End-to-End Performance Enhancement of W-CDMA Mobile Satellite Systems for Web Traffic

By

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End-to-End Performance Enhancement of W-CDMA Mobile Satellite Systems For Web Traffic

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Abstract

The performance of W-CDMA for third generation (3G) land mobile satellite systems for Web traffic is examined. It is assumed that the satellite channel is Rice-lognormal .

It is found that slow fading (due to low mobility) and power control error (due to uncompensated shadowing) inherits in mobile satellites severely degrades the performance of 3 G W-CDMA mobile satellite systems. Hence, a combination of powerful error correction and diversity techniques is proposed to enhance the performance of both the uplink and downlink of 3G W-CDMA mobile satellite systems for Web traffic.

The W-CDMA mobile satellite links must operate at low E_b/N_0 , since they are power limited in the downlink while they are interference limited in the uplink. Thus, this work proposes different error correction and diversity schemes for the uplink and the downlink to minimize both the required E_b/N_0 and fading margin in both links for enhanced performance.

A macrodiversity scheme is proposed for the downlink, which must be employed at the mobile Web terminal rather than at the satellite itself due to the space limitation on board the satellite. Meanwhile, a space-time transmit diversity (STTD) technique is examined for the uplink. The error correction techniques include turbo code for the downlink, convolutional code for the uplink, a radio link protocol (RLP) and interleaving. The RLP uses the same retransmission mechanism as that used in the IS-99 standard for terrestrial code division multiple access (CDMA) systems.

The use of convolutional coding instead of turbo coding in the uplink is justified by the fact that the uplink operates at low data rate (i.e. 12.5 kbps), as it will be used to carry only TCP acknowledgements and HTTP object requests. It is known that at such low data rates the performance of convolutional code outperforms that of turbo code, it is also due to the fact that convolutional decoding is much simpler to implement especially on board the satellite. The use of STTD diversity in the uplink instead of macrodiversity

is due to the fact that macrodiversity cannot be employed on board the satellite due to the space limitation as explained earlier.

This research has shown that the use of diversity techniques and especially macrodiversity in the downlink greatly enhances the Web traffic capacity of 3 G W-CDMA mobile satellite systems in the presence of major degradation factors such as slow fading and power control errors. On the basis of this work, it is strongly recommended that diversity techniques be employed as an essential and integral part of the satellite component of the universal mobile telecommunication services (UMTS). This improvement in performance will also lead to significant reduction in the channel operational cost, which represents a major challenge in the deployment of the satellite component of UMTS.

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List of Abbreviations

3GPP	3 rd Generation Partnership Project
ACK	Acknowledgement
ARQ	Automatic Repeat Request
BER	Bit Error Rate
CWND	Congestion Window
FIR	Finite Impulse Response
GEO	Geostationary Earth Orbit
GIF	Graphic Interchange Format
GPRS	Group Packet Radio System
GSM	Group System for Mobile Communications
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
Inmarsat	International Maritime Satellite Organization
IP	Internet Protocol
JPEG	Joint Photographic Experts Group
MEO	Medium Earth Orbit
MH	Mobile Host
MIME	Multipurpose Internet Mail Protocol
MSS	Maximum Segment Size
OVSF	Orthogonal Variable Spreading Factor
PCE	Power Control Error
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RCVWND	Receive Window
RFC	Request For Comment
RLN	Rice Lognormal
RLP	Radio Link Protocol
RTD	Round Trip Delay
RTT	Round Trip Time
SACK	Selective Acknowledgement
S-PCN	Satellite Personal Communication Network
SSTHRESH	Slow Start Threshold
STTD	Space Time Transmit Diversity
TCP	Transmission Control Protocol
TTI	Transmission Time Interval
UMTS	Universal Mobile Telecommunication Services
VSAT	Very Small Satellite Aperture Terminal
W.R.T	With Respect To
WAN	Wide Area Network
W-CDMA	Wideband Code Division Multiple Access

Chapter 1

Introduction

1.1 Background

The market demand for mobile Internet communications has been increasing since the introduction of wireless Internet access services in 1998. In Europe, projections [1] indicate that by 2005 mobile multimedia devices will be worth up to 60% of the European market for the mobile terminals (up to US \$ 25 billion). This growth has been driven by a number of forces, including, that of business-to-business e-business, which forecast to be a US \$ 1.1 trillion market (worldwide) by 2003[2].

Studies conducted by European space agency (ESA) indicate that even with 60-70 % of area being covered by Pan-European terrestrial systems (i.e. GSM and GPRS), a significant traffic demand exists for areas not covered by the terrestrial systems.

This demand could be satisfied by a mobile satellite system. The mobile satellite element of universal mobile telecommunication service (UMTS) is therefore seen in a complementary role rather than in competition with the terrestrial UMTS or an all IP mobile system (4th Generation Mobile System). One possible scenario may be that initially the mobile satellite system provides Internet services to the rural areas together with areas still not covered by the terrestrial system. This service area is then gradually diminished as the terrestrial system expands until an optimum point is reached where the two systems co-exist optimally.

ING Barings has forecasted recently that the worldwide mobile satellite market will be worth over US \$ 4 billion in 2004 doubling to over US \$ 8 billion in 2009. Data traffic dominated by the Web has been increasing rapidly in some major satellite systems e.g. data communications over Inmarsat satellite network has grown by an average of 50%

each year since 1995, and Inmarsat expects that data traffic will utilize 70% of its current network by 2003[3].

Several companies (e.g., Alcatel, Hughes, INMARSAT) have recently announced plans to build large satellite systems to provide commercial broadband data services. These systems are expected to offer Internet access to remote locations and to support virtual private networks for widely scattered locations [4]. However, the performance of data communications protocols and applications over such future systems is the subject of heated debate in the research community. This debate has been particularly intensive regarding the transport-level protocol in the Internet TCP/IP protocol suite (namely, the transmission control protocol).

Some researchers insist that TCP will work suitably in a satellite environment, while others have suggested alternative protocol options for improved performance. Some researchers are content that TCP cannot work effectively over satellite channels. However, several factor in the satellite systems such large latencies, limited bandwidth, path asymmetries, and high channel error rates provide TCP with a challenging environment in which to operate.

1.2 Problems in Brief

Problems investigated in this thesis will be stated briefly here, while the details will be given in chapter 3 (section 3.5) following review of the results reported in past as well as in more recent works. The issues concerning the transmission of Web traffic in multispot 3G W-CDMA mobile satellite systems operating at S-band that will be investigated in this research are described in the following:

One of the main objectives of this research is to enhance the performance of both uplink and downlink of 3G W-CDMA mobile satellite systems for Web traffic by mitigating the problems caused by power control errors (due to uncompensated shadowing) and slow fading (due to low mobility). The performance of turbo-coded downlink (mobile satellite to mobile Web user) will be enhanced using interleaving, radio link protocol (RLP), and macrodiversity. Meanwhile the performance of convolutional

coded uplink will be enhanced using RLP and space-time transmits diversity (STTD). It is important to note that unlike terrestrial systems; slow fading and shadowing counteracted by neither power control (due to its limited tracking speed) [5] nor finite size interleaver. For mobile satellite systems, slow fading and shadowing represent the most power-demanding link condition.

Figure 1.1: Internet Mobile Satellite Network [6]

It is worth mentioning that in this work, it is assumed that a satellite with on board processing (i.e. only modulation and demodulation is performed) is connected to the Internet via a Gateway as shown in Figure 1.1. The link connecting the satellite and Gateway usually operates at very high speed in both directions and at a high signal to noise ratio, hence these links will be assumed to be error free. Thus only the links connecting the mobile Web users and the satellite, which suffer from power control error and slow fading will be examined in detail.

Power control error and slow fading can be considered as major limiting factors for the operation of 3G W-CDMA mobile satellite systems since these systems are interference limited in the uplink (asynchronous mode), i.e. mobile users cannot be allowed to transmit more power than necessary to support Web traffic, meanwhile they are power limited in the downlink due to the limited number of solar cells on board the satellites.

Thus in both links the main challenge is to minimize the transmitted power for each link (i.e. both uplink and downlink) while maintaining an optimum FER that meet the required quality of service (QoS) for Web traffic (i.e. minimum page download time). Power control errors mainly arise because closed loop power control is ineffective due to long satellite delay. Standard deviation of power control error (σ_s) in mobile satellites was found to be between 1 to 4 dB [7]. Enhancing the performance of both uplink and downlink will be performed using link level simulation.

Finally the research will attempt to enhance Web traffic capacity in both medium earth orbit (MEO) and geostationary earth orbit (GEO) 3G W-CDMA based multispot mobile satellite systems by translating the enhancements made in both up and downlink into capacity gains. Web traffic capacity analysis will be performed using semi-analytical methods.

1.3 Research Significance

This is the first comprehensive study of its kind to analyze and enhance the Web traffic capacity in multispot 3G W-CDMA mobile satellite systems taking into consideration detailed impairments of the physical layer. This information could translate straightforwardly into costs and revenue a mobile Internet satellite operator could expect from enhancement in the Web traffic capacity. This because there is hardly any work done in this area, hence this research gives an original contribution to this field.

The originality of this work arises partly from the identification of the problems of W-CDMA mobile satellite systems that have major impact on the performance and capacity of Web traffic and the development of techniques that mitigate the impact of these problems so that Web traffic capacity can be greatly enhanced. The results provide us with insight and understanding of how various impairments of the physical layer affect the performance of the Web traffic.

1.4 List of Contributions and Publications

1.4.1 List of Contributions

1. Studied analytically the performance of Web protocols namely TCP Tahoe and HTTP/1.1 over 3G W-CDMA mobile satellite systems. Two satellite constellations were considered MEO and GEO. The analysis takes into account the effect of TCP segment size and TCP initial window size as well as user data on TCP throughput and Web page down load time. The effect of using RLP, which is based on IS-99 standard to enhance the performance of TCP over the satellite links with random frame error rate, was examined. Detailed of this study is described in chapter 4.
2. Using TCP Reno and a Web traffic model for heavy browsing, the analytical study for the performance of Web protocols over 3G W-CDMA mobile satellite systems was extended using system level simulation. Two satellite constellations were considered, namely MEO and GEO. The analysis took into account the effect of TCP segment size, TCP initial window size, and user data rate on Web throughput and Web page down load time with random frame error rate. Details of this study are described in section 4.4.
3. Designing a 3G W-CDMA mobile satellite downlink for Web traffic. The design is summarized in chapter 5. The design includes the use of a random frame generator, CRC and turbo encoders and decoders for forward error correction, interleavers, lognormal channel model, AWGN noise, QPSK modulation and demodulation using an OVSF code generator in addition to a spreader and a despreaders using a Gold code generator.
4. Examining the effect of power control errors (PCEs) and slow fading on degrading the performance of a 144 kbps 3G turbo coded W-CDMA downlink for Web traffic. Details of this examination are described in sections 5.4.1 and 5.4.2 respectively.
5. Examining the effect of using RLP and a long interleaver to enhance the performance of the downlink. Details of this examination are described in sections 5.4.3 and 5.4.4.

6. Proposing the combined use of macrodiversity to be used at the mobile Web terminal and RLP to greatly enhance the performance of the turbo coded downlink. A detailed description of this method and its performance can be found in section 5.5.
7. Designing a 3G W-CDMA mobile satellite uplink for Web traffic as described in chapter 5. The design includes the use of a random frame generator, CRC and convolutional encoders and decoders for forward error correction, interleavers, a lognormal channel model, AWGN noise, QPSK modulation and demodulation using OVSF code generator in addition to a spreader and a despreader using a Gold code generator. The uplink is usually used to carry HTTP 1.1 object requests and TCP acknowledgments; hence a much lower data rate was considered (i.e. 12.5 kbps).
8. Examining the effect of power control errors and slow fading on degrading the performance of convolutionally coded 3G uplinks was examined along with the effect of using STTD and RLP to enhance the performance of the link under such degradations. Detailed of this study is described in section 5.7.
9. Evaluating and enhancing Web traffic capacity in multi-spot GEO and MEO 3G W-CDMA mobile satellite systems for both uplink and downlink which suffer from PCEs by using a combination of powerful diversity techniques such as macrodiversity and STTD with RLP. Details of this study are described in chapter 6.
10. Proposing the use of a macrodiversity scheme in the downlink at mobile Web user as an integral and essential part in the satellite component of UMTS in order to greatly combat the effect of PCE and slow fading which severely degrade the Web traffic capacity.

1.4.2 List of Publications

• Journal Papers

1. J. Alsuwaidi and S. Mahmoud, "Enhancing the Web Traffic Capacity in the Downlink of 3G Mobile Satellite Systems", submitted to special issue on Broadband IP Networks via Satellites; *IEEE J. Select. Areas Commun.*

2. J. Alsuwaidi and S. Mahmoud, "Effect of Space Time Transmit Diversity (STTD) on the Web Traffic Capacity in 3G Mobile Satellite Systems", submitted to *International Journal of Satellite Communications*; John Wiley, New York, U.S.A.

- **Conference Papers**

1. J. Alsuwaidi and S. Mahmoud, "Enhancing Web Traffic Capacity in the Uplink of W-CDMA Mobile Satellite Systems", submitted to *IEEE International Conference on Communications (ICC 2003)*, Alaska, USA, May 2003.
2. J. Alsuwaidi and S. Mahmoud, "Performance Enhancement of W-CDMA Uplink in Mobile Satellite Systems for Web Traffic", submitted to *IEEE International Conference on Communications (ICC 2003)*, Alaska, USA, May 2003.
3. J. Alsuwaidi and S. Mahmoud, "Performance Enhancement of W-CDMA Downlink in Mobile Satellite Systems for Web Traffic", *IEEE Global Telecommunications Conference (Globecom2002)*, Taipei, Taiwan, November 2002.
4. J. Alsuwaidi and S. Mahmoud, "Comparison of Web Traffic Performance in W-CDMA Mobile Satellite Systems", *5th International Symposium on Wireless Personal Multimedia Communications (WPMC2002)*, Honolulu, Hawaii, USA, October 2002.
5. J. Alsuwaidi and S. Mahmoud, "Capacity Enhancement of W-CDMA Mobile Satellite Systems for Web Traffic", *4th IEEE Mobile Wireless Communications Conference (MWCN 2002)*, Stockholm, Sweden, September 2002.
6. J. Alsuwaidi and S. Mahmoud, "Performance Analysis of Web Protocols in W-CDMA Mobile Satellite Systems", *Symposium on Personal Communications, Virginia Tech .2002*, Virginia, USA, June 2002.
7. J. Alsuwaidi and S. Mahmoud, "Downlink Performance of 3 GPP W-CDMA GEO Mobile Satellite for Web Traffic", *Wireless2001 Conference*, Calgary, Canada, pp. 350-360, July 2001.
8. J. Alsuwaidi and S. Mahmoud, "Downlink Performance of 3 GPP W-CDMA GEO Mobile Satellite for High Speed Data", *Symposium on Personal Communications, Virginia Tech. 2001*, Virginia, USA, June 2001.

1.5 Thesis Organization

Following this introductory chapter, chapter 2 gives background information about W-CDMA mobile satellite systems. This includes various types of satellite constellations, user terminal categories, mobile satellite channel, space diversity and finally co-channel interference.

Chapter 3 gives background information about TCP and HTTP 1.1 protocols. This includes behavior of TCP in the presence of errors, and the main problems of TCP in a mobile satellite environment. It also gives a review of available literature concerning the performance of TCP and HTTP protocols over fixed satellite networks, how they have been evaluated in the past and work that has been accomplished in this field. Finally, issues to be investigated that have been mentioned briefly in chapter 1 will be described in more detail here including their justification and significance.

Chapter 4 examines the performance of TCP and HTTP 1.1 protocols in both GEO and MEO 3G W-CDMA mobile satellite systems analytically; in particular it investigates the effect of the user's data rate, TCP segment size and initial window size and frame error rate, on TCP throughput and Web page download time. The performance of Web traffic in both GEO and MEO satellite environment is examined, which includes the effect of data rate and TCP segment and window sizes on Web page download time and link utilization.

Chapter 5 presents an analysis of the performance of 3G W-CDMA mobile satellite systems. The performance of both downlink and uplink are examined taking into consideration the effect of various physical layer impairments such as slow fading and power control errors. Methods to enhance the performance of turbo coded downlink and convolutionally coded uplink are introduced. The enhancement methods for the downlink include the use long size interleavers, RLP and macrodiversity. For the uplink, the enhancements include the use of both RLP and STTD diversity.

Chapter 6 evaluates Web traffic capacity in multispot GEO and MEO 3G mobile satellite systems taking into account the effect of beams overlapping, orthogonality, Web

traffic activity factor, cross-polarization frequency reuse and shadowing. The effect of power control error in degrading the Web traffic capacity in both downlink and uplink is examined. Finally, the impact of using macrodiversity in the downlink and STTD in the uplink on enhancing the Web traffic capacity is examined.

Chapter 7 concludes and summarizes the main results of this research and gives an outline of future work.

Chapter 2

Mobile Satellite Systems

2.1 An Overview of Mobile Satellite Communications

Over the last decade digital cellular networks made mobile (voice) communication accessible to almost anyone. To complement current terrestrial cellular networks, several systems based on low/mid earth orbit (LEO/MEO) constellations operating at L/S-band have been or are being deployed to provide global mobile satellite personal communications (S-PCN). In parallel to S-PCNs, satellite systems for portable and mobile multimedia communications are being developed [8-9].

Figure 2.1 shows the basic S-PCN system architecture [11]. Each satellite covers a circular area on the earth's surface, which increases with increasing orbit height and decreasing minimum elevation angle $\epsilon_{\min}$. The choice of orbit planes and the satellite phasing within the orbits must guarantee continuous coverage of the service area (being the full earth surface for global systems). The number of required satellites is determined by orbit height and minimum satellite elevation [12].

Direct communications via satellite using a handheld terminal with low transmit power and an omni directional antenna requires a high antenna gain on board the satellite, which can be achieved with spot beam antennas. Accordingly, the coverage area of the satellite is composed of a large number of spot beams. This allows the reuse of frequency bands $f_1, f_2, \dots$ in separated cells, increasing the bandwidth efficiency of the system.

The gateway stations comprising a fixed earth station and a mobile switching center (MSC) are connected to the terrestrial fixed network typically via international switching centers (ISC). The use of databases (home location register, HLR and visitor location

register, VLR) allows maintaining contact with globally mobile users (mobility management). The network control center (NCC) among other tasks allocates spot beam frequencies and distributes routing tables to the satellites. The satellite control center via telemetry and command links keeps the satellites in their correct orbit positions

Figure 2.1: Architecture of a satellite personal communication network (S-PCN)[11]

For S-UMTS (Satellite Universal Mobile Telecommunication Services), frequency bands at 1.980-2.010 GHz (uplink) and 2.170-2.200 GHz (downlink) have been allocated, which can be globally used. Higher frequencies at 5/7 GHz, 15 GHz, and 20/30 GHz are foreseen for feeder links.

