Adaptation of the IEEE 802.11 Protocol for

Inter-Satellite Links in LEO Satellite Networks

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



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April 2008

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Abstract

Low Earth Orbit (LEO) satellite networks using Inter-Satellite Links (ISLs) offer unique benefits and flexibility for a variety of future space applications. However, despite recent advances in wireless technologies, most protocols and algorithms are specifically designed to address challenges in terrestrial networks. In fact, none of the currently used wireless technologies is sufficiently scalable, efficient and robust to meet the future demands of large scale LEO satellite networks. Design of Inter-Satellite Links in Low Earth Orbit networks is a challenging topic as signal transmissions are affected by variable propagation delays, relative velocities and large Doppler shifts and rates. It is therefore necessary to investigate how changes of orbital parameters influence the use of terrestrial wireless standards for intersatellite communications.

The goal of this thesis is to propose key IEEE 802.11 optimization techniques aiming at adapting the standard for inter-satellite communication in autonomous distributed spacecraft networks. The thesis mainly looks at the problem of adapting the IEEE 802.11 protocol with respect to the physical layer and the medium access control (MAC) sub-layer. Concerns regarding the short range and fixed timing parameters of the IEEE 802.11 standard are addressed with optimisation approaches such as tuning of the physical layer parameters and enhancing the data link layer. Investigation of terrestrial smart antenna integration techniques with both the physical and MAC layers aiming at increasing the capacity while minimizing interference and collision in close proximity links is carried out. WLAN architecture for space networks is defined, which supports an increased capacity in terms of throughput and range in dynamic LEO networks. An IEEE 802.11 MAC adaptation algorithm for LEO channel conditions is proposed. Finally, a case study is presented to demonstrate the effectiveness of the proposed approaches for satellite clusters flying in formation.

In this way, the thesis contributes in a number of vital areas spanning the physical and MAC layers. The key outcomes of this research work are:

- i) Extensive numerical study of the impact of ISL variance on communication parameters between both directly and indirectly connected satellites.
- ii) Re-definition of the IEEE 802.11 Physical Layer and MAC Layer interframe timing parameters for ISL range
- iii) IEEE 802.11 physical layer integration with smart antennas for ISL applications.
 - iv) IEEE 802.11 MAC layer integration with smart antennas for ISL applications.
 - v) A novel MAC algorithm for ISL applications.
 - vi) A novel protocol architecture for LEO formations using the IEEE 802.11 framework.

These collectively constitute a scalable WLAN framework for LEO networks using ISL. The effectiveness of all the proposed mechanisms is evaluated through mathematical analysis, simulation or both.

Key works: Inter-Satellite Links, IEEE 802.11, Smart antennas, Adaptive MAC layer,

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ACKNOWLEDGEMENTS

It gives great pleasure to express my gratitude to all the very special people – family, friends, peers, colleagues and academics who have helped to make this achievement possible.

First and foremost, I would like to thank my supervisor Dr. Tanya Vladimirova for giving me an excellent opportunity to carry out a very innovating and challenging research on LEO satellite networks using IEEE 802.11. I am deeply indebted to her for his enthusiastic encouragement and guidance. Through her encouragement and creative suggestions along with patience and time Dr. Vladimirova has been the most instrumental person in materializing my thoughts through this PhD process. My heart felt thanks to Tanya.

Special thanks go to my colleagues Mark Halsall, Dr. Ergemen Emre, Dr. Roohi Banu and Dr S. Sivavakeesar for the invaluable discussions I have had with them regarding useful issues related to general mobile and satellite networking. Thanks also go to my ESA wireless study and ESPACENET project colleagues, Dr. Xiaofeng Wu, Chris Bridges, Jean Paul, Abdul Halim Jallad and Dave Barnhart. I also want to recognise and thank all the supporting staff in the Surrey Space Centre especially Karen Collar and J. Chong. My thanks also go to Professor Sir Martin Sweeting for his invaluable comments on my monthly reports. I would also like to thank the members of my PhD viva examination committee, Prof. Zhili Sun, Dr. John Thompson and Dr. Richard Forbes for their useful comments on this Thesis.

It is with great affection and appreciation I acknowledge my indebtedness to my wife Mrs Awa-Ceesay Sidibeh and to my parents for giving me necessary inspiration and motivation during my academic career.

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List of Abbreviations

AAS
ACK
AODV
AP
ARP
AL
BEB
BER
BI
BS
BPSK
BWFN
CBR
CCATime
CCK
CCSDS
CCSDS-AOS
CCSDS-AUS
CDMA
CED
CP
CP
COIs
CMA
CSMA
CSMA/CA
CSMA_CD
CSMA-CD
CRC
СТ
CTS
CW
CWD
CWD
DA
DBIMA
DCF
D-CTS
DIFS
DiffServ
DOA
DBPSK
DQPSK
D-RTS

Adaptive Antenna Array Acknowledgement Ad hoc On-demand Distance Vector Access Point Address Resolution Protocol Arbitrary Inter Frame Asynchronous Transfer Mode Azimuth Angle **Binary Exponential Back-off** Bit Error Rate Back-off Interval **Base Station Binary Phase Shift Keying** Beam Width between Nulls **Constant Bit Rate** Collision Contention Avoidance Time Complementary Code Keying Consultative Committee for Space Data Systems **CCSDS-Advanced Orbiting Systems** CCSDS-Proximity-1 protocol Code Division Multiple Access **Contention Free Period Contention Period** Commercial-of-The-Shelf **Constant Modulus Algorithm Carrier Sense Multiple Access** Carrier Sense Multiple Access with **Collision Avoidance** Carrier Sense Multiple Access with **Collision Detection** Cyclic Redundancy Check **Common Transmitter** Clear-To-Send Contention Window **Contention Window Differentiation** Contention Window Separation **Dynamic Assignment Dual Busy Tone Multiple Access Distributed Coordination Function Directional CTS Distributed Coordination Function IFS Differential Service Direction Of Arrival Differential BPSK Differential QPSK Directional-RTS**

DMAC DSB-SC DSM DSSS DSR EDCF EIFS EL **ESA** ETS FAMA FAMA-NCS FAMA-NPS FCS **FDM FDMA** FEC FER FHSS FHRP FTP GEO GFSK **GLONASS** GPS GSM **HIPERLAN** HDLC **HPBW** IBSS ID IEEE **IETF** IFS IntServ IP IR ISL ISI ISP ISM ITU-T LAN LAP LEO

LOS

Directional Medium Access Control Double Side Band with Suppressed Carrier **Distributed Space Missions** Direct Spread Spectrum Sequence **Dynamic Source Routing** Enhanced DCF Extended IFS **Elevation** angle European Space Agency **Engineering Test Satellite** Floor Acquisition Multiple Access Floor Acquisition Multiple Access-Non-Persistent Carrier Sensing Floor Acquisition Multiple Access-Non-Persistent Packet Sensing Frame Control Sequence Frequency Division Multiplexing Frequency Division Multiple Access Forward Error Control Frame Error Rate Frequency Hopping Spread Spectrum Footprint Handover Rerouting Protocol File Transfer Protocol Geosynchronous/Geostationary Earth Orbit Guassian Frequency Shift Keying **Global Navigation Satellite System Global Positioning System** Global System for Mobile communication HIgh PERformance Local Area Network High Data Link Control Half Power Beam Width Independent Basic Service Set Identifier Institute of Electrical and Electronic Engineers **Internet Engineering Task** Inter-Frame Space **Integrated Services** Internet Protocol Infra Red Inter-Satellite Link Inter Symbol Interference Internet Service Provide Instrumentation, Scientific and Medical International Telecommunication Union -Telecommunication Local Area Network Logical Access Point Low Earth Orbit Line Of Sight

LLC	Logical Link Control
LMS	Least Mean Square
LPF	Low Pass filter
LOM	Link Ovelite Indianten
	Link Quality Indicator
LSCMA	Least Square Constant Modulus Algorithm
MAC	Medium Access Control
MACA	Multiple Access with Collision Avoidance
MACA-BI	Multiple Access with Collision Avoidance By
	Invitation
MACACT	
	MACA common Transmitter
MACA-RT	MACA receiver Transmitter
MAPLD	Military and Aerospace Programmable Logic
	Device
MAN	Metropolitan Area Network
MANET	Mobile Ad hoc NETworks
MACAW	MACA for Wireless I ANS
	MACA for wheless LAINS
MEND	Mechanical Electro-Magnetic Systems
MDP	Mean Delay Proportional
MH	Mobile Host
MEO	Medium Earth Orbit
MIMO	Multiple Input Multiple Output
MN	Mahila Nada
MDDI	Mobile Node
MADI	Main Protocol Data Unit
MSDU	Main Service Data Unit
MTT	Maximum Theoretical Throughput
MSLL	Maximal Side Lobe Level
NAV	Network Allocation Vector
NE	North Fast
NW	North East
	North West
ODP (On Board Processing
OFDM	Orthogonal Frequency Division
	Multiplexing
OPAL	Orbiting Picosatellite Automated Launcher
OPNET	Ontimum Network Engineering Tool kit
OLSB	Optimized Link State Routing 1001 Kit
DED	Optimized Link State Routing
	Packet Error Rate
PC DOP	Point Coordinator
PCF	Point Coordination Function
PLCP	Physical Link Convergence Protocol
PHY	Physical Laver
PIFS	PCF Inter-Frame Signal
PN	Paguda random Noise
OPSK	C 1 (Disc Shift Kar'
	Quadrature Phase Shift Keying
	Quality of Service
KAAN	Right Ascension of the Ascending Node
KMS	Root Mean Square
RF	Radio Frequency
RI	Receiver Initiated
RLS	Dooursiva Laget Squares
RRA	Recursive Least Squares
1/1/1/1	Kandom Reservation Access

RSVP
RSSI
RT
RTP
RTS
SAFE
SBSA
SDMA
SE
SFIR
SI
SIFS
SM
SNR
SNRT
SOS
SQM
SSTL
SR
SS
SSP
STK
SW
TCeMA
ТСР
TDD
TDMA
TDRS
TPF
TT&C
TXTRN
UDP
UMTS
DMC
VCS
WIFI
WLAN
WiMAX

Resource reservation Protocol **Received Signal Strength Indicator Receiver Transmitter Reservation Transport Protocol** Request-To-Send Simple Automatic File Exchange Switched Beam Smart Antenna Spatial Division Multiple Access South East Spatial Filtering for Interference Reduction Sender-Initiated Short Inter Frame Space Spectral Multiplexing Signal to Noise Ratio Signal to Noise Ratio Threshold Satellite Over Satellite architecture **Signal Quality Matrix** Surrey Satellite Technology Limited Success Ratio Spread Spectrum Sub-Satellite Point Satellite Tool Kit South West TDMA with CDMA encoding Multiple Access Transmission Control Protocol Time Division Duplex Time-Division Multiple Access Tracking and Data Relay Satellite Terrestrial Planet Finder Telemetry, Telecommand & Control Transmit Training sequence User Datagram Protocol Universal Mobile **Disaster Monitoring Constellation** Virtual Carrier Sensing Wireless High Fidelity Wireless Local Area Network Wireless Metropolitan Access Network

Notation and Symbols

a		Semimajor axis
A _c		Amplitude of signal
B		Total Bandwidth
B _G		Guard band
B_{ch}		Channel bandwidth
B _m		Bandwidth of modulating signal
B _c		Bandwidth of spreading signal
b(t)		Channel response
E _p		Payload packet size
C		Speed of light
C'		Delay component not affected by data rate
Ci		Satellite capacity
c(t)		Chip signal
D _p		Phase deviation of BPSK signal
d _{max}		Maximum distance different orbit planes
d(t)	a	Antenna array reference signal
Dn		Debits
d(n)		Training sequence
E _b /N _o		Energy per bit over noise
E[q]		Mean number of packets in a queue
E[r]		Mean response time
e(n)		Mean square error signal
e		Eccentricity
$\mathbf{f_c}$		Carrier frequency
g(t)		Complex envelop of modulated signal
g _m (t)		Complex envelop of message signal m(t)
$g_{c}(t)$		Complex envelop of chip (spreading) signal
g _{mb}		Maximum gain in the main beam
good		Difference in gain from the main beam in the
	N	ball beam directions
Gr		Receiver gain

Gt	Transmitter gain
h	Altitude of satellite
ISL _{Distance}	ISL distance
J ₂	Perturbation term due to Earth oblateness
J ₄	Higher order perturbation term including J_2
L _{intra}	Intra satellite link length between satellites in the
	same orbit plane
L _{inter}	Inter satellite link length between satellites in the
	different of Planes
L _{data}	Data packet length
m	Factorial between planes defined by Ballard
Μ	Number of elements in an antenna array
M _E	Mass of Earth
m(t)	Message signal
m	Back-off window steps
M _k	Sequence symbol
M _L	Mean number of ISLs
m _k (t)	Normalized baseband modulating signal
Ν	Number of satellites
N _{ch}	Number of channels
N(t)	White Gaussian noise
n _c	Number of collisions
n _s	Number of successful transmissions
NP	Total Number of satellites per Plane
N(t)	Gaussian noise
n	Satellite mean motion
n(t)	Thermal noise
Р	Number of orbit Planes
Ps	Probability of successful transmission
Pc	Probability of collision
Pi	Probability of slot left in idle
P _{tr}	Probability of at least one transmission in slot
	time

Notations and symbols

Ps	Probability of successful transmission
Pr(d)	Received power
P _{sector}	Number of sectors in a cell
P _{loss}	Packet Loss probability
P _{data}	Probability of data transmission
P _{RTS}	Probability RTS transmission
P _{fail}	Probability packet transmission fails
N _{cell}	Number of users in a cell
h _m	Modulation index
Pt	Transmitted power
Q	RSSI window size in frames
q(t)	Modulated carrier frequency
R _c	Chip rate
R _m	Symbol rate of message signal
R _E	Radius of Earth
r	Radius of circular orbit plane
R _b	Base band information rate
r(t)	Received signal
Rxx	Expectation operator in real time
Rsd	Instantaneous value of the covariance metrics
S	IEEE 802.11 maximum throughput
SR	Success ratio between collision and successful
	transmission
s(t)	Transmitted Signal
t	Time
Τ	Orbit period
to	Time of satellite pass across ascending node
T _s	Satellite period
T _{slot}	Slot Time
te	Time of equator crossing
T _m	Pulse width of message signal
T _{chip}	Pulse width of spreading signal
T _E	Earth side real time
T _{sym}	Pulse width of symbol

Delay component of DIFS TDIFS Delay component of SIFS TSIFS Delay component of BO Delay component of CTS Delay component of RTS Delay component of ACK Delay component of DATA Delay component of ISL Delay component of preamble Delay component of physical header Delay component of multiple access scheme Delay component of uplink to satellite Delay component of downlink to ground Delay component within a satellite node Delay component of service time Delay component of back-off time Delay component of slot time Delay component of collision Delay component of successful transmission Delay component of successful data Transmission Additional delay component of DIFS T_{defer} Total RF bandwidth Optimum contention window Antenna array weights Total overhead above MAC layer Antenna array output Angle between satellites in the same orbit plane Off-orbit viewing angle between Satellites in Tropospheric delay Propagation delay Multipath error delay $\delta_{multipath}$ Thermal error delay $\delta_{thermal}$

 T_{BO} TCTS T_{RTS} TACK TDATA TISL Tpreamble TPhyheader Taccess Tuplink T_{downlink} T_{sat} T_{service} T_{back-off} T_{slot} Tc T. T_{data-succ}

W Wopt W Y z(t)α β $\delta_{\scriptscriptstyle trop}$ $\delta_{\scriptscriptstyle prop}$

xix

Notations and symbols

$\delta_{\scriptscriptstyle iono}$	Ionospheric delay
ε	Elevation angle
\mathcal{E}_{\min}	Minimum Elevation angle
ρ	Difference in latitude of two satellites in
	different orbit planes
η	Longitudinal separation of orbits
$\eta_{\prime h}$	Thermal noise coefficient
Ω	Right Ascension of the ascending node (RAAN)
i	Inclination
ω	Nodal angular elongation
$\sigma_{_o}$	Argument of perigee
ω_{c}	Angular frequency
Δ	Angle between counter rotating orbits.
ν	Eccentric anomaly
ΔV	Delta V
θτ	True anomaly
Θ_{g}	Universal gravitational constant
$\sigma_{\scriptscriptstyle 0}$	Latitude of the ascending node
arphi	Angle between orbital planes
ς	Epicycle phase
k	Circular correction to mean motion
9	Nadir angle
\mathcal{G}_{\max}	Maximum nadir angle
ψ .	Earth Centre angle
γ	Throughput at destination satellite
τ	Probability that a node transmits in a randomly
	choosen slot time.
ξ	Wave number in an antenna array
l -	Distance between antenna elements
χ_{\max}	Largest Eigen value in the LMS algorithm

 $arphi_{\max}$ heta heta

Γ

Maximum Eigen value

Elevation angle

Azimuth angle

Service time

Wavelength

Phase elements

Application layer datagram size

Chapter 1. Introduction

Analogous to proliferating terrestrial wireless networks, massively distributed space networks will enable the implementation of an Internet Protocol (IP) based global network by complementing terrestrial networks. Distributed space missions for scientific and commercial applications are emerging, which require constellations of hundreds to thousands of miniaturised satellite nodes [11]. These future distributed satellite missions will require coordination that may be best provided through inter-satellite communications. As the trends move towards increasing autonomous operation of spacecraft the need of seamless control from Earth-based operators will be replaced by new communication and software technologies. The choice of inter-satellite communications protocol will depend upon the mission objectives and requirements, hardware availability and new optimization techniques for the physical and data link (MAC) layers.

The concepts of "Internet in the sky" and space-based wireless sensor networks have stimulated a wave of research in inter-satellite communication for satellite networks in low Earth orbit [4]. LEO satellite networks using inter-satellite links offer unique benefits and flexibility for a variety of applications beyond the boundaries of geographical or political difference, and hence will play a vital role in future leisure, commercial and military projects. However, this comes at the expense of overcoming extremely difficult challenges, namely, the absence of fixed infrastructure, large bandwidth, and energy constrained operations and the dynamic nature and connection pattern of satellites in LEO, which are unique to such networks. These challenges cannot be solved through traditional approaches to physical layer connectivity, medium access control and routing provisioning in the terrestrial wireless environments as most protocols and algorithms are designed to address the specific needs of terrestrial networks. It is not clear if any of the currently used wireless technologies are sufficiently scalable while at the same time being efficient and robust to meet the demands of large scale LEO satellite networks. The question to answer is how to design a viable space wireless network and what the building blocks of such a framework will be. Devising such a framework is fundamental to the success and acceptance of a future seamless IP network with boundary no between terrestrial and the space network.

1.1 Motivation

LEO has a number of advantages over traditional geosynchronous satellite systems, the most important of which are relatively low propagation delays and power requirements, resulting from the low orbit altitude as presented in Table 1.1. This enables the use of small, lightweight and low cost satellite nodes. LEO satellites also have a number of advantages over terrestrial mobile networks, the most important of which is the ability to provide coverage to land, sea, and air-based users. In low-altitude multi-satellite communication systems the network topology is predictable and periodic, but signals suffer variable propagation delays, variable signal-to noise ratios, large Doppler shifts and change of rate of Doppler frequency.

Recent advances in satellite technologies have seen the emergence of active systems having the capability to perform onboard switching and signal processing, and being interconnected by inter-satellite links. This has made possible the development of satellite networks such as the Iridium [1] and the proposed Techsat-21 program [2]. The Iridium constellation is the first LEO satellite network incorporating onboard processing and ISLs to begin commercial service. Iridium provides a low bandwidth service, capable of supporting voice telephony and simple message forwarding (paging) services.

Specifications	LEO	MEO	GEO
Height (km)	500 - 1,500	10,000 - 15,000	35,786 - 42,178
Propagation delay/(ms) Ground-to- Ground	5 - 10	65 -100	238 -280
Satellite handover time	5-10 mins	3 Hours	None
Spotbeam handover/ (min)	1-2	2-4	None
Ground velocity/ (km/s)	7.6 - 7.09	2.5 – 2	0
Path loss/(dB)	150 - 164	180 - 184 ~	~192 - 200
Doppler/(kHz)	~42	~32	0

Table 1.1 Comparison of orbit parameters

A pioneering effort in the field of satellite clusters is the Techsat-21 program, comprising of 35-40 clusters, each with 8 micro satellites. The intention was to perform both geolocation measurements with ISL distances of about 5 km, and radar measurements with ISL distance of 500 m. The entire Techsat- 21 program was a joint effort by the US government and industry, but unfortunately the project was discontinued in 2003. The Surrey

Small Satellite Technology (SSTL), a spin-off company of the University of Surrey flew a Cisco router on board their Disaster Monitoring Constellation satellite, UK-DMC, for a remote sensing satellite as a secondary experimental payload in September 2003 [3]. Placing Cisco's 3251 mobile access router in LEO is a step towards extending the terrestrial networking model as part of a merged space-ground architecture. This router has since been tested successfully, demonstrating how IP can be used to communicate with satellite payloads in space.

ISLs in LEO constellations can use several types of transmission technologies, including microwave radio and laser or other optical transmitters. Optical transmitters are very small and use less power but require very high precision tracking and acquisition due to their narrow antenna beam angles. On the other hand, Radio frequency (RF) links are less affected by pointing precision than optical antennas since the RF beam angles are much larger, however the transmitters are usually larger in size. Interference and power saturation are important issues for RF ISLs. This thesis is concerned with ISLs based on RF transmission.

The main factor affecting ISLs in LEO constellations is the time variant position of the satellites. In order to establish ISLs, it is necessary to determine antenna-pointing requirements such as the azimuth and elevation angular variations with time, and by calculating the exact positions of the satellites with respect to each other. In this thesis, the main motivation is to investigate some of the factors that determine antenna requirements to maintain ISLs in inter-orbital planes and cross-seam.

Present satellite constellations with inter-satellite links, such as Iridium, use fast onboard switching similar to the Asynchronous Transfer Mode (ATM)¹ [4] [5]. The biggest drawback for connection-oriented protocols such as ATM is the on-off switching of traffic between satellites where the physical link needs to be maintained in a transparent way during handover. As the Internet is becoming very popular there must be efforts to implement IP or IP-like switches in satellite networks, which means using schemes at the transport layer such as TCP. The routing decisions in these types of schemes are made at packet level on a best effort basis, thus avoiding the need for handovers of established connections. There are very few literature sources addressing connectionless routing in satellite networks. Table 1.2 presents some comparisons between connection-oriented and connectionless protocols for inter-satellite connectivity. There is a new trend towards independently launched IP-enabled

¹ Asynchronous time-division multiplexing is a technique that organises transmission into unreserved slots, which are filled based on each application's instantaneous need.

