performance. A logical explanation is the effort made by algorithm G to keep one terrestrial channel free for SMTs, while these SMTs account for less than 0.05 of all terminals in the cells.

4.9 Discussion of Results

The introduction of the soft guard channel has paid off. Algorithm G uses this concept and adds a few more processes to reinforce it. This maximizes the probability that all terrestrial channels but one are occupied, therefore it reduces the SMT blocking probability (which, as stated above, is the proportion of time that all terrestrial channels are occupied) and reduces the demand for satellite channels.

CHAPTER 5

ALGORITHMS FOR A MOBILE TERMINAL SCENARIO

5.1 Introduction

In this chapter, terminals are mobile and may cross cellular boundaries. The degree of mobility, as defined in [16] (see section 2.7), is $\theta = 0.2$. All algorithms use one guard channel reserved for inter-cell handoffs. This guard channel is assigned exclusively to handoff requests caused by movement of terminals and the network blocks new calls rather than assigning them this guard channel. For this reason, and for the purpose of eliminating any confusion with “soft guard channel”, this channel is called “hard guard channel” in the remainder of this thesis. The measured grade of service includes the call dropping probability, as per formula (3.1) on page 41. Other parameters are unchanged from chapter 4.

Of the seven algorithms examined in the previous chapter, four proved interesting. These four algorithms (B, E, F and G) are modified to cater for the mobility of terminals and reduce the resulting call dropping probability. Their new versions are algorithms P, Q, R and S respectively. They all make use of one hard guard channel. Algorithm P is the simplest one where each call remains assigned to the same channel from setup to completion. Algorithms Q and R are more sophisticated in their channel release process and channel capture process respectively. Finally algorithm S is the most sophisticated of all. Algorithm Q is also a benchmark for comparison since it uses the satellite-avoidance technique proposed by various authors.

5.2 Algorithm P

Algorithm P is an adaptation of algorithm B where new calls can use up to $(n_t - 1)$ terrestrial channels; the n_t^{th} one is the soft guard channel in algorithm B and becomes the hard guard channel in algorithm P. If one terrestrial channel is free, SMT calls are blocked but SMT handoff requests are assigned the last channel. A call arrival or completion cannot cause another call to be handed off between systems. Calls may be handed off between systems only as a result of a boundary crossing. The channel release process is in its simplest form: channels are released on call completion or when a terminal using a terrestrial channel moves out of a cell. There is no resulting inter-system handoff affecting different calls.

A formal description of the channel capture process of algorithm P is contained in table 5.1.

Table 5.1 Channel capture process for algorithm P .

Event	Conditions	Result
New call from SMT	$m_t < n_t - 1$	SMT takes terrestrial channel
	$m_t \geq n_t - 1$	call blocked
New call from DMT	$m_t < n_t - 1$	DMT takes terrestrial channel
	$(m_t \geq n_t - 1) \text{ AND } (m_s < n_s)$	DMT takes satellite channel
	$(m_t \geq n_t - 1) \text{ AND } (m_s = n_s)$	call blocked
Entry into cell of interest of a SMT using a terrestrial channel in a previous cell	$m_t < n_t$	SMT takes terrestrial channel
	$m_t = n_t$	call dropped
Entry into cell of interest of a DMT using a terrestrial channel in a previous cell	$m_t < n_t$	DMT takes terrestrial channel
	$(m_t = n_t) \text{ AND } (m_s < n_s)$	DMT takes satellite channel
	$(m_t = n_t) \text{ AND } (m_s = n_s)$	call dropped

Algorithm P is illustrated by two markovian state diagrams: one for channel captures (figure 5.1) and one for channel releases (figure 5.2).

Figure 5.1. Channel capture process for algorithm P.

5.3 Algorithm Q

Algorithm Q is based on algorithm E. It minimizes satellite usage by implementing inter-system handoff on terrestrial channel release and ensures that, if a cell uses at least one satellite channel, the terrestrial system is used to its maximum and no channel other than the guard channel is free.