2.2 Satellite Constellations

Satellites can be positioned in orbits with different heights. Based on the orbital radius, all satellites fall into one of the following three categories [12]:

2.2.1 Geostationary (GEO) System Concept

Global coverage (excluding the polar regions) can be provided by only 3 geostationary satellites. However, the large orbit height of 36000 km requires a very high gain satellite antenna, which for frequencies below 2.5 GHz results in extremely large antenna dimensions. Due to the narrow beam, a very large number of spot beams is necessary to

fill up the footprint area, further increasing antenna complexity. Another drawback of the GEO orbit is the large propagation delay (0.5 round-trip between mobile user and fixed earth station).

Even though GEO systems have been used for less demanding applications such as data communications (Inmarsat-C), telephony with brief case/laptop terminals (Inmarsat-M/Inmarsat-3) or truck fleet management (Omnitrass, Euteltraces), the latest GEO systems are capable of providing telephony and low speed data even to mobile handheld phones (Thuraya).

New GEO system concepts aim at broadband and multimedia services (typically up to 1.5 Mb/s), mainly for portable terminals with small (<1 m) antenna dishes. The global spaceway/galaxy system and the asian cellular satellites (ACeS) system belong to this category. The SECOMS/ABATE project of the ACTS program of the European community develops a GEO system for mobile multimedia services [13], which may lead to a commercial system called Euroskway.

2.2.2 Low Earth Orbit (LEO) System Concept

Low earth orbits at 700-1500 km avoid the large signal attenuation and delay of the geostationary orbit. However, a large number of LEO satellites are needed to continuously cover the earth's surface. The Globalstar uses a Walker constellation of 48 satellites in 8 inclined orbits at 1414 km and Iridium is based on 66 satellites in 6 polar orbits at 780 km height. The large number of LEO satellites is partly compensated for by their low weight and complexity, compared to GEO satellites. Due to the non-geostationary characteristic of LEO satellites, spot beam and satellite handovers are necessary during calls.

2.2.3 Medium Earth Orbit (MEO) System Concept

Systems with satellites in medium earth orbits around 10000 km avoid the large signal attenuation and delay of the geostationary orbit and still allow global coverage with few (10 - 15) satellites. Since the required satellite antennas are state of the art, and no ISLs are necessary, the technical risk of MEO systems is acceptable. As an example, the

intermediate circular orbit (Orbit) system is based on 10 MEO satellites at 10354 km orbit height.

These satellite constellations are shown in Figure 2.2. Table 2.1 summarizes the design issues related to different type of satellite constellations [14], while Table 2.2 summarizes the main advantages and disadvantages of LEO/MEO and GEO constellations [6].

Figure 2.2: Satellite constellations [12]

Table 2.1: Summary of the design issues related to different type of satellite constellations.

Type	LEO	MEO	GEO
Description	Low earth orbit	Medium earth orbit	Geostationary
Type of orbit	Circular, or inclined	Circular or inclined	Circular
Orbit period	~ 100 minutes	5 to 12 hours	86164.1 seconds
Orbit altitude	700 to 2000 Km	8000 to 20000 Km	35786 Km
Max. single-hop delay	~20 ms	80 to 120 ms	280 ms
Propagation path losses	Low	Medium	Very high
No. of orbits(typical)	8	2	1
Handovers	~10 minutes between satellites	~90 minutes between satellites	Not needed between satellites
	~2 minutes between spot beams	~15 minutes between spot-beams	Rarely between spot-beams
Min. elevation angle	10 deg.	10 deg	20 deg
Footprint diameter	5850 km (typical)	12900 km (typical)	15900 km (typical)
No. of spot beams	19 (typical)	169 (typical)	160 (typical)

Table 2.2: Summary of the advantages and disadvantages of LEO/MEO and GEO constellations.

Type	LEO/MEO	GEO
Advantages	<ul style="list-style-type: none"> -Much lower propagation delays. -Much better link margin -Easier launch 	<ul style="list-style-type: none"> -Configuration simplicity -Extremely wide spot beam footprint. -Relatively time-invariant satellite ground terminal. -Simple space segment control system. -Fixed propagation delay.
Disadvantages	<ul style="list-style-type: none"> -A large number of satellites. -More complex onboard control subsystems. -Less satellite dwell time. -More frequent handoffs -Much larger Doppler shift 	<ul style="list-style-type: none"> -Power limited links. -Excessive propagation delay for voice and ARQ-based packet data. -Inability to cover polar regions.

2.3 User Terminal Categories

Satellite user terminal types are very much driven by the required set of services. Similar to the terrestrial case, a range of terminal types with different capabilities would best fulfill the varying user requirements. Different types of terminals are therefore associated with diverse user mobility classes as well as peak data rates [5], as shown in Table 2.3. The mobile satellite commonality in terms of frequency band and air interface technology can greatly reduce terminal complexity, size and weight. A dual-mode (terrestrial and satellite) user terminal (UT) should eventually reach a cost comparable to a high-end terrestrial UT.

Table 2.3: Terminal characteristics for W-CDMA mobile satellite

Terminal type	Service rate (kbps)	Mobility
Portable (quasi-static)	144	None
Palmtop	64	Very low
Handheld	Up to 32	Low
Vehicular	64-144	High
Aeronautical	144	Very high
Maritime	144	Medium

2.4 Mobile Satellite Channel

The large satellite free space loss and onboard radio frequency (RF) power scarcity forces mobile satellite systems to operate under line-of-sight propagation conditions under normal conditions. This typically results in a mild Rician (or at most Rice-lognormal) channel with Rice factors ranging from 7 to 15 dB [16], thus causing limited signal envelope fluctuations.

Recent wideband channel measurement campaigns [17] showed that for typical low-earth altitude satellite channels, the delay spread has an average value of 100 ns. Hence, any W-CDMA system designed to combat multipath with a RAKE demodulator would have to adopt chip rates in excess of 10 Mchips/s. Furthermore, it has been found that resolvable multipath rays for a 10-15 Mchip/s signal are characterized by much lower power than the line of sight (typically 15-30 dB less), thereby significantly reducing any potential multipath diversity gain for W-CDMA mobile satellite system. The W-CDMA system considered in this thesis has a chip rate equal to 3.84 Mchip/s, hence only a narrowband channel is considered.

Figure 2.3: Rice-lognormal (RLN) model for a land mobile satellite channel [18]

In the light of the above discussion, the satellite channel in this thesis is assumed to be Rice-lognormal (RLN) as shown in Figure 2.3 above.

The RLN channel model is valid when it is applied to a rural tree-shadowed mobile satellite channel [18]. This is typical operational environment for a mobile satellite system in rural area where the provision of terrestrial coverage is either technically or economically not viable; hence this channel model will be used in this research.

2.5 Power Control

In order to combat large scale shadowing, path loss changes due to satellite and user antenna gain variations, and user speed changes in a land mobile satellite system; an adaptive power control (APC) scheme is essential. When such a scheme is implemented on the uplink, it ensures that all users' signals arrive at the satellite (or base station) with equal power as they move within the satellite spot beam. This is an important requirement in a CDMA system [7]. When implemented on the downlink it ensures precious satellite power is preserved and hence system capacity [5].

2.5.1 Open-Loop Power Control

This is based on the received amplitude of a forward pilot. This power control method is used to compensate power variations due to path loss changes and weak shadowing as caused by trees but not always to mitigate channel fading.

2.5.2 Closed-Loop Power Control

This is based on correction signals received from the satellite or the ground station and is used for fine correction. In satellite networks, the long propagation delay represents a problem for closed loop power control [7]. The fast power variations caused by fading (especially during signal shadowing) cannot be compensated. If sufficient link margin is available, the transmit power can be providently increased during signal shadowing [19].

The power control error, γ , can be modeled as lognormal distribution [7], i.e. $\gamma = e^{\delta}$, where δ is a zero-mean Gaussian random variable with standard deviation σ_{γ} . It has been shown that the value of σ_{γ} is about 1 dB for unshadowed users, and 2-4 dB for shadowed users [7].

2.6 Diversity

In a mobile satellite environment, W-CDMA loses its most important advantages (i.e. the capability to resolve and combine multipath), (see section 2.4), however it should be realized that independent fading paths with sufficient path delays could be introduced artificially in the form of satellite path diversity. Satellite path diversity providing (quasi)-permanent softer handoff condition aims at increased QoS [18] by largely reducing the link margins required to combat fading and partial link fading.

This is quite important because, different from terrestrial systems, slow fading and shadowing is counteracted by neither the power control (due to its limited tracking speed) nor the finite size interleaver. For mobile satellite systems, slow fading characterizing low mobility users and shadowing represents the most power-demanding link conditions. With path diversity it is possible to largely counteract the diverse slow fading and shadowing effects with very modest power control margins [5].

2.6.1 *Space or Antenna Diversity*

In vehicular environments, antenna or space diversity, which is the most common type of diversity, can be used to improve link quality without increasing the transmitted power or bandwidth. With space diversity, two or more spatially separated antennas are used at the receiver. The distance between the antennas must be large enough to ensure that signals received by different antennas are uncorrelated. This means that the probability that all of these signals are simultaneously in fade is much lower than the probability that one signal is in fade; a spacing of at least half a wavelength is required. A distinction is made between the following two types [20]:

- Microdiversity, where the distance between antennas is in order of only a few wavelengths.
- Macrodiversity, where the distance between antennas is at least 10 wavelengths.

A combination of both types is often used to combat both multipath fading (microdiversity) and shadowing (macrodiversity).

2.7 Co-Channel Interference

In order to assess the performance of both up and down links which will be performed in chapter 5 using link level simulation, as well as capacity of W-CDMA mobile satellite system (chapter 6), it is necessary to understand the co-channel interference (CCI) in both the up and down links. For CDMA systems, CCI reduces the system capacity.

2.7.1 Co-Channel Interference for an Asynchronous DS-CDMA Uplink

In a cellular network with CDMA, each radio cell uses the same frequency band (cluster size $K = 1$). Therefore, co-channel interference is produced by other users in the same cell as the wanted user as well as by the users in all other (neighboring) cells. All users are transmitting simultaneously.

Figure 2.4 shows the geometry of the satellite uplink with respect to the user and the characteristics of the satellite spot beam antenna.

Figure 2.4: Own- and other-cell interference scenario. Index c: user (carrier), index i: interference [21]

In Figure 2.4 the following designations have been used [21]:

θ_c : Receive angle of the wanted signal, relative to the center of the spot beam (bore sight angle)

Ψ_i : Receive angle of the interfering signal, relative to the center of the beam of the wanted signal.

$G_c(\theta)$: Antenna characteristic of the spot beam of the wanted signal.

P_c, P_i : Terminal transmit powers.

L_c, L_i : Propagation loss factors.

To analyze the uplink co-channel interference for asynchronous DS-CDMA, the following characteristics are assumed:

- In each cell we consider a single CDMA carrier within the same frequency band.
- The cells are idealized by contiguous hexagons. The area of the idealized radio cell is

$$A_c = \frac{3}{2}\sqrt{3}R^2 \quad (2.1)$$

- There are N users per cell, being uniformly distributed. The user density is

$$\rho = N / A_c = \frac{N}{\frac{3}{2}\sqrt{3}R^2} \quad (2.2)$$

- The user signals are not synchronized, they add up with respect to their power.
- Gaussian transmission channels are assumed (no signal shadowing, no multipath fading)
- Within the cells the spot beam antenna characteristic and differences in the slant range attenuation L_i are perfectly compensated, such that the signals arrive at the corresponding spot beam antenna of the satellite with equal power C .
- In Web traffic pauses, the user signals are switched off or their power is reduced (average Web traffic activity = α).

2.7.1.1 Interference from the Own Cell

In the following, the own spot beam (the spot beam containing the wanted user) is considered the central spot beam in the nadir direction of the satellite.

For a user at nadir (i.e. at center of the cell), the received uplink power is designated as $C = P_o / L_o \cdot G_{\max}$, with $G_{\max} = G_c(0)$. For a user anywhere within the own spot beam

the transmit power is assumed to be increased through power control by a factor of

$$\frac{L_c}{L_0} \cdot \frac{G_{\max}}{G_c(\theta_c)} \quad (2.3)$$

such that the difference in signal attenuation and antenna gain are compensated, and the received uplink power is maintained as C . With this, the interference power from the own cell is

$$I_e = \alpha(N-1)C \approx \alpha NC. \quad (2.4)$$

2.7.1.2 Interference from Other Cells

Similarly as for the users in their own cell, the transmit power of terminals in other cells is controlled according to

$$\frac{L_i}{L_0} = \frac{G_{\max}}{G_i(\theta_i)} \quad (2.5)$$

such that the power received at their (own) spot beam antenna is C . $G_i(\theta)$ is the antenna characteristic of the interfering spot beam. The interference power caused by any terminal within another cell is given by

$$C \cdot \frac{G_c(\psi_i)}{G_i(\theta_i)}, \quad (2.6)$$

Where $G_i(\theta_i)$ is the antenna characteristic of the interfering spot beam, and $G_c(\psi_i)$ represents the interference attenuation due the spot beam antenna of the wanted user's beam. Assuming uniformly distributed users, the interference from other cells is given by [21].

$$I_a = \alpha C \rho \iint_{\text{other cells}} \frac{G_c(\psi_i)}{G_i(\theta_i)} dA. \quad (2.7)$$

The index i designates the beam to which the interferer belongs.

2.7.1.3 The Other-Cell Interference Factor f

Corresponding to the approach in [22], the other-cell interference is related to the interference power of the own cell by other-cell interference factor f where

$$f = \frac{I_a}{I_e} = \frac{1}{A_c} \iint_{\text{other cells}} \frac{G_c(\psi_i)}{G_i(\theta_i)} dA. \quad (2.8)$$

2.7.1.4 Numerical Evaluation of Other-Cell Interference

For the numerical evaluation of other-cell interference factor f , a lower bound of f for small nadir angles is derived in [21] for both Gaussian [23] and tapered-aperture [24] antennas for different values of beam isolation s resulting in the values given in Table 2.4. The parameter s determines the degree of isolation of neighboring spot beams (i.e. the gain decrease at the spot beam contour) through their antenna characteristics, and hence it determines a mount of co-channel interference.

Table 2.4 shows that for $s = 3$ dB, interference is more than doubled due to the influence of other spot beams, leading to a decrease of more than 50% of system capacity. For terrestrial CDMA, it is usually assumed that the signal power decreases with the fourth power of distance, and a typical value for the other-cell interference factor is $f = 0.44$ [25]. This shows that other-cell interference in satellite systems is much more critical than in terrestrial cellular systems.

Table 2.4: Numerical values for the other-cell interference factor f

Scenario	Antenna	f		
		$s = 3$ dB	$s = 4$ dB	$s = 5$ dB
Lower bound for small nadir angles	Tapered-aperture	1.20	0.85	0.65
	Gaussian	1.36	0.97	0.74

2.7.2 Co-Channel Interference for DS-CDMA Downlinks

In the downlink, chip-synchronous CDM with orthogonal spreading codes can easily be realized because the signals are transmitted by a common source (satellite or gateway station). Therefore, no interference occurs between the synchronous user signals of a satellite (although neighboring satellites may cause interference)[11].

Moreover, by means of a pilot tone transmitted by the satellite, coherent detection is possible at the terminal, allowing a lower signal-to-noise ratio.

Chapter 3

Web Protocols

In this chapter only the transport control protocol (TCP) and hypertext transfer protocol (HTTP/1.1) that are relevant to this research will be described in detail.

3.1 An Overview of Transport Control Protocol (TCP)

TCP is the most widely used transport protocol, employed by the majority of applications that use the TCP/IP protocol suite e.g. electronic mail (SMTP), virtual terminal (Telnet), file transfer (FTP) and Web browsing (HTTP), etc. It provides a reliable byte streaming (i.e. application layer boundaries are not necessarily maintained), full duplex connection [26].

TCP is connection oriented because two hosts must setup and establish a connection before any data is transmitted. TCP provides point-to-point connection, i.e. each connection has exactly two end points (sockets = IP address/TCP port pair), and it adapts to network conditions (i.e. network congestion) by dynamically updating timers and the transmission rate [27-28]. Figure 3.1 shows the location of TCP (and HTTP) in the TCP/IP reference model; and how it distinguishes between different applications that use it.

TCP is a windowed protocol that uses acknowledgements from the receiver to clock the sender's output. New data cannot be introduced into the network until the sender has received an acknowledgement. This indicates that data has been removed from the network. The windows control the amount of data that can be transmitted at any particular time. A maximum window size (generally corresponding to the receiver's buffer size) is negotiated at the connection setup and a congestion window is used to control the amount of data introduced into the network. Congestion window (CWND) is

defined as the number of data segments that the sender is allowed to transmit without an acknowledgement.

Figure 3.1: TCP distinguishing application traffic [28]

Two algorithms, slow start and congestion avoidance make TCP behave gently and prevent data from blasting out onto the network at the beginning of a connection or after a loss [29]. These algorithms gently probe the network to find the proper level of data transmission. TCP assumes any loss is due to congestion of the network and reduces the transmission rate severely.

3.1.1 TCP Congestion Control Mechanisms

TCP's congestion control mechanisms are described in detail in [30-31]. TCP uses a window based flow control policy. The variable RCVWND (i.e. receive window) is used as measure of the receiver's buffer capacity. When a destination TCP host receives a segment, it sends an acknowledgement (ACK) for the next expected segment. TCP congestion control is built on this window based flow control policy.

3.1.1.1 Slow Start and Congestion Avoidance

Slow-start controls the rate at which a session can send data. This algorithm is used to limit the increase in the data transmission rate to the same rate that acknowledgements are received. Slow-start was added to TCP to protect the Internet from sudden bursts of traffic, which could overload the network. The individual user's throughput is therefore

limited to improve overall network stability. Slow-start does increase the time required to reach the maximum throughput both at the beginning of a TCP session and whenever a segment is lost or received in error.

The sender TCP maintains a variable called congestion window (CWND) to measure the network capacity. The number of unacknowledged packets in the network is limited to CWND or RCWND (max receiver's buffer size) whichever is lower. Initially CWND is set to one segment and it increases by one on the receipt of each new ACK until it reaches a maximum (typically 65536 bytes). It can be shown that CWND doubles every round trip time and this corresponds to an exponential increase in the CWND every round trip time [30].

If a segment is lost, the receiver sends duplicate ACKs on receiving subsequent segments. The sender maintains a retransmission timeout for the unacknowledged packet. Congestion is indicated by the expiration of the retransmission timeout. When the timer expires, the sender saves half the CWND in a variable called slow start threshold (SSTHRESH), and sets CWND to one segment. The sender then retransmits segments starting from the lost segment. CWND is increased by one on the receipt of each new ACK until it reaches SSTHRESH.

This is called the **slow start phase**. After that, CWND increases by one segment every round trip time. This results in a linear increase of CWND every round trip time; this is called **congestion avoidance phase**. Figure 3.2 shows the slow start and congestion avoidance phase for a typical connection.

Figure 3.2: TCP slow start and congestion avoidance [32]

3.1.1.2 Fast Retransmit and Fast Recovery

To account for any lost segments during a TCP session, two algorithms have been incorporated as part of the TCP standard to improve throughput. These are **fast retransmits and fast recovery** [31].

Current TCP implementations use a coarse granularity (typically 500 ms) timer for the retransmission timeout. As a result, during congestion, the TCP connection can lose much time waiting for the timeout. In Figure 3.2, the horizontal CWND line shows the time lost in waiting for a timeout to occur. During this time, the TCP neither sends new packets nor retransmits lost packets. Moreover, once timeout occurs, the CWND is set to one segment, and the connection takes several round trips to efficiently utilize the network.