LEO satellites, with limited size, cost and technological advances that can achieve a density of coverage similar to terrestrial wireless networks, where technology evolved from the circuit-switched GSM and UMTS to wireless network paradigm based on WLAN, WiMAX, ZigBee, etc.

Protocol Procedure	ISL Connection-Oriented Protocols	ISL Connectionless-Oriented Protocols
Spotbeam handover < 2mins	Frequent handover; Depends on switching speed and LEO topology; ATM- like switching	Depends on switching speed and LEO topology; IP-like switching
Satellite handover (5 to 10 mins)	Large buffers, reassembly and re-sequencing; No handover at seam and poles	No need for handover of established connection paths
Routing	Ground initial set-up phase and at network level; LEO path affects routing optimality.	Independent routing decision for each packet
Delay	Longer delay High handover probability loss	Smaller delay but affected by LEO delay variance.

Table 1.4 Comparison of Connection-Offented and Connectioness-Offented Flotocols to	Table	e 1.2	Comparison of	Connection-Oriented	and Connectionless-	Oriented	Protocols	for	ISL
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IP routing in LEO satellite networks can reduce delays in broadcast and multicast applications such as IP-based video/teleconferencing on a global scale. The use of IP based technologies employing medium access control schemes will further enhance the inter-operability between satellite networks for different applications such as the future distributed space missions [6][7] illustrated in Figure 1.1 and Figure 1.2. For example long-range protocols such as High Data Link Control (HDLC) protocol could be used for GEO-LEO ISL and Inter-planetary constellations, whiles short range protocols such as IEEE 802.11 (Wi-Fi) [8] could be used for LEO clusters in formation flying missions, and IEEE 802.16e (WiMAX) [9] for ISL lengths of few hundred kilometers.







Figure 1.2 A Distributed Satellite Network

Lower layer protocols for autonomous LEO networks were investigated in [5], including consideration of X.25/LAP-B/HDLC, ATM, IEEE 802.11, CCSDS Proximity-1 and CCSDS AOS. A survey of existing and planned ISL protocols is presented. Regarding the use of both 802.11 physical and MAC, it is indicated that "It remains to be determined whether or not IEEE 802.11 can adequately scale up to ISL power and range requirements" but the use of the MAC was acknowledged as a possibility. In this thesis, our main objective is to investigate the use and optimization of the IEEE 802.11 physical and MAC layers for future ISL applications.

1.2 Scope and Objectives

In most studies on LEO satellite networks, simulation models are used for the evaluation of devices and protocols. Typically, such simulations focus on the specific higher layer protocols that are being proposed, and tend to ignore details of models at other layers, particularly the interaction with physical layer models. IEEE 802.11 is one of the fastest growing technologies in the area of wireless communications and networking. It has witnessed tremendous interest in areas such as ISL and new and emerging IP services. What makes the IEEE 802.11 popular is the spread spectrum technique in the physical layer and the Medium Access Control at the data link layer. Both the physical and the MAC can sense the medium for contention and flow control.

The research presented in this thesis is focused on inter-satellite links using the IEEE 802.11 wireless communication standard in a broadband LEO satellite network. This research aims to develop a LEO satellite WLAN procedure that minimizes the perceivable loss in throughput during communications. To achieve this aim 1) the physical layer must be reliable and scalable to ISL length and variations 2) the MAC level layer must be less complex, adaptive and minimize delays. As a basis, this research applies the IEEE 802.11b terrestrial WLAN procedure to a LEO satellite network based on a star polar constellation. The new optimization procedures specified in this thesis are designed to integrate within the standardized WLAN terrestrial framework. The focus is on LEO satellite networks that use IP space-based backbone network. A space-based backbone network provides the ability to communicate end-to-end using only the satellite network.

There are presently very few solutions to LEO network design using inter-satellite links. Our approach is based on wireless Commercial-Off-The-Shelf technologies. By doing so, we aim to reduce cost, deployment and risk. In this thesis a holistic view of the issues of ISL

connectivity and capacity provisioning is taken by identifying the required components of an overall satellite network in LEO. Two main architectural concepts are considered: close proximity spacecraft systems flying in formation and widely separated constellations.

This thesis is one of the first systematic investigations on using Wi-Fi for inter-satellite communication. Higher throughput provisioning using radio frequency (RF) signals is an extremely challenging task given that connectivity in LEO satellite networks can be intermittent and IEEE 802.11 is error prone. Previous research has only identified and understood the major challenges of using IEEE 802.11 for ISL communications, but enhancement techniques to exploit some of the unique desirable features of the protocol, namely physical and MAC adaptation to LEO ISL dynamics have not been investigated [5, 111, 113].

Given that the maximum distance and bandwidth of a WLAN using IEEE 802.11 is limited and cannot scale up to ISL length and variations, one of the feasible options is to integrate smart antennas to increase the effective capacity. Another option is to optimise the IEEE 802.11 medium access control scheme for ISL variance- in order to gain optimum throughput and stability. The goal of this thesis is to develop a moderate bandwidth solution that can meet the inter-satellite communication needs of LEO networks in general and that of satellite formations in particular. The specific objectives are as follows:

- 1. Develop a data communication system based on the IEEE 802.11 standard (Please refer to Appendix E) to provide reliable communication between satellites in LEO networks.
- 2. Study the impact of ISL variance on communication parameters between both directly and indirectly connected satellites in LEO networks.
- 3. Modify and re-define the IEEE 802.11 physical and MAC interframe timing parameters responsible for variable ISL lengths.
- 4. Develop a scalable MAC algorithm to improve the throughput for ISL applications.
- 5. Integrate a smart antenna algorithm with IEEE 802.11 using switched beam-forming and steering techniques to improve capacity in LEO networks.
- 6. Evaluate the general performance of the proposed IEEE 802.11 over a formation flying system.

1.3 Outline of the Thesis

The structure of the thesis indicating the relationship between different chapters is schematically depicted in Figure 1.3.

In Chapter 2, a general overview of satellite constellations is presented, with particular emphasis on LEO networks using ISLs. It first reviews the geometry of satellite constellation and the state of art in constellation design.

Chapter 3 presents a detailed investigation into the effects of the LEO ISL variant on communication parameters, hence the justification of our reasoning behind the need to optimize IEEE 802.11 for ISL conditions. The effect of LEO dynamics on communication parameters is investigated, not only from the perspective of the physical layer but also from the perspective of the MAC layer. The off-orbit viewing angle between satellites in different orbit planes is calculated to determine antenna specifications. It is also found that the ISL length variation due to Earth's oblateness effect known as J_2 increases as the mean latitude difference between the two connected satellites increases.



Figure 1.3 Thesis structure showing relationships between chapters

The results of the investigation indicate that by providing phase offset between two connected satellites in inter-orbital planes minimum delay and ISL length variation could be achieved with a significant effect on communication parameters such as Doppler shift. These dynamic geometric characters of ISLs are important for ISL communication performance analysis and the design of the devices on the LEO satellite.

Chapter 4 delves into the problem of IEEE 802.11 scaling up to ISL length and variations in LEO networks. Given that the scalability of IEEE 802.11 physical to ISL variance is the key to establish efficient inter-satellite connectivity between two satellites, the thesis first review the effects of increasing range, mobility and other communication factors on different IEEE 802.11 physical layers – in order to select the best modulation, spreading technique, etc for ISL channel conditions. It then identifies the main drawbacks existing in the mechanisms defined in the 802.11 standard and then proposes a novel way to redefine the interframe timings that control the medium in order to enhance the physical layer for ISL range. This is optimized depending on the length of the ISL and the relative mobility between satellites. The results indicate that tuning the IEEE 802.11 physical layer characteristics, such as slot time, AckTimeOut and the Minimum Contention Window, can greatly improve the performance of IEEE 802.11 in space for inter-satellite link communication.

Chapter 5 deals with another contribution of this thesis. Since medium access control has been identified as a component that plays a vital role in capacity provisioning, this thesis presents a scalable MAC scheme based on a novel adaptive contention window algorithm for LEO constellations. This chapter first reviews the state of art in the field of medium access control schemes in wireless terrestrial environments. It then justifies the need for adapting the DCF mode of operation of the IEEE 802.11 MAC sub-layer as part of our effort to optimize the throughput to near theoretical values for large scale LEO networks. In our space-aware MAC scheme, each satellite keeps count of both successful and collided packets to find a success ratio, which adapts the minimum contention window to provide constant throughput. This is adaptive and network aware depending on the type and intensity of traffic, and relative mobility between satellites in a LEO constellation.

Chapter 6 presents the integration of smart antenna techniques with IEEE 802.11. The 802.11 standard is designed for omni-directional antennas, and has serious flaws if operated with smart antennas. The main drawback is the proximity-independent carrier sensing problem known as the hidden, exposed and capture effects. This provides enough motivation and justification to devise a way of integrating smart antennas with IEEE 802.11 to improve capacity in LEO networks. A full description of our proposed Smart-WLAN using IEEE 802.11 integrated with smart antennas is provided, with clear justification why such a solution has to be adopted. A MAC timing scheme to integrate the standard with switched beam antennas that attempts to support a stronger notion of per-antenna service guarantees in terms of spatial multiplexing in LEO networks is presented. The use of high-gain antennas with the integration of an adaptive timing scheme in the MAC-layer will enable finding and tracking-over-time of every in-range neighbor satellite with minimal interference while maximizing gains towards target satellites. Our proposed adaptive IEEE 802.11 MAC scheme in chapter 5

combined with smart antennas will allow achieving seamless connectivity between spacecraft in a changing LEO network

Chapter 7 presents a case-study based on LEO networks flying in formation. All the proposed schemes described in the previous chapters such as enhancing the physical layer in chapter 4, adapting the MAC layer for ISL in chapter 5 and integrating the IEEE 802.11 with smart antennas in chapter 6 are investigated in this case study to validate our proposed Space-Aware IEEE 802.11 framework. It first reviews the effects of formation shape and the choice of classical orbital elements on communication parameters. It then introduces a simple concept of formation design using regular polar orbit with almost the same classical orbit elements for all the satellites. Therefore the perturbation effect kept almost uniform for all the satellites in the formation, hence keeping the satellites tightly together with minimal ISL length variations. It is shown that changes of a special orbit parameter can influence the use of ISL. The results show clearly that adaptive algorithms are needed in both the IEEE 802.11

Finally, chapter 8 provides the conclusions and points towards future research directions in this exciting field.

In this way, this thesis will contribute in a number of vital areas spanning from the physical to the MAC layers. A deeper understanding of the effects of LEO dynamics on communication protocols, an enhanced physical layer for range, a novel contention window algorithm and a smart IEEE 802.11 using directional antennas are the key outputs of this research work, resulting in a scalable Space-Aware 802.11 framework for inter-satellite links in LEO constellations.

1.4 List of Publications

The following lists the author's publications:

Journal Publication

J₁. K Sidibeh, T.Vladimirova, *The Effect of Angular velocity on Inter-satellite Link in LEO Constellations*, to appear in International Review of Aerospace Engineering (IREASE), April 2008.

Conference Publications

- C1. K Sidibeh, T.Vladimirova, WLAN for LEO Formations, to appear in proceedings of 2008 ECSIS Symposium on Bio-inspired, Learning, and Intelligent Systems for Security BLISS-2008, August 4-6, 2008, Edinburgh, Scotland, UK.
- C2. K.Sidibeh, T.Vladimirova, Wireless Communication in LEO Satellite Formations, to appear in proceedings of the 3st NASA/ESA Conference on Adaptive Hardware and Systems (AHS-2008), Paper ID: 88, 22-25 June 2008, ESTEC, Noordwijk, The Netherlands.
- C₃ X.Wu, T.Vladimirova, K.Sidibeh, Signal Routing in a Satellite Sensor Network Using Optimisation Algorithms, to appear in proceedings of 2008 IEEE Aerospace Conference, Paper ID: 1264, 1-8 March 2008, Big Sky, MT.
- C4. T.Vladimirova, C.P.Bridges, G.Prassinos, X.Wu, K.Sidibeh, D.Barnhart, A.Jallad, J.Paul, A.Baker, K.Maynard, V.Lappas, R.Magness, *Characterising Wireless Sensor Motes for Space Applications*, Proceedings of the 2st NASA/ESA Conference on Adaptive Hardware and Systems (AHS-2007), Vol. 00, pp. 43-50, IEEE, 05-08 August, Istanbul, Turkey, 2007.
- C5. K. Sidibeh, T. Vladimirova, A. Baker, Adapting the IEEE 802.11 Protocol for Inter-Satellite Links in LEO Constellations, Proceedings of ESA Wireless for Space Applications Workshop, 10-13 July 2006, ESTEC, Noordwijk, The Netherlands (invited paper).
- C₆. T. Vladimirova, W.Xioafeng, K.Sidibeh, D.Banhart, A.H. Jallad, *Enabling Technologies for Distributed Picosatellite Missions in LEO*, Proceedings of the 1st NASA/ESA Conference on Adaptive Hardware and Systems (AHS-2006), pp. 330-337, IEEE, 15-18 June, Istanbul, Turkey, 2006.
- C7. K. Sidibeh and T. Vladimirova, *IEEE 802.11 Optimization Techniques for Inter-Satellite Links in LEO Networks*, Proceedings of the 8th International Conference on

Advanced Communication Technology, IEEE/ICACT'06, "Towards the Era of Ubiquitous Networks and Societies", vol. II, pp.1177-1182, 20-22 February 2006, Phoenix Park, Korea

C8. K. Sidibeh and T. Vladimirova, A Fault Tolerant High Speed Network for Inter Satellite Links, Proceedings of the 8th Military and Aerospace of Programmable Logic Devices and Technologies International Conference (MAPLD2005), P-144, September 7-9, Washington DC, USA, NASA, 2005.

Chapter 2. Satellite Networks with Inter Satellite Links

In this chapter an overview of satellite constellations are presented. The remainder of the chapter is organized as follows. Section 2.1 describes some of the constellations planned and in operation. Section 2.2 gives an overview of types of polar constellations in present use. In section 2.3 an overview of inter-satellite links in LEO constellations is given with the needs and requirements outlined. In section 2.4 the effect of LEO dynamic on handover and routing is briefly explained. Section 2.5 presents the system architecture and our design philosophy. Fundamentals of satellite geometry are presented which includes the general idea behind constellation design and the factors that determine the choice of constellation are given in Appendix B. Finally, section 2.6 gives a summary of the chapter.

2.1 Introduction to Satellite Networks

The emergence of satellite technologies including onboard routing and Inter-Satellite Links, will be a major enabling factor for the vision of the next generation of the internet [11], which is capable of providing location independent high-quality access to common communications applications (e.g. telephony, email, World Wide Web). Traditionally, GEO play an important role, particularly in providing broadcast services, but increasingly low earth orbit satellites will be used to provide personal communications services comparable in performance to terrestrial wireless services. Current and proposed satellite communications networks use low earth orbit constellations as well as geosynchronous satellite systems. GEO satellites have a high propagation delay but a few satellites are enough to provide connectivity across the globe. LEO satellites have lower propagation delays due to their lower altitudes, but many satellites are needed to provide global service. While LEO systems have lower propagation delay, they exhibit higher delay variation due to connection handovers and other factors related to orbital dynamics. The effects of the propagation delays are further intensified by the buffering delays that could be of the order of the propagation delays especially for best effort TCP/IP traffic. The large delays in GEOs, and delay variations in LEOs, affect both real time and non-real time applications. As a result, the congestion control issues for satellite networks are somewhat different from those of low latency terrestrial networks.
LEO or Medium Earth Orbit (MEO) satellites may be categorized depending on the altitude at which the satellite orbits the Earth. LEO satellites, and to a lesser extent MEO satellites, exhibit terrestrial wireless-like characteristics, including a small propagation delay ideal for interactive communications, and low transmit power requirements making small handheld terminals a reality.

The evolution towards LEO satellite networks has resulted in a multitude of proposals, including Iridium (LEO), Globalstar [12] $(LEO)^2$, ICO [13] (MEO), Courier (LEO) [15], M-Star/Celestri [18] (LEO), (MEO), Orbcomm [21]. Please refer to Appendix A for details of some of the constellations mentioned. Each constellation is targeted at a particular market, such as voice, broadband data, satellite radio, remote sensing or messaging. However, most of these constellations were never built due to a lack of funding; however Iridium, ICO and Globalstar, targeting the voice market, and Orbcomm, targeting the messaging market, were built and are in operation today.

Other satellite constellation missions targeting the distributed navigation market such as Global Positioning Satellites (GPS) [14] and GLONASS [16] constellations are presently in operation. Remote sensing is a growing market using satellite constellations. For example, the Disaster Monitoring Constellation (DMC) [49] is the first commercial Earth-imaging constellation which offers a revisit time of 24 h, compared to days or weeks available from other systems such Formosat-3 [23] launched in 2006.

There has been an explosion of distributed spacecraft mission concepts such as formation flying and clusters using very small satellites. For example the CubeSat concept developed at Stanford University for student built satellite, OPAL- the Orbiting Picosatellite Automated Launcher [17] which was launched in 2000. OPAL primary mission objectives were to explore new mothership/daughtership mission architecture for distributed sensing. Currently under study at NASA is the Terrestrial Planet Finder (TPF) [19] mission concept of formation flying for science and exploration scheduled for launch in 2012-2015. The primary scientific goal of TPF is to employ a formation-flying cluster for direct detection and characterization of Earth-like planets that orbit nearby stars.

While the future profitability of such constellations remains unclear, future technological advancements should lower development, launch, and management costs, and increase data rates, resulting in a more cost/performance competitive service than is currently available today.

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² Lloyd's Satellite Constellations [32] presents an excellent overview and history of these projects.

2.2 LEO Satellite Networks

In order to eliminate long round-trip delays, the satellite has to be positioned in a mush lower orbit. The low Earth satellite operates at altitudes of 1,500 km or less (note that from 1500 to approximately 7,000 km is not suitable for communications due to the radiation in the inner Van Allen belt). Using the maximum altitude of 1500 km and the minimum elevation of 10 degrees and the round trip delay is only 10 msec, which is far less than delays encountered in GEO and MEO satellites; thus making LEO satellites more suitable for connecting distant points on the surface of Earth using ISLs. There is a price to pay in reducing delay in LEO networks. First, due to the lower altitude, the footprints of the satellites are much smaller. This warrants the use of a larger number of satellites for global coverage. To avoid the use of terrestrial networks for communication between two distant Earth stations, ISLs have to be employed, creating a multi-hop system of Inter-satellite network. Secondly, the lower altitude decreases the time to orbit resulting in satellite constantly moving against the surface of Earth, and also against each other. The result of which is frequent handovers with fix Earth stations, and dynamic changes in the distances between satellites. These are major challenges for building a communication network connecting LEO satellites are relative velocities between satellites, high Doppler shifts and rate of change of Doppler frequency and delay variations. The following sections will elaborate further into the main issues involved.

2.2.1 Types of LEO Constellations

Many satellite constellations have been studied in the last decade to provide optimal ground coverage, with minimal number of satellites whiles reducing the complexity of LEO satellite dynamics on building communication networks. Most of this research have been focused on designing regular constellations with constant footprints throughout the orbit. The two most regular constellations used in all the relevant literature in LEO networks are the Walker Star Constellations and the Walker Delta constellations, named after J.G.Walker, who originally dubbed the two types as Star pattern and Delta pattern constellations [27], [28]. In these constellations the orbital pattern viewed from the poles appear either as a "star" (*) or as a "Delta" (Δ). Included in Table 2.1 are other names mentioned in the literature, as will be explained later.

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Criterion	Type (1) Polar and near polar	Type (2)
Constellation pattern (polar)	Star	Delta
Constellation pattern (overall view)		Rosette
Inclination	(near) Polar	Inclined
Equatorial angle subtended by ascending nodes	π	2π

Table 2.1 LEO Polar Classifications

2.2.1.1 Star Constellations

In this type of constellation, a number of orbit planes are used with an inclination of $i \sim 90^\circ$, the main reason why they are classified as Polar constellations. These types of orbits are arranged in such a way that the total of their ascending or descending nodes make an angle of 180° in the equatorial plane; thus, the name π -constellation [29], [30]. As a result of this 180° plane spacing, the satellites form a configuration where adjacent orbits are co-rotating, At any given longitude on Earth the satellites appear to be either ascending (south to north) or descending (north to south). At the poles all the intercepting orbital planes seem to form a star in a polar view. As a result, this type of configuration has two counter-rotating orbits at the edges of the ascending and descending hemispheres: called the cross-seam, as illustrated in Figures 2.1 and 2.2. In Figure 2.1, the ISLs can be classified as: 1) intra-plane ISLs, which connect neighboring satellites in the same orbital plane, and 2) inter-plane ISLs, which connect neighboring satellites in adjacent orbital planes. The inter-plane ISLs are turned off near at certain latitudes near the poles and communication is not possible across the satellite constellation cross-seam in present systems, due to the large relative velocities between satellites, which cause large Doppler frequency shifts and requires unfeasibly high speed ISL antenna pointing.

Star constellations can be summarized as follows:

- The inclination $i \sim 90^{\circ}$ is the same for all the orbit planes, *P*, and *N* is the number of satellites in the constellation.
- N = N/P denotes the number of satellites per orbit plane. With the satellites evenly spaced in the orbit plane, in which satellites can handover connections to the following satellites.

Chapter 2 Satellite Networks with Inter-Satellite Links



Figure 2.1 LEO Satellite Model Showing ISLs

- The angular difference between satellites in the same orbital plane can be given as 2π/N. The satellites form a street of coverage as shown in Figure 2.2, in which satellites hand over connections to following satellites and this concept was first proposed by L[°]uders [31] and details are given in [32].
- The satellites in adjacent planes are shifted relative to each other in such a way not to leave gaps in order to provide full coverage. The phase shift between planes is given as π/N.
- As illustrated in Figure 2.2, ψ denotes the one-sided Earth central angle of the satellite footprint (coverage angle), to provide continuous coverage the co-rotating orbital planes must not be spaced by an angle separation larger than Δ+ψ, where Δ can be calculated using spherical geometry given by [33].

$$\cos\Delta = \frac{\cos\psi}{\cos\left(\frac{\pi}{N}\right)} \tag{2.1}$$

• On the other hand, in order to provide continuous coverage between counterrotating satellites, the spacing between satellites must be smaller than: 2Δ .