Figure 5.2. Channel release process for algorithm P.

The channel capture process is the same as with algorithm P (table 5.1). Table 5.2 contains a formal description of the channel release process of algorithm Q.

Algorithm Q is illustrated in figures 5.1 (channel capture) and 5.3 (channel release)

Table 5.2 Channel release process for algorithm Q.

Event	Conditions	Result
SMT of DMT using a terrestrial channel moves out of the cell or completes its call	$(m_t \leq n_t - 1) \text{ AND } (m_s = 0)$	terrestrial channel is released
	$(m_t \leq n_t - 1) \text{ AND } (m_s > 0)$	terrestrial channel is released, followed by automatic handoff of a DMT call from the satellite to the terrestrial system
	$m_t = n_t$	terrestrial channel is released
DMT using a satellite channel moves out of the cell or completes its call	any	satellite channel is released

Figure 5.3. Channel release process for algorithm Q.

5.4 Algorithm R

Algorithm R is based on algorithm F which supports inter-system handoff on SMT call setup and allows a SMT to be assigned the hard guard channel upon call setup as long as this can be immediately followed by an inter-system handoff. There is no handoff on call completion and the channel release process is the same as with algorithm P.

The formal description of the channel capture process for algorithm R is in table 5.3.

Table 5.3 Channel capture process for algorithm R .

Event	Conditions	Result
New call from SMT	$m_t < n_t - 1$	SMT takes terrestrial channel
	$(m_t = n_t - 1) \text{ AND } (m_v > 0)$ $\text{AND } (m_s < n_s)$	SMT takes terrestrial channel with immediate handoff of one DMT from terrestrial to satellite
	$(m_t = n_t - 1) \text{ AND}$ $((m_v = 0) \text{ OR } (m_s = n_s))$	call blocked
	$m_t = n_t$	call blocked
New call from DMT	$m_t < n_t - 1$	DMT takes terrestrial channel
	$(m_t \geq n_t - 1) \text{ AND } (m_s < n_s)$	DMT takes satellite channel
	$(m_t \geq n_t - 1) \text{ AND } (m_s = n_s)$	call blocked
Entry into cell of interest of a SMT using a terrestrial channel in a previous cell	$m_t < n_t - 1$	SMT takes terrestrial channel
	$(m_t = n_t - 1) \text{ AND } (m_v > 0)$ $\text{AND } (m_s < n_s)$	SMT takes terrestrial channel and immediate handoff of one DMT from terrestrial to satellite
	$(m_t = n_t - 1) \text{ AND}$ $((m_v = 0) \text{ OR } (m_s = n_s))$	SMT takes terrestrial channel. No resulting handoff
	$m_t = n_t$	call dropped

Table 5.3 Channel capture process for algorithm R (Continued).

Event	Conditions	Result
Entry into cell of interest of a DMT using a terrestrial channel in a previous cell	$m_t < n_t - 1$	DMT takes terrestrial channel
	$(m_t \geq n_t - 1) \text{ AND } (m_s < n_s)$	DMT takes satellite channel
	$(m_t = n_t - 1) \text{ AND } (m_s = n_s)$	DMT takes terrestrial channel
	$(m_t = n_t) \text{ AND } (m_s = n_s)$	call dropped

Algorithm R is illustrated in figures 5.4 (channel capture) and 5.2 (channel release).

5.5 Algorithm S

Algorithm S is based on algorithm G. The channel capture process is the same as with algorithm R (table 5.2 and figure 5.4); again, the hard guard channel can be assigned to a new call setup from a SMT, as long as an inter-system handoff can immediately free another terrestrial channel to assume the role of hard guard channel. The channel release process is exactly the same as with algorithm G (figure 4.13 on page 66). Its set of equations is at annex B.