TCP Reno implements the fast retransmit and recovery algorithms that enable the connection to quickly recover from isolated segment losses [31-32]. When a TCP receives an out-of-order segment, it immediately sends a duplicate acknowledgement to the sender. When the sender receives three duplicate ACKs, it concludes that the segment indicated by the ACKs has been lost, and immediately retransmits the lost segment. The sender then reduces CWND to half (plus 3 segments) and also saves half the original CWND value in Ssthresh.

Now for each subsequent duplicate ACK, the sender inflates CWND by one and tries to send a new segment. Effectively, the sender waits for half round trip before sending one segment for each subsequent duplicate ACK it receives. As a result, the sender maintains the network pipe at half its capacity at the time of **fast retransmit**.

Approximately one round trip after the missing segment is retransmitted; its ACK is received (assuming the retransmitted segment was not lost). At this time, instead of setting CWND to one segment and proceeding to do slow start until CWND reaches Ssthresh, the TCP sets CWND to Ssthresh, and then does congestion avoidance. This is called the **fast recovery algorithm**. This is shown below in Figure 3.3.

Figure 3.3: TCP fast retransmit and recovery [32]

3.2 Hypertext Transfer Protocol

The hypertext transfer protocol (HTTP) is an application-level protocol for distributed, collaborative, hypermedia information systems. It is a generic, stateless, protocol that can be used for many tasks beyond its use for hypertext. A feature of HTTP is the typing and negotiation of data representation, allowing systems to be built independently of the data being transferred. HTTP is layered over TCP as shown earlier in Figure 3.1.

3.2.1 Basic Protocol Operation

HTTP is a transaction-oriented client/server protocol. A typical use of HTTP is between a Web browser and a Web server. To provide reliability, HTTP makes use of TCP. Nevertheless, HTTP is a “stateless” protocol: Each transaction is treated independently. Accordingly, a typical implementation will create a new TCP connection between client and server for each transaction and then terminate the connection as soon as the transaction completes [33].

The stateless nature of HTTP is well suited to its typical application. A normal session of a user with a Web browser involves retrieving a sequence of Web pages and documents. The sequence is ideally performed rapidly, and the locations of the various pages and documents may be a number of widely distributed servers.

Figure 3.4 illustrates an example of HTTP operation in which a user agent establishes a direct connection with an origin server. The user agent is the client that initiates the request, such as Web browser being run on the behalf of an end user. The origin server is the server on which a resource of interest resides; an example is a Web server at which a desired Web home page resides.

Figure 3.4: Example of HTTP operation [33]

For this case, the client opens a TCP connection that is used end-to-end between the client and the server. The client then issues an HTTP request. The request consists of a specific command, referred to as a method, a URL (Uniform Resource Locator) i.e. `http://www.w3.org/RDF`. This means “Transfer the resource named RDF from the computer named `www.w3.org` using http”; and MIME-like message contains request parameters, information about the client, and perhaps some additional content information.

When the server receives the request, it attempts to perform the requested action and then returns an HTTP response. The response includes status information, a success/error code, and MIME-like message containing information about the server, entity meta information, and possibly entity-body content.

3.2.2 Structure of a Typical Web Page

Web data is by all means the most relevant component of Internet traffic and given the interactive nature of its service, is one of the most critical in terms of delay and transmission times. To analyze the performance of a satellite links used for Web access it is necessary to derive experimentally a model that describes a typical Web page.

The logs of a heavily used Web proxy server describing the size of each downloaded component for over 23 Gigabytes of HTML (Hypertext Markup Language) traffic are

used as experimental data [34]. Using a clustering procedure the files downloaded with each HTTP connection can be effectively classified in four classes based on size:

- The first class, including mostly HTML page, consists of files with mean size of 6586 bytes.
- The second class, mostly small GIF (Graphic Interchange Format) icons, consists of files with mean size of 1360 bytes. There is a mean of 1.6 icons for each HTML page.
- The third class, typically large GIF and JPEG (Joint Photographic Experts Group) images or applets consists of files with mean size of 17175 bytes. There is a mean of 0.9 images or applets for each HTML page.
- The last class, typically very large zip or multimedia files, consists of files with mean size of 741043 bytes. There is a mean of 0.026 multimedia files for each HTML page.

Surprisingly the last class accounts for nearly half of the traffic (45%), while the first, the second and the third are 15%, 5% and 35% of the total respectively. The typical structure of a Web page obtained with this method is shown in Table 3.1

Table 3.1: Experimentally derived typical Web page (year 1997)

Web page structure	File size (mean, bit)	Mean # in page	% of the traffic
HTML text	52,688	1	15%
Icon	10,880	1.6	5%
Image or applet	137,400	0.9	35%
Multimedia	5,928,344	0.026	45%

Thus the average Web page size is 43.5 Kbytes (year 1997).

3.2.3 Packet Exchanges in HTTP/1.1

The interaction between HTTP clients and servers as it appears on the network will be discussed with particular emphasis on how this affects the latency. Figure 3.5 depicts the exchanges at the beginning of a typical interaction: the retrieval of an HTML document with N uncached images as was described in [35] and is shown below:

“The mandatory round trips are:

- 1. The client opens the TCP connection, resulting in an exchange of SYN packets as part of TCP’s three-way handshake procedure.*
- 2. The client-transmits an HTTP request to the server; the server may have to read from its disk to fulfill the request, and then transmits the response to the client. In this example we assume that the response is small enough to fit into a single data packet, although in practice it might not. The server then keeps the TCP connection open since more packets are expected be transmitted in the future.*
- 3. After parsing the returned HTML document to extracts the URLs for the N inline images, the client transmits N HTTP requests simultaneously in one or more data packets, this time for all the N inline images. The server obtains N image files and starts transmitting them to the client sequentially.*

Therefore, the earliest time at which client could start displaying the first inline image would be three network round-trip times after the user requested the document. Each additional inline image requires at least two further round trips. In practice with networks of finite bandwidth or documents larger than can fit into a small number of packets, additional delays will be encountered.”

Figure 3.5: Exchanges at the beginning of a typical interaction for HTTP/1.1[35]

3.3 Problems of TCP in Mobile Satellite Environment

TCP/IP was developed without taking into consideration its performance over long-delay links (e.g. satellite links), or error-prone links (mobile satellite links in particular). Satellite links have characteristics that can degrade the performance of TCP [36]. These include:

3.3.1 Long Delay Path

For example the Geo satellite has an altitude of 36000 km, hence it contributes about 0.5 seconds to the round trip time (RTT), and connection establishment will take longer over satellite. To avoid congestion in the network TCP ramps up the connection rate using the “Slow Start” algorithm [31]. Because slow start is directly proportional to the round trip time (RTT), the long RTT makes slow start over a satellite much slower than for terrestrial connections. Slow start time (the time to reach full connection speed after connection establishment in absence of loss) is given by:

$$\text{Slow start time} = \text{RTT} \log_2(W)$$

$$\text{Where } W \text{ is the window size in packets [30]} = \frac{\text{RTT} * \text{ChannelDataRate}}{\text{TCPMaxSegmentSize}}$$

Thus assuming RTT = 1 sec, which accounts for satellite + terrestrial + network congestion delays, channel data rate = 144 kbit/sec and assuming TCP max segment size = 530 bytes.

Then $W = 34$ segments, and slow start time = $\log_2(34) = 5.1$ seconds

When using a delayed acknowledgements algorithm (which acknowledges two packets with one ACK), the Slow Start Time increases to roughly:

$$\text{Slow start time} = \text{RTT} \log_{1.5}(34) = 8.7 \text{ seconds}$$

Thus, avoiding the use of delayed ACKs during slow start would appear to help in a satellite channel in case of small file transfers. For large file transfers, delayed ACKs can help avoid congestion loss by controlling the burstiness from large bunches of ACKs and so it beneficial. Delayed ACKs may also be helpful in highly asymmetric channels where ACK bunching may occur which can lead to burstiness and congestion loss. However,

delayed ACKs also cause slower congestion window growth during congestion avoidance.

The use of selective acknowledgements (SACK)[32] can allow better handling of retransmission queue in the event of multiple packet losses in a single window.

3.3.2 Transmission Errors (as opposed to congestion loss)

The effect of transmission errors is well described in [36] as shown below:

“The long feedback time discussed above in (3.3.1) also affects the response of congestion avoidance, which has an even slower growth phase than slow start. In congestion avoidance (see section 3.1.1.1), the congestion window can be increased by no more than one segment per RTT (and when delayed ACKs are used has an increase rate of only one segment per two RTTs).

As mention in section 3.1.1, a loss event in TCP is always interpreted as an indication of congestion and always cases TCP to enter congestion avoidance. If a loss occurs during slow start, then slow start is terminated and TCP enters congestion avoidance. Premature termination of slow start by losses other than congestion losses should be avoided because the congestion avoidance algorithm increases the transmission rate at a slower pace than slow start. A loss during steady-state operation will usually result in a drastic reduction of the effective window size at the sender, followed by congestion avoidance.

For TCP to operate efficiently, the channel characteristics should be that all loss is due to network congestion. Because of the effect of long RTT, errors on a satellite link have more severe repercussions than on a slower RTT terrestrial channel. In a mobile satellite system, where forward error correction (FEC) a lone cannot be expected to solve multipath, interference and power control problems. Hence other methods such as radio link protocol (RLP) and space (antenna) diversity are needed to enhance the performance of satellite links.”

3.3.3 Asymmetric Satellite Channels

Mobile satellite systems have large bandwidth asymmetries between forward and backward data channels [37]. This is mainly due to two reasons:

- Cost limitations associated with increased transmitter power and antenna size requirements for higher bandwidth transmission. Using slower reverse channels allows more cost-effective receiver designs, and also conserves valuable satellite bandwidth.

- The nature of most TCP traffic is asymmetric with data flowing in one direction (e.g., from Web servers to mobile hosts) and acknowledgments in opposite direction. Hence slower reverse channels can be acceptable to an extent.

Fundamentally, channel asymmetry affects the performance of reliable transport protocols such as TCP because these protocols rely on feedback in the form of cumulative acknowledgements, to make steady progress and fully utilize the available bandwidth of the path [38]. Thus, any disruption in the feedback process could potentially impair the performance of the forward data transfer. For example, a low bandwidth acknowledgement path could significantly slow down the growth of the TCP sender window during slow start, independent of the link bandwidth in the direction of data transfer.

3.4 Literature Survey

There have been several recent investigations on different facets on the performance of TCP over satellite. All of these studies assumed point-to-point communications and did not analyze the performance of Web traffic over mobile satellite systems. A brief survey of works conducted on analyzing the performance of TCP and Web traffic over satellite links is given below.

In [34] a simple theoretical model of TCP behavior over long delay links was defined. It used experimental data describing traffic patterns generated by Web browsing (which is by all means the most relevant component) to estimate download times for various Web components (i.e. HTML page, Icon, Image, Multimedia) over 1 Mbps satellite link. GEO and LEO delay models were calculated. The channel was assumed to be error free.

The effect of different file sizes and TCP flow control windows on the throughput of a point-to-point very small aperture terminal (VSAT) using 1.536 Mbps T1 GEO satellite link was investigated experimentally in [39]. Here the result of this experiment showed that the throughput is determined by two factors:

- TCP window size determines the achievable throughput for very long, sustained transmissions.
- Slow-start algorithm dominates the first 100 k bytes of the transmission.

Performance of TCP on a faded satellite link was investigated in [40], the fading on the satellite link was experimentally performed on VSAT network by mispointing the VSAT antenna dish w.r.t the satellite to increase bit error rate. The main aim of this investigation was to find the rate at which TCP performance declines as the bit error rate increases. The result of this experiment has shown that TCP performance begins to degrade noticeably for bit error rates (BER) above $3 \cdot 10^{-8}$ on a T1 link (1.536 Mbps). The results showed an exponential decline in TCP throughput for error rates above this level; with throughput cut roughly in half by the time the bit error rate reaches 10^{-7} .

In [41] comparison of performance of end-to-end TCP flow and that of split connection (one TCP connection for terrestrial segment and another for satellite segment) are made. In this investigation the effect of the GEO satellite channel impairments on TCP was modeled as simple random errors e.g. $BER = 10^{-5}, 10^{-6}, 10^{-7}$. This investigation showed that by using spilt TCP i.e. removing TCP congestion mechanism in the satellite segment, the performance of TCP (i.e. its throughput) and HTTP (i.e. page download times) are greatly improved.

In [42] the performance of different transport protocols e.g. SACK-New Reno, SACK-Reno and SACK-New Reno (split) over GEO and LEO satellite connections was investigated. The channel was assumed to be error free. Only the delay due to the satellite and terrestrial networks was taken into account (round trip delay for GEO network was assumed to equal 600 msec and that for LEO was assumed to equal 80 ms). The effect of a single competing short-delay TCP connection on the satellite connection was also investigated, in addition to TCP latency effects on HTTP transfers for GEO and LEO satellite connections.

3.5 Issues to be Investigated and Research Methodology

The research attempts to examine and enhance the system design of Web access in 3G W-CDMA mobile satellite systems that have not been addressed so far in the literature. There are three issues that the thesis would investigate.

- i) Examining the performance of TCP and Web traffic (using HTTP1.1) over 3G W-CDMA mobile satellite links in GEO and MEO satellite environments. The effect of user's data rate, end-to-end round trip delays (GEO and MEO constellations), satellite link frame error rates, TCP segment size, TCP initial window size on TCP throughput and Web page download time (QoS) will be investigated. This will be done first analytically and then by system level simulation. The simulation tool used is OPNET.
- ii) Examining the performance of most critical links in MEO and GEO 3G W-CDMA mobile satellite systems, namely the uplink and downlink connecting a mobile Web user and the satellite. This will be done using SPW simulation tool, which performs link level simulation. The investigated factors include the effect of two most important degradations of W-CDMA in mobile satellite environment, namely power control errors (due to uncompensated shadowing) and slow fading (due low mobility) on the performance of turbo coded downlink and convolutionally coded uplink. The effect of channel interleaving, diversity (macrodiversity for the downlink and space-time transmit diversity (STTD) for the uplink) and RLP on enhancing the performance of the links will be examined.
- iii) Evaluating Web traffic capacity in both MEO and GEO 3G W-CDMA based multispot mobile satellite systems for both uplink and downlink taking into account the effect of beams overlapping, orthogonality, Web traffic activity factor, cross-polarization frequency reuse and shadowing. The effect of power control error in degrading Web traffic capacity will be examined. Finally the effect of macrodiversity for the downlink and STTD diversity for the uplink in enhancing Web traffic capacity will also be examined.

The application scope of the expected results include at least the following scenario:

- Web access in wideband CDMA option for the satellite component of IMT-2000 “SW-CDMA”[43].
- Web access in wideband CDMA option for the satellite component of all IP UMTS “Fourth Generation Mobile Communication System”[44].

Chapter 4

Performance Analysis of Web Traffic in 3G W-CDMA Mobile Satellite Systems

4.1 Introduction

In this chapter we analyze and compare the performance of TCP and Web traffic (using HTTP1.1) over two 3G W-CDMA mobile satellite systems, namely GEO and MEO constellations. The following issues will be investigated here:

- The effect of using various TCP initial window and segment sizes on the performance of TCP in W-CDMA mobile satellite links with random frame error rate.
- The effect of using different data rates (i.e. 64kbps and 144kbps), TCP initial window and segment sizes on Web page download time (QoS) and link utilization assuming random frame error rate in W-CDMA mobile satellite environment.

4.2 Analytical Model for TCP Throughput in 3G W-CDMA Mobile Satellite Systems

In this section two important aspects of a TCP/IP network, namely variations of the average congestion window W_{avg} and the total average round trip delay (RTD_{avg}^{total}) due to segment losses are considered. Here an expression for the average segment transmission rate ($\bar{\lambda}$) of the TCP source, which will be referred to as TCP throughput in presence of random frame error at the physical layer, is of interest. The average segment transmission rate can be approximated as [45]:

$$\bar{\lambda} = \frac{W_{avg}}{RTD_{avg}^{total}} \quad (4.1)$$

In the analysis that follows expressions for W_{avg} and RTD_{avg}^{total} will be derived using a TCP model similar to “TCP-Old Tahoe”; this is primarily used to keep the analytical model tractable.

4.2.1 TCP Window Model

As mentioned in section 3.1.1, TCP uses a slow start mechanism to avoid congestion, which means that for every (or a group of) successful transmission, the window is increased by a certain amount. On the other hand when there is a segment loss, which is notified to the source by a retransmission time-out or several duplicate acknowledgements, the window size is decreased.

This increase or decrease of window size takes place in units of segments. There are two parameters namely the maximum window size (W_{max}) and the minimum window size (W_{min}) to restrict the variations of the TCP window.

In the following model, a simplified general version of this scenario has been assumed. According to the TCP standard, the initial congestion window size (W_{min}) must be less or equal to $2 \cdot MSS$, where MSS is the maximum segment size whose smallest value is 512 bytes. The maximum window size (W_{max}) must be equal to either the *receiver's advertised window* or *bandwidth*roundtrip delay* of the path, whichever is lower both must be expressed in term of MSS.

It is worth mentioning however, that a non-standard experimental TCP extension [46] makes use of a larger initial window (W_{max}) as defined in equation 4.2:

$$W_{max} = \min (4 \cdot MSS, \max (2 \cdot MSS, 4380 \text{ bytes})) \quad (4.2)$$

with this extension a TCP sender may use a 3 or 4 segment initial window, provided the combined size of the segments does not exceed 4380 bytes.

It can be shown that the window increment process can be represented by a discrete Markov chain [45] with state space $\{ S_i = i \}$, where i is the window size. In our example

$i \in \{2,3,4,5,6\}$. This is a simplified model which captures the essence of modeling the congestion window with $W_{\min} = 2$, $W_{\max} = 6$. If the initial window size is two, three, four, or five (segments) and if there is a successful transmission the window is incremented by one (see Figure 4.1). When the window has a size of six, five, four or three, on failing to transmit, the window is set to two segments (corresponding to state 2). When the system is in state 6 and there is a successful transmission, the window size remains unchanged.

Given these constraints, a Markovian model is developed as shown in Figure 4.1. The following transition probabilities are computed.

Figure 4.1: Modeling the TCP congestion window

Probability of a successful transmission (i.e. P_{23} , P_{34} , P_{45} , P_{56}) is given by

$$P_{23} = \sum_{i=1}^{\infty} P_{seg}(i) \quad (4.3)$$

where $P_{seg}(i)$ is the probability that the segment is transmitted successfully at the i_{th} attempt (by the TCP source) and is given by:

$$P_{seg}(i) = [1 - (1 - P_{seg}^{loss})^2]^{i-1} (1 - P_{seg}^{loss})^2 = [P_{seg}^{loss} (2 - P_{seg}^{loss})]^{i-1} (1 - P_{seg}^{loss})^2 \quad (4.4)$$

where P_{seg}^{loss} is the probability of a segment loss due to the air link (between the mobile and the satellite) or wire line network specific error conditions (e.g. congestion) and can be written as

$$P_{seg}^{loss} = 1 - (1 - P_{segloss}^{airlink})(1 - P_{segloss}^{wireline}) \quad (4.5)$$

$$\text{where } P_{segloss}^{airlink} = 1 - P_f^{N_s} \quad (4.6)$$

P_f is the probability that a frame can be transmitted successfully over the radio link protocol (RLP) [47] and is given by:

$$P_f = 1 - p + \frac{p(1-p)^2}{1-p(2-p)} \left[1 - (p(2-p))^{\frac{n(n+1)}{2}} \right] \quad (4.7)$$

where p is the frame error rate (FER) in the satellite channel between a mobile host (MH) and the satellite, while n is the number of retransmissions at RLP that will be restricted here to 2. N_s is the number of RLP frames per TCP segment. Here RLP frame size is always equal to 20 ms. The RLP here uses the same retransmission mechanism as that used in IS-99[48].