Hence, a condition for global coverage can be formulated as:

$$\pi = (P-1) \bullet (\psi + \Delta) + 2\Delta$$

(2.2)

Several optimization techniques for star constellation can be found in [33], [34] and [35]. These techniques are geared towards either optimizing multiple coverage area or to providing coverage above certain latitude. A typical example of a star constellation is the Iridium constellation.



Figure 2.2 Illustrating a star constellation: a) Co-rotating with street of coverage, b) Counter rotating with cross-seam and c) Star polar view and angles between planes

2.2.1.3 Delta Constellations

In this type of constellation the orbital planes, P, are equally inclined with inclination less than 90° and their ascending nodes being equally spaced along the full 360° of the equatorial plane, hence the name 2π -constellation [29], [30]. A situation is created where both the ascending and descending planes and their coverage continuously overlap, rather than being separated as shown in the Walker star constellation. Polar view in these types of constellations, form a triangular orbital shape consisting of three planes or a Greek Delta shape " Δ " is formed around the poles [32], hence the name Delta given to such constellations by Walker. Ballard modified the Delta constellation by interleaving low-inclination of multiple planes containing few satellites and with careful phasing to fill in the gaps between satellite footprints in the same plane [36]. Ballard calls the delta constellation an inclined rosette constellation which does use the street of coverage approach. Although the rosette approach of interleaving and careful phase alignment of coverage planes, e.g. SkyBridge and Globalstar, (Please refer to Appendix A) can reduce the number of satellites required, their inclined orbits generally place more severe constraints on satellite networking with intersatellite links. In comparison with polar (star) constellations, there is an increase in relative velocities between satellites, tracking requirements and Doppler shifts for inter-plane links in rosette constellations. Hence this type of constellation is not considered further in this thesis.

2.2.1.3 Constellation Notations

In the literature constellation types are described as follows;

Walker notation: $N/P/\varphi^{\circ}$

Where N is the number of satellites per plane P and φ° is the number of distinct phases of planes to control spacing offsets in planes.

Ballard notation: (NP,P,m)

Where NP is the total number of satellites in the constellation, P is the number of planes and m is the harmonic factor describing the phasing between planes.

The most commonly used notation is the Walker notation, although the Ballard notation accurately describes possible offsets between planes, especially when m is a factorial [32, 36].

2.3 Inter-Satellite Links in LEO Networks

A comprehensive overview of some existing wireless ISL examples is given in [5]. The majority of the ISL links listed utilize the Ka Band, including the Iridium satellite network at 23 GHz. Some systems use S Band for ISLs, such as TDRS 1 to 6 [6], ETS-6 and ETS-7 [64]. Table 2.2 shows a list of some of the LEO satellites using ISLs and the protocols used [5].

Constellation	ISL Type	ISL Band	ISL Data Rate	Connection Description	ISL Protocol
Iridium	RF	22.55-23.55 GHz	25 Mbps	4 Per satellite	Motorola proprietary
		a series lines	a second and	2 intra-plane	ATM-like switching
12000				2 inter-plane	
Orblink	RF	65-71 GHz	15 Gbps	2 per satellite	Proprietary simple
				2 intra-plane	switching
Telesdesic	RF	69 GHz	155 Mbps	8 per satellite	Teledesic proprietary
Lieberg (25%)	dicaip al fer	a soft for short	legaed by got	Permanent and	ATM-like switching
gaigss? 'nbii				dynamic links	

Table 2.2 List of LEO Satellite using ISLs

Iridium provides an advanced example of ISL application in LEO networks. The job of the ISLs is to provide network traffic routing without the need of many terrestrial gateways. Each Iridium satellite maintains up to four ISL links. Two of them are permanent intra-plane links for satellites located in front and behind of the satellite in the same orbital plane. Inter-plane links are for satellites located in adjacent planes³ - they are dynamically established and terminated as the satellite traverses its orbital path. The horizontal pointing angle between two inter-plane satellites varies over one orbital period. The variation is most rapid over the poles when the orbits cross and slowest over the equator when the orbits are most separated. Steerable antennas are used to maintain the links and are designed to be steerable over 30 to 45 degrees range. The modulation method used on Iridium is not publicly published but is believed to be QPSK. A summary of some the requirements for ISLs are given in Table 2.3.

ISL	TechSat- 21	NMP ST5	SSTL SNAP-1
Power	<15 W	<10W	~400mW
Range	~10km	100-10,000Km	?
Data Rate	0.1-2 Mbps	~1Kbps	9.6 Kbps
Band	Ku-band	S-band	S-band
S/C Mass	~120 Kg Micro	~21.5 Kg Nano	6.5 Kg Nano
Multi-access	Yes	Yes	No
Altitude	700 Km	200-35,000 km	650 km
Protocol	?	Proximity-1	HDLC

 Table 2.3
 Communication requirements for satellites with ISLs

 $^{^{3}}$ The 4 ISLs consist of 2 intra-plane ISLs (1 ISL to each closest fore and aft satellites, and 1 ISL to each 2_{nd} closest fore and aft satellites), and 1 or 2 inter-plane ISLs to satellites in the adjacent left and right orbital planes.

2.3.1 The Benefits of ISL in Distributed Spacecraft Missions

Distributed Spacecraft Missions (DSM) using ISLs can be divided into two main categories: constellation and formation flying missions [11]. DSMs using ISLs have minimal dependence on ground stations for communication purposes. ISLs used in DSMs allow small satellites to share their individual information and their combined resources to have significant advantages over large single-mission satellites [115]. Constellations differ from formation flying missions in the manner in which the members of these distributions interact with each other. These constellation topologies are characterized by groupings of spacecraft in circular or elliptical orbits about a central body. Their positions are routinely maintained by station keeping operations that are governed by navigation information obtained from the ground segment or on-board navigation sensors. Their relative positions are maintained by their nearest neighbors for ISL antenna pointing purposes. On the other hand, spacecraft in formation flying missions exchange their positional information across the ISLs so that feedback based corrections to their locations can be made in order to keep the structure of the formation within the geometrical tolerances specified by the mission objectives. The degree of navigational coupling between members of the formation is determined by the level of precision needed to maintain the spacecraft within the geometrical tolerances specified by the mission objectives. The following are the benefits for ISL in satellite constellations and formation flying missions:

- Knowledge of the where about of member satellites within their orbits is reasonably well constrained.
- Formation Flying and/or clusters- contact with one satellite in the cluster may eliminate multiple, successive uplink contacts for each satellite in cluster.
- Close proximity links will bring low power communications on-board satellites.
- > Uplink and route commands to one, some or all satellites in emergency.
- > Drives need for standard communication protocol stacks.
- > Facilitates interoperability between satellite and ground station
- Reduce implementation and operational cost
- > Point-to-point, multicast and broadcast possible
- Implementation of "Internet in the Sky"[3, 4]

2.3.2 Requirements for ISL in Distributed Spacecraft Missions

An evolutionary space network can be formed from satellites serving as both backbone and user-access nodes connected via high-speed ISLs. Such LEO satellite networks will have to compete with and/or complement terrestrial fixed and mobile networks. Thus, satellite networks should have performance equal or close to that of terrestrial fixed and mobile networks. This allows for a unification and simplification of communications to different missions [5].

The following are some of the requirements and issues related to ISL in DSM to achieve global interconnectivity between satellites in LEO constellations.

- 1. Multiple Access
 - Broadcasting
- 2. Physical layer performance
 - Reliable transfer of information, error free, no duplicates and no added delay.
 - Megahertz data rates, range and power
 - Margins, modulation, coding, Line-of-Sight (LOS) etc.
- 3. Coverage
 - Regional and global
- 4. Latency
 - Minimum propagation and processing delays

2.4 Handover and Routing in LEO Constellations

2.4.1 Handover in LEO Satellite Networks

If we consider a fixed point on the Earth's surface, LEO satellites will appear to rise from below the horizon, move across the sky, and then set below the horizon, in a similar manner to that of the Sun or the Moon. There is at least one satellite above the horizon at all times. To provide a continuous communications service to an end-user, the communications connection to the setting satellite must be transferred to another in-view satellite. The transfer of a connection across satellite coverage areas is referred to as handover. There are two techniques used in handover: Hard and soft handover: the hard handover is similar to a make or break switch and the soft handover is similar to a make and break switch. In soft handover there is no traffic loss but it is more complex and mostly implemented in software while hard handover is less efficient and less complex and can be implemented in hardware [37]. Handover takes place based on a number of criteria:

- Signal strength from the satellite
- Signal to Noise ratio measurement
- Satellite to FES distance
- Latency
- Power budget at the satellite
- Interference

Note that one or more of these metrics stated above can be used to initiate handover and the choice depends on the design and application.

As illustrated in Figure 2.3 the linear motion from spotbeam-1 to spotbeam-2 is assumed and handover must occur between time t_0 and t_1 for efficient data transfer.



Figure 2.3 A simple illustration of handover time between spotbeams

For example, in the Iridium constellation, an end-user is in the coverage area of a satellite for approximately nine minutes. During this period, the spot beam coverage areas move over the end-user, resulting in a number of spot beam handovers, and eventually the satellite sets below the horizon, resulting in a satellite handover. The mobility of an end-user is insignificant to the mobility of the LEO satellite. For example, a satellite in the Iridium constellation has a spot beam diameter of 600 km, and a relative velocity to Earth of 26,804 km/h [38]. To determine typical handover rates, consider a satellite in the Iridium constellation that (for simplicity) manages 49 spot beams arranged in a 7×7 grid, each capable of supporting 80 simultaneous users, with visibility for nine minutes [39]. From a single satellite perspective, 3,920 intra-satellite handovers occur every 77 seconds, which equates to 51 handovers per satellite per second⁴.

Thus, it takes roughly 77 seconds⁵ for the spot beam coverage area to move over the enduser, and prompt a handover. In contrast, communications devices located onboard humans, automobiles, and marine vessels have velocities ranging up to roughly 100 km/h, at which speed it takes six hours to travel the 600 km spot beam diameter required to prompt a handover. Even if the communications device were located onboard an aircraft traveling at 1,200 km/h, it would still take 30 minutes to travel the distance required to prompt a handover. Hence, end-user mobility is insignificant, and satellite handover occurs frequently and predictably as a result of satellite mobility.

Handover in LEO satellite networks can be classified as: 1) intra-satellite handover, which is defined as handover between spot beams managed by a common satellite, and 2) intersatellite handover, which is defined as handover between spot beams managed by neighboring satellites. Since each satellite produces many narrow spot beams as illustrated in Figure 2.4, intra-satellite handover occurs most frequently. However, because the same satellite manages both spot beams, the intra-satellite handover does not have a significant functionality or performance impact on network layer protocols [37] (i.e. end-user information is still routed via the same satellite).





Figure 2.4 Illustration of Intra-Satellite handover between spotbeams of the same satellite

⁽⁴⁹ spot beams × 80 users per spot beam) / (9 minutes / 7 spot beam handovers per visibility period) \approx 51 intra-satellite handovers per satellite per second.

⁽⁹ minutes / 7 spot beam handovers per visibility period) \approx 77 seconds per intra-satellite handover.

Inter-satellite handover occurs relatively less frequently. Considering the iridium system again, inter-satellite handovers occur every nine minutes, which equates to seven handovers per satellite per second⁶. However, because communications must be transferred to a spot beam managed by another satellite, it has a significant impact on the functionality and the performance of network layer protocols. The inter-satellite handover is therefore the most complex in terms of the functionality required to support the handover, and is most critical in terms of the Quality of Service provided during the handover. Thus inter-satellite handover can be further decomposed into intra-orbit and inter-orbit handover. An intra-orbit handover refers to a handover between satellites in the same orbital plane, and an inter-orbit handover refers to a handover between satellites in adjacent orbital planes, as illustrated in Figure 2.5 (a) and Figure 2.5(b)., respectively [39]. There is also a third classification of handover referred to as link handover.



(a) Intra-orbit inter-satellite handover







The need for link handover arises in a connection-oriented network when the network connectivity changes (e.g. when ISLs are turned off near the poles), hence a major motivation and justification for using connection-less oriented protocols. A link handover re-establishes the intermediate connection segment, and transfers communications onto the new segment, in order to provide a continuous communications connection to the end-user.

Uzunalioglu et al [40, 41] proposed algorithms for rerouting connections during handovers in polar constellations. The study is focused on handovers between a ground

⁶ (49 spot beams × 80 users per spot beam) / (9 minutes) \approx 7 inter-satellite handovers per satellite per second.

station and the satellite covering the area in which the station is located as a result of the satellite motion. In [41] a Footprint Handover Rerouting Protocol (FHRP) is proposed, based on the fact that the position of the satellites periodically repeats once a successor satellite takes the position of its predecessor. The proposed routing algorithm uses a shortest path algorithm to establish the initial route for a new call connection. Handovers among the inter-orbital links are addressed in Uzunalioglu [40]. Similar to [41], this paper also assumes a polar constellation whose inter-orbital links are turned off in the Polar Regions and across the seams. Due to the motion of the satellites during their orbits a link contained in a previously established end-to-end path may be turned off as it moves into a polar area resulting in a link handover and the need for a rerouting. The paper presents an algorithm called Probabilistic Routing Protocol (PRP) aimed at minimizing the number of link handovers. The algorithm modifies the initial route selection during the establishment of a new call connection in order to minimize the probability of a link hand-over occurring on a selected link prior to the termination of the call and to the handover of one of the ground-satellite links.

A hierarchical architecture consisting of satellites at different altitudes, and a corresponding routing protocol was proposed by Lee and Kang [42]. The proposed architecture, called Satellite Over Satellite (SOS) Network, which consists of several layers of satellite constellations each at different altitudes at LEO and MEO respectively. The satellites are connected with ISLs both within one layer and to the next higher and lower layer(s). The satellites in the lowest layers are responsible for connecting to the ground stations and for routing data within smaller distances. The satellites in the higher layer(s) are used to route traffic to more distant areas of the earth to reduce the switching delay at the expense of an increased propagation delay.

The IEEE 802.11 standard includes mechanisms to allow a mobile node to roam among multiple Access Points or bridges that can be operating on the same or separate channels. Each AP transmits a beacon signal every T_{beacon} seconds. The beacon includes a time stamp for node synchronization, a traffic indication map, an indication of the supported data rates and other parameters. Roaming mobile nodes use the beacon to gauge the strength of their existing connection to an AP. If the signal strength is judged to be too low, the roaming node can attempt to associate itself to a new AP. The roaming station first performs a scanning function to locate a new AP on the same or a different channel. The mobile node can send probes to a number of APs and receive probe responses from each to select the most suitable AP. Upon finding the strongest signal, the mobile node sends a re-association request to the new AP. The AP will accept and acknowledge the request to complete the handoff procedure. During the

handoff procedure, the exchanging of management packets and the eventual scanning on other channels cause a latency in which the mobile node is unable to receive or send traffic.

Research work on IEEE 802.11 handover has been published [22] mainly focusing on terrestrial WLANs, but none on LEO satellite networks to our knowledge. However, LEO satellites using the IEEE 802.11 standard can use only one AP and one channel, which will be determined before launch, and hence there is no roaming facility. In general, deficiencies will exist using the IEEE 802.11 handover procedure in satellite networks due to increase ISL distances, relative mobility and propagation delays between satellites. However, if there is sufficient link budget and signal quality to let the handoff, the system performance will not be affected by the relative mobility between satellites.

2.4.2 Routing in LEO Satellite Networks

An important factor for the choice of a LEO network topology is the important question of how to route the data in the most efficient way. Many routing techniques have been studied in terrestrial systems; however the characteristics of LEO systems are such that routing has to be revisited. The topology in a LEO system is time varying but it is deterministic and periodic as a result of satellite motion. In LEO systems, deterministic changes can be pre-computed in advance by routing algorithms, although the routing might not be optimal due to unpredictable degradations of the link quality or traffic distribution. On the other hand, terrestrial networks are seldom regular where new nodes are added or removed during mobility with time. In LEO ISL, variable delays can be experienced since adaptive routing should be provided, to find alternative routes according to channel conditions and user requirements (minimizing end-to-end delay). Additionally, adaptive routing provides better reaction to congestion in a network than static routing. In cases of satellite failure, the routing must be able to find alternate routes to take care of data transfer from satellite to satellite.

LEO Satellites networks connected by ISL and employing On-Board-Processing (OBP) can perform signal regeneration, error detection and correction, and routing or switching of the data. In effect, satellites employing ISL, OBP and spot beam techniques can create circuit and packet switched networks in the sky. Performing a networking task in the sky can be very complex due to the orbital plane, high velocities and satellite-to-satellite hand-offs. Generally satellites are limited in processing resources and memory and therefore satellites with OBP

and ISL cannot be realistically considered peer of land-based IP routers, maintaining large routing tables.

The on-board routing can be split into UP-Down link routing and ISL routing. Up link routing involves the process of a ground station selecting the source satellite where to send packets or data. The Downlink routing involves a process where the destination ground station selects the destination satellite from which packets will arrive. After the selections of the source and destination satellite as provided by the up-down routing, ISL routing computes an optimal route or path between these two satellites. Inter-satellite routing protocols will have to rely on sensible aggregation of a well-designed hierarchy of address blocks with minimum routing tables on board satellites. However, in a satellite constellation the topology is dynamic with handover as terminals move between spot beams and satellites, making it difficult to define and use an addressing hierarchy for the satellite nodes. However, interaction between adaptive routing algorithms and regular geometry in LEO networks can provide additional opportunities such as easy implementation. Additionally, the connectivity of a LEO network is known in advance and stable.

A simple study of routing suitability is presented in Wood [32]. The work considers networks with 2, 4, 6 and 8 links per satellite. It studies minimum hop count paths in the network, i.e. it disregards the actual link length and the resulting propagation delay. It calculates hop counts between each pair of nodes, and uses the results to estimate the load on the network links - This work is done for seamless/infinite grids since the calculations become more complex otherwise. The shortest-path routing method for polar constellations taking the propagation delay into account is proposed in Werner [43], [44]. It assumes a fixed network topology. An example is the Iridium system. The method is based on the fact that the position of the satellites periodically changes with period equal to the orbit time. It suggests to discretize the time of one period into fixed-length intervals, and to pre-compute the shortest paths between each pair of satellites for every time interval using Dijkstra's shortest path algorithm [45]. For robustness purposes, it actually suggests to compute several link-disjoint paths for each pair. Due to the constant motion of the satellites, the shortest path routes change between two time intervals. Another source of required changes is the off-periods of satellites over the poles modeled after the Iridium system. In addition to the minimization of the path length, [45] also investigates the minimization of the delay jitter, which is the difference of the path lengths due to the rerouting. The paths are pre-computed off-line and stored in tables listed during the actual connection set-up. While the work of Werner [43] was done for a connection-oriented path set-up, Ekici et al. [46] use a similar approach for connectionless

transmission. They characterize the shortest path in a polar constellation with inter-orbital links turned off in the Polar Regions and across the seams. Each satellite stores the direction of the next routing hop according to the location of the destination satellite. Each packet is routed independently according to the stored tables. In case of a link congestion or failure, they are rerouted through an orthogonal link. Note that the algorithm does not attempt to balance the load to reduce or prevent congestion, which is particularly likely to occur on the inter-orbital links closest to the polar areas that are turned off. The work of Chang et al. [47] studies an adaptive version of the routing algorithm which changes the routes within one time interval.

Although the IEEE 802.11 standard is initially designed for infrastructure-based networks, the distributed coordination function allows mobile nodes to access the radio medium without the need for an AP. Thus, studies in multihop wireless networks, called ad hoc networks, often rely on the use of IEEE 802.11 for the physical and MAC layers. The performance offered by IEEE 802.11 can often be error prone and directly impacts the performance of higher-layer protocols. However, the IP-layer above the MAC layer defined in the IEEE 802.11 protocol is well studied and known to support any type of routing mechanism. Lastly, due to the complexity of LEO networks, an isolated MAC layer may not be the right choice and information from both lower and higher layers may help the MAC layer to efficiently adapt to the routing problem.

2.5 System Architecture

The space segment model used in the thesis consists of multiple satellites in polar (star) orbit, which are interconnected by inter-satellite links allowing long-distance transmission within the space segment. Each satellite covers a circular area on the Earth's surface, in LEO orbit altitude of 686 km with minimum elevation angle, ε_{\min} of 10 degrees. The choice of orbit planes and the satellite phasing within the orbits must guarantee continuous coverage of the service area (being the full surface of the Earth for global systems).

From a networking viewpoint, employing ISLs in the system or not makes a major difference: with ISLs, the system is not longer a pure access network for the first or last hops, but rather provides global backbone facilities at the same time, thus making it an autonomous system. Evidently, satellites in an ISL-based system need to carry a much more sophisticated payload than in a non-ISL system, including ISL terminals, true on-board processing (OBP), and switching or routing functionality. This is illustrated in Figure 2.6.



Figure 2.6 Illustration of a LEO Polar (star) Constellation in STK

2.5.1 Satellite Ground Tracks

With reference to Appendix B, the satellite position can be determined within the orbit in space, but not with respect to the rotating Earth. Hence, ground tracks can be described as locus points formed by satellites on the Earth's surface directly below them, as they travel through their orbits. Figure 2.7 shows typical examples of satellite ground tracks. The point of the track with highest latitude is called the vertex and corresponds to the inclination *i*. Notice that as the altitude increases (semi-major axis) the satellite travels over less ground and the location at the end of one revolution tends to shift west.



Figure 2.7 Satellite ground tracks of different orbit types⁷

⁷ The following orbit parameters are used for geostationary: $\lambda_0 = 13^\circ$, T = TE, inclination i = 0°, geosynchronous: $\lambda_0 = 40^\circ$, T = TE, inclination i = 40°; polar LEO: $\lambda_0 = 0^\circ$, T = 6 000 s, inclination i = 86; and inclined MEO: $\lambda_0 = 0^\circ$, T = TE/4, inclination i = 45°.

2.5.2 Satellite -Earth Coverage

Satellite coverage or footprint can be defined as the area on the Earth's surface where a satellite is seen by the elevation angle, ε greater than a given ε_{\min} as shown in Figure 2.8. The minimum elevation angle ε_{\min} is used to define the coverage area shown in circle. The minimum elevation angle, ε_{\min} affects the choice of number of satellites in a constellation and the number of orbital planes for global coverage of a system. The maximum nadir angle \mathscr{G}_{\max} gives the deflection of the user from the nadir angle as seen from the satellite. The Earth central angle ψ is between the user terminal and the sub-satellite point (SSP) and the slant angle d denotes the distance between the user and the satellite.