5.6 Performance analysis

The grade of service provided by algorithm P is computed for 13 different traffic loads and at 11 different DMT proportions varying between 0 and 1. The results are illustrated in figure 5.5. Again, the blocking probability increases monotonically with the offered load and decreases monotonically with the DMT proportion.

Figure 5.4. Channel capture process for algorithm R.

Figure 5.5. Grade of service versus traffic load and DMT proportion for algorithm P.

Figure 5.6 shows the traffic load supported by all four algorithms for a DMT proportion varying between $\gamma = 0$ and $\gamma = 1$. In this chapter, a new definition of “supported load” is required. Since the call dropping probability is accounted for in the grade of service $G = 0.9 \cdot P_d + 0.1 \cdot P_b$, the supported load is defined as the traffic load per cell for which the grade of service equals 0.002. P_b is not set and could take any value between 0 and 0.02. Therefore, the results of chapter 4 are not comparable with those of chapter 5. However, it should be noted that the

Figure 5.6. Supported loads, at which the grade of service equals 0.002, for algorithms P, Q, R and S.

empirical data collected has P_b as approximately equal to 0.01 (within 10%) when $G = 0.002$. No explanation is offered for this.

As expected, since the algorithms of chapter 5 are based on corresponding algorithms of chapter 4, there are striking similarities between the curves in figure 5.6 and those in figure 4.11 on page 61, especially when curves are compared on a one-to-one basis (B with P; E with Q; F with R;

G with S).

Some similarities also apply to more than one curve in each group. For instance, all curves converge toward the same supported load of 3.88 erl/cell for $\gamma = 0$ in the mobile scenario (4.46 erl/cell in the stationary scenario). Algorithms R and S coincide for $\gamma < 0.2$ and exhibit a steep slope, in the same fashion that algorithms F and G do.

Algorithms P and R share the same supported loads at $\gamma = 1$, for the same reason that B and F share the same plateau: when there is a high probability that the satellite is saturated (because of the large DMT proportion), the inter-system handoff peculiar to algorithm R is rarely implemented. Algorithm R without this handoff is like algorithm P (see page 65).

There are a few noticeable differences. For instance, the absolute value of the supported loads is lower in the mobile terminal scenario. This is due to the difference in the performance measurement (blocking probability counts for only 0.1 of the grade of service in chapter 5).

The main difference however is the absolute superiority of algorithm S over the complete range of DMT proportions, unlike algorithm G which does not perform as well as E for $0.95 < \gamma < 1$. The use of a hard guard channel for all algorithms in the mobile scenario prevents algorithm Q from overtaking S even when the DMT proportion approaches $\gamma = 1$.

5.7 Performance analysis of algorithm S under varied conditions

Given the impressive performance of algorithm S, it is important to submit it to varying environment conditions. Up to now, these conditions were set as $L_c = 350$ satellite channels, $N_{Cell} = 1024$

cells in the footprint, OOTC load = 70 erlangs, $G = 0.002$ as the grade of service used in the definition of supported load and a degree of mobility $\theta = 0.2$. Many of these can be set during the design of the network, as opposed to the traffic load and the DMT proportion which are mainly dependent on subscribers. Therefore a close examination of the performance with different parameters is in order.

Figure 5.7. Supported loads, at which the grade of service equals 0.002, for algorithms Q and S and $L_c = 87, 350$ and 1400 channels available at the satellite. $N_{Cell} = 1024$, OOTC = 70 erls, $\theta = 0.2$.

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PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
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Figure 5.8. Supported loads, at which the grade of service equals 0.002, for algorithms Q and S and $N_{Cell} = 256, 1024$ and 4096 terrestrial cells covered in the footprint. $L_c = 350$ channels, OOTC = 70 erls, $\theta = 0.2$.

Figures 5.7 to 5.11 illustrate this performance when the parameters are set to a few different values.

In all cases, it can be seen that the performance curve of algorithm S keeps the general shape and that algorithm S performs always as well as algorithm Q and often much better.