$P_{segloss}^{wireline}$ denotes the TCP segment loss probability in the terrestrial (wireline) network due to congestion or other types of network specific error conditions and it will be assumed here to equal 0.00001.

The probability of a successful transmission in first attempt is given by

$$P_{34} = P_{seg}(1) \quad (4.8)$$

The probability of an unsuccessful transmission (i.e. $P_{32}, P_{42}, P_{52}, P_{62}$) is given by

$$P_{32} = P_{seg}^{loss} (2 - P_{seg}^{loss}) \quad (4.9)$$

This Markov chain can be easily solved for the steady state probabilities Π_i (for state i) as follows:

$$\Pi_2 = \frac{1}{1 + \frac{P_{23}}{P_{32}+P_{34}} + \frac{P_{23}P_{34}}{(P_{32}+P_{34})P_{42}} + \frac{P_{23}P_{34}P_{45}}{P_{42}(P_{34}+P_{32})(P_{52}+P_{56})} + \frac{P_{23}P_{34}P_{45}P_{56}}{P_{42}(P_{34}+P_{32})(P_{52}+P_{56})P_{62}}} \quad (4.10)$$

$$\Pi_3 = \frac{P_{23}}{P_{32} + P_{34}} \Pi_2 \quad (4.11)$$

$$\Pi_4 = \frac{P_{23}P_{34}}{(P_{32} + P_{34})P_{42}} \Pi_2 \quad (4.12)$$

$$\Pi_5 = \frac{P_{45}P_{23}P_{34}}{(P_{52} + P_{56})(P_{32} + P_{34})P_{42}} \Pi_2 \quad (4.13)$$

$$\Pi_6 = \frac{P_{56}P_{45}P_{23}P_{34}}{P_{62}(P_{52} + P_{56})(P_{32} + P_{34})P_{42}} \Pi_2 \quad (4.14)$$

The average congestion window size is then given as

$$W_{avg} = 2\Pi_2 + 3\Pi_3 + 4\Pi_4 + 5\Pi_5 + 6\Pi_6 \quad (4.15)$$

4.2.2 Total Average Roundtrip Time Duration (RTD_{avg}^{total})

Here a simplified model of the network as shown in Figure 4.2 is considered. The total average roundtrip delay (RTD_{avg}^{total}) can be assumed to consist of three components in a typical mobile satellite network. Considering a satellite with on board processing is used, RLP can be implemented between a mobile host and the satellite. The three delay components are as follow:

4.2.2.1 Round Trip Delay in the Terrestrial Network ($RTD_{avg}^{terrestrial}$)

In the absence of any single model that can track the dynamics of the traffic build-up in the terrestrial network (i.e. the Internet), experimentally derived data will be used. In [34] the round trip delay from a European terrestrial network ($RTD_{avg}^{terrestrial}$) has been experimentally measured with reference to a set of the most popular Web servers in medium traffic hours from MAE-EAST, one of the major interconnection points in the of US network. Results are presented in Table 4.1.

Figure 4.2: Typical model for the network

Table 4.1: Experimentally derived mean round trip time ($RTD_{avg}^{terrestrial}$)

Typical RTT (ms)	Average	Minimum	Maximum
US MAE-EAST	160	150	200

4.2.2.2 Round Trip Delay between a Mobile Host and the Satellite ($RTD_{avg}^{host-satellite}$)

The average end-to-end delay (i.e. one-way delay) for transmitting a TCP segment over an RLP protected air link between a mobile host and the satellite is given [45] as:

$$D_{seg}^{avg} = T + (N_s - 1)\tau + pN_s \sum_{j=1}^n \sum_{i=1}^j P(C_{ij})[2jT + 2(i-1)\tau] \quad (4.16)$$

where $P(C_{ij}) = p(1-p)^2(p(2-p))^{\frac{j(j-1)}{2} + (i-1)}$

for $1 \leq i \leq j$ and $1 \leq j \leq 2$

The term T is the one-way delay in the air link (i.e. physical layer) without the effect of RLP. T is equal to 225 ms for GEO and 150 ms for MEO (assuming MEO altitude of 15000 Km) W-CDMA satellite systems. This delay (T) includes all the delays in the physical layer such as transmission, interleaving and coding delays in addition to the propagation delay. In chapter 5 a delay model for the physical layer will be derived [49]. τ is the RLP frame size and is equal to 20 ms. p is the FER due to the satellite channel without the effect of RLP. i is the number of RLP attempts at j^{th} trail, while j is the number of RLP trails. The round trip delay ($RTD_{avg}^{host-satellite}$) is just twice D_{seg}^{avg} . N_s is the number of RLP frames per TCP segment and depends on both the size of TCP segment and the data rate being used. Considering TCP segment size equal to 512 bytes (this doesn't include 20 bytes for TCP header, 20 bytes for IP header and 10 bytes for RLP header that is needed to calculate N_s), then for 64 kbps N_s is equal to 3.5 while for 144 kbps it is 1.5.

For the range of FER of interest, i.e. between $1-P_f = 10^4$ to 10^6 and a data rate of 64 kbps, D_{seg}^{avg} is about 0.275 second for a GEO satellite, and 0.2 second for a MEO

satellite, while for 144kps, D_{seg}^{avg} is about 0.235 second for a GEO satellite and 0.16 second for a MEO satellite.

4.2.2.3 Round Trip Delay between a Satellite Gateway and the Satellite

($RTD_{avg}^{satellite-gateway}$)

The round trip delay between a satellite gateway and the satellite ($RTD_{avg}^{satellite-gateway}$) is just twice the term T (i.e. the delay in the air link without the effect of RLP). This is because the air link connecting a satellite gateway and the satellite usually operates at both very high data rate and as well as high signal to noise ratio, hence no retransmission is assumed. Thus the transmission time per TCP packet can be ignored. Assuming interleaving size = 20 ms, then T is equal to 225 ms for a GEO satellite and 150 ms for a MEO satellite as will be described in chapter 5.

Thus for FER of interest, (i.e. $1-P_f=10^{-5}$), the *Total average round trip delay* (RTD_{avg}^{total}) is shown in Table 4.2 assuming TCP segment size = 512 bytes, while Table 4.3 is for TCP segment size = 1460 bytes.

Table 4.2: Total round trip time (RTD_{avg}^{total}) and its components in second (512 bytes).

Round trip time(s)	MEO (64kbps)	GEO (64kbps)	MEO (144kbps)	GEO (144kbps)
MH-Sat link	0.4	0.55	0.32	0.47
Sat-Gateway link	0.3	0.45	0.3	0.45
Terrestrial link	0.16	0.16	0.16	0.16
Total (RTD_{avg}^{total})	0.86	1.16	0.78	1.08

Table 4.3: Total round trip time (RTD_{avg}^{total}) and its components in seconds (1460 bytes).

Round trip time(s)	MEO (64kbps)	GEO (64kbps)	MEO (144kbps)	GEO (144kbps)
MH-Sat link	0.635	0.785	0.427	0.576
Sat-Gateway link	0.3	0.45	0.3	0.45
Terrestrial link	0.16	0.16	0.16	0.16
Total (RTD_{avg}^{total})	1.095	1.395	0.887	1.186

4.2.3 Numerical Results for Performance of TCP

4.2.3.1 Effect of Round Trip Delay on the Performance of TCP

Figure 4.3 shows TCP throughput over GEO and MEO satellite links, assuming the network shown in Figure 4.2[50]. This is obtained by solving equations (4.1), (4.15) and (4.16) for various frame error rates (with the effect of RLP).

As the frame error rate increases, the TCP window shrinks, since TCP interprets any segment loss (or error) as a sign of network congestion. This leads to a decrease in the throughput of the source (e.g. Web server). Note that, as the frame error rate increases, TCP throughput decreases slowly at first, but later plunges down drastically as the window decreases fast due to a large amount of congestion signals. As it can be seen, the performance of TCP in a MEO constellation is significantly better than that in a GEO due to lower round trip delay in MEO in comparison to that in GEO, but still very low FER is needed in both systems in order to maintain adequate TCP throughput.

Figure 4.3: 64kbps satellite link, TCP segment = 1460 bytes, $W_i = 3$.

4.2.3.2 Effect of Initial Window Size on the Performance of TCP

Figure 4.4: 64 kbps MEO satellite link, TCP segment = 1460 bytes.

Figure 4.4 shows the performance of TCP as function of its initial window size in MEO satellite constellation. Even though the general shape of the curve is similar to that shown in Figure 4.3. The effect of employing a large TCP initial window size is evident at low FER. A large TCP initial window size slightly limits the rate of TCP throughput from plunging down drastically as FER increases.

4.2.3.3 Effect of Segment Size on the Performance of TCP

Figure 4.5: 64 kbps MEO satellite link speed, $W_i = 3$.

Figure 4.5 shows the performance of TCP in MEO constellations as function of its segment size. As can be seen the performance of TCP has improved significantly at low FER for larger TCP segment.

4.3 Analytical Model for the Performance of HTTP/1.1 in 3G W-CDMA Mobile Satellite Systems

In this section the performance of HTTP/1.1[51] over TCP in mobile W-CDMA satellite systems will be examined for the network shown in Figure 4.2 assuming error free conditions. In this analysis a typical Web page as described in (3.2.2) will be assumed. TCP and HTTP/1.1 protocols and their relationship were described in chapter 3. It will be assumed that Web server processing time is negligible. Under these hypotheses the following are defined:

- Total round trip delay (rtt) in seconds is as shown in Table 4.2 and 4.3.
- Bandwidth (bw) available to the connection = 64 kbps or 144 kbps.
- Typical Web page size = 43.5 Kbytes.
- Maximum segment size (mss) for application data in WAN = 512 or 1460 bytes
- Maximum useable window size (muws) = bw*rtt

Now considering the packet exchange between a mobile host (MH) and a Web server shown in Figure 4.2 and assuming mss equal to 512 bytes, an algorithm can be derived as follows:

1. During the first round trip (rtt), no real data is transmitted - only handshaking packets SYN are transmitted. The TCP window size has now increased from 1 to 2 at the end of this exchange. The size of each TCP packet in this exchange is 40 bytes, thus for this rtt the connection can be considered as almost idle (i.e. $t_0^{wasted} = rtt$).
2. During the second round trip time (rtt) two data packets ($2*512$ bytes = $2*4096$ bit) are sent. Under the above-defined hypotheses, the packet is transmitted in

$t_1^{used} = \{2 * 4096 / bw\}$. During the remaining $t_1^{wasted} = rtt - t_1^{used}$ the interconnection is idle.

3. During the third round trip time (rtt) four packets ($4 * 512$ bytes = $4 * 4096$ bits) are sent. Used and waste times are $t_2^{used} = \{4 * 4096 / bw\}$ and $t_2^{wasted} = rtt - t_2^{used}$ respectively. During the fourth round trip time these values will be $t_3^{used} = \{8 * 4096 / bw\}$ and $t_3^{wasted} = rtt - t_3^{used}$ respectively. Assuming no bottlenecks in the links this goes until all the round trip time rtt is used up.
4. During the generic round trip time (rtt) i where $i > 0$, the useful transmission time is $t_i^{used} = \min\{d, 2^{i-1} * 4096 / bw\}$ and the time wasted is $t_i^{wasted} = d - t_i^{used}$. During each rtt, $t_i^{used} * bw$ are transmitted.
5. During the last round trip time (when the data still to be sent is less than $t_{last}^{used} * bw$), the transmission time $t_{last}^{used} = f_r / bw$ where f_r is the last remaining part of the Web page in bits.

Using these results the transmission time of a single Web page can be computed algorithmically.

4.3.1 Numerical Results for Performance of HTTP/1.1

Now, the above algorithm will be applied for the network shown in Figure 4.2 with the following characteristics:

Table 4.4: Network characteristics for mobile W-CDMA satellite.

rtt (Round trip for MEO and GEO)	As shown in Table 4.2 and 4.3
bw (Satellite channel bandwidth)	64Kbps and 144Kbps
mss (Application data)	512 and 1460 bytes
Internet overheads	20 + 20 bytes (TCP and IP headers)
Satellite overhead	10 bytes (RLP header)
muws	rtt * bw

Now in order to show how the model described in 4.3 can be used to predict the performance of the HTTP/1.1 protocol in mobile W-CDMA networks, an example is

given as shown by Table 4.5. The example assumes a typical Web page of size 43.5 kbytes being requested by a mobile host from a Web server over a 144kbps Geo satellite link.

Table 4.5: Predicting the performance of HTTP/1.1 over 144 kbps GEO satellite link

Round trip (rtt) number	Total number of bytes sent per rtt	Number of payload bytes sent per rtt	Satellite link is used per rtt	Satellite link is wasted per rtt
1	40+20+10 = 70	--	0.1057 %	99.8943 %
2	2*562 = 1124	2*512 = 1024	1.7 %	98.3 %
3	4*562 = 2248	4*512 = 2048	3.4 %	96.6 %
4	8*562 = 4496	8*512 = 4096	6.8 %	93.2 %
5	16*562 = 8992	16*512 = 8192	13.6 %	86.4 %
6	32*562 = 17984	32*512 = 16384	27.2 %	72.8 %
7	22.96*562 = 12905	22.96*512 = 11756	19.5 %	80.5 %

The download time for the average Web page = $7 * 1.08 = 7.56$ second.

Average transmission rate during the download = Total number of bytes transmitted/download time = $47819 / 7.56 = 6325$ bytes per second = 50.6 kbps.

Average link utilization = $50.6 / 144 = 0.351388 = 35.138 \%$

Table 4.6 and 4.7 show the summary for the performance of HTTP/1.1 over mobile W-CDMA satellites GEO and MEO, assuming the TCP initial window size is equal to $2 * 512$ and $2 * 1460$ bytes respectively. Table 4.8 and 4.9 show the performance of HTTP/1.1 for a TCP initial window size equal to $4 * 512$ and $3 * 1460$ bytes respectively (i.e. nonstandard or experimental TCP initial window sizes).

Table 4.6: Results for the performance of HTTP/1.1 over satellites ($2 * 512$ bytes).

Numerical results	MEO (64Kbps)	GEO (64Kbps)	MEO (144Kbps)	GEO (144Kbps)
Average link utilization	0.698	0.57	0.426	0.35
Download time(s)	8.6	10.44	6.24	7.56

Table 4.7: Results for the performance of HTTP/1.1 over satellites (2*1460 bytes).

Numerical results	MEO (64Kbps)	GEO (64Kbps)	MEO (144Kbps)	GEO (144Kbps)
Average link utilization	0.735	0.58	0.47	0.37
Download time(s)	7.665	9.765	5.322	7.1

Table 4.8: Results for the performance of HTTP/1.1 over satellites (4*512 bytes).

Numerical results	MEO (64Kbps)	GEO (64Kbps)	MEO (144Kbps)	GEO (144Kbps)
Average link utilization	0.775	0.598	0.4858	0.409
Download time(s)	7.74	9.28	5.46	6.48

Table 4.9: Results for the performance of HTTP/1.1 over satellites (3*1460 bytes).

Numerical results	MEO (64Kbps)	GEO (64Kbps)	MEO (144Kbps)	GEO (144Kbps)
Average link utilization	0.735	0.672	0.5644	0.422
Download time(s)	7.665	8.37	4.435	5.93

From Table 4.6 and 4.7 the following points can be observed:

- It can be seen that by reducing the satellite delay i.e. choosing MEO constellations instead of GEO constellations reduces the download time of a typical Web page between 8.5% to 25% depending on the choice of data rate and segment size being used.
- Using 1460 bytes in the TCP segment instead of 512 bytes can reduce the page download time between 6 to 11% depending on the choice of satellite constellations (i.e. MEO or GEO) and the data rate being used. Hence it may be advantageous to use larger size TCP segment in mobile satellites.
- Using a 144 kbps data rate instead of 64kbps can reduce the Web page download time by 27% to 40% depending on the choice of the satellite constellations and the size of TCP segment being used. Hence in mobile satellite networks, it is highly recommended to use a high data bit rate (i.e. 144kbps instead of 64 kbps) to significantly reduce page download time.

Table 4.8 and 4.9 show the effect of using larger initial window size. As expected, doubling the initial window size (e.g. from 4*512 bytes to 3*1460 bytes) resulted in reducing the page download time by one round trip delay.

4.4 Performance of Web Traffic in 3G W-CDMA Mobile Satellite Systems

In this section the performance of Web traffic in 3G MEO and GEO mobile W-CDMA satellite systems will be analyzed and compared using system level simulation, assuming random frame error rate. The effect of using different data rates (i.e. 64 and 144 kbps) and TCP initial window and segment sizes on Web page download time will be analyzed for the two satellite constellations.

4.4.1 Simulation Model

4.4.1.1 Network Characteristics

The model consists of a workstation node (i.e. client) and a server node, representing a satellite mobile Web terminal and a server respectively. The Web server is located in the terrestrial element of the Internet. The simulated network is shown in Figure 4.2. The simulation model consists of a workstation that is attached to a Web server via two point-point links as shown in Figure 3.4. The links are characterized by adjustable parameters such as delay, frame error rate and transmission rate.

The downlink that connects the Web server to the client can be adjusted to operate at data rate of either 64 kbps or 144 kbps; while the uplink connecting the client to the Web server is fixed at a data rate of 12.2 kbps. The downlink is used to download Web pages from the Web server to the workstation while the uplink is used to send requests for HTTP Web page objects and TCP acknowledgements from the workstation to the Web server. In W-CDMA parlance, these channels are called dedicated channels. The frame size for these channels is 20 milliseconds, which is specified in 3 GPP W-CDMA standard and shown in Figure 5.2.

4.4.1.2 Modeling Delay in the Terrestrial Network

As mentioned in 4.2.2.1, in the absence of any single model that can track the dynamics of the traffic buildup in the terrestrial network (i.e. the Internet), experimentally derived data is used to model the delay in the terrestrial network as shown in Table 4.1.

4.4.1.3 Modeling the Delay in the Satellite Network

The average end-to-end delay (i.e. one way delay) for transmitting a W-CDMA frame of 20 ms (smallest re-transmissible block of data on the air-interface) between a satellite mobile host (i.e. Web terminal) and the satellite, and between the satellite and the gateway were described in 4.2.2.2 and 4.2.2.3 respectively and shown in Table 4.2. The total average round trip delay between a mobile host and the Web server is also shown in Table 4.2 for mobile satellites using MEO and GEO constellations.