Figure 2.8 Satellite Footprint (Coverage Area)

Using the sine and cosine law for the triangles STN and OTS, the Earth central angle and the nadir angle can be given as a function of the elevation angle [34, 35],

$$\psi_{\max} = ar \cos(\frac{R_E}{r} \cos \varepsilon_{\max}) - \varepsilon_{\max}$$
(2.3)
$$\mathcal{G}_{\max} = ar \sin\left(\frac{R_E}{r} \cos \varepsilon_{\max}\right),$$
(2.4)

And the maximum slant range d_{max} can be calculated from

$$d_{\max} = \sqrt{R_E^2} + r^2 - 2R_E r \cos\psi.$$
(2.5)

For non-geostationary satellites these parameters will vary with time since the satellite are moving with respect to Earth. As can be seen from Figure 2.9 the coverage area increases with the satellite altitude and the minimum elevation angle. Examples of coverage area of satellites in different orbital altitudes are shown in Figure 2.9 for minimum elevation angles.



Figure 2.9 Coverage area of satellite of different orbit types

2.6 Summary

In this chapter, an overview of LEO satellite constellation is discussed and in particular the difference between star and delta networks interconnected by ISLs is explained. Because of the limited geometric coverage of single LEO satellite the communication interval between LEO and terrestrial ground stations is very short; the need for many satellites to provide global coverage including multiple LEO satellites connected by ISLs is discussed. In this respect, we first examined satellite network design in general and LEO networks in particular and discussed how this differs from terrestrial wireless networks. Secondly, the choice of using ISL in LEO networks with the needs and requirements for ISL communication is outlined in order to complement terrestrial networks.

The concept of LEO satellite handover and routing is examined in detail. The causes of handover due to satellite movement, user mobility, and the QoS requirements are briefly explained. In LEO systems using ISL, variable delays can be experienced, hence the need for adaptive routing to find alternative routes according to channel conditions and user requirements (minimizing end-to-end delay). ISL communication based on IEEE 802.11 should consider schemes that try to make handoff procedure more reliable in the future. The dynamics of LEO networks will affect the performance of IEEE 802.11, which would affect applications based on TCP, because of the high packet loss and jitter. Hence, new transmission algorithms based on TCP protocol should be investigated and optimized for use with IEEE 802.11 for ISL applications.

The characteristic of LEO satellite constellations is also presented. Types of LEO satellite constellations (e.g. Iridium) are briefly examined with the star constellation used as the reference constellation in the discussions and examples presented in this thesis. The reason for choosing the star constellation is due to the fact that ISL length variation is minimal compared to the delta constellation.

In conclusion, it is shown that it is necessary to understand the three types of links between satellites: Intra-orbit plane ISL, which can be treated as fixed links in the topology; Inter-plane ISL and cross-seam ISL, which connect satellites in adjacent, co-rotating planes are variable for a number of reasons. Firstly, the inter-satellite links between planes changes as a function of latitude. Secondly, phasing may not be maintained between planes, causing the satellites in different planes to slowly drift with respect to each other. In order to establish steady and efficient inter-satellite links it is necessary to calculate both the exact static geometric and dynamic parameters of the ISL. The challenges are not limited to the above-mentioned only; there are still quite a number of problems that are open such as effective ISL routing and handover, rate and power management, mobility management, and of principal interest to this thesis, physical and MAC optimization issues.

Chapter 3. The Effect of Variation in Satellite Relative Velocity on Communication Parameters

In this chapter, we propose basic models to investigate the effect of orbit dynamics on communication parameters in polar LEO satellite networks. Due to the movement of LEO satellites along orbits, communication devices cannot be optimized for static geometric parameters only, otherwise the performance of ISL communication between satellites will degrade with time. In LEO constellations, because of the continuously changing position of the LEO satellite, geometric parameters of the ISL vary a lot. In order to describe the dynamic properties of ISL, we should investigate these dynamic parameters: the variation of azimuth angle with time, the variation of elevation with time and the variation of ISL distance with time. Section 3.1 introduces the effect of LEO orbit dynamics on ISLs. Section 3.2 presents the satellite system model used in this thesis. Section 3.3 describes the geometry of ISLs in LEO networks and effect of angular variation on communication parameters. Section 3.4 describes new analytical models showing the effects of the off-orbit viewing angle between two connected satellites on antenna requirements. Section 3.5 describes the effect of the Earth oblateness on ISL length. Section 3.6 discusses the effect of ISL patterns on delay and delay variations. Section 3.7 describes the delay performance of multiple satellites connected by ISLs using the M/M/1 model.

3.1 Introduction to Effects of LEO Dynamics on Inter-Satellite Links

As mentioned in section 2.2, one advantage of polar (star) constellations is the tracking requirements between two inter-orbit neighboring satellites tend to be somewhat periodic and predictable, and not too extreme over time. However, there exist rapid changes of latitude between satellites at the Polar Regions. The distance and pointing angle variation between satellites in co-rotating planes is fairly low, but it is extreme over the poles and across the seam (between counter-rotating planes). As a consequence, Iridium as a current reference system for an ISL-based star constellation switches off ISLs over polar regions and has not implemented cross-seam links at all [10, 38]. The assumption in this thesis is that all of the polar

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Chapter 3 The Effect of Variation in Satellite Relative Velocity on Communication Parameters

orbits use the same inclination relative to the earth's axis of rotation. Our models address two factors of LEO network the modeling of link lengths and the selection of inter-satellite links. It studies the impact of various parameters such as inclination, J_2 , the number of satellites and orbits, and interconnection pattern between satellites on the communication parameters. Since the inclination and the number of satellites and orbits are most likely determined by the desired coverage, the main focus is on the interconnection between satellites and the effect it has on communication parameters. It is shown how delay, Doppler shift and rate of change of Doppler frequency vary when interconnecting different pairs of satellites.

Our study of the impact of ISL connections on communication parameters starts with a general satellite geometry in sections 3.2 and 3.3.

3.2 Satellite Model

As described in sections 2.2 and 2.3 two main types of circular orbit satellite constellations have been proposed, depending on the orbits they use: star (polar or near-polar) or delta (inclined). In this thesis we concentrate only on the star constellation. Assuming that the satellite network resides in *P* polar orbital planes then the planes will be separated by an angle 0° of $180^{\circ}/P$.



Figure 3.1 A LEO Polar Constellation showing angular variation between satellites in different orbit planes

If there are *N* satellites per plane then the satellite constellation will be classified as Star (Walker) constellation type with parameters $N / P/0^{\circ}$. Each satellite has four neighboring satellites; two in the same orbital plane (intra-satellite links) and two in different orbital planes (inter-satellite links). Polar (star) constellations include a seam, an interface where satellites on two adjacent orbits are traveling in opposite directions as shown in Figure 3.1.

3.3 Geometry of Inter-Satellite Links

To derive the formulae of the length of ISLs, we will consider a coordinate system centered at the centre of the Earth whose *xy*-plane coincides with the equatorial plane. Note that all the orbital planes intersect at the centre of the Earth. To simplify the formulae, the latitude and longitude will refer to the fixed sphere associated with the coordinate system, not to a rotating Earth, with 0° longitude in the direction of the x-axis.

If we consider two satellites S_{11} and S_{12} at equal altitude *h* over the Earth's surface as illustrated in Figure 3.2. Let R_E be the radius of the Earth, and let α be the angle between S_{11} , S_{12} and the centre of the Earth at a time instant *t*. Then the length of a straight link, line of sight (LOS) between S_{11} and S_{12} at time t is

$$L_{Intra} = 2(R_E + h) \sin \frac{\alpha_t}{2} = \sqrt{2}(R_E + h) \sqrt{1 - \cos \alpha_t}.$$
(3.1)

The angle, α , between satellites in the same plane is given as $360^{\circ}/N$. There is a minimal variation between satellites in the same orbital plane, which indicates constant signal propagation and Doppler shift⁸ with constant azimuth and elevation angles requiring fixed antennas as shown in Figures 3.3 and 3.4



Figure 3.2 LEO ISL Satellite Model

⁸ Doppler frequency shift is a function of node mobility with a positive value when node moving away from each other and a negative when node are moving towards each other.

Chapter 3 The Effect of Variation in Satellite Relative Velocity on Communication Parameters

The inter-satellite link model has been simulated with the Satellite Tool Kit (STK) [48] using the parameters of the Disaster Monitoring Constellation [49] developed by the Surrey Satellite Technology Ltd, which are presented in Table 3.1

Parameters	Value
Altitude	685 km
Planes	11
Orbit inclination (deg)	98.14
Satellites per plane	8
Inter-orbit separation (deg)	10
Max. ISL per satellite	4









Figure 3.4 Intra-orbit plane variation with propagation loss and frequency Doppler shift

The intra-orbit satellite links are maintained at all times and ISLs to the rest of the satellites in the network are established through the adjacent satellites in the same plane. In contrast, for the case of satellites in different orbital planes shown in Figure 3.5, the range varies from 340 to 2000 km as the satellites move from poles to the equator. As a result, there are variable propagation delays and smart agile antennas are required to track satellites in orbit. The ISL length L_{inter} is variable and is given by

$$L_{\text{int}\,er} = \sqrt{2} \left(R + h \right) \sqrt{1 - \cos\beta t} \cdot \cos(\sigma_o) \tag{3.2}$$

where β is the angle between satellites in different orbital planes and σ_o is the argument of latitude in which ISL lies.



Figure 3.5 Inter-orbit plane variations with AZ and EL angles

Figure 3.6 and Figure 3.7 compares the attenuation and Doppler shift characteristics of the ISM band frequencies of 2.4 GHz and 5.5 GHz. Figure 3.6 show that the transmit frequency of 2.4 GHz has better attenuation characteristics of more than 10 dBs than 5.5 GHz when used between satellites in different orbit planes. The frequency Doppler shift increases rapidly as the satellites move towards the poles (minimum range) due to rapidly changing ISL length, as shown in Figure 3.7. There is a frequency variation of 10 KHz and 30 KHz as the satellites move towards the poles from the equator and a further variation of 10 KHz and 30 KHz as the

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satellites move away from the poles again using the ISM band transmit frequencies of 2.4 and 5 GHz respectively. The results show that Doppler shift is directly proportional to the transmit frequency. Hence, the 2.4 GHz in the ISM band is used throughout the rest of this thesis. Transmit and receive frequencies must be synchronized using smart agile antennas during frequency Doppler shift.





Figure 3.6 Inter-orbit plane range variation with propagation loss and frequency Doppler shift

Figure 3.7 Inter-orbit plane range variation with propagation loss and frequency Doppler shift

In Figure 3.8, the variation of Doppler shift and angular variation are simulated as a function of the argument of latitude between satellites in inter-orbit planes. The results show that the antennas slew rates must satisfy the angular rate especially at high latitude in order to maintain connectivity.







On the other hand, in cross-seam ISL the satellites are moving at very high velocities past each other. This has a high impact on azimuth angle, as shown in Figure 3.9. Visibility duration (Coverage)⁹ between counter rotating satellites lasts for only 14 minutes. This short visibility duration requires fast handover algorithms to transfer traffic and brings in the need for deployment of smart antennas using narrower beams to maintain the crosslink.



Figure 3.9 Cross-seam range variation with AZ and EL angles

The result in Figure 3.10 shows that the transmit frequency of 2.4 GHz has better attenuation characteristics than 5.5 GHz when used between satellites in cross seam. The relative velocity between the satellites increases as they approach the same latitude causing a rapid change in the Doppler frequency of 100 KHz and 200 KHz as the satellites approach

⁹ Coverage and visibility are used inter-changeably

and a further 100 kHz and 200 KHz as they recede again, for transmit frequencies of 2.4 GHz and 5 GHz respectively, is shown in Figure 3.11.



Figure 3.10 Cross-seam variations with propagation loss and frequency Doppler shift



Figure 3.11 Cross-seam variations with propagation loss and frequency Doppler shift

The antenna beam angular variation, antenna pointing precision, transmission power control and Doppler shift are all factors that affect the RF cross-link implementation. The limitations of current antenna technology make it very difficult to implement and maintain ISL communications between satellites in cross-seam [10].

3.4 The Effect of Angular Variation on ISL Length

To investigate the effect of orbit dynamics on ISL and in order to define a set of antenna requirements, we consider the model shown in Figure 3.12, where $\beta(t)$ represents the offorbit viewing angle of one satellite from the other in different orbit planes. Let $\rho(t)$ denote the difference in latitude of two satellites between which there is an inter-satellite link, found by differencing the arguments of latitude, σ_o of the two satellites, $\rho = \sigma_2 - \sigma_1$. Using spherical trigonometry, the longitudinal separation of the orbits, η can be expressed as $\cos\eta = \sin^2\sigma_2 + \cos^2\sigma_2\cos\varphi^{10}$ (3.3)

where φ is the angle between orbital planes, and therefore

 $\sin\eta\eta = \sin 2\sigma_2 \sigma_2 (\cos\varphi - 1)$



Figure 3.12 Model of angular variation with ISL range

We note that σ_2 is simply the angular velocity of the satellite around the orbit, which is always equal to the mean motion in the circular orbit case. From spherical analysis the longitudinal separation of the orbits is given as

 $\sin \eta = \sin \varphi \cos \sigma_2$

We then find the partial derivative with respect to time

$$\dot{\eta} = \frac{2\sin\sigma_2(\cos\varphi - 1)\dot{\sigma_2}}{\sin\varphi}$$
(3.6)

¹⁰ If
$$\aleph = \frac{\pi}{2} - \sigma_2$$
 then $\cos \aleph = \cos \frac{\pi}{2} \cos \sigma_2 + \sin \frac{\pi}{2} \sin \sigma_2$, therefore $\cos \aleph = \sin \sigma_2$

(3.5)

(3.4)

The latitude difference ρ and the angle between the orbital planes φ will normally be known for satellites in a LEO constellation and will be dependent on N and P. The off-orbit viewing angle β is given by

$$\tan \beta = \frac{\tan \eta}{\sin \rho}$$

and therefore

$$\sec^{2} \beta \dot{\beta} = \frac{\sin \rho \sec^{2} \eta \eta + \tan \eta \cos \rho \dot{\rho}}{\sin^{2} \rho}$$
(3.8)

If we assume a spherical Earth and circular orbits such that $\dot{\rho}=0$ and if we substitute (3.6) and (3.7) in (3.8), we can then obtain an expression for $\dot{\beta}$ in terms of known quantities as below:

$$\dot{\beta} = \frac{2(1 + \tan^2 \beta \sin^2 \rho) \sin \sigma_2(\cos \varphi - 1) \dot{\sigma_2}}{\sin \varphi \sin \rho (1 + \tan^2 \beta)}$$
(3.9)

where

$$\tan \beta = \frac{\sin \varphi \cos \sigma_2}{\sin \rho \left(\sin^2 \sigma_2 + \cos^2 \sigma_2 \cos \varphi \right)}$$
(3.10)

The variation of β and β with the argument of latitude of the leading satellite is shown in Figure 3.13 for the example constellation with 11 orbital planes and 8 satellites per plane detailed in Table 3.1.. The argument of latitude is a measure of the orbital phase, which takes the value of 0 at the initial ascending node and grows continuously over successive orbits.

Figure 3.13, therefore, shows two orbital periods, where β is the antenna slew rate¹¹.

(3.7)

¹¹ The antenna slew rate, typically measured in degress per second or radians per second is the angular velocity of the antennas between satellites in different orbit planes. The ratio of the minimum and maximum slew rates is an indication of the variation in required speed. Very high speeds may be difficult to achieve.





Figure 3.13 Variation of β and β as a function of the argument of latitude of the leading satellite

As can be seen from Figure 3.13 the slew rate is maximal at the poles with argument of latitude values of 90, 270, 450 and 630 degrees and minimal at the equator with argument of latitude values of 180, 360, 540 and 720 degrees. From (3.7), we see that the maximum value of β , β_{max} occurs when η takes its maximum value η_{max} . From (3.5), the maximum value of $\sin \eta$ and hence η_{max} occurs when $\cos \sigma_2 = 1$, that is when $\sigma_2 = 0$ and therefore $\eta = \varphi$ at β_{max} . From (3.7), this gives us

$$\beta_{\max} = \tan^{-1} \left(\frac{\tan \varphi}{\sin \rho} \right), \tag{3.11}$$

where $\varphi = \frac{180^\circ}{P}$ and $\rho = \frac{180^\circ}{N}$.

Figure 3.14 gives the dependence of β_{max} on the number of orbital planes (based on 8 satellites per plane). It can be seen that β_{max} decreases exponentially as the number of planes increases. As the maximal off-orbit viewing angle decreases with increasing the number of orbital planes, the required maximal antenna slew rate decreases too. However, increasing the number of planes means more satellites and an increase in cost of the system and therefore the number of satellites is likely to be determined by the desired coverage and by economics.

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Figure 3.14 Variation of maximum beta with the number of orbit planes

3.5 The Effect of J_2 on ISL Length

The Earth oblations cause perturbations on the motion of a satellite in a nominally circular orbit. These perturbations affect several orbital elements; however it is the effect on the argument of latitude that we are interested in here. This effect is seen as a periodic variation on top of the uniform motion of a satellite around its orbit. If this periodic term is not in phase for all the satellites in an orbit then the distance between the satellites, and hence the length of the ISL, will vary periodically. The cost of the differential J_2 on communication parameters such as variable propagation delay must be properly investigated and taken into account for future ISL communication protocol design. Here we present a method for finding spacecraft initial conditions that minimize the ISL drift resulting from J_2 disturbance. The expected ISL drift due to differential J_2 effects¹² as the mean latitude difference between two connected satellites increases is investigated.

Using the epicycle orbit model derived in [50], and assuming a non-eccentric orbit, we have an expression for the argument of latitude, σ_o under the influence of the J_2 perturbation:

$$\sigma_o = \varsigma (1+\kappa) - \frac{1}{8} J_2 \left(\frac{R_E}{a}\right)^2 (6-7\sin^2 I_0) \sin 2\varsigma$$

(3.12)

¹² The effect of J_2 is very minimal above altitudes of 1000 km.

Where ς is the epicycle phase, κ is a secular correction to the mean motion to account for the effect of J_2 , R_E is the Earth's radius and a and I_0 - the orbital semi-major axis and inclination, respectively. The epicycle phase ς is given by

$$\varsigma = n(t - t_e) \tag{3.13}$$

where n is the satellite mean motion, t - the time variable and t_e - the time of equator crossing. The mean motion is given by

$$n^2 a^3 = \Theta_g \tag{3.13}$$

where Θ_g is the gravitational parameter, $\Theta_g = 3.986004415 \times 10^5 \text{ km}^3 \text{s}^{-2}$. The secular correction to the mean motion is given by:

$$\kappa = \frac{3}{4} J_2 \left(\frac{R_E}{a}\right)^2 \left(4 - 5\sin^2 I_0\right)$$
(3.14)

To find the latitude difference between two satellites, ρ we subtract the σ values of the satellites. Assuming that the satellites have the same semi-major axis and inclination this gives:

$$\rho = n(1+k)(t_{e1} - t_{e2}) - \frac{1}{8}J_2\left(\frac{R}{a}\right)^2 (6 - 7\sin^2 I_0)(\sin 2\varsigma_2 - \sin 2\varsigma_1)$$
(3.15)

The first term in (3.15) represents the mean separation of the satellites and the second term the periodic variation. Figure 3.15(a) and Figure 3.15(b) show the ISL length between two satellites in polar orbit with a mean angular separation of 10° and 45°, respectively. The values for R_E and J_2 used in Figure 3.13 are $R_E = 6378.1363$ km and $J_2 = 0.0010826269$.

We can conclude from Figure 3.15 that the effect of J_2 on ISL lengths and ISL length variations increases as the mean angular separation between the orbital planes increases. In our models, the phase between the orbital planes is limited by 10 km separations, in order to have minimum effect of J_2 on ISL length.





Figure 3.15 The effect of J2 on the ISL Length

3.6 The Effect of the Choice of ISL Pattern on Delay

It is important to consider delay and delay variations for quality of service in real time, voice and video communications, as they cause distortion in the received signal. The propagation delays for ISLs vary according to the type of link. Intra-orbit ISLs experience constant propagation delays while inter-orbit ISL delay varies at different latitudes. In order to derive the distance and the ISL propagation delay between two spacecraft in different orbital planes we consider the propagation delay δ_{prop} of a radio signal traveling from the one satellite to the other:

$$\delta_{\text{prop}} = \frac{ISL_{\text{distance}}}{C} + \delta_{\text{iono}} + \delta_{\text{trop}} + \delta_{\text{multipath}} + \delta_{\text{thermal}}$$
(3.16)

where $ISL_{distance}$ is the distance between the two spacecraft, C - the speed of light, δ_{iono} - the ionospheric delay, δ_{trop} - the tropospheric delay, $\delta_{multipath}$ - the multipath error delay and $\delta_{thermal}$ - the thermal error delay.

An ISL pattern is the selected interconnection scheme between two spacecraft that use ISL. The choice of ISL pattern has a significant effect on the delay and the off-orbit viewing angle, β .

The STK is used to simulate the choice of ISL pattern on the delay and the angular rate between two connected satellites in different orbital planes. The STK J4 propagator used in these scenarios accounts for 1^{st} and 2^{nd} order J_2 effects as well as 1^{st} order J_4 effects which includes other effects given in (3.16). In order to obtain the network topology we have to take into account the seam and the relative positions of the satellites when crossing the poles. We have considered two possible patterns that can be obtained by using inter-orbit crosslink between Sat P and Sat Q in adjacent orbits as illustrated in Figure 3.16. The ISL pattern A, shown in Figure 3.16 (a), comprises diagonal ISLs with a non-zero off-orbit viewing angle between orbital planes permitting both intra-orbit and inter-orbit routes for data transfer. The ISL pattern illustrated in Figure 3.16(b) has a zero phasing (the same latitude) between satellites in different orbital planes and permits links in both intra-orbit and inter-orbit routes for data transfer. The variation in inter-orbital link length in pattern B as the satellites move towards the poles from the equator is mainly responsible for the ISL and delay variations. For the purpose of delay variation analysis, the initial ISL length between Sat P and Sat Q for both patterns in Figure 3.16 is made to be equal at the equator. In order to ensure that this initial ISL length is the same for both ISL patterns the mean angular separation between orbital planes, φ must be

(3.17)

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SEAM SEAM

where α is the angle between satellites in the same orbital plane given as $360^{\circ}/N$.