Figure 5.9. Supported loads, at which the grade of service equals 0.002 for algorithms Q and S and OOTC = 0, 70, 140 and 350 erlangs. $L_c = 350$ channels, $N_{Cell} = 1024$, $\theta = 0.2$.

5.8 Discussion of Results

Among the four algorithms studied in this chapter, algorithm Q, the one that implements the satellite-avoidance policy recommended by many authors, offers the worst performance for $0 \leq \gamma \leq 0.9$.

Figure 5.10. Supported loads, at which the grade of service equals $1.25e-04$, $5e-04$ and $2e-03$ for algorithms Q and S. $L_c = 350$ channels, $N_{Cell} = 1024$, $\theta = 0.2$.

With algorithm S, the last terrestrial channel fulfills two roles: it acts as the soft guard channel (concept developed for algorithms F and G in the stationary scenario) and as the hard guard channel (developed to reduce the dropping probability). Three inter-system handoffs developed for algorithm G are also incorporated to ensure a maximum use of the terrestrial system, while the soft

Figure 5.11. Supported loads, at which the grade of service equal 0.002 for algorithms Q and S and for a degree of mobility $\theta = 0, 0.2$ and 0.4 . $L_c = 350$ channels, $N_{Cell} = 1024$, OOTC = 70 erls.

guard channel remains free. It also allows the assignment of the guard channel to SMT new calls for the short period required to complete the handoff of a different call. Algorithm S offers the best grade of service, G , for all DMT proportions. Only in the extreme cases of $\gamma = 0$ and $\gamma = 1$, does it perform only as well as algorithm Q. This outstanding performance holds even if external conditions (L_c , N_{Cell} , OOTC and θ) cover a wide range.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Conclusion

We have examined an integrated satellite-terrestrial cellular network and the grade of service provided to a mixed population of SMTs and DMTs. The grade of service was based on the blocking probability and call dropping probability. Both probabilities were computed by a hybrid method of analysis and Monte Carlo simulation. We have concentrated on finding the algorithms that dictate which connection DMTs should use during call setup or handoff.

The aim of the thesis was to study the consequences of restricting the DMT access to the satellite when not all terminals have dual mode capability and to investigate other satellite access policies. The aim was met and the thesis showed that minimizing the use of the satellite offers a good performance only when all terminals have dual mode capability. When there are some SMTs in the population, the performance decreases rapidly with an increase in the SMT proportion and the satellite-avoidance algorithm soon becomes the worst performer of all.

Many other algorithms were investigated to correct this situation. The objective was to maximize the use of the terrestrial system by DMTs without creating a prohibitive SMT blocking probability.

The best performance is reached when DMTs use a soft guard channel on the terrestrial system and take every possible measure to exploit its advantages, such as combining it with the hard guard channel required to reduce the call dropping probability and protecting it with inter-system handoffs that involve a dynamic interaction of independent calls within the same cell. When such a strategy is employed, the supported load is increased by as much as 57% for certain DMT proportions.

Most significantly, this strategy outperforms all others for any DMT proportion. This is a major finding since operating companies, when delivering service to a mixed SMT-DMT proportion, have very little control over the SMT-DMT ratio. Moreover, this SMT-DMT ratio is subject to variations on both temporal and spatial dimensions.

6.2 Summary of Contributions

1. When the blocking and call dropping probabilities are the only considerations, restricting access to the satellite unless it is absolutely necessary will generally reduce the supported load.
2. Using a soft guard channel in the terrestrial system improves the performance of the network, especially for small DMT proportions.
3. Using two soft guard channels instead of only one improves the performance for some DMT proportions and reduces it for some others. Overall, there is no significant improvement.
4. Handing off some calls between systems when other calls are set up or completed improves the performance significantly, as long as these extra measures are used to strengthen the soft guard channel principle. This improvement is felt for all DMT proportions.