4.4.1.4 TCP and Web Traffic Models

The TCP/IP model is based on the Internet engineering task force (IETF) request for comment (RFC) 1122, and RFC 2001. The main features implemented include:

- a) End-to-End reliability based on acknowledgements and retransmissions triggered by exponential backed-off timers.
- b) Flow control
- c) Reordering out-of-sequence data frames.
- d) Slow-start and congestion avoidance
- e) Connection establishment and closing using a three-way handshake (SYN-ACK-SYN).
- f) Fast retransmit, Fast recovery algorithms.

Details of TCP parameters are shown in Table 4.10.

The traffic model used is an ON/OFF exponential model. The traffic load is generated at a rate of 60 pages per hour to simulate the behavior of heavy browsing user. Each page contains 12 objects that are roughly 12 Kbytes each [52].

Table 4.10: TCP RENO parameters.

Maximum segment size (bytes)	512 or 1460
Receive buffer (bytes)	65536
Maximum ACK delay (sec)	0.200
Slow-start initial count (MSS)	2 or 4
Initial RTO (sec)	3.0
Minimum RTO (sec)	0.5
Maximum RTO (sec)	64
RTT gain	0.125
Deviation gain	0.25
RTT deviation coefficient	4.0
Timer granularity (sec)	0.5
Persistence timeout (sec)	1.0

4.4.2 Simulation Results

Simulation runs were conducted under frame error rate (FER) conditions for two transmission rates (i.e. 64 kbps and 144kbps) for the downlink (satellite to mobile Web user) to download Web pages, while the uplink (mobile Web user to satellite), which is usually used to send TCP acknowledgements and HTTP requests was fixed at 12.2 kbps. Data was gathered for two data rates (64 and 144 kbps), two TCP parameters e.g. TCP segment sizes (512 and 1460 bytes), and TCP initial window sizes (2 and 4). The FER values are assumed residual, i.e. FER after interleaving, coding and radio link protocol (RLP).

4.4.2.1 Comparison of Web Traffic Performance in MEO and GEO Satellites

Tables 4.11 and 4.12 show a summary for the performance of Web traffic over GEO and MEO W-CDMA mobile satellites in term of page response time and link utilization respectively as function of FERs [53]. The TCP initial window size is assumed to be equal to 2×512 bytes. Table 4.11 shows that the 144 kbps data rate provides substantial improvement in performance in terms of reduction in Web page download time in comparison to that of a 64 kbps data rate in both satellite constellations (i.e. GEO and MEO).

Meanwhile, using a lower altitude MEO (15000 km) satellite provides only a slight reduction in Web page download time which can be attributed to the fact that the delay reduction in using MEO is not significant in comparison to the overall end-to-end delay between the Web mobile terminal and the Web server. However, the critical value of FER at which the Web page download time starts to increase significantly depends on

the type of constellation (i.e. MEO or GEO) as well as the data rate (i.e. 64 kbps or 144kbps). For example at a 144 kbps data rate, Table 4.11 shows that the critical value of FER in a GEO system is equal to 5×10^{-3} while in MEO the critical value of FER is equal to 9.6×10^{-3} . It should be noted that the average response times in Table 4.11 for FER = 0 agrees with theoretical results shown in Table 4.6 for download time.

Table 4.11: Average Web response time in seconds (2*512 bytes)

FER	MEO (64kbps)*	GEO (64kbps)*	MEO (144kbps)*	GEO (144 bps)*
0	27.3	30.4	16.5	19.8
9.6×10^{-5}	27.3	30.4	16.5	19.8
5×10^{-4}	27.3	30.5	16.6	20
9.6×10^{-4}	27.5	30.6	16.6	20
5×10^{-3}	27.8	31.3	17.6	21.6
9.6×10^{-3}	28.7	32.8	19	24
4.5×10^{-2}	42.5	53.8	37.7	49.4

*The data rate here shows only that for the downlink (DL), while the uplink (UL) is always set at 12.2 kbps in all cases.

Table 4.12: Average uplink (UL) and downlink (DL) utilization in percentage during Web page download time.

FER	MEO (64kbps)		GEO (64kbps)		MEO (144kbps)		GEO (144 kbps)	
	UL	DL	UL	DL	UL	DL	UL	DL
0	12	26	11.6	24.7	11.3	12.2	11	11.5
9.6×10^{-5}	12	26	11.7	24.7	11.3	12.2	11	11.5
5×10^{-4}	12.2	26	11.7	24.7	11.3	12.2	11	11.5
9.6×10^{-4}	12.4	26	11.7	24.7	11.3	12.2	11	11.5
5×10^{-3}	12.6	26	12.12	24.7	11.9	12.2	11.4	11.4
9.6×10^{-3}	12.8	26	12.4	24.5	12.4	12	12	11.3

*The data rate here shows only that for the downlink (DL), while the uplink (UL) is always set at 12.2 kbps.

In addition to the information regarding mean Web page response time and link utilization, Figure 4.6 provides the CDF (cumulative distribution function) for Web page download time under various FER settings for a GEO system. The critical value of FER at which Web page download time starts to increase significantly is evident ($5 \cdot 10^{-3}$ in this particular case).

Figure 4.6: CDF for Web page download time assuming GEO system, 144kbps data rate, TCP segment size-512 bytes, TCP initial window size = 2.

Figure 4.7: CDF for Web page download time assuming 144kbps data rate, TCP segment size 512 bytes, TCP initial window size = 2 , FER = 0.

Meanwhile Figure 4.7 provides a comparison in term of CDF of Web page download time for both a MEO and GEO systems assuming FER = 0. The graph shows that the page downloads time in a MEO system only slightly lower than that in a GEO system. Hence this slight improvement in performance alone does not merit the selection of a MEO system over a GEO system taking into consideration the complexity and the risk associated with a MEO system. This topic will be discussed in more detail in chapter 6 when assessing the Web traffic capacity in both MEO and GEO systems.

4.4.2.2 Effect of the TCP Window Size on the Web Page Response Time

Table 4.13 shows the effect of increasing TCP initial window size from 2*512 to 4*512 bytes on Web page response time. Comparing Table 4.13 with Table 4.11, the effect of doubling TCP initial window size results in a small reduction in Web page download time. This small reduction in Web page download time can be attributed to the fact that increasing TCP initial window size from 2 to 4 has resulted in reducing the total delay during Web page download time by only one round trip.

Table 4.13: Average Web response time in seconds (4*512 bytes).

FER	MEO (64kbps)	GEO (64kbps)	MEO (144kbps)	GEO (144 kbps)
0	26.9	29	15.9	18.3
9.6×10^{-5}	26.9	29	15.9	18.3
5×10^{-4}	26.9	29	15.9	18.5
9.6×10^{-4}	27	29	16	18.7
5×10^{-3}	27.5	29.9	16.9	20
9.5×10^{-3}	28.2	31.3	18.4	22.5
4.5×10^{-2}	41.5	52	36.6	47.6

*The data rate here shows only that for the downlink (DL), while the uplink (UL) is always set at 12.2 kbps in all cases.

4.4.2.3 Effect of TCP Segment Size on Web Page Response Time

Table 4.14 shows the effect of increasing TCP segment size from 512 to 1460 bytes on Web page response time. Comparing the results in Table 4.14 with Table 4.11, it can be seen that using a large TCP segment size (i.e. 1460 instead of 512 bytes) has resulted in a significant reduction in Web page download time. Hence, it is highly recommended to

use large TCP segment size in mobile satellite systems where the round trip delay is quite large.

Table 4.14: Average Web response time in seconds (2*1460 bytes)

FER	MEO (64kbps)	GEO (64kbps)	MEO (144kbps)	GEO (144 kbps)
0	25.2	27.3	14.7	17.4
9.6×10^{-5}	25.2	27.3	14.75	17.4
5×10^{-4}	25.2	27.3	14.75	17.5
9.6×10^{-4}	25.3	27.5	14.8	17.6
5×10^{-3}	25.9	28.1	15.4	18.7
9.5×10^{-3}	27.1	29.5	16.6	20.4
4.5×10^{-2}	42.7	48.8	34.5	43

*The data rate here shows only that for the downlink (DL), while the uplink (UL) is always set at 12.2 kbps in all cases.

Chapter 5

Performance Enhancement of 3G Mobile Satellite System for Web Traffic

5.1 Introduction

In this chapter, the performance of 3G W-CDMA mobile satellite systems for Web traffic is examined, and then methods to enhance it are proposed. The aim of the enhancements is to allow the required frame error rate for Web traffic (e.g. $FER = 5 \cdot 10^{-3}$ in a GEO system) to be achieved at the lowest possible signal-to-noise ratio (E_b/N_o) and fading margin. These enhancements must be achieved in presence of large power control error (PCE) and interference levels.

This is extremely important since mobile satellites are power limited in the downlink while they are interference limited in the uplink. As mentioned in section 1.2, PCEs mainly arise in mobile satellites because closed loop power control is ineffective due to long satellite delay. It was found that PCE in mobile satellites has lognormal distribution with standard deviation (σ_s) between 1 to 4 dB [7]. Thus before attempting to enhance the performance of a W-CDMA mobile satellite system; a detailed understanding of the performance of both uplink and downlink is necessary.

The performance of W-CDMA links will be examined taking into consideration the effect of channel impairments such as slow fading (due to slow mobility), interference noise, and power control errors (due to uncompensated shadowing). This will be done using link level simulation. It is important to first examine the effects of such impairments before any enhancement method can be proposed, since they are expected to greatly influence the performance of the links and hence system capacity. The following

techniques will be examined to enhance the performance of 3G turbo-coded downlink and convolutionally coded uplink.

- a) Channel Interleaving
- b) Diversity: macrodiversity for the downlink and space-time transmit diversity (STTD) for the uplink.
- c) Radio link protocol (RLP)

5.2 System Model

Figures 5.1 and 5.12 illustrate the block diagram for the downlink (i.e. satellite to web user) and the uplink (i.e. web user to satellite) of the 3G W-CDMA mobile satellite systems respectively. The transmitted signal $s(t)$ can be described as follows:

$$s(t) = \text{Re}\{ u(t) \exp(-j\omega_c t) \}, \quad (5.1)$$

For the downlink $u(t) = \sqrt{2p} b(t)a(t)$, while for the uplink $u(t) = \sqrt{2p} b(t)[a(t) - a(t)^*]$

Where p is the total power, $b(t)$ is user information, $a(t)$ is the spreading sequence and $a(t)^*$ is complex conjugate of $a(t)$. The lognormal-Rician channel model used in this work is well analyzed in [54] and shown in Figure 2.3.

5.2.1 Receiver Model

The received signal for a W-CDMA system in a narrowband-fading channel can be written as [55]:

$$r(t) = \sum_{m=0}^{M-1} u(t - \tau_m(t))\alpha_m(t) + n(t) \quad (5.2)$$

Where $u(t)$ is low-pass equivalent transmitted waveform, $\tau_m(t)$ is time-varying propagation delay for the m^{th} receive antenna, $\alpha_m(t)$ is the time varying complex fading factor, and $n(t)$ is complex zero mean additive white Gaussian noise. In the downlink case (see Figure 5.1), which uses space diversity, the receiver adds the m signals ($M = 2$ in our case) using an equal gain combiner (EGC) and then performs coherent demodulation. In the uplink case, which uses STTD, type of diversity (see Figure 5.12), the receiver adds

the m signals after being coherently demodulated. After the signal is demodulated, it will be fed into a channel decoder.

5.3 Structure of 3G W-CDMA Mobile Satellite Downlink

5.3.1 Transmitter Side

Figure 5.1 shows a simplified structure of a simulated 3G W-CDMA downlink [56-59] with macrodiversity (space) being implemented at the receiver. Fig 5.2 shows the frame structure for the combined dedicated physical channels, (i.e. the dedicated physical data channel (DPDCH) and dedicated physical control channel (DPCCH). Major downlink parameters are listed in Table 5.1.

The random frame generator generates frames of random data. The length of the output vector is floor [(data rate * time transmission interval (TTI))], where the data rate is fixed to 144kbps, which is the maximum rate recommended for Web traffic in the satellite segment of IMT-2000. TTI is the smallest unit that is re-transmissible on the air-interface and always equal to 20 ms. It should be noted, however, that, the frame duration in the air interface is always 10 ms (i.e. one TTI equal to two frames of the air interface).

The 20 ms TTI is first fed into cyclic redundancy check (CRC) encoder, where 8 CRC bits are generated. This is done using the generator polynomials shown in Table 5.1.

The encoded CRC TTI is then fed into a turbo encoder [60-62]. The turbo code is an 8-state rate 1/3 code. The output formed by multiplexing the original sequence, a recursive convolutionally encoded version of the sequence and a recursive convolutionally encoded version of an interleaved version of the sequence. The generator matrix of the turbo code is as shown below:

$$G(D) = \begin{bmatrix} 1 & \frac{1+D+D^3}{1+D^2+D^3} \end{bmatrix} \quad (5.3)$$

Rate matching allows data arriving at a given data rate to be matched to the aggregate data rate of the channel. Thus if the input data rate is higher than the maximum

Figure 5.1: Simulated downlink for 3G W-CDMA mobile satellites for dedicated physical channels (DPDCH/DPCCH) with macrodiversity (space) at the receiver.

Figure 5.2: Frame structure for the downlink dedicated physical channels (DPDCH/DPCCH)

supported by the channel, the data is punctured and if it is lower the data is repeated, in order to make the data fit into the bandwidth available.

The channel interleaver interleaves the encoded data signal to minimize the effects of burst errors. In interleaving, data for one radio transmission time interval is reordered to protect against bursts of errors from time varying channel. The algorithm in interleaving is to place the input data in a matrix with N columns, where N is the number of 20 ms frames in the TTI. The matrix is filled along the first row, and then the second and so on until the input data is exhausted.

The downlink slot format takes the frame of data and produces 15 correctly formatted slots for the frame. The block internally adds the pilot bits. The transmission power control (TPC) bits are just random data.

The QPSK mapping block multiplexes the stream of data from the formatted frame into in-phase (I) and quadrature paths (Q), with the first datum going to the I path, the second to the Q path, and so on. The I and Q signals are then spread by the same orthogonal variable spreading factor (OVSF) code to provide channelization. The complex signal (I and Q signals) is then scrambled at the spreader by multiplying by a complex Gold sequence. The pseudo-noise scrambling codes are satellite-specific. Different spot beams of a satellite use different cyclic shifts of the same scrambling code. Finally, the CDMA chips are filtered with a square root raised cosine filter with a roll-off factor of 0.22.

5.3.2 The Satellite Channel

The channel model used in the simulation is lognormal-Rician channel, which is described in section 2.4. The parameters for the channel are as follow:

- a) The Rician fading is characterized by direct-to-multipath signal power ratio (Rice-factor) $K_R = 10$ dB.
- b) The lognormal fading is characterized by mean attenuation (due to shadowing), $\mu_s = -10$ dB and standard deviation of power level $\sigma_s = 4$ dB [16].

The lognormal fading process models slow variations in the logarithmic path loss from a source (i.e. the satellite) to a receiver as a function of distance. This variation has a Gaussian distribution [63-65], and normalized autocorrelation function of

$$R(d) = e^{-d \ln(2) / d_c} \quad (5.4)$$

Where d is the distance between points, and d_c the decorrelation distance. Once the distance has changed by d_c , the normalized correlation has dropped to one half. A typical value for d_c is 20 meters. For simulation purposes μ_s will be assumed here to equal to 0 dB since it is usually taken into account in the satellite link budget.

5.3.3 Noise

As mentioned in section 2.7.2, in the downlink chip-synchronous CDM with orthogonal spreading codes can easily be realized; hence it is assumed that downlinks do not suffer from co-channel interference [10]. The only noise considered here is thermal noise, which is modeled as additive white Gaussian noise.

5.3.4 Receiver Side

The input signal from each antenna is first filtered with a square root raised cosine matched filter (FIR) with alpha of 0.22. Each received signal is then descrambled at the despreader by multiplying it by a complex conjugate of the downlink scrambling sequence (i.e. complex Gold sequence) to descramble the data and then the two descrambled signals are combined using equal gain combiner (EGC). This is shown in Figure 5.1.

Demodulation is performed at the QPSK demapping block by first splitting the signal into real and imaginary parts and multiplying them by the complex conjugate of the orthogonal variable spreading factor (OVSF), then performing an integrate and dump over one bit period. Finally, the complex data is converted to a real sequence by first outputting the real part and then the imaginary part of the combined signal.

The downlink slot deformat block reads in the despread data, packs the data into slots and then splits each slot into the various fields. The slot format is as shown in Fig. 5.2. The output fields are real valued vectors, and no quantization occurs in this block so that soft decision can be performed on the output data.

The turbo scale block estimates the signal amplitude and noise power in every radio frame to properly scale the signal data before turbo decoding with a MAP decoder. As mentioned in [64], the map decoder is very sensitive to input scaling. The proper scaling factor is

$$\text{Scale factor} = 4 * \text{signal_amplitude} / \text{noise_power}. \quad (5.5)$$

This block estimates the signal amplitude and noise power using the pilot's bits. Correlating the received pilot bits with the known pilot bits over an entire frame gives an estimate of the signal amplitude. Subtracting the signal amplitude squared from the total power in the received data bits yields the noise power. Given these values, the block calculates and applies the scaling factor to the data bits.

The channel deinterleaver de-interleaves data using the inverse of the algorithm of the interleaver as described in 5.3.1. The rate dematching performs the inverse rate matching, if the data was originally punctured, zeros are inserted at the puncture point.

Before decoding takes place, radio frame de-segmentation is performed (i.e. blocks of data for multiple radio frames (10 ms each) are joined to form a block of data for the transmission time interval (TTI) which is 20 ms). The turbo decoder decodes the received downlink data using a soft decision iterative MAP algorithm [60-61]. The decoding is iterative.

Table 5.1: Simulation parameters for downlink of 3G W-CDMA mobile satellites.

Bit rate	144 kbps
Carrier frequency	2.125 Ghz
Service	Web browsing
Coding block size	2880 bits
CRC Bits	8
CRC generator polynomial (octal)	0xc8f
Tail Bits	12
Physical layer	
Multiple access method	DS-CDMA
Carrier chip rate	3.84 Mcps
Spreading factor	16
Frame length (air interface)	10 ms (1 Frame = 15 Time Slot)
Forward error correction (FEC)	Turbo code of $R = 1/3$, $K = 4$, number of iterations = 5
Channel interleaving	20 ms or 160 ms
Rate matching	8700 $\rightarrow$ 8464
Modulation	Data: QPSK, spread: QPSK
Pulse shaping	Root raised cosine, roll-off = 0.22
Open loop power control error	1 to 4 dB
Environment	
Channel profile	Rice-lognormal, Rice factor (K_R) = 10, Mean (μ_s) = 0 dB, Standard deviation (σ_s) = 4 dB
Mobile speed (km/h)	20 and 80
Noise	Gaussian noise
Diversity	Macrodiversity (space)

5.4 Simulation Results for Performance of 3G W-CDMA Downlink with no Diversity

Here simulation is focused on the degradation in the performance of turbo-coded downlink due to the impact of power control errors and slow fading. The effect of using an RLP and channel interleaver to combat such degradations will also be examined here. Table 5.1 shows the simulation parameters used in the simulation.