Figure 3.16 a) Diagonal ISL pattern A b) Zero phasing ISL pattern B

Pattern A exhibits a higher delay (max of 12 ms) but has a lower delay variation from 8 ms to 12 ms as shown in Figure 3.17. The main reason for this high delay is the non-zero phasing between two connected satellites in different orbital planes.



Figure 3.17 Angular rate and delay variation with ISL length for crosslink pattern A

The results given in Figure 3.18 show that pattern B yields a lower delay (max of 9 ms) but with higher delay variation from 2 ms to 9.4 ms. The delay variation is due to ISL length variation in the longitudinal direction as the satellites move around their respective orbits from
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the equator to the poles, which creates a surge in angular velocity. The angular rate is almost constant near the equator but experiences a surge of about 0.4 deg/sec near the poles.



Figure 3.18 Angular rate and delay variation with ISL length for crosslink pattern B

In conclusion, the comparison of ISL patterns A and B shows that a minimum delay variation is achieved when the phase of two connected satellites differ. However, lower delays are experienced when two connected satellites are at the same latitude.

3.7 Delay Performance Analysis of ISL Networks

Although multi-hopping could significantly save the transmission power, it is obvious it costs more time to reach the destination from the source node. Time-delay is especially important in applications which need to meet hard real-time requirements, e.g. real-time formation-flying control. Typically for such wireless real-time control, the total latency including sensing, communication, computation, and actuation is expected to be no more than 10ms. Shorter time-delay is always expected for real-time control, but it is not recommended considering the delays in communication and its associated signal processing.

To calculate the time delay required by signal transmissions over the optimised route, the average end-to-end time delay T is defined. As an example let the message takes the route $A \rightarrow B$ in Fig. 3.19. We assume that the input to satellite 2 has an exponential arrival time with the average rate of the message flow λ and the lengths of the messages are variable, so that the transmission time is exponentially distributed with a mean length of $1/\mu$. Since the output of satellite 1 is the input for satellite 2, the transmission time for the message at satellite 2 will also be exponential with the same mean $1/\mu$. Hence, knowledge of the inter-arrival time at

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satellite 2 will provide a complete picture of its traffic activity. Again since the output of satellite 1 is the input for satellite 2, if the inter-departure time distribution for satellite 1 is known, then we also have the inter-arrival time distribution for satellite 2. This is known as an M/M/1 queuing network as illustrated in Figure 3.19. Hence the transmission delay *T* can be obtained by

$$T = T_{Access} + T_{Uplink} + \sum_{i=1}^{N-1} T_{isl\,i} + \sum_{j=1}^{N-1} T_{sat} + T_{Downlink} , \qquad (3.18)$$

Where T_{ACCESS} is the delay associated with the multiple access technique used by the ground station to access the first satellite (source), and it can be Code Division Multiple Access; T_{Uplink} and $T_{Downlink}$ are the up and down link delays; N is the number of satellites, including the source and destination nodes, on the route to multi-hop the signal; T_{isl} is the propagation delay between two satellites with a direct inter-satellite link and T_{sat} is defined as the mean response time for the whole network consisting of a tandem of M/M/1 queues of satellites.



Figure 3.19 The ISL network model using the M/M/1 queue network with flow control at data link layer

The T_{UPLINK} and $T_{DOWNLINK}$ can be calculated thus:

 $T_{Uplink \, / \, Downlink} = \frac{Satellite \, Altitude}{c}$

(3.19)

 T_{isl} can be obtained by

$$T_{lsl} = \frac{L_{lsl}}{c}, \qquad (3.20)$$

where L_{isl} is the inter-satellite link length; and c is the speed of light. The propagation delays for the ISLs T_{ISL} vary according to the type of link. The intra-satellite links where satellites are in the same plane are constant while the inter-satellite link length varies at different latitudes. Using an average distance of 5405 km between satellites where 8 satellites are in the same plane at an altitude of 648 Km will give an average T_{ISL} of

$$\frac{L_{lsl}}{c} = \frac{5405km}{3 \times 10^8} = 18ms$$

If the traffic has to be routed through 5 satellites from source to destination then the T_{ISL} will be (N-1). $T_{ISL} = (5-1) \times 18 \text{ms} = 72 \text{ms}.$

To calculate T_{sut} the M/M/1 model is taken into consideration. M/M/1 refers to negative exponential arrivals and service times with a single node. It depends on the amount of buffers, queuing discipline, severs and the packet arrival rate. If we denote by λ_i the traffic carried on one satellite and by C_i the capacity of the satellite, we can yield many performance metrics. T_i = Mean response time E[r] spent in one satellite node is given as

$$E[r] = \frac{1}{\mu C_i - \lambda_i} \operatorname{or} \frac{\left(\frac{1}{\mu C_i}\right)}{(1 - \rho_u)}$$
(3.21)

Where $\rho_u = \lambda_i / \mu C_i$ is called the system utilization. Figure 3.20a & 3.20b show the mean number of packets E [Nq] in queue and mean response time E[r] in system as a function of the utilization factor. In Figures 3.20, as the rate increases, the utilization approaches 1 and the queue size in the system and response time (delay) approach infinity. This infinite response

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time is the key reason why queuing systems are not expected to run close to capacity. For an M/M/1 queuing system to be stable, the traffic intensity must be less than 1.



(a)



Figure 3.20 a) M/M/1 Stability b) M/M/1 Response Time

First we define the total (external) traffic carried by the network from source satellite j, to the final destination satellite k, where γ is the throughput of the network at the final destination, k, as below

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$$\gamma = \sum_{j,k=1}^{N} \gamma_{jk} , \qquad (3.22)$$

Then it can be shown that the average rate of message flow, λ_i on the satellites must be equal to the sum of the average message flow of all paths (γ_{jk}) that traverse this satellite, that is

$$\lambda_i = \sum_j \sum_k \gamma_{jk} , \qquad (3.23)$$

and the total internal network traffic by the satellites as

$$\lambda = \sum_{i=1}^{M} \lambda_i \,. \tag{3.24}$$

Let $\overline{M_L}$ be the average number of ISL hops that a message must take in its journey through the network (averaged over all origin-destination pairs), then it can be shown that the following is true

$$\bar{M_L} = \frac{\lambda}{\gamma}.$$
(3.25)

It can be shown that after applications of Little's results [29] that T_{sat} can be obtained by

$$T_{sat} = \sum_{i=1}^{M_i} \frac{\lambda_i}{\gamma} T_i \,. \tag{3.26}$$

If we substitute equation (3.21) into (3.26) we end up with an explicit and simple expression for the mean message delay T_{sat} as follows:

$$Tsat = \sum_{i=1}^{M_i} \frac{\lambda_i}{\gamma} \left(\frac{1}{\mu C_i - \lambda_i} \right).$$
(3.27)

Equation (3.27) is very important in performance analysis but it ignores certain realities such as the nodal processing delay (K) and the propagation time (P_i) within the satellite. The

assumption is that only messages are travelling through the network while a certain amount of control traffic should also be included. The message delay in an M/M/1 queuing system consists of two quantities, namely the service time and the waiting time on queue. The service time depends on the average length of the true data traffic and the QoS demands, while the waiting time depends on the interference of all other traffic from other satellites in the network and is composed partly of data and control traffic. If we denote by $\frac{1}{\mu}$ the average

length of data packets and by $\frac{1}{\mu'}$ the average length of all other packets then we can derive a more accurate representation of T_i as follows

$$T_i = \frac{\frac{\lambda_i}{\mu' C_i}}{\mu' C_i - \lambda_i} + \frac{1}{\mu C_i}.$$
(3.28)

And if we account for K and P_i then we obtain an expression for average message delay in the satellite nodes as below

$$Tsat = \sum_{i=1}^{M} \frac{\lambda_i}{\gamma} \left[\frac{\frac{\lambda_i}{\mu' C_i}}{\mu' C_i - \lambda_i} + \frac{1}{\mu C_i} + P_i + K \right].$$
(3.29)

From the analysis of the above time delay model, the time delay of a signal routing is decided by the total length of the inter-satellite links and the number of nodes in the route.

3.7.1 Control Issues

One of the most important considerations where many nodes share a medium in a communications network is the control. It is a necessity to impose control procedures on networks for a number of reasons, in a number of places with a variety of mechanisms. The three major forms of control in satellite constellations are routing control, flow control and handover control.

3.7.1.1 Routing Control

The routing control algorithm is simply a decision rule that determines the next path to be taken by a packet as it travels from satellite to satellite. The routing control takes place at the network layer (layer 3) of the OSI model. Routing techniques have been extensively studied for terrestrial networks, but satellite constellations are not similar and their geometry has a significant impact on the routing performance. In trying to find an analytical solution to routing control problem, an adaptive routing algorithm will be the assumption, which makes use of real-time information about the network. In particular, it selects which paths a flow should follow based on a shortest path calculation which locates the global minimum (network delays due to topology, flow control, etc). The problem global minimum can be solved by finding a method to solve the local minimum (delays due to processing, queueing, etc within a node). Assume that the network in Figure 3.19 where each channel is labeled with some length. The length of a link is used as the shortest path calculation, and it is the incremental increase in network delay T_{sat} as the amount of flow is increased on the link. If we examine T_{sat} in Equation (3.27). We can noticed that this performance measure can be measured as separable in the sense that it may be expressed simply as sum of terms, each of which depends only on the flow in the single channel. Furthermore, we can observe from Equation 3.27, that the length, l_i of the *ith* satellite channel, given that it is carrying an

amount of flow equal to $\frac{\lambda_i}{\mu}$ is simply given as [121, 122].

$$l_{i} \geq \frac{\partial T}{\partial \left(\frac{\lambda_{i}}{\mu}\right)} = \frac{C_{i}}{\gamma \left(C_{i} - \frac{\lambda_{i}}{\mu}\right)^{2}}$$
(3.30)

The shortest path length calculation uses these minimum channel lengths, and the resulting paths represent the minimum delay paths to which some of the current flow can be deviated.

3.7.1.2 The Flow Control

Whenever two information processing systems exchange data, carefully designed control procedures are necessary to ensure safe and correct transfer of the information [122]. The routing control procedures are used to direct packets that have been already accepted by the

satellite, but the flow control deals with the admission of the packets into the satellite node. Networks cannot afford to accept any traffic that is thrown at them without any control, or else there will be congestion and the whole network will lock up. Flow control algorithms are the rules that govern the acceptance of traffic from outside. There are two types of flow control: Local flow control and global flow control. The local flow control is a direct consequence of the limited buffer space in each satellite node, while the global flow control is the limitation of packets that can be handled by the network simultaneously without congestion. The main performance metrics for any communication network are throughput, response time and packet loss probability. One would like to maximize the first and minimize the last two quantities. If we denote that T is the response time of the network, γ is the throughput of the network and let λ be the offered input traffic rate to the network and the maximum capacity of the network as γ_o . As shown in Figure 3.21 some of the offered traffic will be lost due to the flow control scheme given by $\lambda - \gamma$.



Figure 3.21 Flow Control in Satellite Network

The flow control function $\gamma(\lambda)$, which is an indication of how much traffic γ , is carried by the network when offered of input traffic an amount λ . In an ideal situation where maximum throughput is required then $\gamma = \lambda$ and there would be no loss, but this is impossible since the network has a maximum capacity γ_o . Below the input rate of γ_o , we have no loss but above we have minimum loss of $\lambda - \gamma$. The trade-off between maximum throughput and minimum delay cannot be achieved simultaneously, so an operating point must be considered for the system. A quantity known as the 'power' (P) has been studied [122] which combines these two performance variables into a single measure as follows:

$$P = \frac{\gamma(\lambda)}{T(\gamma(\lambda))}$$
(3.31)

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Where *P* is defined as throughput divided by delay.

The aim is to find the optimum value of λ which maximizes *P*. It is shown in [121, 122] that the optimum power occurs when the input is such that the derivative of the response time with respect to the throughput is exactly equal to the value of the response time divided by the throughput, as follows:

$$T(\gamma(\lambda))/\gamma(\lambda) = dT(\gamma(\lambda))/d\gamma(\lambda)$$
(3.32)

If we apply this principle of maximum power to the M/M/1 queuing system in Figure 3.17, we find that the optimum operating point is at $\rho_u = 1/2$, hence $\gamma_{opt} = \gamma_o/2$. At this point the response time is twice its minimum, the throughput is half its maximum and the average number of packets in the system is 1(N = 1).

3.7.1.3 Delay Analysis for IEEE 802.11 Wireless in Satellite Networks

We model a multi-hop IEEE 802.11 network as a graph G = (Q, L), where Q is the set of satellite nodes and L denotes the set of ISL links. Each element of L is denoted by (s, z), which consist of the source satellite, s and the destination satellite, z. $\lambda(s, z)$ (pts/s) is the average traffic over (s, z). The performance metrics of interest are ISL traffic rate and the packet loss rate, P_{loss} and their relationship with service delay. The capacity of (s, z) is inversely proportional to the average service time, T_{service}(s, z), which is the average delay taken by the source, s to transmit a data packet to the destination, z correctly (or eventually discard the data). The traffic rate on each link is constrained by its capacity given as

$$\lambda(s,d) \leq \frac{1}{T_{service(s,d)}}$$
(3.33)

Hence the key is to solve $T_{service}$ and P_{loss} of the wireless link.

Using the Finite State Machine (FSM) in Figure 3.22 the behaviors of IEEE 802.11 can be described within a satellite node to have m DATA and n RTS re-transmission due to collision. To simplify the analysis, we ignore the failure of CTS and ACK frames and set n =

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m. The dashed lines in Figure 3.22 denote the transition probability and the delay that occurs when switching between states.



Figure 3.22 The simplified FSM of the IEEE 802.11

As shown in Figure 3.22, $T_{service}(s, z)$ is the expectation of the delay that occurred when transmitting from state "START" to "RECV" or "DROP". The packet loss probability $P_{loss}(s, z)$ is the probability of transferring from state "START" to "DROP", i.e., the probability that the source fails *n* times of transmission for one data. In each failed transmission, either the transmission of RTS frame fails or RTS succeeds but the data frame collides. Thus the packet loss rate, P_{loss} can be calculated as follows:

$$P_{Loss} = \prod_{k=1}^{n} \left[P_{RTS}(k) + (1 - P_{RTS}(k)) . P_{DATA}(k) \right],$$
(3.34)

Where $P_{RTS}(k)$ and $P_{DATA}(k)$ are the probabilities that the k^{th} attempt of RTS and DATA frame transmission fails.

If we consider Figure 3.22 again, we can also find that the average service time for delivering a data packet is the expectation of the average delay in all the possible transmission attempts (up to n times), which can be shown as follows.

$$T_{Service} = \sum_{i=1}^{n} P_{fail}(i-1)(1-P_{RTS}(i))(1-P_{DATA}(i))(T_{fail}(i-1)+T_{s}(i)) + P_{fail}(n)T_{fail}(n)$$
(3.35)

where $P_{\text{fail}}(i-1)$ is the probability that all previous *i*-1 times of transmission failed, $T_{\text{fail}}(i-1)$ is the average time spent when all previous *i*-1 times of transmission fail ($T_{\text{fail}}(0) = 0$), $T_s(i)$ is the expectation of the time spent in the *i*th successful transmission attempt. Similar to (3.34), $P_{\text{fail}}(i)$ is calculated as

$$P_{fail}(i) = \prod_{j=1}^{\prime} \left[P_{RTS}(j) + (1 - P_{RTS}(j)) \cdot P_{DATA}(j) \right],$$
(3.36)

In each transmission attempt, the failure is due to the collision of either RTS or DATA frame. Therefore $T_{data-fail}$ is defined as

$$T_{data-fail} = T_{RTS} + T_{SIFS} + T_{CTS} + T_{SIFS} + T_{DATA} + T_{ACKTimeOut},$$
(3.37)

where T_{CTS} , T_{DATA} , T_{SIFS} , $T_{ACKTimeOut}$ are the durations of transmitting CTS, a DATA frame, waiting for SIFS period and waiting for ACK timeout, respectively. Similarly,

$$T_i(i) = T_{back-off}(i) + T_{data-succ}$$

where T_{data_succ} is the duration of transmitting a DATA frame correctly, which can be denoted as

$$T_{data-succ} = T_{RTS} + T_{SIFS} + T_{CTS} + T_{SIFS} + T_{DATA} + T_{SIFS} + T_{ACK} + T_{DIFS},$$
(3.38)

where T_{ACK} , T_{DIFS} are the durations of transmitting an ACK frame, waiting for DIFS period, respectively.

3.8 Summary

In this chapter a novel analysis is proposed to study the effect of the time variant nature of LEO systems in order to handle antenna angular requirements for efficient RF ISL

communication between satellites, which to the best of our knowledge is carried out for the first time. It takes into account LEO dynamic geometric characters such as azimuth rate, elevation rate, phasing between satellites and ISL variation to control antenna beam angle, pointing precision, Doppler frequency shift and rate of change of Doppler frequency.

The results show that due to the time variant nature of ISLs in LEO polar constellations, azimuth angular variations are large, but this can be kept to a minimum by selecting the appropriate orbital parameters of polar constellation such as the phasing of satellites. By providing phase offset between two connected satellites in inter-orbital planes minimum delay and ISL length variation could be achieved with significant effect on communication parameters such as antenna angular rate and Doppler shift and rates. Our analysis show that the off-orbit viewing angle between two connected spacecraft is a function of the argument of latitude, the number of planes and the number of satellites per orbit plane. In this respect, the off-orbit viewing angle is calculated to determine antenna specifications. As the maximum off-orbit viewing angle decreases with the number of orbital planes, the maximum antenna slew rate decreases thus less antenna steering requirements.

Additionally, it is also found for the first time, that there is a further increase in ISL length variation due to J_2 as the mean latitude difference between the two connected satellites increases. The effect of J_2 on ISL length must be taken into account, as it will have a substantial impact on communication parameters with ISL lengths more than 10 km.

The results also show that the choice of the inter-orbital crosslink pattern can have a significant impact on the maximum delay, delay variation and antenna angular rate. Non-zero phase offset between satellites in different orbital planes provide minimum ISL length variation thus providing minimum variation in communication parameters such as antenna slew rate.

Delay analysis using the M/M/1 model is performed for multiple satellites using ISLs in order to investigate the timing requirements for the IEEE 802.11 proposed for space communication. The results show that the main delay requirements that will affect the IEEE 802.11 inter-frame timing for flow control are the propagation delay, service time and packet inter-arrival rate. The key feature of this model is to calculate the path capacity in an IEEE 802.11 network for packet loss due to delay.

The need for smart antenna technologies to improve crosslink antenna pointing to maintain communication at much higher antenna angular rates is also justified in this chapter.

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Chapter 4. Adaptation of the IEEE 802.11 Physical layer

This chapter looks into the range extension, capacity and connectivity aspects of the IEEE 802.11b from the perspective of the physical layers (PHY). The main objective of this chapter is to investigate the effect of channel conditions on the IEEE 802.11 physical layers in an effort to supporting capacity requirements in a dynamic LEO network. Section 4.2 first looks at the characteristics of the IEEE 802.11b PHY layer schemes. It then identifies under section 4.3 the unique aspects of the terrestrial WLAN (802.11b) that necessitate PHY-related research for LEO inter-satellite communication. Performance evaluation of the different layers of 802.11b is then presented to investigate which physical layer best suits the LEO channel condition. By identifying major drawbacks of the different PHY layers defined in the standard, the need to enhance and re-define the physical and MAC layer timing parameter that control the contention period is justified in section 4.4. In section 4.5, a basic description on our motivation behind the effort to make the IEEE 802.11 PHY Space-Aware This is followed by evaluation of our proposed Space-Aware PHY framework in section 4.6. Section 4.7 concludes this chapter with a chapter-summary that highlights the unique aspect of our PHY layer protocol. An overview of modulation and multiple access schemes that underpin the behaviour of the IEEE 802.11 physical layers are presented in Appendix D, with emphasis on the DSSS using BPSK.

4.1 Introduction

In this chapter, we present a set of factors at the physical layer of the 802.11b protocol that are relevant to the performance evaluations of higher layer protocols. Such factors include signal reception, path loss, fading, interference and packet length. We start the discussion with the comparisons of the different physical layers in IEEE 802.11 and then quantify the impact of the proceeding factors under typical WLAN outdoor scenarios used for the performance evaluation of wireless ah hoc networks. Our simulation results show that the factors at the physical and MAC layers not only affect the absolute performance of the IEEE 802.11 protocol, but their impact on different physical layers schemes is non-unifo

4.2 The IEEE 802.11 Physical Layer Schemes

A comparison between the IEEE 802.11 physical layer schemes is presented using performance metrics which include bit error rate, packet size, and mobility and contention window. Given that there exist four types of PHY layers in IEEE 802.11 and this thesis is mainly interested in the PHY's ability to resist fast fading, interference, noise, and support for longer range, it is appropriate to review the different scheme from a high-level perspective before having a closer look at individual approaches.

4.2.1 Classification of the Wireless Physical Layers

Three types of physical layers are defined in IEEE 802.11b, namely Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS), and Infra radiation. The IEEE 802.11b standard is an extension of the IEEE 802.11 standard [8]. It is operates at the 2.4 GHz band and sends data up to 11 Mbps. The Orthogonal Frequency Division Modulation (OFDM) physical layer is defined for IEEE 802.11a standard [51] and operates in the 5 GHz band with data rates up to 54 Mbps. Further details are given in Appendix D and Appendix E. The IEEE 802.11g standard [52] extends the data rate of the IEEE 802.11b to 54 Mbps in an upgraded PHY layer named Extended PHY layer (ERP). Different PHY transmission modes are defined with different modulation schemes, and coding rates. The performance of the physical layer schemes for ISL can be measured by the robustness against path loss, interference and fading that causes variation in the received Signal-to-Noise Ratio (SNR) due to LEO dynamics. Such variations also cause variations in the bit error rate, since the higher the SNR, the easier it is to demodulate and decode the received signal. The basic transmission rate for each standard is given in Table 4.1.