6.3 Recommendation for future research

Studies similar to this one should be conducted on variations of the scenario, namely with different channel allocation strategy or handoff prioritization schemes. Different types of traffic and switching techniques should also be studied.

New factors could be introduced to measure the quality of service, such as cost, propagation delay, and signaling load (which may be considerable, relatively to the narrow band of compressed voice channels).

More complex research could be done with heterogeneous traffic loads. If the population density varies from very high (in a city core) to almost zero, cell dimensions and offered traffic loads vary considerably. Also, in a city core, the quality of a satellite link suffers much from the shadowing created by high rise buildings. If DMTs avoid the satellite completely and rely exclusively on the terrestrial system, only a small traffic load is supported. On the other hand, having DMTs go back and forth between both systems as the quality of the link varies in time and location, creates a large demand for inter-system handoffs and increases the signalling load dramatically. The advantages and disadvantages of each option should be investigated.

Finally, continuation of this study with a LEO satellite beaming a moving footprint would be a challenge. In this new scenario, the number of terrestrial cells within the footprint would vary rapidly in time. Since the first part of the methodology of this thesis (the mathematical analysis) computed the behaviour of a cell at steady state, it would not be appropriate to apply it here; a new methodology would have to be used. Such research is nevertheless required since most

commercial proposals of PCS via LEO satellite call for moving footprints.

ANNEX A

RELIABILITY OF THE SIMULATION

The type of simulation run as part of this research is explained in chapter 3. Since all the curves in chapters 4 and 5 were based on results of this simulation, it was subjected to some analysis in order to validate its reliability. Three tests were conducted to determine:

- (1) the number of events required to reach steady state,
- (2) the autocorrelation of the output, and
- (3) estimation of the 95% confidence interval of the results.

Steady state

The aim of the first test was to determine what is the appropriate number of events at the beginning of each simulation that have to be judged as making the transient phase and have to be discarded.

In this test, the simulation was run with algorithm A and the parameters were $\rho = 7$ erl/cell and $\gamma = 1$ which are “demanding” on the satellite channels. Initial conditions were set as each cell occupying 0 satellite channel, including the OOTC cell. The number of busy satellite channels, l_s , was recorded at each event. Recall that an event is the capture or release of a satellite channel by any cell. The simulation lasted over 4000 events. It was assumed that the first 1000 events made the transient phase. The average number of busy satellite channels over the last 3000 events was 347.282. This simulation was run over three more replications and the four averages had a mean

of 347.14 and a 95% confidence interval ranging from 345.91 to 348.36.

These same four replications were examined again to determine in each case, the number of events required by l_s to reach its average. The mean length of the transient behaviour was 1050 events, with the upper limit of the 95% confidence interval being 1123. Four different replications were run with $\rho = 5$ erl/cell and $\gamma = 0.4$. The upper limit of the 95% confidence interval was 977.

Consequently, for all simulations conducted in this thesis, the length of the transient behaviour was taken as lasting for 1200 events. To increase the probability that these 1200 events included the whole transient phase, each simulation started with initial conditions of each cell occupying 0 satellite channel, but the OOTC cell occupying a number of channels equal to the offered load. This is a valid starting approximation since the carried load of a queuing system at steady state (the average number of busy servers) is equal to its offered load if the blocking probability is negligible.

Autocorrelation of l_s

The simulation was run with three new sets of values for ρ and γ , with three replications each. The autocorrelation of the number of busy satellite channels, l_s , was computed and was found to drop below 0.3 in absolute value for a lag of 100 events. Consequently, an interval of 200 or 201 events between measurements was chosen for all simulations in this thesis.

The random choice of either 200 or 201 events is required for the following reason. We know that

when all L_c satellite channels are busy, the blocking probability is much larger than if at least one satellite channel is free. We also know that between two saturations of these L_c channels, there is an even number of events (as many captures as releases). Therefore, in order to avoid any correlation of the probability that all L_c satellite channels are occupied, the exact length of the interval was chosen as odd or even at random after each measurement.