5.4.1 Degradation of the Downlink due to Power Control Error

The bottom curve in Figure 5.3 shows the performance of the downlink with no power control error (perfect power control). The shadowing effect has been completely compensated for by the power control and the channel appears as Rician fading channel with $K_R = 10$. The curve roll-off is typical performance of turbo code in Rician fading channel [60].

The upper curve shows the effect of power control error with a standard deviation (σ_s) of 1dB [66]. Even a small power control error has significantly degraded the performance of the link. This mainly due to shadowing effect, which could not be compensated by the power control mechanism due to long satellite delay. This resulted in degrading the received signal to noise ratio (E_b/N_o) for a given FER.

Figure 5.3: Channel interleaver size = 20 ms and mobile speed = 80 km/h.

5.4.2 Degradation of the Downlink due to Slow Fading

Figure 5.4 shows the performance of the link as function of mobile speed. A low mobile speed of 20km/h (i.e. Doppler frequency = 39.35 Hz) the performance of the link is significantly worse than when the mobile speed is 80km/h (i.e. Doppler frequency = 157.4 Hz). This improvement in the performance at high mobile speed is mainly due to increase in the interleaving effect (due to the higher Doppler frequency) that increases the error correction capability of the turbo code [66].

Figure 5.4: Power control error $\sigma_s = 2\text{dB}$, and channel interleaver size = 20ms.

5.4.3 Enhancing the Performance of the Downlink using RLP

The performance of the downlink shown in Figure 5.3 or 5.4 will not be sufficient to support Web traffic in a mobile satellite environment because as shown in Figure 4.6, Web traffic requires low frame error rate e.g. $\text{FER} \leq 5.10^{-3}$ in GEO mobile satellite otherwise its throughput will be extremely low. This is mainly due to TCP algorithm that interprets any segment loss as an indication of congestion, and hence it reduces throughput drastically as described in section 3.1.1. Thus, in order to enhance the performance of the downlink for Web traffic, a radio link protocol (RLP) between a mobile Web terminal and the satellite is necessary.

Figure 5.5 shows the performance of the downlink suffering from power control error with a standard deviation (σ_s) of 2 dB [49]. It can be seen that the effect of using RLP has resulted in drastically reducing the FER, which is essential to carry Web traffic over mobile satellite links. The effect of increasing the number of retransmissions (n) is also very effective on reducing FER. The FER performance of the link with RLP has been obtained by applying equation 4.7 (i.e. $1-P_f$) to the FER performance of the link obtained directly from the simulation.

Figure 5.5: Power control error $\sigma_s = 2\text{dB}$, channel interleaver size = 20ms and mobile speed = 80 km/h.

Meanwhile Figure 5.6 shows the effect of using RLP with $n = 2$ on the performance of the downlink shown in Figure 5.3. The general shape of the curves in Figure 5.6 are the same as those shown in Figure 5.3 but with FER being reduced drastically due to the use of RLP. Figure 5.7 shows the effect of using RLP on the performance of the downlink, which suffers from a large PCE (σ_s) of 4 dB.

Figure 5.6: Channel interleaver size = 20ms and mobile speed = 80 km/h and RLP ($n = 2$).

Figure 5.7: Channel interleaver size = 20 ms, PCE (σ_s) = 4dB, mobile speed = 80 km/h and RLP (n = 2).

Figure 5.8: Power control error $\sigma_s = 2$ dB, mobile speed = 80 km/h and RLP (n = 2).

5.4.4 Enhancing the Performance of the Downlink using RLP and Long Size Channel Interleaver

Figure 5.8 shows the effect of increasing the interleaver size on the performance of an RLP protected downlink suffering from power control error. Using a long channel interleaver is only effective within a certain range of E_b/N_o . This because below $E_b/N_o = 4.75$ dB, the power control error is causing long burst of errors, hence even a long channel interleaver is ineffective. Above $E_b/N_o = 5.75$ dB the effect of power control error has completely diminished and the channel errors are no longer bursty (i.e. random); hence there is no advantage in using long size interleavers [49].

5.5 Simulation Results for the Performance of the Downlink with Macrodiversity

In order to further enhance the performance of turbo-coded downlink and combat the degradation due to shadowing (which cannot be compensated by a power control mechanism), space diversity, namely macrodiversity; with an equal gain combiner (EGC) at the mobile Web terminal is proposed [67].

Figure 5.1 shows the simulated W-CDMA mobile satellite downlink with macrodiversity. A brief description about macrodiversity is given in section 2.6.1. The macrodiversity will greatly reduce the probability that two satellite paths suffer from shadowing simultaneously, since they are uncorrelated. The use of macrodiversity will allow the downlink to operate at much lower power margin and operate at low operating point level (E_b/N_o), which in turn reduces the satellite's power needed to support each mobile Web user. This should allow the capacity of the system to increase substantially since mobile satellites are power limited in the downlink. Web traffic capacity analysis will be dealt with in the next chapter.

The implementation of the proposed macrodiversity at the receiver of a vehicle mounted Web terminal is significant for two reasons. First it is not practical to implement space diversity on board the satellite due to lack of space and especially when antennas with very high gain are needed on board the satellite. The second reason is that since the wavelength (λ) is only 0.14 meter (for carrier frequency of 2.125 GHz), macrodiversity can be easily implemented at a vehicle mounted Web terminal, which requires at least 10λ spacing between adjacent branches. Two antennas can easily be placed 10λ apart in the horizontal plane to form macrodiversity. This is especially true when considering low gain (6-8 dBi) vehicle mounted microstrip patch antennas [6].

5.5.1 Enhancing the Performance of the Downlink with Macrodiversity

Figure 5.9 shows the effect of using macrodiversity on enhancing the performance of the downlink [67], which suffers from large power control error with $\sigma_s = 4$ dB. It can be

seen that the effect of using macrodiversity is very effective in reducing the required E_b/N_o for a given FER, and more importantly it has the effect of substantially reducing the required power margin of the link. This is especially advantageous for mobile satellites since they are power limited in the downlink, hence this should translate straight forwardly into substantial capacity gain as it will be shown in the next chapter.

Figure 5.9: Power control error $\sigma_s = 4\text{dB}$, interleaver size = 20ms and mobile speed = 80 km/h

5.5.2 Enhancing the Performance of the Downlink using Macrodiversity and RLP

Figure 5.10 shows the combined effect of using RLP and macrodiversity on the performance of the downlink. Here two cases are considered, the first one is when the link does not suffer from PCE and the other one is when the link suffers from PCE with $\sigma_s = 4\text{dB}$ [67]. It can be seen that the combined effect of using macrodiversity and RLP is very powerful in enhancing the performance of the link and mitigating the effect of large power control error. This method not only resulted on reducing the frame error rate to a very low level that is essential to carry Web traffic over mobile satellite links without degradations, but also allows the link to operate at much lower operating point i.e. E_b/N_o . Thus this method will greatly reduce the amount of satellite power needed to support Web traffic in shadowed mobile satellite links; hence it should result in substantial increase in mobile satellite capacity.

Figure 5.10: Interleaver size = 20ms, mobile speed = 80km/h, and RLP (n = 2)

5.6 Downlink Delay Model

In this section, a simple delay model for the downlink will be developed. This model will be used to estimate the end-to-end delay of the downlink due to both the physical and RLP layers.

5.6.1 Delay at the Physical Layer

The data frame delay traversing the downlink is the sum of the frame transmission delay ($t_{transmit}$), the turbo encoder transmission delay ($t_{encoder}$), channel interleaver delay ($t_{interleave}$), satellite propagation delay (t_{prop}), channel deinterleaver delay ($t_{deinterleave}$) and the turbo decoding delay ($t_{decoder}$). Thus the end-to-end delay (T) at the physical layer is given by:

$$T = t_{transmit} + t_{encoder} + t_{interleave} + t_{prop} + t_{deinterleave} + t_{decoder} \quad (5.6)$$

Transmission Delay: The transmission delay ($t_{transmit}$) is the time taken to transmit a single frame (TTI) at the link data rate. Here the frame transmission delay is equal to the frame length. Hence $t_{transmit} = 20$ ms.

Turbo Encoder Delay: The delay incurred in the turbo encoder is just the transmission delay of the transmitted frame. Hence $t_{encoder} = 20$ ms.

Channel Interleaver Delay: The delay incurred in the channel interleaver is given by:

$t_{interleave} = \text{Interleaver Size (number of TTI frames)} * \text{frame transmission time}$. Here, the frame transmission time (TTI) is always equal to 20 ms. The interleaver size is either one or eight TTI frames.

Hence $t_{interleave}$ is either 20 ms or 160 ms respectively.

Satellite Propagation Delay: This delay due to the frame being transmitted from the satellite to the mobile Web terminal (one way delay). Here only GEO and MEO (15000 km) satellites with regenerative capabilities are considered. Hence, this delay (t_{prop}) is either 125 ms or 50 ms respectively.

Channel De-interleaver Delay: Similarly the delay incurred in the de-interleaver is the same as that occurred in the interleaver ($t_{deinterleave} = t_{interleave}$), i.e. it is either 20 ms or 160 ms depending on the size of the de-interleaver one or eight respectively.

Turbo Decoding Delay: Assuming that decoding iteration is performed very fast (i.e. fast processor), then the delay due to decoding can be neglected. The only delay occurred in the decoder is the decoder transmission time, which is the same as the encoder transmission time, i.e. $t_{decoder} = t_{encoder} = 20$ ms.

Thus the **Total end-to-end delay (T)** for GEO satellite = $20+20+20 +125+20+20 = 225$ ms (for interleaver size = 20 ms), or $T = 20+20+160+125+160+20 =505$ ms (for interleaver size = 160 ms frames). Similarly the **Total end-to-end delay (T)** for MEO satellite is either 150 ms or 430 ms.

5.6.2 Delay at the RLP layer

The end-to-end frame transportation delay at the physical layer, denoted by T as before is assumed fixed. Denoting τ as the inter-frame time (frame size), the average time taken to transmit an RLP frame is given [45] as

$$\begin{aligned}
T_{avg}^{RLP} &= T(1-p) + \sum_{j=1}^n \sum_{i=1}^j P(C_{ij})(2jT + 2(i-1)\tau) \\
&= T(1-p) + p(1-p)^2 \sum_{j=1}^n (p(2-p))^{\frac{j(j-1)}{2}} (2jT \frac{1-(p(2-p))^j}{1-p(2-p)} \\
&\quad + 2\tau(\frac{p(2-p)(1-(p(2-p))^{j-1}}{(1-p(2-p))^2} - \frac{(j-1)(p(2-p))^j}{1-p(2-p)}))
\end{aligned} \tag{5.7}$$

Where p is the channel frame error rate, i is the number of RLP attempts, j is the number of RLP trails and $P(C_{ij}) = p(1-p)^2 (p(2-p))^{\frac{j(j-1)}{2} + (i-1)}$.

5.6.3 Effect of the Interleaver Size on the Average Delay at the RLP Layer

Figure 5.11 shows the average one-way delay of an RLP frame (T_{avg}) incurred during transmission from a Geo satellite to a mobile Web user as function of FER. The delay has been calculated using equation 5.7. It can be seen from Figure 5.11 that increasing the interleaver size from 20 ms to 160 ms has resulted in the average RLP delay to increase by a factor of two [49]. Thus extra care must be taken when considering the use of channel interleaving to enhance the performance of mobile satellite systems, especially when interactive service such as Web browsing is involved.

Figure 5.11: T_{avg} (RLP) in seconds for downlink with power control error $\sigma_s = 2\text{dB}$, mobile speed=80 km/h, and $n=2$

5.7 Structure of 3G W-CDMA Mobile Satellite Uplink

5.7.1 Transmitter Side

Figure 5.12 shows a simplified structure of the simulated 3G W-CDMA uplink [56-59] i.e. between a mobile Web user and a satellite with space-time transmit diversity (STTD) being implemented at both the transmitter (mobile Web user) and the receiver (satellite). It is important to note that the mobile Web user transmits two signals simultaneously with one being STTD encoded while the other one is not. Each signal is transmitted from separate antenna (two antennas separated by 10λ apart). The satellite receives the two signals via single antenna and performs STTD decoding as shown in the Figure 5.12.

The frame structure for the combined dedicated physical channels, i.e. the dedicated physical data channel (DPDCH) and dedicated physical control channel (DPCCH) is the same as for the downlink shown in Figure 5.2 except that the size of various fields in each slot are much smaller as shown in Figure 5.13.

As in the downlink, the random frame generator generates frames of random data. The length of the output vector is floor (data*time transmission interval (TTI)), where the data rate is fixed and is equal to 12.2 Kbps, which is adequate for transmitting very short messages such as HTTP object requests and TCP acknowledgements. The 20 ms TTI is first fed into cyclic redundancy check (CRC) encoder, where 16 CRC bits are generated. This is done using the generator polynomials shown in Table 5.2.

The encoded CRC TTI is first fed into a convolutional encoder. The convolution code is 256-state and rate 1/3. The description of rate matching, channel interleaver and uplink slot format is the same as that described for the downlink in 5.3.1

In order to perform encoding for space time transmit diversity (STTD), the output of the uplink slot format is fed simultaneously into STTD encode block and one of QPSK mapping block as shown in Figure 5.12. The STTD block performs encoding for the STTD on the input signal. In STTD encoding each set of four consecutive signal values

b_0, b_1, b_2, b_3 are replaced with signal values $-b_2, b_3, b_0, -b_1$. Since pairs of signal values are combined into complex symbols, this encoding has the effect of replacing complex symbols S_0, S_1 with $-S_0^*, S_1^*$.

The QPSK blocks perform the same function as described in the downlink. The signals in these two blocks are spread by the same orthogonal variable spreading code (OVSF) for channelization. The spread output of each QPSK mapping block is then fed into a scrambler where each scrambler uses different Gold code. The scrambler scrambles the spread signals by multiplying them by a complex Gold sequence. The purpose of scrambling is to make signals from adjacent spot beams uncorrelated. Finally, the CDMA chips are filtered with a square root raised cosine filter with a roll-off factor of 0.22.

5.7.2 The Satellite Channel

The channel model used in the simulation is lognormal-Rician channel as described in 5.3.2.

5.7.3 Noise

The uplink will suffer from co-channel interference as the mobile users transmit their signals in asynchronous mode. This co-channel can be approximated by additive white Gaussian noise assuming large number of users [68].

5.7.4 Receiver Side

The input is first filtered with a square root raised cosine matched filter with alpha (i.e. roll-off factor) of 0.22. The filtered signals are then fed into two separate despanders. Each received signal is then descrambled at the despander by multiplying it by a complex conjugate of the downlink scrambling sequence (i.e. complex Gold sequence) to descramble the data and then the two descrambled signals are coherently demodulated before being combined using equal gain combiner (EGC) as shown in Figure 5.12.

The demodulation process is the same as described in 5.3.4 for the downlink. The STTD decode performs the reverse operation of STTD encode as described earlier in 5.7.1. The uplink slot deformat block performs the same operation as that described for

the downlink in 5.3.4. Similarly the functions of rate dematch and channel deinterleaver blocks are the same as that described for the downlink in 5.3.4. The soft viterbi decoding block decodes the received downlink data using a soft decision viterbi algorithm.

Table 5.2: Simulation parameters for 3G mobile satellites W-CDMA uplink

Bit rate	12.2 kbps
Carrier frequency	2.1125 Ghz
Service	Web browsing
Coding block size	244 bits
CRC bits	16
CRC generator polynomial (octal)	0x8408
Physical layer	
Multiple access method	DS-CDMA
Carrier chip rate	3.84 Mcps
Spreading factor	128
Frame length (air interface)	10 ms (1 Frame = 15 time slot)
Forward error correction (FEC)	Convolutional code R = 1/3, K = 9, with soft decision viterbi decoding.
Channel interleaving	20 ms
Rate matching	804→688
Modulation	Data: QPSK, Spread: QPSK
Pulse shaping	Root raised cosine, roll-off = 0.22
Open loop power control error	1 to 4 dB
Environment	
Channel profile	Rice-lognormal, Rice factor (K_R)=10, mean (μ_s) = 0 dB, standard deviation (σ_s) = 4 dB
Mobile speed (km/h)	20 and 80
Noise	Gaussian noise
Diversity	Space time transmit diversity (STTD)

Figure 5.12: Simulated uplink for 3G W-CDMA mobile satellite systems with STTD for dedicated physical channels (DPDCH/DPCCCH)

Data Rate (kbps)	Data1 (bits)	TPC (bits)	TFI (bits)	Data2 (bits)	Pilot (bits)
12.2	6	2	2	22	8

TPC: Transmit Power Control bit
TFI: Transport Format Combination Indicator

Figure 5.13: Frame structure for the uplink dedicated physical channels (DPDCH/DPCCCH)

5.8 Simulation Results for Performance of 3G W-CDMA Uplink with no STTD

Similar to the performance analysis that was performed on the downlink, the effect of power control errors and slow fading on degrading the performance of convolutionally encoded uplink will be examined here. The effect of using RLP in enhancing the performance of the uplink will also be examined here. Table 5.2 shows the simulation parameters used in the simulation.

5.8.1 Degradation of the Uplink due to Power Control Error

The bottom curve in Figure 5.14 shows the performance of the uplink with no power control error (no PCE) i.e. it shows the shadowing as if it has been completely compensated for by the power control mechanism and the channel appears just as Rician fading channel with $K_R = 10$. The curve roll-off is typical performance of convolution code in Rician fading channel [69]. The upper curve (with PCE = 2dB) shows the effect of power control error with standard deviation (σ_s) of 2 dB. As it can be seen that even small power control error has significantly degraded the performance of the link. This mainly due to the effect of shadowing that could not be compensated for by the power control mechanism due to long satellite delay. This resulted in degrading the received signal to noise ratio (E_b/N_o).

It should be noted however that for $E_b/N_o < 3.25$ dB, the performance of the link with PCE = 2 appears slightly better than that with no PCE. This is mainly due to the fact that at low E_b/N_o i.e. when the link is in deep fade, the variations due to PCE ($\pm \sigma_s$) as result of uncompensated shadowing appears to help the performance of the link in comparison to that with no PCE.

Figure 5.14: Degradation due to the effect of PCE assuming mobile speed=80km/h

5.8.2 Degradation in the Performance of the Uplink due to Slow Fading

Figure 5.15 shows the performance of the uplink as function of mobile speed. It can be seen that at low mobile speed of 20km/h (i.e. Doppler frequency = 39.35 Hz) the performance of the link is significantly worse than that when the mobile speed is 80 km/h (i.e. Doppler frequency = 157.4Hz). This improvement in the performance at high mobile speed is mainly due to increase in interleaving effect (due to higher Doppler frequency) that increases the error correction capability of the convolutional code.

Figure 5.15: Degradation due to slow fading assuming no PCE.

5.8.3 Enhancing the Performance of the Uplink using RLP

The performance of the uplink shown in Figures 5.14 or 5.15 will not be sufficient to support Web traffic in a mobile satellite environment because as shown in Figure 4.6, Web traffic needs very low frame error rate e.g. $FER \leq 5 \cdot 10^{-3}$ in GEO mobile satellites otherwise its throughput will be extremely low as described in section 4.4.2.1. Thus in order to enhance the performance of the uplink for Web traffic, a radio link protocol (RLP) between the satellite and mobile Web terminal is necessary as described before for the downlink.