There is a basic transmission mode (usually used to send ACK, RTS, CTS and PLCP¹³ header) in each physical layer which has the maximum coverage range among all transmission modes. This maximum range is obtained using BPSK or DBPSK modulations which have the minimum probability of bit error rate for a given SNR compared to other modulation schemes. The basic rates have the minimum data rates as well. For instance, the basic transmission rate for 802.11b is 1 Mbps with DBPSK and CRC 16 bits and 6 Mbps for 802.11a with BPSK and FEC rate equal to ¹/₂.

¹³ PLCP layer is responsible for carrier sensing and forming packets for different physical layers.

Characteristic	802.11a	802.11b	802.11g
Frequency	5 GHz	2.4 GHz	2.4 GHz
Rate (Mbps)	6, 9, 12, 18, 24, 36, 48, 54	1, 2, 5.5, 11	1, 2, 5.5, 6. 9, 12, 18, 22, 24, 33, 36, 48, 54
Modulation	BPSK, QPSK, 16QAM, 64 QAM (OFDM)	DBPSK, DQPSK, CCK, (DSSS, FHSS, IR)	BPSK, DBPSK, QPSK, DQPSK, CCK, 16 QAM, 64QAM (OFDM, DSSS)
FEC Rate	1/2, 2/3, 3/4	NA	1/2, 2/3, 3/4
Basic Rate	6 Mbps	1 or 2 Mbps	1, 2, or 6 Mbps

As shown in Figure 4.1, each packet may be sent with two different rates [8]: its PLCP header is sent at the basic rate while the rest of the packet might be sent at a higher rate. The higher rate used to transmit the physical layer payload is defined in the PLCP header. The receiver can verify that the PLCP header is correct using CRC or Viterbi decoding with parity and uses the transmission mode specified in the PLCP header to decode the MAC header and payload.



Figure 4.1 PLCP Frame structure of the IEEE 802.11 standard

4.3 Performance Evaluation of the IEEE 802.11b Physical Layers

As explained in section 4.2, four transmission modes are defined in 802.11b. In this section, we evaluate the performance of these transmission modes.

4.3.1 Interference and Signal Reception

Interference and noise at each receiver is a critical factor in wireless communication, as these help determine the Signal to Interference and Noise Ratio (SINR) or signal-to-noise ratio which has a strong correlation with Frame Error Rate (FER) on the channel. The power of the interference and noise is calculated as the sum of all signals on the channel other than the one being received by the radio plus receiver thermal noise. The resulting power is used as the base of SNR, which determines the probability of successful signal reception for a given frame. For a given SNR value, two signal reception computations are often used in wireless networks.

The SNR threshold (SNRT) uses the SNR value directly by comparing it with the SNR threshold and accepts only signals whose SNR values have been above SNRT at any time during reception. The BER based schemes probabilistically decides whether or not each frame is received successfully based on the frame length and the BER value, which is deduced by SNR and modulation scheme used at the transceiver. As the receiver evaluates each segment of the frame with a BER value every time the interference power changes, it is considered to be more accurate than the SNR threshold based scheme. However, the SNR threshold based scheme requires less computational cost and can be a good abstraction if each frame length is long. The BER model is used in both OPNET and the STK simulation tools.

4.3.1.1 IEEE 802.11 Transmission Modes

In this section, we focus on the BER performance of the 1 Mbps and 2 Mbps transmission modes in an IEEE 802.11b based WLAN. As explained in Appendix D, for 1 Mbps and 2 Mbps transmission modes the modulation schemes could be GFSK for FHSS and D-BPSK or D-QPSK for DSSS according to the receiver structure.



Figure 4.2 Performances of the IEEE 802.11 modulation schemes [116]

Comparing the two spread spectrum modulations, the probability of the bit error is plotted based on Eb/No in Figure 4.2 [116]. The 802.11 FHSS narrowband Gaussian Frequency Shift

Keying (GFSK) signal, which is power inefficient within the given constraints, requires 19 dB E_b/N_o when used with the greatest modulation index that will fit in the allocated bandwidth. DSSS offers a more robust wireless link than the 1 Mbps FHSS. More specifically, for a channel with a given E_b/N_o , DSSS offers a link with much lower error rate. That is because DSSS employs a BPSK/QPSK modulation, which is more power efficient than GFSK. The reason for the moderate power efficiency of GFSK stems from the limited spectrum availability from regulations which impacts the deviation ratio of the modulation. For the same reason, DSSS can tolerate considerably more interference than FHSS systems.

To improve FHSS performance more bandwidth should be allocated, while at the same time strong coding must be employed. However, these aspects are not foreseen by the current standard. As a result, for current implementations the difference between DSSS and FHSS for the minimal required E_b/N_o results in different allowable path loss. The D-QPSK modulation yields a 4 to 6 dB E_b/N_o advantage relative to GFSK. This E_b/N_o advantage translates into a considerable advantage coverage area for a DSSS system in the same bit rate and transmitting power as FHSS.

ISL Range	1 km	10 km	100 km	1000km
EIRP (dBW)	0	0	0	0
Data rate (Mbps)	2	2	2	2
Tx Freq.(Ghz)	2.4	2.4	2.4	2.4
Eb/No (dB)	15.04	5.24	-4.76	-14.75
BER	6.9E-15	4.8E-3	3.9E-1	10E-1
Path Loss	-100	-120	-140	-160
Tx Ant Gain (dBi)	0	0	0	0
Rx Ant Gain (dBi)	0	0	0	0

Table 4.2 Effect of increasing ISL range on BER and Eb/No Performance

In Table 4.2, the effect of increasing the inter-satellite range on BER and E_b/N_o using BPSK at 2 Mbps is given for the case of satellites flying in the same orbit plane. In Table 4.2 the link budget shows that the IEEE 802.11 protocol has acceptable BER and E_b/N_o performance for ISL ranges of 1 and 10 km when used with the nominal transmit power of 0 dBW. In Table 4.3 variation of BER and E_b/N_o performance is given with an ISL range of 1000 km for

different data rates using BPSK modulation scheme when used 16 dBi directional antennas. The results show an increasing BER with degradation of E_b/N_o as the data rate increases.

Data rate (Mbps)	1	2	5.5	11	54
EIRP (dBW)	0	0	0	0	0
BER	1E-015	2.5E-09	2.12E-04	6.3E-03	1.3E-01
Eb/No (dB)	15.33	12.33	7.93	4.92	-1.98
Path Loss (dB)	-160	-160	-160	-160	-160
ISL Distance (km)	1000	1000	1000	1000	1000
Tx Ant Gain (dBi)	16	16	16	16	16
Rx Ant Gain (dBi)	16	16	16	16	16

Table 4.3 Effect of increasing data rate on BER and Eb/No performance

4.3.1.2 The Effect of Packet Size on IEEE 802.11 Throughput

In all packet switching networks such as satellite networks with ISLs, the maximum and average packet size will have a crucial role on the performance of the system. The packet size will have influence on the maximum buffer size at each node. Long packets can tie up buffers. and the network response time becomes erratic. This problem is due to instability in the queuing process, which is sensitive to high variance in transmission time such as in ISL networks as shown in chapter 3, section 3.7. When the BER due to random noise and interference changes, so does the Packet Error Rate (PER). Future terrestrial wireless networks will also need packet size adaptation to changing interference and flat-fading channels as experienced in LEO ISL Networks. The results in Figure 4.3 show the effect of increasing packet size on the IEEE 802.11b throughput at a rate of 11 Mbit/s. There is a steady increase in throughput with increasing packet size until the throughput reaches a packet saturation point. As the number of nodes increase, the throughput overheads in DCF increases faster due to the non-linear contributions from collisions and back-off. The use RTS/CTS can make improvements to throughputs, which are more pronounced for larger number of nodes and for larger packets. Any further increase in packet size from this saturation point will produce no further increase in throughput but will only increase the queuing delay in the network. In conclusion, there is a maximum packet size for any network size and packet

fragmentation will be needed so that they do not exceed the packet saturation point i.e 1500 bytes.



Figure 4.3 Effect of packet size on the throughput performance of the IEEE 802.11 standard

4.3.2 Variable Propagation Delay

In LEO satellite networks, terminal-to-satellite and inter-satellite link propagation delays are typically in the order of milliseconds which are two orders of magnitude larger than the delays present in terrestrial mobile networks. The IEEE 802.11 MAC parameters that control the media will need to be either set to their optimum values or set dynamically to appropriately scale them up according to ISL length variations.

4.3.2.1 The Effect of Mobility and Range on IEEE 802.11b PHY Layers

This sub-section addresses the impact of some of the IEEE 802.11 parameters on the throughput for both DSSS and FHSS physical layers, for saturated networks. Unless stated otherwise, the parameters used are as defined in the IEEE 802.11 standard. Propagation factors such as effects of mobility, rate of change of frequency and path loss are part of the physical layer, since they control the input to a given environment and have a great impact on performance; therefore these factors are relevant to the emphasis of the Inter-satellite connectivity in this thesis. Fading is a variable of signal power at receivers, caused by the node mobility that creates varying path conditions from transceivers.

We use OPNET to run simulations on a network with a size of 10 nodes. All nodes transmit to some other nodes in the network according to Constant Bit Rate (CBR) source rate with fixed packets sizes of 1500 bytes (IP packets). We pick a source rate high enough to saturate the nodes in the network. Nodes are randomly placed in an area of 1000 X 1000 meters with 100 km/s mobility. Each run corresponds to 8000 seconds of data traffic. We trace each node in the network and compute the time and throughput for each PHY layer as shown in Figure 4.4 and 4.5. Regarding the PHY layers, we use a raw bit rate of 2 Mbps for both DSSS and FHSS.





Figure 4.4 The effect mobility and increased range on the IEEE 802.11 PHY layers

Figure 4.5 The effect of mobility and increased range on the IEEE 802.11 performance

The data link protocols for DSSS and FHSS are slightly different to accommodate the peculiarities of each physical layer. In particular the inter-frame spacing and Slot Times are different, and the recommended packet sizes are smaller for FHSS (400 bytes vs. 1000 bytes). The net effect is a slight edge for DSSS in overall throughput at 2 Mbps as shown in Figure 4.4 and Figure 4.5. The 2 Mbps rate is optional for FHSS and required for DSSS. If the throughput and MAC delay are of greatest concern, then DSSS is the winner.

4.3.2.2 The Effect of the Minimum Contention Window on IEEE 802.11b PHY Layers

In this section, we consider the impact of the initial contention window size on the throughput for different PHY layers. Figure 4.6 shows the results of FHSS PHY and Figure 4.7 shows the results of DSSS. From the results, we see that, overall, DSSS performs better than FHSS with regards to throughput.





Figure 4.6 Effect of CWmin on the FHSS PHY layer

Figure 4.7 Effect of the CWmin on the DSSS PHY layer

An important observation to be made here is that, as far as throughput in saturated networks is concerned, increasing the initial contention-window size improves the performance of the system in both physical layers. In particular, if we look at the performance for their real parameters as defined in the IEEE 802.11b standard [8] (CWmin = 32 for DSSS and CWmin

= 16 for FHSS), we see that the DSSS throughput is far better than the value of the FHSS physical layer. The results show very clearly the impact of the initial contention-window size on throughput. Using the same CW_{min} parameter for both PHY layer confirms the better throughput performance of DSSS (see Figure 4.8).



Initail Contention Window, CWmin for DSSS and FHSS



Based on these results, the DSSS PHY layer is used throughout this thesis with a raw data rate of 2 Mbps, until otherwise stated.

4.4 The Need for Adaptation of the Inter-Frame Timings for Space

The feasibility of designing an outdoor cellular network based on the IEEE 802.11b specifications is discussed in [53, 54, 81, and 82]. In [53, 54], it is investigated how the MAC and the physical layer can be applied and how they will perform in an outdoor network. By exploiting the fact that the inter frame time out intervals are not explicitly specified in 802.11 and it is meant for indoor use of a few meters range, the effect of increasing the delay on the MAC and the physical layer, as the range increases up to 6 km is investigated. It was concluded that the MAC layer can operate up to 6 km although with some degradation to some performance parameters but the physical layer is not. In this scheme [53], the arrival delay of ACK is extended from the SIFS to the DIFS interval since ACK has to arrive at the sender within a specified ACK-Time-Out period, or else the original transmission will be considered to have failed and is subject to retransmission by the back off mechanism. Extending the ACK from SIFS to DIFS comes with a penalty on the computation of the

Network Allocation Vector (NAV)¹⁴ which assumes that the ACK returns within the SIFS interval-thus incorrect virtual sensing. The assumption in this scheme [53] is that the MAC operation is based on both physical and virtual carrier sensing, and as long as the former works properly, the malfunctioning of the virtual carrier sensing due to incorrect NAV value will cause no apparent negative impact.

In LEO satellite networks, inter-satellite links experience long and variable propagation delays typically in the order of milliseconds which are orders of magnitude larger than the delays present in terrestrial mobile networks, therefore the IFS timings computed in the IEEE 802.11 standard cannot be directly applied without modification. ISLs are inherently time varying in a deterministic manner and offer possibilities for increased performance by using optimum or adaptive methods. For example, the performance of the inter-satellite link is determined by the received energy per information bit over noise spectral density, E_b/N_o . In a time varying link, the system parameters of the IEEE 802.11 must be adaptive to maintain adequate link budget, hence optimum throughput.

There are four main types of inter-frame spacing defined in the IEEE 802.11b standard, namely Short Inter Frame Space (SIFS); DCF Inter Frame Space (DIFS), PCF Inter Frame space (PIFS) and Extended Inter Frame Space (EIFS). These inter frame timings are provided to set different priority levels for access to the medium. Beyond IFSs, two more timing parameters are defined: SlotTime and AcKTimeout. The duration of each timing (delay) component was determined from the standards [8]. All delay components vary with the spread spectrum technology but not with the data rate. The transmission time of a Main Packet Data Unit (MPDU) depends on its size and data rate. Table 4.4 lists the constant and varying delay components and the total delay per MPDU is calculated as a summation of all the delay components as follows:

$$Delay per MPDU = (T_{DIFS} + T_{SIFS} + T_{BO} + T_{RTS} + T_{CTS} + T_{ACK} + T_{DATA}) \times 10^{-6}s.$$

Figure 4.9 illustrates how data packets are transmitted. The same pattern will be repeated with a specific cycle when back-to-back traffic is offered at the transmitting node. The timing diagram is different for CSMA/CA and RTS/CTS. The exact duration of each block varies for different spread spectrum technologies and basic data rates.

¹⁴ NAV is the message transmission duration that alerts all other nodes in the medium to back-off for the duration of the transmission.

Scheme	Constant and varying delay components $(10^{-6}s)$							
	TDIFS	TSIFS	TBO	TRTS	TCTS	TACK	T _{DATA} (MSDU in butes)	
CSMA/CA			-	-			5	
FHSS-1	128	28	375	N/A	N/A	240	$128 + 33/32 \times 8 \times (34 + MSDU)/1$	
FHSS-2	128	28	375	N/A	N/A	240	$128 + 33/32 \times 8 \times (34 + MSDU)/2$	
DSSS-1	50	10	310	N/A	N/A	304	$192 + 8 \times (34 + MSDU)/1$	
DSSS-2	50	10	310	N/A	N/A	304	$192 + 8 \times (34 + MSDU)/2$	
HR-5.5	50	10	310	N/A	N/A	304	$192 + 8 \times (34 + MSDU)/5.5$	
HR-11	50	10	310	N/A	N/A	304	$192 + 8 \times (34 + MSDU)/11$	
OFDM-6	34	9	67.5	N/A	N/A	44 ²	$20 + 4 \times [(16 + 6 + 8 \times (34 + MSDU))/24]$	
OFDM-12	34	9	67.5	N/A	N/A	32 ²	$20 + 4 \times [(16 + 6 + 8 \times (34 + MSDU))/38]$	
OFDM-24	34	9	67.5	N/A	N/A	28 ²	$20 + 4 \times [(16 + 6 + 8 \times (34 + MSDU))/96]$	
OFDM-54	34	9	67.5	N/A	N/A	24 ²	$20 + 4 \times [(16 + 6 + 8 \times (34 + MSDU))/216]$	
RTS/CTS								
FHSS-1	128	28×3	375	288	240	240	$128 + 33/32 \times 8 \times (34 + MSDU)/1$	
FHSS-2	128	28×3	375	288	240	240	$128 + 33/32 \times 8 \times (34 + MSDU)/2$	
DSSS-1	50	10×3	310	352	304	304	$192 + 8 \times (34 + MSDU)/1$	
DSSS-2	50	10×3	310	352	304	304	$192 + 8 \times (34 + MSDU)/2$	
HR-5.5	50	10×3	310	352	304	304	$192 + 8 \times (34 + MSDU)/5.5$	
HR-11	50	10×3	310	352	304	304	$192 + 8 \times (34 + MSDU)/11$	
OFDM-6	34	9×3	67.5	521	44 ²	44 ²	$20 + 4 \times [(16 + 6 + 8 \times (34 + MSDU))/24]$	
OFDM-12	34	9×3	67.5	361	32 ²	32 ²	$20 + 4 \times \left[(16 + 6 + 8 \times (34 + MSDU)) / 38 \right]$	
OFDM-24	34	9×3	67.5	281	28 ²	28 ²	$20 + 4 \times [(16 + 6 + 8 \times (34 + MSDU))/96]$	
OFDM-54	34	9×3	67.5	241	24 ²	24 ²	$20 + 4 \times [(16 + 6 + 8 \times (34 + MSDU))/216]$	

Table 4.4 Delay component for different MAC schemes and SS technologies [8]





In order to calculate the Maximum Theoretical Throughput, (MTT), all of the overheads at each sub layer must be converted into a common unit - time. To obtain the maximum throughput, we will divide the MPDU by the time it takes to transmit it:

$$MTT = \frac{MPDU \ size}{Delay \ per \ MPDU} \tag{4.22}$$

Limitations to the maximum distance in IEEE 802.11b networks between nodes are due to the following considerations which define the way to compute the timing parameter values:

Short Inter Frame Space: SIFS is used to separate transmissions belonging to a single dialog like ACK, RTS and CTS. SIFS is the minimum inter frame space, and there is always at most one single node to transmit at this given time, hence having the highest priority over all other nodes. This is a fixed value per physical layer and it includes the delay for the transmitting node to switch back to the receive mode and get ready for decoding the incoming packet. The 802.11 defines the way to compute the SIFS timing parameter values according to the following relations:

SIFS should not end before the signal reaches the destination station as defined in 802.11b and considering the speed of light we obtain:

$$300m/\mu s \times 10\mu s = 3km$$

The Slot Time: is the time needed by any station to detect the transmission of a packet from any other station. SlotTime is calculated thus

MacProcessingTime.

The slottime should not end before the signal reaches the destination station as calculated below taken the speed of light.

$$300m/\mu s \times 20\mu s = 6km$$

The Distributed Coordination Function IFS: is the minimum time that a node has to sense the channel to start a new transmission in order to avoid collision with a frame sent from the furthest node, which is calculated as:

$$DIFS = SIFS + 2 * SlotTime.$$

If we consider the speed of light, we obtain:

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(4.25)

(4.24)

$300m/\mu s \times 50\mu s = 15 km$

In order to avoid collision due to DIFS time, the maximum distance between two stations must be less than 15 km.

The Point Coordination IFS: is used in the contention free period of the IEEE 802.11 (PCF) by the Access Point (or point coordinator) to control access to the medium by nodes. This value is given by:

$$PIFS = SIFS + SlotTime$$

The Extended IFS: is the longest IFS used by a node that has received a corrupted packet. This is needed to prevent a station (which could not decode the duration information for the virtual sense mechanism) from colliding with future packets belonging to the current dialog.

The Acknowledgement Time: is the time a node waits for an acknowledgement, before assuming the frame is lost. Its value is calculated as:

AckTimeout = frameTXtime + AirPropagationTime + SIFS + AckTXtime + AirPropagationTime. (4.27)

4.5 Space-Aware IEEE 802.11 Physical Layer

Using a propagation delay of 1 μ s (defined in 802.11b), we encounter a very restrictive distance of 300 m. With any distance longer than 300 m, the ACK timeout expires before the reception of the ACK and the sender assumes the packet is lost and triggers an exponential back-off procedure until the maximum number of transmission attempts per packet is reached. The packet is dropped and a new packet transmission starts.

CCATime is the minimum time (in μ s) the Contention Collision Avoidance (CCA) mechanism has available to access the medium within every time slot to determine whether the medium is busy or idle. RxTxTurnaround is the maximum-time (in μ s) that the physical layer requires to change from receiving to transmitting the start of the first symbol. AirPropagationTime is the anticipated time (in μ s) it takes a transmitted signal to travel from the transmitting station to the receiving station. MACProcessingDelay is the nominal time (in μ s) the MAC uses to process a frame and prepare a response to the frame.

As given in the definition, it can be noticed that DIFS, SlotTime and AckTimeOut depend on the AirPropagationTime value. By increasing the maximum distance between nodes, the AirPropagationTime increases and all the parameters have to be re-defined. The values

(4.26)

defined in the 802.11b standard for the rest of the timing parameters are ~ 20 μ s for SlotTime, <15 μ s for CCATime, <5 μ s for RxTxTurnaroundTime, ~1 μ s for AirPropagationTime, ~0 μ s for MacProcessingTime and ~1 μ s for AckTimeOut. To improve efficiency, the solution is to compute the timing parameters according to the predefined maximum or real ISL distances between satellite nodes. The main motive behind this proposal in essence is for the IEEE 802.11 PHY layer to scale up to LEO ISL range (last mile) and capacity. This will lead to a Space-Aware IEEE 802.11 PHY layer.

For example, a LEO constellation using 8 satellites in the same plane at 648 km altitude has an intra-orbit ISL length of 5,000 km. Since RF signals travel at the speed of light, this translates to 34 ms round trip time with other delays such as processing and queuing [Please refer to the M/M/1 model in section 3.7] taken into account. Compared with the IEEE 802.11 MAC timing (SIFS) for access control of 10 μ S in Figure 4.10(a), the MAC inter-frame timing for control and data transfer will need to be completely re-defined for ISL ranges as illustrated in Figure 4.10(b).



Figure 4.10(a) Inter-Frame Parameters as defined in IEEE 802.11 standard



Figure 4.10(b) IEEE 802.11 IFS Re-definition for Space-Aware PHY

Figure 4.10 Comparison of IEEE 802.11 Inter-Frame Timing Parameters for ISL

4.6 Evaluation of the Proposed Space-Aware Physical Layer

There are many technical challenges for adaptation of 802.11 to outdoor environments and in particular to space. The evaluation of our proposed Space-Aware physical layer in section 4.4 and 4.5 has resulted in some guidelines to setting the 802.11b inter-frame timing parameters in order to extend the coverage of 802.11 to long ISL distance in satellite networks.