Confidence Interval on P_b

The confidence interval on the actual output of the simulation (P_b or G) was calculated and found to depend heavily on the number of measurements taken in the simulation and on the DMT proportion γ . As stated in section 4.2.2, the confidence interval was 0 when $\gamma = 0$ regardless of the number of measurements. As γ is raised, the number of measurements has to increase in order to give reliable results. For instance, with algorithm S, this number can be kept as low as 30 when $\gamma < 0.2$ but must go up to 2000 when $0.5 < \gamma \leq 1$ to get a confidence interval of 0.0025 for $P_b = 0.01$ (or 0.0005 for $G = 0.002$) on a set of 5 replications. The extreme case is for algorithm Q with a target grade of service $G = 1.25e-04$ (figure 5.10 on page 83): for $\rho = 6.82$ and $\gamma = 1$, a set of 5 replications of 30,000 measurements each gave a 95% confidence interval ranging from $G = 1.11e-04$ to $1.46e-04$.

ANNEX B

EQUATION SET

DESCRIBING ALGORITHM "S"

Let $P_{m_v, m_w, m_s}(t)$ the probability that the cell is in state (m_v, m_w, m_s) at time t . Then

$$\begin{aligned} \frac{d}{dt} P_{m_v, m_w, m_s}(t) = & -(\lambda_T + m_v \mu + m_w \mu) \cdot P_{m_v, m_w, m_s}(t) & \text{for } m_v + m_w < n_t - 1 \\ & + \gamma \lambda_T \cdot P_{m_v - 1, m_w, m_s}(t) & m_s = 0 \\ & + (1 - \gamma) \cdot \lambda_T \cdot P_{m_v, m_w - 1, m_s}(t) \\ & + (m_v + 1) \cdot P_{m_v + 1, m_w, m_s}(t) \\ & + (m_w + 1) \cdot P_{m_v, m_w + 1, m_s}(t) \end{aligned}$$

$$\begin{aligned} \frac{d}{dt} P_{m_v, m_w, m_s}(t) = & -(\gamma \lambda_{ho} + m_w \mu) \cdot P_{m_v, m_w, m_s}(t) & \text{for } m_v = 0 \\ & + (1 - \gamma) \cdot \lambda_T \cdot P_{m_v, m_w - 1, m_s}(t) & m_w = n_t - 1 \\ & + (m_w + 1) \cdot P_{m_v, m_w + 1, m_s}(t) & m_s = 0 \\ & + (m_s + 1) \cdot P_{m_v, m_w, m_s + 1}(t) \end{aligned}$$

$$\begin{aligned}
\frac{d}{dt}P_{m_v, m_w, m_s}(t) &= -(\lambda_T + m_v\mu + m_w\mu) \cdot P_{m_v, m_w, m_s}(t) & \text{for } m_v > 0 \\
&+ \gamma\lambda_T \cdot P_{m_v-1, m_w, m_s}(t) & m_v + m_w = n_t - 1 \\
&+ (1-\gamma) \cdot \lambda_T \cdot P_{m_v, m_w-1, m_s}(t) & m_v = 0 \\
&+ (m_v+1) \cdot P_{m_v, m_w, m_s+1}(t) \\
&+ (m_w+1) \cdot P_{m_v-1, m_w+1, m_s+1}(t)
\end{aligned}$$

$$\begin{aligned}
\frac{d}{dt}P_{m_v, m_w, m_s}(t) &= -(\gamma\lambda_T + m_w\mu + m_s\mu) \cdot P_{m_v, m_w, m_s}(t) & \text{for } m_v = 0 \\
&+ (1-\gamma) \cdot \lambda_{ho} \cdot P_{m_v, m_w-1, m_s}(t) & m_w = n_t \\
&+ (m_s+1) \cdot P_{m_v, m_w, m_s+1}(t) & m_v < n_v
\end{aligned}$$