Figure 5.16 shows the performance of the uplink suffering from large power control error. The standard deviation (σ_s) of power control error is 4 dB, which is considered an upper limit in mobile satellite environment. The upper curve shows the performance of the link with no RLP, while the lower curve shows the effect of applying RLP with $n = 2$ on the performance of the uplink. This has been obtained by applying equation 4.7 (i.e. $1 - P_f$) to the FER performance of the link obtained from the link level simulation. Meanwhile Figure 5.17 shows the effect of applying RLP ($n = 2$) on the performance of the link shown in Figure 5.14.

Figure 5.16: Power control error $\sigma_s = 4$ dB, and mobile speed = 80 km/h

Figure 5.17: Effect of RLP with $n = 2$, mobile speed = 80 km/h

5.9 Simulation Results for the Performance of the Uplink with STTD

In order to further enhance the performance of convolutionally coded uplink and combat the degradations due to shadowing and slow fading, which cannot be compensated by power control mechanism, the use of space-time transmit diversity (STTD) is proposed for the uplink. STTD is described in 5.7 and shown in Figure 5.12. The use of STTD will allow the uplink to require lower power margin and operate at low operating point (E_b/N_o). These two factors should allow the system capacity to increase significantly as they reduce the interference level at the satellite. Web traffic capacity analysis will be dealt with in the next chapter.

5.9.1 Enhancing the Performance of the Uplink with STTD

Figure 5.19 shows the effect of using STTD on enhancing the performance of the uplink, which does not suffer from power control error (i.e. no PCE). It can be seen that the effect of using STTD is significant in reducing E_b/N_o for a given FER especially at high E_b/N_o [70], but its most significant effect is in reducing the required power margin for the link and hence the interference at the satellite.

Figure 5.18: No Power control error and mobile speed = 80 km/h

5.9.2 Enhancing the Performance of the Uplink with STTD and RLP

Figure 5.19 shows the combined effect of using RLP and STTD on the performance of the uplink. Similar to the downlink case, here also two cases were considered, the first case is when the link does not suffer from PCE, while the second case is when the link suffers from large PCE with $\sigma_s = 4$ dB. It can be seen that the combined effect of using STTD and RLP is powerful in enhancing the performance of the link and mitigating the degradation due to power control error.

This method not only resulted on reducing the frame error rate to a very low level that is essential to carry Web traffic over mobile satellite links without degradation, but also allows the link to operate at lower power margin and operating point (i.e. E_b/N_0). Thus this method will significantly reduce the amount of interference at the satellite, resulting in significant increase in Web traffic capacity for mobile satellite system.

Figure 5.19: Combined effect of STTD and RLP ($n = 2$) and mobile speed = 80 km/h.

Chapter 6

Capacity Enhancement of Web Traffic in 3G W-CDMA Mobile Satellite Systems

6.1 Introduction

It was shown in the last chapter that power control errors (PCEs) seriously degrade the performance of both the uplink and downlink of mobile satellite systems. In this chapter, the influence of power control errors on the Web traffic capacity of these systems will be evaluated first. Then we will examine the effect of the proposed diversity schemes (i.e. macrodiversity for the downlink and STTD for the uplink), which were analyzed in the pervious chapter to mitigate the degradations due to power control errors, and hence enhance the Web traffic capacity.

The evaluation of Web traffic capacity here will be performed using pervious simulation results of both system level as described in 4.4 (performance of Web traffic in mobile satellite systems) and that of link level as described in chapter 5 (both the uplink and the downlink)[71]. The capacity evaluation will assume imperfect power control and accounts for: beams overlapping, orthogonality, Web traffic activity factor, cross-polarization frequency reuse and shadowing.

6.2 Web Traffic Capacity in the Downlink

Throughout the analysis, the following hypotheses have been assumed: the total load of the satellite of K users, which are uniformly distributed among N_b spot beams. There is

only one carrier (i.e. frequency reuse factor of one is assumed) and is accessed according to the W-CDMA concept of the UMTS radio interface [72]:

6.2.1 Interference Analysis in the Downlink

Let I denote the multiple access interference (MAI). In a multi-beam transmission, it may assume the following form [73].

$$I = (K - 1)E_b R_u \alpha \rho \frac{\gamma}{N_b} A_s \quad (6.1)$$

where:

E_b is the user's received bit energy.

R_u is the user bit rate.

α is the Web traffic activity factor.

ρ is the polarization isolation factor and equal to $(1 + 1/A_x)/2$, where A_x being the cross-polarization attenuation.

A_s is a factor taking into account the excess power required by a shadowed user.

γ is the ratio of the total MAI to the interference I_b that a user experiences only from its own spot beam [74]. Taking into account the effect of orthogonality then the following holds:

$$\gamma = \gamma_0 - f_{orth} \quad (6.2)$$

where f_{orth} , is the interference reduction term due to orthogonality which reduces to zero in non-orthogonal case and turns out to be a function of the number of users K . γ_0 is the beam overlap factor [68].

6.2.1.1 Beam Overlap

When the antenna pattern arranged so that the intersection of adjacent cells is at -3 dB contour and a Gaussian mask approximation $G(\theta)$ is assumed to estimate the beam overlap factor γ_0 , the following holds [72]:

$$\gamma_0 \cong \frac{I}{I_b} \Big|_{no-orth} = \frac{I}{\int_0^{\theta_R} G(\theta) d\theta} = \left[1 - \exp\left(-\frac{R^2}{2\sigma^2}\right) \right]^{-1} = 2 \quad (6.3)$$

Where θ_R denotes the beam-width of the antenna at -3 dB. R is the related footprint radius which, according to the beam definition equals $\sqrt{2\sigma^2 \ln 2}$. σ is the radius where the power received is at -3 dB. Notice that the recovered value of γ_0 quite tightly approaches typical values appearing in the literature (in [74] for example γ_0 , denoted by I_0 , equals 2.02).

6.2.1.2 Orthogonality

The interference reduction term f_{orth} has now to be subtracted from the beam overlap factor γ_0 , which is computed above in order to take advantage of the orthogonality between spreading sequences, which is employed on the downlink. In multirate concept of UMTS, this is realized by means of OVS (orthogonal variable spreading) codes as mentioned in 5.3.1 [72]. Actually, the assumption of full orthogonality is quite unrealistic if one considers the available processing gains of the UMTS air interface ($N \leq 256$) and the maximum load of a satellite for mobile communications, which is expected to be far greater than 1000 users. In fact, assuming the full orthogonality constraint, it is not possible to exceed the codebook limit of $2N$ low-rate users, i.e. 512 users per carrier. Hence, in order to approach the capacity limit, non-orthogonal transmissions have to be superimposed on top of the orthogonal multiplexing, so that the interference reduction term f_{orth} , will assume the following values [74]:

$f_{orth} = \gamma_0$	$K \leq 2N$	orthogonality
$1 \leq f_{orth} < \gamma_0$	$2N < K \leq 2NN_b$	orth. within the beam
$f_{orth} = 0$	$K \rightarrow \infty$	non-orthogonality.

Here f_{orth} will be assumed to equal zero, i.e. non-orthogonal (worse case).

6.2.1.3 Effect of Shadowing

Assume that a shadowed user is given a power advantage to compensate for the increased fading due to shadowing. This leads to a multiple access interference (MAI) increase with respect to the unshadowed case, which is denoted by the term A_s . In [74], the following expression has been derived:

$$A_s = 1 - P_s + P_s M_s K_R$$

where P_s denotes the probability of a given user being shadowed, M_s is the system margin required to the shadowed user to compensate for scattering and K_R is the Rice factor, i.e. the ratio of the specular component's power to the power of the diffusive one.

6.2.2 Web Traffic Capacity Evaluation in the Downlink

Let the capacity be defined as the maximum number K of users, which can be served by a satellite. If the satellite capacity K is constrained to the available received power P and a large number of users are assumed, namely $K \rightarrow \infty$, the following holds [73]:

$$\begin{aligned} K &= \frac{P}{E_b A_s R_u} \frac{1}{\alpha} = \frac{P}{R_u (E_b/N_o)_d^* (N_o + I/W)} \frac{1}{\alpha} \\ &\equiv \frac{W}{R_u \alpha (E_b/N_o)_d^*} \frac{1}{N_b + \beta P A_s} \end{aligned} \quad (6.4)$$

where $(E_b/N_o)_d^*$ is the required energy-per-bit-to-noise spectral density ratio in the downlink. $\beta \equiv P/(N_o W)$ is the interference-to-noise spectral density ratio in a single spot, single carrier system and W is the spreading bandwidth.

6.2.3 Numerical Results for Web Traffic Capacity in the Downlink

As mentioned in section 6.1, the results of system level simulation (performance of Web traffic in mobile satellite systems) and that of link level simulation (both up and down links) will be used here to evaluate the Web traffic capacity in both MEO and GEO constellations of 3G W-CDMA mobile satellite systems.

6.2.3.1 Web Traffic Capacity in the Downlink assuming no Power Control Error

It has been shown by system level simulation in 4.4.2.1 (see Table 4.11) that Web traffic in GEO mobile satellite system requires frame error rate (FER) of at least 5×10^{-3} in order to avoid any significant increase in Web page download time with respect to that of error free condition (i.e. 21.6 seconds) for 144kbps data rate. Meanwhile Table 4.11 shows that in MEO satellite system the Web traffic requires FER of 9.5×10^{-3} to achieve the same Web download time as that in GEO system and for the same data rate (i.e. 144 kbps). In 4.4.2.1 also the Web traffic activity factor was found to be 0.12 (see Table 4.12).

Meanwhile in 5.4.3 using link level simulation for turbo-coded and ARQ protected 3G W-CDMA downlink of 144 kbps data rate has shown that it requires $(E_b/N_o)_d$ * of 1.7 dB to achieve the required FER of 5×10^{-3} for Web traffic in GEO system and $(E_b/N_o)_d$ * of 1.5 dB to achieve the required FER of 9.5×10^{-3} for Web traffic in MEO system both under the assumption of no power control error as shown in Figure 5.6.

Thus using these results and the parameters used in the system (section 4.4) and link level simulations (chapter 5), the following values are used to evaluate the Web traffic capacity in MEO and GEO 3G W-CDMA mobile satellite systems under the assumption of no power control error:

$$W = 5 \text{ MHz}; R_u = 144 \text{ kbps};$$

$$\alpha = 0.12 \text{ (Web traffic activity factor);}$$

The following somewhat conservative values have been assigned to the other parameters:

$$\rho = 0.55, \text{ i.e. } A_x = 10 \text{ dB [68];}$$

$\gamma_0 = 2$, this is when the antenna patterns are arranged so that the intersection of adjacent cells is at -3 dB and Gaussian mask approximation is assumed [74];

$$f_{orth} = 0, \text{ assuming non orthogonality (worse case);}$$

$$P_s = 0, \text{ assuming no shadowing, hence } A_s = 1;$$

$\beta = 13$ dB (GEO), 16 dB (MEO), typical values[73];

$N_b = 160$ (GEO), 169 (MEO) typical number of spot beams per satellite [14];

Applying the above values to equation (6.4), the Web traffic capacity in the downlink of 3G W-CDMA mobile satellite systems under no power control error (ideal case) is shown in Table 6.1 [75].

Table 6.1: Web traffic capacity in the downlink under no PCE condition.

Satellite constellations	GEO	MEO
Total number of Web users	3439	6887

The higher Web traffic capacity in MEO system is attributed to the term β , which shows that the downlink in mobile satellite systems can tolerate higher level of interference but not satellite power; it is power limited, rather than interference limited.

6.2.3.2 Web Traffic Capacity in the Downlink Assuming Imperfect Power Control

In the capacity analysis here, the effect of power control error will be taken into account. Power control errors due to uncompensated shadowing mainly arise in mobile satellite systems because closed loop power control is ineffective due to long satellite delay.

Now using the same values for parameters as in 6.2.3.1 but with following exception:

For Web traffic in GEO system, the required $(E_b/N_o)_d^*$ is equal 2.2 dB in order to achieve the required FER of 5.10^{-3} for the downlink with power control error (σ_s) of 1 dB (see Figure 5.6). Meanwhile the required $(E_b/N_o)_d^*$ is equal to 4 dB (see Figure 5.7) to achieve the same FER but with PCE (σ_s) of 4 dB.

For Web traffic in MEO system, the required $(E_b/N_o)_d^*$ is equal to 1.85 dB in order to achieve the required FER of 9.5×10^{-3} in the downlink with power control error (σ_s) of 1 dB (see Figure 5.6). Meanwhile, the downlink requires $(E_b/N_o)_d^*$ of 4 dB (see Figure 5.7) in order to achieve the same FER but with PCE (σ_s) of 4 dB.

$P_s = 0.3$, probability of shadowing [74];

$M_s = 6.62 \text{ dB}$, system margin for shadowing [68];

$A_s = 11.6 \text{ dB}$; excess power required by shadowed user;

Applying the above values to equation (6.4), the Web traffic capacities in the downlink of 3G W-CDMA mobile satellite systems under power control error with $\sigma_s = 1 \text{ dB}$ and 4 dB are shown in Table 6.2 and 6.3 respectively.

Table 6.2: Web traffic capacity in the downlink under PCE with $\sigma_s = 1\text{dB}$.

Satellite constellations	GEO	MEO
Total number of Web users	1167	1586

Table 6.3: Web traffic capacity in the downlink under PCE with $\sigma_s = 4\text{dB}$.

Satellite constellations	GEO	MEO
Total number of Web users	771	967

Comparing the results shown in Tables 6.2 and 6.3 with those shown in Table 6.1, the effect of power control error in degrading Web traffic capacity is substantial. Power control error due to uncompensated shadowing in the downlink has resulted in reduction of satellite Web traffic capacity by almost 66% and 78% for PCE with $\sigma_s = 1$ and 4 dB respectively for mobile satellites using GEO constellation. Meanwhile, the Web traffic capacity reduction in MEO satellites is 77% and 86% for PCE with $\sigma_s = 1$ and 4 dB respectively.

The reduction in Web traffic capacity here in comparison to that shown in Table 1 is mainly attributed to the required system power margin for shadowed users in order to support Web traffic in the downlink. It should be noted however that only 30% of the total users here are assumed to suffer from shadowing and hence imperfect power control.

6.2.3.3 Web Traffic Capacity Enhancement in the Downlink

In the capacity analysis here, the effect of employing macrodiversity in the downlink as described in 5.5 to enhance the Web traffic capacity in mobile satellites using GEO and MEO constellations will be examined. The effect of macrodiversity will be considered for two cases of PCEs. The first case is when there is no power control error due to shadowing while the second case is when there is PCE with $\sigma_s = 4\text{dB}$.

The major advantage of employing macrodiversity in the downlink is the reduction of the amount of system (or power) margin required to support Web traffic, in addition to lower operating point $(E_b/N_o)_d^*$. Now, using the same values for parameters as in section 6.2.3.1 but with the following exceptions:

For Web traffic in GEO system, the required $(E_b/N_o)_d^*$ is equal to -0.9 dB in order to achieve the required FER of $5 \cdot 10^{-3}$ for the downlink with no power control error (PCE), while it requires $(E_b/N_o)_d^*$ of -0.7 dB to achieve the same FER but with PCE (σ_s) of 4 dB (see Figure 5.10); These values of E_b/N_o will also be taken for MEO system since at FER equal $9.5 \cdot 10^{-3}$ the operating points E_b/N_o for both cases of PCEs are too close to those at FER of $5 \cdot 10^{-3}$.

$M_s = 1.38\text{ dB}$, system margin for shadowing [68];

$A_s = 6.832\text{ dB}$, excess power required by shadowed user;

Applying the above values to equation (6.4), the effect of macrodiversity in enhancing Web traffic capacities in 3G W-CDMA mobile satellite systems under no PCE and with PCE (σ_s) of 4 dB are shown in Table 6.4 and 6.5 respectively.

Table 6.4: Web traffic capacity with macrodiversity under no PCE

Satellite constellations	GEO	MEO
Total number of Web users	4282	6313

Table 6.5: Web traffic capacity with macrodiversity under PCE ($\sigma_s = 4\text{dB}$).

Satellite constellations	GEO	MEO
Total number of Web users	4088	6029

The results shown in Table 6.5, show that the effect of employing macrodiversity in the downlink is so powerful that it has resulted in substantially increasing the Web traffic capacity e.g. capacity has increased by more than five folds for GEO with PCE ($\sigma_s = 4\text{dB}$) w.r.t no diversity case as shown in Table 6.3. Table 6.5 also shows that the Web traffic capacity has increased by more than six folds for MEO with PCE ($\sigma_s = 4\text{ dB}$) w.r.t no diversity case. Meanwhile both Tables 6.4 and 6.5 show that the effect of using macrodiversity has resulted in Web traffic capacity that exceeded even that shown in Table 6.1 (i.e. no PCE case).

6.3 Web Traffic Capacity in the Uplink

Similar to the analysis performed for the downlink, the following hypotheses have been assumed for the uplink: the total load of the satellite is of K users, which are uniformly distributed among N_b spot beams. There is only one carrier (i.e. frequency reuse factor of one is assumed) and is accessed according to the W-CDMA concept of UMTS radio interface.

6.3.1 Inference and Capacity Analysis for the Uplink

The transmission of the mobile-to-satellite link is considered non-orthogonal, namely $f_{orth} = 0$. Similar to the downlink the excess power term A_s can be written as $A_s = 1 - P_s + P_s M_s$ [73]. The multi access interference (MAI) contribution is given by [73]:

$$I = KE_b R_u \alpha \rho \frac{\gamma_0}{WN_b} A_s; \text{ all the terms in this expression have the same meaning as those}$$

described for the downlink in 6.2.1

The expression for capacity, obtained after having introduced the service quality requirement, namely: $E_b / (N_o + I) = (E_b / N_o)_u^*$, assuming that $E_b / I \approx (E_b / N_o)_u^* \gg (E_b / N_o)$ turns out to be [76]:

$$K \equiv \left[\frac{I}{(E_b / N_o)_u^*} - \frac{N_o}{E_b} \right] \frac{W}{R_u} \frac{N_b}{\alpha \rho \gamma_0 A_s} \quad (6.5)$$

where $(E_b / N_o)_u^*$ is the required energy-per-bit-to-noise spectral density ratio in the uplink.

6.3.2 Numerical Results for Web Traffic Capacity in the Uplink

Similar to the Web traffic capacity analysis in the downlink, the Web traffic capacity evaluation for the uplink here will be performed using the results system level simulation for the performance of Web traffic in mobile satellite systems and that for link level as mentioned in 6.1.

6.3.2.1 Web Traffic Capacity in the Uplink assuming no Power Control Error

It has been shown by system level simulation in 4.4.2.1 (see Table 4.11) that Web traffic in GEO mobile satellite system requires FER of at least $5 \cdot 10^{-3}$ in order to avoid any significant increase in Web page download time (i.e. 21.6 seconds) with respect to error free condition. Meanwhile Web traffic in MEO system requires FER of at least $9.5 \cdot 10^{-3}$ to achieve almost the same Web page download time in GEO system. In 4.4.2.1 (see Table 4.12), the Web traffic activity factor was found to be 0.12.