4.6.1 Simulation Results

As discussed section 4.4, it can be noticed that DIFS, SlotTime and AckTimeout depend on the AirPropagationTime value. The solution is to avoid timeout expiration by calculating the timeout values according to the predefined maximum distance between nodes. Table 4.5 reports the timing parameter values based on the maximum distance of 15, 100, 1000 km and 5,000 km compared with the settings defined in the 802.11 standard. The frame size used in this scenario is 1500 bytes at a rate of 2 Mbps. By increasing the maximum distance between nodes, the AirPropagationTime increases and all the parameters have to be defined. As can be seen in Table 4.5, the FrameTXtime which depends on the frame length and data rate used is due to the longer timing requirements of the AckTimeOut as given by Equation (4.27).

	802.11b Std	15 km Timing (optimal Value)	100 km	1000 km	5000 km
Slottime	20µs	75 µs	355 µs	3355 µs	16720 µs
SIFStime	10 µs	10 µs	10 µs	10 µs	10 µs
DIFStime	50 µs	160 µs	720 µs	6678 µs	3350 us
CCAtime	<15 µs	15 µs	15 µs	15 µs	15 us
RxTxTurnaroundTime	<5 µs	5 µs	5 µs	5 µs	5 µs
AirPropagationTime	1 μs	55 µs	334 µs	3334 µs	33400 µs
MacProcessingTime	0 µs	0 µs	0 µs	0 µs	0 µs
AckTimeout	1 μs	6696 µs	7254 µs	13254 µs	40586 us

Table 4.5 Timing requirements for the IEEE 802.11b standard for 15, 100, 1000, 5000 km range

To improve efficiency, the solution is to compute the timing parameters according to the predefined maximum or real distance between the nodes as shown in Table 4.5 for 15, 100 1000 and 5000 km.

Figure 4.11 depicts results obtained from OPNET simulation [55] with two 802.11b stations, as function of the distance between nodes.





Figure 4.11 Comparison of standard and optimum IFS values with increasing range

Figure 4.11 reports the throughput when the timing parameters are set according to maximum distance (i.e. 15 km @ 1 Watt Tx power) and when they are set as defined in the IEEE 802.11 standard (i.e 1 km @ 1 Watt Tx power). Using the maximum distance criteria, the throughput is independent of the distance between nodes (about 1.4 Mbps). It means that two stations 50 m apart from each other, communicate at the same throughput as two stations 15 km apart. This result shows that DCF MAC suffers from degradation at large distance but constant throughput is achieved if optimum IFS values are used.

4.7 Summary

In this chapter, a detailed description of the proposed enhancement of the IEEE 802.11b physical layer parameters is presented with results showing how throughput stability is maintained with increasing propagation distance by re-defining the inter-frame timing parameters to optimum values. The performance of the wireless network is observed to degrade with increasing distance in the communication scenarios. In this respect, we first discuss the state of art of the physical layer presently used in the IEEE 802.11 standard. Performance matrix such as mobility, increasing range and minimum contention window and their effect on different IEEE 802.11 physical layers were discussed and verified by simulation results. With reasons and results put forward, the DSSS scheme with a better performance than the rest is selected as the physical layer scheme in this thesis.

As analysed, fixed inter frame timing values defined in the IEEE 802.11 standard has some range limitations and cannot be directly applied to LEO ISL networks. This provides us with enough motivation and justification for our effort to re-define some of the IFS responsible for range and capacity in LEO ISL networks. The results show that IEEE 802.11 can scale up to variable and long propagation delays experienced in LEO networks using ISL by redefining the AckTimeOut, DCF and Short InterFrame parameters. We propose optimization measures via variations in these parameters. For example, switching the AckTimeOut, at suitable ISL separation in certain scenarios can help enhance the ad-hoc network performance of IEEE 802.11.

The results presented in this chapter are used as performance references for IEEE 802.11 development of inter-satellite communication applications.

Chapter 5. Adaptation of the IEEE 802.11 Medium Access Control Scheme

This chapter looks into the optimization aspects of WLAN in space applications from the perspective of the IEEE 802.11 Medium Access Control layer. The methods employed in this thesis to improve the performance of the IEEE 802.11 MAC for ISL applications are:

- Enhancing the hardware in the physical layer to achieve better physical layer parameters, such as optimum slot time and optimum short interframe time.
- Introducing adaptive back-off algorithms in the IEEE 802.11 MAC layer.

This chapter is structured as follows: Section 5.1 identifiers the unique aspects of space-based wireless networks that necessitate MAC-related research. This is then followed by a review of the state of art in section 5.2. Section 5.3 presents our motivation behind the efforts to optimise the IEEE 802.11 MAC for LEO ISL applications with reference to related work. This is followed by a detailed description of our proposed Space-Aware MAC framework for ISL applications in section 5.4. In section 5.5, simulation of the required throughput by modifying the WLAN station in OPNET is presented. Evaluations of simulation results in are given in section 5.6. Section 5.7 concludes this chapter. Appendix C describes the simulation methodology used

5.1 Introduction to MAC Protocols

MAC protocols are designed for coordination of packet transmission, retransmissions of damaged packets and resolution of collisions during contention periods among nodes sharing the same media. The MAC protocols in LEO satellite networks using ISL should provide: high channel throughput, low transmission delay, channel stability, protocol scalability, channel reconfigurability and low complexity of the control algorithm. A new MAC may be designed depending on the mission requirements such as synchronization, and the criticality of the data being transmitted between satellites in a formation or constellation. However, it will be highly desirable to develop Commercial-Off-the-Shelf (COTS) solutions and constellation designs that will be able to use existing MAC techniques such as the IEEE 802.11 or IEEE 802.16e wireless standards.

In addition to the normal wireless channel characteristics such as the time-varying nature of the channel and burst channel errors, unique properties such as the variant nature of LEO satellite networks make the design of MAC protocols very different from, and more challenging than, terrestrial wireless networks [56], [57]. Several factors that directly affect the performance of a MAC protocol for space-WLAN applications, such as traffic model, half-duplex mode of operation and proximity-dependant carrier sensing are described below.

5.1.1 Traffic Model

The performance of a MAC protocol depends strongly on the nature of the traffic transmitted on the multiple access control. The main components of the traffic include the message arrival distribution, the message length distribution and the traffic burstiness. Traffic burstiness can influence the design and the selection of a MAC protocol for satellite WLAN. Large burst will require extra buffers and higher processing capability to support reliable ISL communications. To improve the throughput in broadcast channel shared by users with random burst traffic, hybrid protocols that take advantage of random access and TDMA-based access must be studied. Random access protocols provide low latency when traffic is light while TDMA-based protocols provide high throughput when traffic is high. The technology used for time-code multiplexing, called TDMA with CDMA-encoding Multiple-Access (TCeMA) with respect to ISL is described in [58].

5.1.2 Half-Duplex Mode of Operation

Unlike wired networks, in wireless network systems it is very difficult for any node to listen to the common communication medium while making a transmission attempt. Due to the transmission power being much higher than the receive signal power, if a node tries to listen to the channel while transmitting, it may tend to receive what is being transmitted by itselfknown as self interference. As a result collision detection mechanisms cannot be used as in the Ethernet-like, e.g. Carrier Sense Multiple Access- with Collision Detection (CSMA-CD). All proposed wireless protocols attempt to decrease the probability of a collision by using collision avoidance mechanisms since collision cannot be detected by the sender, and hence inherently bringing inefficiency. Hence, in this respect, it is very difficult to design a wireless MAC protocol which is as efficient as a wireline MAC protocol. Chapter 5 Adaptation of the IEEE 802.11 Medium Access Control Scheme

5.1.3 Proximity-Dependant Carrier Sensing

The received signal strength between a transmitter and a receiver in free space conditions decays with the square of the distance. As a result, carrier sensing is a function of the relative location of receiver with respect to transmitter, since the signal strength decays according to a power law with distance in a wireless medium. Only nodes that a within a specific radius of the transmitter can listen to the channel. This location dependant carrier sensing results in three types of problems in protocols that use carrier sensing.

Hidden Node Problem: The hidden node problem arises when two nodes are out of range of each other are unaware of each other's transmission; transmit packets to the same receiver, thus causing collision at the receiver. Consider the case in Figure 5.1. If node A is transmitting to node B, node C cannot hear the transmission of A. During this transmission when node C senses the channel, it will falsely think that the channel is idle. If node C starts transmitting to node B, it will interfere with the data reception at B from A. In this case node C is a hidden node to node A.



Figure 5.1 Effect of location-dependant sensing: Hidden-node, Exposed-node and Capture effect problems

Exposed-node Problem: Another problem is the exposed node, where communicating nodes are unaware of the communication of other nodes. If we consider Figure 5.1 again, when node B is transmitting to node A, node C can hear the transmission from B. When node C senses the channel, it thinks that the channel is busy. However, transmission from node C will not reach node A, and therefore will not interfere with data reception at node

A. In this case node C is an exposed node to node B. If exposed nodes are not minimized in wireless networks, the bandwidth is under-utilized.

Capture-Effect: The capture effect can occur when a receiver can cleanly receive transmission from two simultaneous transmissions, both within range. Consider the case in Figure 5.1 again, when node A and D transmit simultaneously to node B, the signal strength from D is much higher than from A, and D's transmission can be decoded by B with errors in the presence of transmission from A. Capture can improve performance, but it results in unfair sharing of bandwidth with preference given to nodes closer to the tagged node. Fairness under such conditions will be needed in wireless MAC protocols.

There are several unique characteristics that well distinguish LEO satellite networks from terrestrial based wired and wireless counterparts, and therefore the MAC layer in the case of LEO networks using ISLs becomes even more complicated. The first and most serious challenge is the absence of any centralised controller in satellite constellations due to the lack of infrastructure support. Without perfect coordination, a collision could take place when several nodes simultaneously access the shared medium. These can also result from transmissions that are multiple hops away. Secondly, due to hardware constraints, satellite nodes cannot immediately detect collisions during their transmission, which may lead to channel inefficiency. Thirdly, as every satellite node in the LEO network is mobile, although the network topology is periodic and predictable, it may change from time to time. Accordingly, each node may experience different degree of channel contention and collision. As a result, the selection of the MAC scheme can interfere even with best effort routing protocols.

While supporting high throughput is a multilayer problem, there have been increased research interests in the design of cross-layer optimised MAC protocols that attempt to relax the traditional rigid layered architecture [68]. However, until now, a MAC based on the distributed coordination function of IEEE 802.11 a/b is the most prevalent in use today. Although multiple non-overlapping channels exist in the ISM bands of 2.4 GHz and 5 GHz, most IEEE 802.11 based WLANs today use only a single channel [8]. Although 54 Mbps and 11 Mbps bandwidths are defined in the IEEE 802.11 a/g and 802.11b respectively as the peak link-layer data rate, when all the overheads such as RTS, CTS, ACK and packet errors etc. are taken into consideration, the actual net throughput available is almost a half of that, as shown in Figures 5.2 and 5.3. In Figure 5.2 the throughput is decreasing as the number of nodes increase mainly due to the MAC operation. Figure 5.3 shows the effect of RTS/CTS control

signals on the throughput of the IEEE 802.11 protocol. The result in Figure 5.3 indicates a drop in throughput if the options of control signals RTS/CTS are enabled but with more data transfer reliability when used. Since the IEEE 802.11 MAC is based on random access method of carrier sense multiple access with collision avoidance (CSMA-CA), its ability to support high throughput especially when the contention is high is very small.





Figure 5.2 The effect of the number of nodes on the IEEE 802.11b throughput



Unavoidable packet collisions, unbounded delay, and increased jitter are often results of techniques using random access schemes when multiple users access a common medium. The time required to resolve collisions is a function of the network load [59]. In addition, the DCF's "capture effect", extensive use of control frames, the use of a binary exponential back-off scheme, and the time-varying nature of the bandwidth often results in insufficient throughout for time-sensitive applications [60][61]. Because of these reasons, a wide range of

MAC protocols have been proposed or developed for different operating environments with different user requirements. The following section provides a survey and classifications and performance assessments of wireless MAC protocols for LEO satellite communications.

5.2 Overview of Wireless MAC Protocols

Comparing different wireless MAC protocols is very difficult since each has been developed for a different architecture and application in mind. The most widely used performance metric used to compare different MAC protocols are delay, throughput, fairness, support for multimedia and stability. In this thesis we are mainly interested in the MAC's ability to support smart antennas (range), stability and throughput. In section 5.3, a comparison of related work from a high-level perspective is provided before moving on to have a closer look at individual approaches in section 5.4.

5.2.1 Classifications of Wireless MAC Protocols

MAC protocols are broadly classified into two main categories; distributed and centralised, accordingly to the type of network architecture and application for which they are designed. They are further classified based on the mode of operation into random access protocols (contention-based), guaranteed access protocols (allocation-based) and hybrid access protocols as shown in Figure 5.4 [56].



Figure 5.4 Classifications of Wireless MAC Protocols
In random access protocols, there is contention for access to the medium by nodes. Access to the medium by one node is usually delivered successfully, but simultaneous transmission attempts by multiple nodes to access the same medium can often result in a collision. This collision is resolved by nodes in an orderly manner according to rules defined by a contention resolution algorithm. In guaranteed access protocols, nodes access the medium in a polling fashion, usually in a round-robin manner.

The two most common ways to implement these protocols are a master-slave configuration or a distributed protocol. In the master-slave configuration, the master polls each node and the nodes send data in response to the poll. These are called polling protocols. In distributed protocols, the nodes operate by exchanging tokens. The main advantage of contention-based protocols is that the MAC is mobility transparent. However, contention-based protocols cannot provide deterministic delay bounds, while allocation-based protocols are delay bounded. On the other hand, hybrid access protocols try to blend the best qualities of the above two protocols to derive more efficient MAC protocols. Hybrid access protocols are mostly based on request-grant mechanisms. Hybrid access protocols are further classified into Random Reservation Access (RRA) and Demand Assignment (DA) protocols. In an RRA protocol, a Base Station or Access Point has implicit rules for reserving upstream bandwidth. A typical example can be the periodic reservation of an upstream slot by a successful request. On the other hand, in a DA protocol, the AP/BS controls the upstream data transmissions according to their QoS requirements. A request is collected from all the nodes and scheduling algorithms are implemented to make bandwidth allocations. According to their modes of operations, both polling and hybrid access protocols require a central node, therefore they can be categorised as centralised MAC protocols. Random access protocols can operate in either architecture. Although token passing protocols could be used in distributed access protocols, due to the time varying nature of the wireless channel, token loss would be common and token recovery would incur a huge overhead. As a result, all proposed distributed MAC protocols are based on random access protocols.

All distributed MAC protocols are based on carrier sensing and collision avoidance, except for ALOHA [122]. Carrier sensing is done by listening to the physical medium to detect any ongoing transmission. Due to location-dependent carrier sensing which results in hidden and exposed-node problems, such nodes play a very important role in carrier sensing multiple access (CSMA) protocols. In wireless networks, senders do not necessarily hear collisions that occur at the destination nodes, so the destinations need to relay feedback to the senders. However, because wireless transceivers operate in half-duplex mode, nodes cannot listen

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while transmitting and the feedback information has to be sent using out of band signals or the node has to stop and listen to the medium for feedback. Most distributed MAC protocols therefore use collision avoidance techniques built into the protocol to minimise the probability of a collision. The two most widely used mechanisms are: the out-of-band approach [62] and the handshaking approach [63].

In centralised MAC protocols the arbitration and complexity is passed on to the AP/BS to explicitly control who can access the medium and when. A key assumption in this setup is that the nodes can hear and talk to the AP/BS, hence the likelihood of hidden and exposed node problems is minimised. In addition, all communication must go through the central node. The only class of guaranteed access protocol studied is the polling protocol in the context of wireless networks. Although polling protocols are efficient when the size of the network is small, random access protocols are more robust and can multiplex a large number of nodes. These protocols have additional advantages when used with smart antenna arrays. Also based on who initiated the communication request, the MAC protocol can be further categorised as Sender-initiated (SI) or Receiver-initiated (RI).

In this thesis, MAC protocols for satellite communications will be classified based on their functionality with respect to the static or dynamic nature of the channel, the centralised or distributed control mechanism of the channel assignments, and the adaptive behaviour of the control algorithms.

As far as MAC protocols are concerned, the space environment can pose major constraints that eliminate a large number of MAC protocols from consideration. First, the impact of long and variable propagation delays imposes certain restriction on MAC protocols. The current MAC propagation delays are calculated based on performance requirements for terrestrial networks and hence these delays need to be re-evaluated for LEO satellite communication. Secondly, physical changes to hardware medium access controllers in space are limited if not impossible, which necessitates a simple control mechanism for the MAC protocol under consideration. Thirdly, as fault tolerance and network survivability must be provided, the MAC protocol is expected to easily accommodate topological changes such as activating and deactivating of a satellite from the network. Finally, limitations in satellite power implies stringent use of the buffer memory and processors.

5.2.2 Medium Access Control for Wireless Local Area Networks

As mentioned above it is the distributed and hence random-access approach which is well suited to LEO satellite networks using ISLs. There are several variations to IEEE 802.11 that make use of CSMA technique with some addendums. The following subsections briefly explain the main MAC protocols that are present in terrestrial wireless networks and can be applied to LEO satellite networks with some modification. They are classified based on the underlying technology on which they are built.

5.2.2.1 Simple Random Access Schemes

Simple random access schemes support best-effort services and are not space or QoS-aware, but the purpose is to shed light on the development cycle been made in the MAC protocol design for terrestrial wireless networks. Additions are made and built upon previous protocols either through control overhead or carrier sensing in order to mitigate the effects of the hidden node problems and to achieve better network throughput. Further details can be found in Appendix E.

5.2.2.1.1 Carrier Sense Multiple Access

The simplest and most primitive of the MAC protocols is the carrier sense multiple access protocol. The technique used in this scheme can be summarised as follows. Whenever a node makes an attempt to initiate a communication it needs to sense the medium for any ongoing transmission. If the medium is not busy, the node begins transmission. On the other hand, in the event that the medium is busy, the node will set a random timer and then it will wait for this period before sending any packet.

5.2.2.1.2 Multiple Access with Collision Avoidance

Unlike CSMA, the Multiple Access with Collision Avoidance (MACA) protocol does not perform carrier sensing [56]. The assumption is that carrier sensing before transmitting is not an efficient approach because it reduces collision but does not completely eliminate them. A three-way handshaking for data transmission is introduced in MACA to cope with the hidden node problem. Before a node makes a transmission, it sends RTS frame containing the length of the following transmission. The stations within transmission range of the sender

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will defer for the time announced in the RTS. Upon receiving the RTS, the destination node will also broadcast the CTS packet to the sender and to all others within transmission range. The nodes within transmitter range will also set their defer timer according to the time announced in the CTS frame. Thus, the medium is reserved for transmission of the upcoming frame, avoiding collision and interference. If the CTS is not received after a RTS transmission, a collision is inferred and the nodes enter a collision resolution phase. To resolve collision, the nodes perform a binary exponential back-off. If any node within range sees the CTS frame only, it must back-off for the duration of the length of the CTS frame, partly solving the hidden node problem. If any node with transmission range sees the RTS frame only but not the CTS frame, it is free to transmit, solving the exposed node problem.

The MACA for Wireless LANs (MACAW) protocol [64] extends the protocol by adding the link level acknowledgement (ACK) for data frames. The data acknowledgement at the link layer is an important improvement because it accelerates the loss frame recovery, which was only initiated at the transport level. The MACAW also altered the back-off scheme to improve fairness. The MACA –Receiver-Initiated (MACA-BI) [65] also extends the MACA by using two-way handshake instead of the three-way in MACA. The RTS frame does not exist in MACA-BI and the CTS frame is renamed as receiver-to-receiver (RTR) in this scheme. Under this scheme, any node cannot arbitrarily initiate transmission, unless it has received invitation from a receiver. Although the MACA-BI has reduced the overhead by control frame to a minimum but it very difficult for the receiver to accurately know that a particular sender has data to be transmitted to it. Hence, the requirement for the receiver to predict whether a sender has data to transmit to it. Communication performance will therefore be affected by the timeliness of the invitation from the receiver. The efficiency of MACA-BI will be high for constant bit rate traffic provided the prediction scheme works well but it will be no better than MACA for bursty traffic.

5.2.2.1.3 Floor Acquisition Multiple Access

In Floor Acquisition Multiple Access scheme, (FAMA) [56], [66] any node wishing to attempt transmission must acquire the channel called the floor. The performance of FAMA is good in network with no hidden-nodes as MACA, but as bad as CSMA in the presence of hidden-node. There are many supplements in FAMA such as FAMA-Non-Persistent packet Sensing (FAMA-NPS) and FAMA-Non-persistent Carrier Sensing (FAMA-NCS). The FAMA-NPS scheme require nodes sensing packets in the medium to back off whiles in

FAMA-NCS carrier sensing is employed to prevent neighbouring nodes from transmitting when the channel is sensed busy. FAMA-NPS is not very efficient in the presence of hiddennode, unless CTS frames are transmitted multiple times. On the other hand FAMA-NCS is more efficient than both CSMA and FAMA in multihop environments due to its in-built carrier sensing and floor acquisition mechanisms.

5.2.2.1.4 CSMA with Collision Avoidance

The IEEE 802.11 [8, 63] standard defines a physical layer and a MAC layer for WLAN as shown in Figure 5.5. The basic access method defined in the MAC is the distributed coordination function (DCF) which is based on the CSMA-CA MAC protocol. The IEEE 802.11 incorporates an alternative access method, besides the DCF, known as the point coordination function (PCF). The PCF is very similar to a polling scheme and uses a point coordinator (PC) to determine which node has the right to transmit. Given that LEO satellite networks are similar to IEEE 802.11 ad hoc networks, known as "Independent Basic Service Set" (IBSS) and that our proposed Space-Aware MAC (SA-MAC) is based on the IEEE 802.11b, a basic description of its working mechanism is provided here. Since our work on the MAC sub-layer is on the DCF, we review the IEEE 802.11 with greater emphasis on the DCF mode.

The time period in the IEEE 802.11 network operates in the DCF mode is called the contention period (CP). Access to the medium is controlled through the use of inter frame spaces. Transmissions that are only required to wait for the SIFs have the highest priority over the medium. The shorter the period a transmission has to wait, the higher the priority it has over the medium. The PCF interframe space (PIFs) (>SIFs) is used to initialize contention free period. The DIFs (>PIFs) is used to initiate contention periods between nodes.