$$\begin{aligned}
\frac{d}{dt}P_{m_v, m_w, m_s}(t) &= -(m_w\mu + m_s\mu) \cdot P_{m_v, m_w, m_s}(t) & \text{for } m_v = 0 \\
&+ (1-\gamma) \cdot \lambda_{ho} \cdot P_{m_v, m_w-1, m_s}(t) & m_w = n_t \\
&+ (m_s+1) \cdot P_{m_v, m_w, m_s+1}(t) & m_v = n_v
\end{aligned}$$

$$\begin{aligned}
\frac{d}{dt}P_{m_v, m_w, m_s}(t) &= -((1-\gamma)\lambda_{ho} + \gamma\lambda_T + m_w\mu + m_s\mu) \cdot P_{m_v, m_w, m_s}(t) & \text{for } m_v = 0 \\
&+ \gamma\lambda_T \cdot P_{m_v, m_w, m_s-1}(t) & m_w = n_t - 1 \\
&+ (1-\gamma) \cdot \lambda_T \cdot P_{m_v+1, m_w-1, m_s-1}(t) & 0 < m_v < n_v \\
&+ (m_w+1) \cdot P_{m_v, m_w+1, m_s}(t) \\
&+ (m_v + m_s + 1) \cdot P_{m_v, m_w, m_s+1}(t)
\end{aligned}$$

$$\begin{aligned}
\frac{d}{dt}P_{m_v, m_w, m_s}(t) = & -(\lambda_T + m_v\mu + m_w\mu + m_s\mu) \cdot P_{m_v, m_w, m_s}(t) & \text{for } m_v > 0 \\
& + (1 - \gamma) \cdot \lambda_T \cdot P_{m_v, m_w, m_s - 1}(t) & m_v + m_w = n_t - 1 \\
& + (1 - \gamma) \cdot \lambda_T \cdot P_{m_v + 1, m_w - 1, m_s - 1}(t) & 0 < m_s < n_s \\
& + (m_w + 1) \cdot P_{m_v, m_w + 1, m_s}(t) \\
& + (m_v + m_s + 1) \cdot P_{m_v, m_w, m_s + 1}(t) \\
& + (m_w + 1) \cdot P_{m_v - 1, m_w + 1, m_s + 1}(t)
\end{aligned}$$

$$\begin{aligned}
\frac{d}{dt}P_{m_v, m_w, m_s}(t) = & -(\lambda_{ho} + m_v\mu + m_w\mu + m_s\mu) \cdot P_{m_v, m_w, m_s}(t) & \text{for } m_v + m_w = n_t - 1 \\
& + \gamma \cdot \lambda_{ho} \cdot P_{m_v - 1, m_w, m_s}(t) & m_s = n_s \\
& + (1 - \gamma) \cdot \lambda_{ho} \cdot P_{m_v, m_w - 1, m_s}(t) \\
& + (m_v + m_s + 1) \cdot P_{m_v + 1, m_w, m_s}(t) \\
& + (m_w + 1) \cdot P_{m_v, m_w + 1, m_s}(t)
\end{aligned}$$

$$\begin{aligned}
\frac{d}{dt}P_{m_v, m_w, m_s}(t) = & -(m_v\mu + m_w\mu + m_s\mu) \cdot P_{m_v, m_w, m_s}(t) & \text{for } m_v + m_w = n_t \\
& + \gamma \cdot \lambda_{ho} \cdot P_{m_v - 1, m_w, m_s}(t) & m_s = n_s \\
& + (1 - \gamma) \cdot \lambda_{ho} \cdot P_{m_v, m_w - 1, m_s}(t)
\end{aligned}$$

$$P_{m_v, m_w, m_s}(t) = 0$$

otherwise.

where $P_{m_v, m_w, m_s}(t) = 0$ for $m_v < 0$ or $m_w < 0$ or $m_s < 0$ or $m_v > n_t$ or $m_w > n_t$ or $m_s > n_s$,

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