Thus using these results and parameters used in system and link level simulations, the following values are used to evaluate Web traffic capacity in the uplink for MEO and GEO 3G W-CDMA mobile satellite systems under the assumption of no power control error:

$$W = 5 \text{ MHz},$$

$$R_u = 12.2 \text{ Kbps},$$

$$(E_b / N_o)_u^* = 2.85 \text{ dB to achieve the required FER of } 5 \cdot 10^{-3} \text{ for Web traffic in GEO; and}$$

$$(E_b / N_o)_u^* = 2.7 \text{ dB to achieve the required FER of } 9.5 \cdot 10^{-3} \text{ for Web traffic in MEO.}$$

These values obtained from simulation results are shown in Figure 5.17;

$$\alpha = 0.12 \text{ Web traffic activity factor (see Table 4.12);}$$

$$\rho = 0.55, \text{ is polarization isolation factor as described in 6.2.1 (conservative value);}$$

$\gamma_0 = 2$, this is when the antenna patterns are arranged so that the intersection of adjacent cells is at -3dB and Gaussian mask approximation is assumed [74];

$$N_b = \text{Number of spot beams per satellite, it is 160 for GEO and 169 for MEO [14];}$$

$P_s = 0$, assuming no shadowing, hence $A_s = 1$;

Applying the above values to equation (6.5), the Web traffic capacity in the uplink of 3 G W-CDMA mobile satellite systems under no power control error (ideal case) is shown in Table 6.6

Table 6.6: Web traffic capacity in the uplink under no PCE.

Satellite constellations	GEO	MEO
Total number of Web users	257000	281801

The higher Web traffic capacity in the uplink for both MEO and GEO systems in comparison to that of the downlink (shown in Table 6.1) is mainly attributed to the fact that the uplink is using much lower data rate i.e. 12.2 kbps instead of 144kbps for the downlink. This has resulted in much higher processing gain for the uplink case hence much higher capacity. This disparity between Web traffic capacity in the uplink and the downlink suggests that more bandwidth must be allocated for the downlink.

6.3.2.2 Web Traffic Capacity in the Uplink assuming Imperfect Power Control

Similar to the analysis performed on the downlink, the effect of power control error will be taken into account. Now using the same values for parameters in 6.3.2.1 but with following exception:

$(E_b / N_o)_u^* = 2.6$ dB to achieve FER of 5.10^{-3} for Web traffic in GEO with power control error (σ_s) of 4 dB, while $(E_b / N_o)_u^* = 2.3$ dB to achieve FER of $9.5 \cdot 10^{-3}$ for Web traffic in MEO with PCE(σ_s) of 4 dB. These values obtained from simulation result shown in Figure 5.16.

$P_s = 0.3$, probability of shadowing [74];

$M_s = 6.62$ dB, system margin for shadowing [68];

$A_s = 11.6$ dB; excess power required by shadowed user.

Applying the above values to equation (6.5), the Web traffic capacity in the uplink of 3 G W-CDMA uplink in mobile satellite environment under power control error with $\sigma_s = 4$ dB is shown in Table 6.7.

Table 6.7: Web traffic capacity in the uplink under PCE ($\sigma_s = 4$ dB)

Satellite constellations	GEO	MEO
Total number of Web users	131226	141455

Comparing the results shown in Table 6.7 with that shown in Table 6.6, the effect of power control error on reducing Web traffic capacity is substantial. Power control error due to uncompensated shadowing in the uplink has resulted in reduction of satellite Web traffic capacity by about 49% for both GEO and MEO satellite systems.

6.3.2.3 Web Traffic Capacity Enhancement in the Uplink

In the capacity analysis here, the effect of employing STTD diversity in the uplink as described in 5.7 to enhance the Web traffic capacity in 3G mobile satellites using GEO and MEO constellations will be examined. Similar to the analysis performed on the downlink, the effect of STTD in enhancing Web traffic capacity will be considered for two cases of PCEs. The first case is when there is no power control due to shadowing while the second case is when there is PCE with $\sigma_s = 4$ dB.

The major advantage of employing STTD diversity in the uplink is the reduction of the amount of system (or power margin) required to support Web traffic, in addition to lower operating point $(E_b / N_o)_u^*$. This will result in significant reduction in the amount of interference at the satellite, which will be translated into an increase in system capacity. Now using the same parameters values as in 6.3.2.1 but with the following exception:

$(E_b / N_o)_u^*$ is equal to 2.65 dB to achieve the required FER of $5 \cdot 10^{-3}$ for Web traffic in GEO and FER $9.5 \cdot 10^{-3}$ in MEO (since the operating points in this case are too close) under no power control error, while it is 2.85dB to achieve the same FER but with PCE(σ_s) of 4 dB (see Figure 5.19);

$M_s = 5.92$ dB, system margin for shadowing [68];

$A_s = 2.7$ dB, excess power required by shadowed user;

Applying the above values to equation (6.5), the effect of STTD in enhancing Web traffic capacities in 3 G W-CDMA uplink operating in mobile satellite environment under no PCE or with PCE ($\sigma_s = 4$ dB) are shown in Table 6.8 and 6.9 respectively.

Table 6.8: Web traffic capacity with STTD under no PCE.

Satellite constellations	GEO	MEO
Total number of Web users	269984	285170

Table 6.9: Web traffic capacity with STTD under PCE ($\sigma_s = 4$ dB).

Satellite constellations	GEO	MEO
Total number of Web users	137822	145575

Table 6.9 shows that the effect of employing STTD diversity in the uplink has resulted in small but significant Web traffic capacity e.g. capacity has increased by 5% for both MEO and GEO with PCE ($\sigma_s = 4$ dB) w.r.t no diversity case as shown in Table 6.7. Meanwhile Table 6.8 shows that the effect of using STTD has resulted in Web traffic capacity that slightly exceeded that shown in Table 6.6 for no PCE case. The much lower capacity gain achieved here via the use of STTD in comparison to that via macrodiversity in the downlink is mainly attributed to much lower diversity gain provided by STTD and hence larger required system margin.

Chapter 7

Conclusions and Future Research

7.1 Summary of Results

The thesis examined six main aspects of Web traffic in 3G W-CDMA mobile satellite systems, which can be summarized as follows:

7.1.1 Performance Analysis of Web Protocols in 3G W-CDMA Mobile Satellite Systems

In this thesis two analytical models were derived. These two models are described as follows:

7.1.1.1 Analytical Model for TCP Throughput in 3G W-CDMA Mobile Satellite Systems

In this model an expression for TCP throughput in MEO and GEO mobile satellite systems in presence of channel frame errors was derived. The TCP window was modeled for “TCP Tahoe” using Markovian chain, while the average delay was modeled using both analytical and experimentally derived data.

It was found that TCP requires very low FER ($\leq 10^{-4}$) in mobile satellite systems otherwise its throughput would be drastically reduced. The performance of TCP in MEO (15000 km orbit height) mobile satellite system was only slightly better than that in GEO mobile system. The effect of increasing the initial window size had almost no effect on the performance of TCP, while using large TCP segment sizes significantly improved the performance of TCP in mobile satellite environment.

7.1.1.2 Analytical Model for the Performance of HTTP/1.1 in Mobile W-CDMA Satellite Systems

In this model, download time for an average Web page was derived in addition to the average link utilization assuming error free condition. The error free condition is valid for normal operation where errors are very rare. Using this model the following results were obtained:

- Choosing lower orbit satellite constellations, i.e. MEO instead of GEO, was found to reduce the download time of a typical Web page between 17 to 20% depending on the choice of data rate (i.e. either 64kbps or 144kbps) and TCP segment size (i.e. either 510 bytes or 1460 bytes).
- Using large TCP segment size such as 1460 bytes instead of 510 bytes was found to reduce the page download time between 6 to 11 % depending on the choice of satellite constellations (i.e. MEO or GEO) and the data rate being used.
- Using 144 kbps data rate instead of 64kbps was found to reduce the page download time by about 17.6% to 30.5% depending on the choice of satellite constellations and the size of TCP segment being used. The higher the data rate, the lower the difference in performance between MEO and GEO networks in terms of page download time.
- Doubling the initial window size i.e. from 4*512 bytes to 2*1460 bytes resulted in the reduction of page download time by only one round trip delay.

7.1.2 Performance Analysis of Web Traffic in Mobile Satellite Systems

The performance of Web traffic over MEO and GEO mobile satellite systems was investigated by means of system level simulation and assuming random frame error rate. The objective of the simulation investigation was to confirm and extend the analytical results shown in 6.1.1.2 to include the effect of frame error rate and the dynamic behavior of heavy browsing user. The effect of using different data rates (i.e. 64 kbps and 144kbps), TCP initial window (2*512 and 4*512 bytes) and TCP segment sizes (512 and 1460 bytes) on Web page download time was also investigated.

Simulation results presented here show that for 144 kbps data rate, the Web traffic requires $FER \leq 9.5 \times 10^{-3}$ and $FER \leq 5 \times 10^{-3}$ in order to avoid any significant increase in Web page download time in both MEO and GEO systems respectively. It was found that the use of data rate ≥ 144 kbps is essential in both systems in order to avoid unacceptable increase in Web page download time. It was also shown that MEO system (15000-km altitude) only provides slight reduction in Web page download time in comparison to that in GEO system. Similarly using larger TCP segment sizes such as 1460 bytes was found to provide only slight reduction in Web page download time in comparison to that of 512 bytes.

7.1.3 Enhancing the Performance of 3G W-CDMA Downlink in Mobile Satellite Systems for Web Traffic

The performance of a 3G turbo coded W-CDMA mobile satellite downlink for Web traffic was investigated. It was concluded that slow fading due to low mobility and power control errors drastically degrade the performance of the downlink. Thus, in order to alleviate such degradations, a very effective method was proposed where both macrodiversity and RLP were used in the downlink between the satellite and mobile Web terminal. It was found that the combined use of the macrodiversity that uses equal gain combiner (EGC) and RLP allowed a very low FER (which is essential for Web traffic) to be achieved at very low E_b/N_0 . This method allowed FER of 10^{-5} to be achieved at $E_b/N_0 = 1$ dB for 144 kbps turbo coded downlink which suffered from large power control error with $\sigma_s = 4$ dB assuming mobile speed of 80 km/h.

Macrodiversity was employed at the mobile Web terminal rather than at the satellite itself due to space limitation on board the satellite, as it requires at least 10λ spacing between antennas. The main advantage of employing macrodiversity is the large reduction in the amount of power margin required to support Web traffic in the downlink as well as allowing the link to operate at lower operating point E_b/N_0 . This reduction in the required power allows mobile W-CDMA satellites to support substantially more mobile Web users than otherwise possible. This is especially true for mobile satellites systems, as they are power limited in the downlink.

The use of long size channel interleavers in the downlink, meant to minimize the effect of channel bursts due to power control errors, was found to have both an advantage and disadvantage. The advantage is that it can significantly reduce the FER but only within a certain range of E_b/N_0 , while the disadvantage is that it introduces significant delay which might seriously degrade the quality of service (QoS) for satellite mobile Web users, i.e. longer Web page download time is an example. Hence, long size interleavers should be used with great care in mobile satellite links.

7.1.4 Enhancing the Performance of 3G W-CDMA Uplink in Mobile Satellite Systems for Web Traffic

The performance of a convolutionally coded 3G W-CDMA mobile satellite uplink that usually used to carry TCP acknowledgements and HTTP objects requests was investigated. Similar to the downlink, it was concluded that slow fading and power control errors drastically degrade the performance of the uplink. Thus, in order to alleviate such degradations, space-time transmit diversity (STTD) and RLP were proposed for the uplink. The use of STTD in the uplink was proposed because macrodiversity cannot be employed on board the satellite itself due to space limitation.

The main advantage of employing STTD is the slight reduction in the amount of power margin required supporting Web traffic in the uplink as well as allowing the link to operate at lower operating point E_b/N_0 . This small reduction in the required power margin should allow mobile W-CDMA satellites to support slightly more mobile Web users than otherwise possible. This is especially true for mobile satellites systems, as they are interference limited in the uplink.

7.1.5 Web Traffic Capacity Enhancement in the Downlink of 3G W-CDMA Mobile Satellite Systems

The effect of power control errors (PCEs) due to uncompensated shadowing on Web traffic capacity in the downlink of 3G W-CDMA mobile satellite systems was investigated. It was shown that PCEs inherited in mobile satellite systems could seriously degrade the Web traffic capacity. It was found for example that Web traffic capacity

reduces by 66% and 78% for downlink that suffers from PCE with $\sigma_s=1$ and 4 dB respectively for mobile satellites using GEO constellations. Meanwhile the Web traffic capacity reduction in MEO satellites was found to be 77% and 86% for downlink that suffers from PCE with $\sigma_s = 1$ and 4 dB respectively. The main reason for the reduction in Web traffic capacity in the downlink of mobile satellite systems in presence of PCE is the need for large fade margin in order to maintain the required QoS (i.e. FER) for Web traffic.

The effect of macrodiversity to enhance the Web traffic capacity was then investigated. It was shown that macrodiversity is a very powerful method that allowed the Web capacity of mobile satellite systems with large PCE (i.e. $\sigma_s = 4$ dB) in the downlink to exceed even that of no PCE case for both MEO and GEO systems. Meanwhile, it allowed the Web capacity to increase by five and six folds in the downlink that suffers from PCE with $\sigma_s = 4$ dB for MEO and GEO respectively with respect to no diversity case. The main reason for the substantial increase in Web traffic is the reduction in the amount of required fade margin in the downlink due to macrodiversity as mobile satellites are power limited. Hence, the proposed macrodiversity in the downlink is strongly recommended for use as an integral and essential component in the satellite element of UMTS

7.1.6 Web Traffic Capacity Enhancement in the Uplink of 3G W-CDMA Mobile Satellite Systems

Similar to the downlink analysis, the effect of PCE in degrading Web traffic capacity in the uplink of 3G MEO and GEO W-CDMA mobile satellite systems was investigated. It was found that PCE with σ_s of 4 dB in the uplink results in reduction in Web traffic capacity by about 49% for both MEO and GEO W-CDMA mobile satellite systems. The effect of STTD in enhancing Web traffic capacity in the uplink was then investigated. It was shown that STTD has increased Web traffic capacity by only 5% in the uplink which suffers from PCE with $\sigma_s = 4$ dB in both MEO and GEO W-CDMA mobile satellite systems with respect to that of no STTD case.

7.2 Future Research

The objective of this study is to present an overall end-to-end performance enhancement of multispot GEO and MEO 3G W-CDMA mobile satellite systems operating in 2 Ghz band for Web traffic. For the purposes of this study some assumptions were necessary to simplify the tackled problem and to be able to obtain reasonable results in a limited time. However, if a particular aspect of this project is to be further analyzed, more detailed and realistic models can be used to obtain more accurate results.

An example of such an area is on the physical layer side, the study assumes macrodiversity with two independent paths can be achieved with two antenna separated by 10 wavelength (λ) apart at the mobile Web terminal. A more realistic model will take into consideration some effects of correlations between the two paths. Thus the two independent paths can be considered as an upper bound for the performance of macrodiversity.

The study assumes ideal coherent demodulation is being performed at the receiver; the effect of non-ideal demodulation on the performance of both the uplink and downlink must be investigated.

Finally, the system described in this study is tailored for Web traffic in mobile satellite environment in 2 Ghz band. Recently, research is focusing on broadband satellite communications operating in Ka band. A research topic will be an extension of this study taking into account propagation impairments in the Ka band as well as the effect of real time traffic such as video and audio on the performance of Web traffic in mobile satellite environment.

A- Validation of System Level Simulation

A.1 Introduction

The Simulation results shown in section 4.4 were validated via three known verifications steps. These steps are described here.

A.2 Simulation Verification

It was important to verify the simulator so that the results collected match as closely as possible those of real world. Thus the simulator was first tuned to the parameters of a real world experiment conducted by NASA Lewis Center at Ohio University over NASA advanced communication technology satellite (ACTS) as shown in reference [39], which includes end-to-end delay, various TCP parameters and channel data rates... ect.

It was found that link throughput given by the simulator during various downloads of FTP file sizes (i.e. 45 Kbytes, 100 Kbytes, 100 Mbytes) closely matches that of the experiment within less than 5% of margin error. This was conducted for five channel data rates (192, 256,384,768,1152 Kbps) as in the experiment. Then the simulator was tuned to the network characteristics of the simulation model shown in section 4.4.1.

A.3 Simulation Stability

In order for the assigned frame error (e.g. $FER = 10^{-3}$) on the links connecting the mobile Web user and the satellite to be achieved during Web page download time. It was necessary for the simulation run time to be very long. The simulation for each FER value was run for 1000 hours of simulation time. Figure A3.1 shows an example of convergence process of mean Web page download time during the first 24 hours of simulation time (total simulation time was 1000 hours per given FER). The vertical axis of Figure A3.1 shows the mean page download time in seconds while the horizontal axis shows the simulation time in hours.

Similarly Figure A3.2 shows the convergence process of mean link (Web server to mobile Web terminal) throughput during the first 24 hours of simulation i.e. during Web

page download time. The vertical axis of Figure A3.2 shows the mean throughput in bits/second while the horizontal axis shows the simulation time in hours.

FigureA3.1: Convergence process of mean Web page download time during the first 24 hours of simulation time

Figure A3.2: Convergence process of mean link throughput during the first 24 hours of simulation time

A.4 Simulation Statistical Confidence

The confidence interval for the obtained Web page download time was found to be very tight due to the long simulation time. For an estimated Web page download time of 21.634 second at $\text{FER} = 5.10^{-3}$ for example, the confidence interval was found to be [21.601 second, 21.666 second] with 95% confidence. This tight confidence interval is also true for all the estimated Web page download times in the system level simulation.

Similarly for an estimated mean link (server to mobile Web terminal) throughput of 16.461 kbps at $\text{FER} = 9.595.10^{-3}$ for example, the confidence interval was found to be [16.347 kbps, 16.575 kbps] with 95% confidence.

B-Validation of Link Level Simulation

B.1 Introduction

The simulation results in sections 5.5, 5.8 and 5.9 were also validated via the three verifications steps mentioned in appendix A. These steps are described here.

B.2 Simulation Verification

In the downlink, the performance of macrodiversity with equal gain combiner (EGC) assuming satellite channel with Rician factor ($K_R = 10$) obtained from the link level simulation in section 5.5 closely agree with that shown in reference [77]. In [77] the diversity gain obtained was 4-to7 dB, while that shown in Figure 5.9 is about 5 to 7 dB.

Meanwhile in the uplink, the performance of the space-time transmit diversity (STTD) very closely matches that of real world experiment shown in reference [78]. It was shown in reference [78] that the diversity gain obtained from STTD is approximately 0.7 dB, which closely agrees with result shown in Figure 5.17.

B.3 Simulation Stability

In order to plot the performance curves of FER (moving mean average of frame error rate) against E_b/N_0 for both the uplink and downlink, It was necessary to run the simulation long enough so that the FER stabilizes around one value. The simulator always displays the FER values of the last 1500 frames being received. Each value of FER was only accepted after its value stabilizes over a long period of time, which is usually much greater than $100/(\text{expected FER})$.

B.4 Simulation Statistical Confidence

The confidence interval for the obtained FER for both the uplink and downlink was reasonably tight. For an estimated FER of 0.230 for example, the confidence interval was

found to be $[0.214, 0.247]$ with 95 % confidence. This reasonably tight confidence interval is also true for all estimated FERs in the link level simulation.

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