(b) IEEE 802.11 MAC Operation Timing



Chapter 5 Adaptation of the IEEE 802.11 Medium Access Control Scheme

The DCF is a random access scheme, which has two modes of packet transmission. The default mode is a two-way handshaking technique called the basic access mode. This scheme is characterized by an immediate transmission of a positive acknowledgement for every successful reception of a packet by a destination to the sender. In a wireless medium, a transmitter cannot determine if a packet is successfully received by listening to its own transmission, hence the requirement of an explicit transmission of ACK is required by the destination. To implement the carrier sensing and collision avoidance mechanism, the basic operation of DCF uses a physical carrier sensing, where the nodes determine whether the channel is idle or busy by monitoring the energy level of the channel. However, this leaves the nodes vulnerable to so called hidden-node problems, which increases the risk of collision. To solve this problem, an optional four way handshaking technique has been standardized. known as the Virtual Carrier Sensing (VCS) mechanism. In VCS, short control messages i.e. RTS/CTS frames are exchanged between nodes prior to any actual data transmission to determine whether or not data transmission may take place or not, and to make sure that hidden nodes remain silent during the transmission. An RTS frame is used to reserve the medium after waiting for a minimum period of DIFs. The receiving node acknowledges the receipt of an RTS from the sender by sending back a CTS frame after SIFs, indicating it is ready to receive data. After normal packet transmission, an ACK response is sent back to the sender. On the other hand, if the medium is not idle or busy for a period of DIFs, the transmission is deferred until the end of the current transmission. A random interval in the range of zero to the contention window (CW) is then computed by the node to initialize its back-off timer. The general problem with DCF is that it is fundamentally a random access scheme and its performance under higher loads is poor.

The PCF scheme provides contention free transfer of data known as the contention free period (CFP). The point coordinator function is performed by the AP, by gaining control of the medium in the beginning of the CFP, after sensing the medium idle for the period of PIFS. On receiving a poll, a node transmits its data after the period of SIFs. During the CFP period the AP polls nodes that pollable i.e PCF enabled, by keeping a polling list of the nodes. The CFP must alternate with CP. The sum of the two periods is called the "Super Frame "as shown in Figure 5.5. The AP initializes the CFP by transmitting a Beacon frame, and ends it by transmitting a CF-end frame. Positive ACKs are used in both DCF and PCF modes to support error correction.

5.2.2.1.5 Dual Busy Tone Multiple Access

In Dual Busy Tone Multiple Access, (DBTMA) [62], two out-of-band busy tones such as the transmit-busy-tone and the receive-busy-tone are used to notify neighbouring nodes of any ongoing transmissions. In DBTMA, a single channel is split into two sub-channels such as the data channel and the control channel. As in the CSMA/CA, the RTS and CTS control frames are used in DBTMA to initialise a data transmission. A node setup the transmit-busy-tone signal before it starts to transmit a data packet until the transmission is completed. A node in receive mode also sets up a receive-busy-tone signal before it replies to the initiator with a CTS packet until the reception is completed. These two tone approach serve as a notification for all nodes with transmission range and reception range in order to minimise collision.

5.2.2.2 Fairness Facilitating Schemes

Due to the existence of hidden-node problems and the absence of any central administration, partially connected network topologies like LEO constellations using existing MAC protocols based on IEEE 802.11 DCF may lead to a "Capture effect". This means that some satellite nodes grab the shared channel and other nodes suffer from starvation- known as "Fairness Problem [67], [68], [69]. In [67] an algorithm is proposed, where fairness between wireless access users is archived by pre-calculating a link access probability. The link access probability, PAB between node A and B is calculated in two ways using contention-based and time-based media access methods. Each active user broadcasts information on either number of logical connections or average contention time to the nodes within its communication reach. Based on this information, each node can have a fair share of the channel bandwidth. On the other hand, the proposal in [68] tries to conserve bandwidth by not broadcasting any information regarding fairness to others. According to [68], a predefined fair share is allocated to each node and it is determined at admission control. It is determined when a node joins the ad hoc network (i.e. at admission control). To achieve the fairness goal, a different back-off algorithm is proposed in [68] where each node estimates its share and other nodes' share of the channel and then adjusts the contention window accordingly. In this algorithm, RTS and CTS frame transmissions are counted towards the estimated share because RTS and CTS frames are used as a channel reservation scheme. In order to equalise the channel throughput obtained by different nodes in the network, the contention window is adjusted. Accordingly, if a node estimates that it has got more than the fair share, it will double its contention window size until it reaches CWmax so that its neighbours can have more chances

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to have a fair share. These fairness schemes are based on the mechanism of DCF of IEEE 802.11, and considers only the MAC protocol aspects not the underlying channel impairments (e.g. fading) into account.

5.2.2.3 Protocols Enabling MAC-Level Service Differentiation

The main objective of the Differential Serve enabled MAC based on the IEEE 802.11 DCF [63] or the enhanced DCF (EDCF) [70] is to provide service differentiation by allowing faster access to the common channel to traffic classes with higher priority or certain nodes. There are many priority treatments that can be introduced with the use of several parameters at the MAC layer in the case of either DCF or EDCF, [63, 67, 71, 72, 73, 74] as illustrated in Figure 5.6:

- i) Different inter frame spaces for different priority classes/nodes/flows
 - ii) Different values for the lower and upper bounds of the contention window depending on priority.
 - iii) Different maximum frame size for different priority classes/nodes/flows.
 - iv) Different scheduling policies for different priority classes/nodes/flows

There is, however no explicit guarantee of the level of service differentiation under each of these schemes, and the following subsection briefly explores the possible causes of such uncertainties in each category.



Figure 5.6 Distributed MAC-Level Service Differentiations

5.2.2.3.1 Binding Channel Access to Different Priority Classes

As illustrated in Figure 5.6, by allocating either a smaller waiting time (IFS) or a smaller CW through priority-based access can result in a smaller back-off interval for higher priority classes in service differentiation. In either case binding the channel access makes this differentiation mechanism unfair. This is due to the fact that as the number of nodes generating higher priority traffic increases, they tend to grab the channel and thus starving or preventing other nodes with lower priority fair access.

5.2.2.3.2 Employing Different IFSs for Different Priority Classes

By assigning a smaller IFS value to higher priority classes it is possible to facilitate service differentiation by adopting different IFSs for different priority classes. Allocating smaller IFS values to higher priority classes will enable frames belonging to higher priority classes to access the channel faster than lower priority frame when the channel is idle. Using this method, the existing IFSs in the IEEE 802.11 standard can be exploited or new IFSs can be introduced. The latter has been defined in IEEE 802.11e, where a new type named arbitrary IFS (AIFS) has been introduced [70]. As mentioned before in section 5.4.2, this approach may lead to serious unfairness. Also if this approach is used in conjunction with a normal back-off mechanism as defined in the IEEE 802.11 DCF, the differentiation will not be achieved- as the back-off mechanism would eliminate the priority provided by different IFS values. It has also been shown quantitatively in [73, 75] that different transport protocols react differently to this mechanism, as such the user datagram protocol (UDP) shows more priority effect than TCP.

5.2.2.3.3 Employing Different Contention Windows for Different Priority Classes

This is a very popular method of adopting MAC-level service differentiation; it is made possible by having back-off times for different priority classes [70, 71]. Two ways exist in which this mechanism can be devised. The first method – termed contention window differentiation (CWD) achieves service differentiation by setting different values for the minimum (CWmin) and maximum (CWmax) of the contention window for different priority classes. Let us denote the back-off interval (BI) by the number of slots that a node has to wait in contention beyond the DIFs period before initiating its transmission. This BI is calculated using the following equation.

$$BI = int(random() * CW(k))$$

$$CW(k) = min(2^{k-1}CW_{min}, CW_{max})$$
(5.1)
(5.2)

In equation (5.1) random() function returns a pseudo-random number uniformly distributed in [0, 1] and CW(k) represents the contention window after k unsuccessful transmission attempts and is given in Equation (5.2). Accordingly, given two priority classes A and B there exist two ranges of CW: CW_A (between CW_{min,A} and CW_{max, A}) and CW_B (between CW_{min,B} and CW_{max,B}). Since BI is a random number uniformly distributed between CWmin and CW_{max} as given in equation (5.1), the two traffic classes are differentiated by the average BI values. However these CWs could overlap [70, 71, 72].

In the second method termed contention window separation (CWS) - higher priority classes are allocated shorter CWs that result in smaller BIs, whereas lower priority classes are allocated longer CWs larger BIs. Hence a modified version of Equation (5.2) to calculate CW(k) is given below:

$$CW(k) = \left[P_i^{2+k} * ramdom()\right]$$
(5.3)

In Equation (5.3) P_i is the priority factor of either a traffic class-i or node-i. The priority factor for each class is selected such that, the higher the priority factor (for lower-priority classes or nodes), the larger the back-off interval, and the lower the chance to first access the channel, hence the lower the throughput. However, both CWD and CWS may lead to high variability of throughput and delay, as result of which mechanism employing different CWs for different priority classes tends to develop inconsistencies in desired behaviour over time [67, 75].

5.2.2.4 Fair Scheduling

Mechanisms used in fair scheduling schemes aim to partition the network resources fairly among flows/node/class in proportion to a given flow/node/class weight. Fair opportunity to send is archived by regulating the wait time for traffic in each flow/node/class- this concept is different from the schemes employing bind channel access to priority.

5.2.2.4.1 Adapting Contention Windows

Given that the size of CW actually decides the throughput and delay performances, this scheme adapts the value of CW based on the differences between the experienced (actual) throughput and the desirable (expected) throughput of a given flow/node/class. If the throughput is lower than the expected, the CW will be decreased. On the other hand if the experienced throughput is greater than the expected, the CW will be increased to reduce the priority. The randomness associated with adapting CW still remains since this scheme still make use of CWs, hence increasing variability of the throughput and delay [75].

5.2.2.4.2 Employing Different IFSs for Different Priority Classes

Fair queuing with different IFS values are used in this scheme to improve absolute as well as relative QoS guarantees. In this scheme, each traffic class has its own allocated service quantum rate that represents its expected throughput requirements. Accordingly each traffic class maintains a deficit counter of the accumulated quanta and can transmit only when the deficit counter value is positive. This deficit counter value is reduced by the size of the transmitted frame. The deficit counter value is mapped to an appropriate IFS value with larger deficit counter resulting in smaller IFS value. In this scheme no back-off mechanism is employed, and hence each node has to wait for the assigned IFS period.

5.2.2.4.3 Maximum Frame Size

Another possibility that can be used to facilitate service differentiation is to limit the maximum frame size used by the different priority classes/nodes/flows. This scheme can give rise to two possibilities for handling the packets that exceed their maximum limit:

- i) Packets are dropped that exceed the maximum frame size assigned to a given flow/node/class.
- ii) Fragmentation of packets- After a successful access to the channel with the first fragment, the subsequent fragments of a packet can be sent without requiring any additional RTS/CTS handshake as long as corresponding ACKs are received.

It has been analysed in [67] that under perfect channel conditions where there is no fragment loss, throughput share is directly proportional to the maximum frame size allowed for each flow/node/class. However, it is very difficult to always assume a perfect channel

condition in wireless networks- which contradicts the basic approach on which this scheme is built upon. Longer packets are more likely to be corrupted than shorter ones.

5.2.2.5 Schemes Employing Spread Spectrum Technology with MACA

In these schemes code division multiple access (CDMA) and collision avoidance contention based multiple access techniques are made use of in order to form a new set of MAC protocols for wireless networks. In [80], it is argued that the MACA described in sub-section 5.2.2.1.2 does not address the issues that arise due to node mobility. In this the authors try to combine the advantages of MACA and spread spectrum techniques. For this purpose, two spread spectrum protocols are adopted:

- i) Receiver-Transmitter (RT) based protocol: In this scheme, whenever a transmitter initiates a data transmission, it first has to transmit a control packet on the receiver's own spreading code, and then to send the data packet on its own spreading code. For this purpose, each node is assigned a unique spreading code, and hence a unique channel.
- ii) Common Transmitter (CT) based protocol: In this approach, control packets are sent on a common channel and data packets are sent in the same way as in RT.

Accordingly, two techniques, MACA-CT and MACA-RT are proposed in [80]. As expected in MACA-CT, since RTS/CTS are exchanged using the common channel, collisions of control packets might occur if more pairs try to initiate data transmission within the same region. However, no collisions of data transmission may occur. On the other hand, in MACA-RT collision of control packets would not occur, unless more than one transmitter tries to communicate with the same receiver. MACA-RT is shown to have a better performance than that of the MACA-CT – as intuitively expected.

5.3 Comparison of MAC Protocols for Inter-Satellite Communication

Table 5.1 gives a comparison of the considered MAC protocols in section 5.2 above. The IEEE 802.11 MAC scheme is a combination of CSMA and collision avoidance (CA) mechanism which can support multiple channels as shown in Table 5.1. Furthermore, IEEE 802.11 is a more mature technology with supplements to the standard incorporating mobility, QoS, mesh networking etc. as detailed in Appendix E. Another major advantage of IEEE 802.11 compared to other schemes is its two modes of operation – DCF and PCF. Hence in

this thesis the best choice is the IEEE 802.11 MAC protocol. However, it still remains to be seen whether IEEE 802.11 can adequately scale up to ISL power and range requirement in a LEO network environment where thousands of kilometers may be required for an ISL length. However, the IEEE 802.11 MAC is already acknowledged as a possibility in [5]. In this thesis, we further investigate the use and optimization of the IEEE 802.11 physical and MAC layers for ISL application.

Protocol	Channel	Single/multiple- hop and flat/hierarchical	Trans. Initiation	Fairness Problem Exist?	Hidden/Exposed Node problems	QoS Aware	Complex Time Synchronisation Needed?
1.CSMA	Single	Multiple and Flat	SI	No	High	No	No
2.MACA	Single	Multiple and Flat	SI	Yes	Minimal	No	No
3.MACA- BI	Single	Multiple and Flat	RI	Yes	Minimal	No	No
4.FAMA	Single	Multiple and Flat	SI	Yes	Minimal	No	No
5.IEEE 802.11	Multiple (FHSS/DSSS	Multiple and Flat	SI	Yes	Minimal	No	No
6.DBTMA	Two channels	Multiple and Flat	SI	Yes	less	No	No

 Table 5.1
 Comparison of the considered MAC Protocols

The dynamic character of the complex and variable network environment is the key problem that puzzles protocol designers of wireless LANs. The DCF of IEEE 802.11 MAC protocol, which is based on CSMA/CA using constant timing parameters, cannot perform well when the network environment changes such as range in mobile ad-hoc networks. As presented in sub-section 5.2.2.1.4, there have been initial efforts to make the IEEE 802.11 MAC based on DCF more efficient, but each mechanism has its own drawbacks. The first mechanism as discussed in sub-section 5.2.2.3.1 known as the binding priority to channel access, leads to unfairness and sometimes leads to starvation being caused by higher priority traffic classes to lower priority ones. Another undesirable characteristic is its susceptibility to bring variability in throughput and delay. The service differentiation achieved through the fair scheduling mechanism also incorporates some of the above-mentioned drawbacks, as it also makes use either a contention window or IFS in the process. The use of different maximum frame sizes for different priority classes also has serious flaws that become noticeable in the presence of channel error. On the other hand, if the frame size is allowed to be arbitrarily large depending on the size of the network-as adopted in [83, 84] - other undesirable effects will be introduced. For example, large networks will have longer MAC superframes which will lead to unbounded delay for time-sensitive applications. There are other proposals to make the DCF "per-stream-fair" as the DCF of the legacy IEEE 802.11 tends to be unfair due to the capture-effect [67, 68]. Fairness is achieved by dynamically modifying the CW of each traffic source. However, this fairness approach does guarantee QoS.

In summary, each work presented above has its own drawback(s) and IEEE 802.11b does not have the capacity to provide MAC-level throughput and QoS for highly volatile LEO networks. This provides enough motivation for us to delve into the problem of the Space-Aware MAC.

5.4 Space-Aware IEEE 802.11 MAC Protocol

We propose a new Space-aware MAC scheme which feature an adaptive back-off mechanism for the reduction of contention in a Space-based WLAN that utilizes random access MAC protocols. This mechanism can be implemented in the existing access scheduling protocol DCF, although it does introduce additional overhead. The proposed Space-aware MAC protocol that takes the LEO satellite network requirements into consideration. It is adaptive and network-aware with respect to the type and intensity of the traffic and relative mobility patterns of the nodes. The main idea of the adaptive back-off mechanism is to estimate the contention level of the shared channel by adapting CW according to the collision and success statistics. The nodes can keep track of the number of collided packets, n_c , via carrier sensing and the number of successful packets, n_s , by counting the number of ACKs. By finding an optimal ratio between the collided packets and the successfully delivered packets, namely the success ratio (n_c/n_s) , and relating this ratio to the optimal CW, the nodes can adjust their CW_{min} values so as to operate at the optimal conditions. Our proposed scheme is similar to the mechanism described in sub-section 5.2.2.4.1 but there is no priority differentiation between the nodes and every node keeps track of the success ratio and contends for the medium fairly using the optimum minimum contention window.

The proposed MAC protocol is targeted at multiple satellite networks using ISLs where the number of satellite nodes contending for the medium known before launch. The DCF of the IEEE 802.11 is optimized and used for the first time for satellite networks. The motivation for this work comes from the observation that the DCF operation in terrestrial wireless networks based on CSMA/CA using constant timing parameters could not perform well when network geometry changes such as range in LEO ISL networks.

5.4.1 The Need for Adaptation of the Contention Window for Space

The selection of an efficient medium access scheme is an important issue in the design of any communication system in which large numbers of nodes which may be independently accessed through a common channel with a limited frequency spectrum. For LEO satellite systems employing many nodes in close proximity, multiple access techniques are essential. This is evident from the following facts 1) Many LEO satellites are needed for global coverage; 2) Communications channels in mobile satellite systems suffer many imperfections such as thermal noise, interference from other satellites, and rapid change of frequency. Another major factor for satellite employing ISLs is the delay and delay variations, which lead to uncertainty with respect to resource allocation using MAC protocols. This leads to inaccuracy with respect to knowledge of the available capacity and offered traffic load at any given time, resulting in inefficient use of resources. For example, a higher priority class satellite with a longer ISL distance could make a request for service first but a satellite with a less distant ISL and with a lower priority service class could then be granted resources. This results in the higher priority satellite user either failing to be allocated available resources or suffering undue end-to-end delay, which degrades QoS and throughput. This may be more noticeable in the case of frequent handovers between satellites. To accommodate these facts, satellite access techniques must evolve from connection-oriented to connectionless protocols with contention (random access) and CDMA such as CSMA/CA in IEEE 802.11.

Several research projects [81, 82, 85] have investigated different aspects of mobility issues in mobile and stationary nodes in WLAN for terrestrial networks. As inter-orbit and crossseam ISL ranges are variable it is necessary to investigate these aspects of IEEE 802.11 in order to achieve high connectivity between satellite nodes in space.

The CSMA/CA protocol of IEEE 802.11b uses a Binary Exponential Back-off (BEB) algorithm that is executed in the following cases: 1) if the node senses the medium as busy before the first transmission of a packet; 2) after each re-transmission; and 3) after each successful transmission. The BEB works as follows: if a medium is determined as busy at the first attempt, the node defers until the end of the current transmission. Prior to attempting to transmit again, immediately after a successful transmission, the node selects a random back-off interval, equal to the Back off Time. The Contention Window is the time during which the network can avoid a collision between packets. After collisions at each attempt, the CW is increased by a factor of two from 31 to 255 [8]. The back-off interval is decremented while the medium is idle and it is frozen when a transmission is detected in the channel. When a

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successful transmission is obtained CW is set to CW_{min} . The effects of setting the CW_{min} to fixed values in a dynamically changing network are 1) Large back-off limits the throughput by introducing unnecessary MAC delay. 2) Unfairness between contenting nodes 3) Long delays in lightly loaded networks and 4) many collisions in heavily loaded networks.

To adapt the stations to LEO satellite network conditions, we should determine the best contention window size for the density of the network. In this thesis, we are proposing a new Space-aware MAC protocol, that includes the adaptation of the CW_{min} to LEO satellite systems. With this feature, our proposed protocol enables angular CSMA, adaptive CW_{min} , Optimum IFSs and Space Division Multiple Access (SDMA).

5.4.2 Space-Aware MAC Protocol Description

5.4.2.1 Selection of Minimum Contention Window Size

Our Space-aware MAC protocol is based on a hierarchical approach consisting of two layers on a common channel. In the DCF mode, a node must sense the medium before initiating the transmission of the packet. If the medium is sensed as being idle for a time interval greater than DIFS then the node transmits the packet. Otherwise, the transmission is deferred and a back-off process is initiated. More specifically, the station computes a random value in the range of 0 to the so-called contention window. A back-off time interval is computed using the random value: T_{back-off} = Rand (0, CW)*T_{slot}, where T_{slot} is the slot time. This back-off interval is than used to initialize the back-off timer. This timer is decreased only when the medium is sensed idle. This timer is frozen when another node is detected as transmitting. Each time the medium becomes idle for a period longer than DIFS, the back-off timer is periodically decremented by one for every slot-time. As soon as the back-off timer expires, the node can access the medium. After each successful transmission by a node, the CW is reset to an initial value CW_{min}. An acknowledgement is used to notify the sending node that the transmitted frame has been successfully received. If no ACK is received, the node assumes that the frame transmission failed and schedules a retransmission by re-entering the back-off process. To reduce the probability of collisions, where two or more nodes start transmission in the same slot time, the contention window is doubled until a predetermined maximum (CW_{max}) is reached. After collisions at each attempt, the CW is increased by a factor of two from 7 to 255, as shown in Figure 5.7. After a successful or unsuccessful frame transmission, if a node has frames queued for transmission; it must execute a new back-off process.

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Figure 5.7 Exponential increase Contention Window size

If we consider a crowded satellite network, setting the CW to a small value may cause collisions and force nodes to increment their contention window size, so some amount of time is wasted due to collisions, and after a while successful transmission can be possible. On the other hand, if the network is lightly loaded, back-off due to CW_{min} may be too long for a small network, where contention is low. In order to adapt the stations to LEO network conditions, we should determine the best contention window size for the density of the network. In this scheme a feedback from the channel status is used to tune the back-off algorithm in a random access protocol.

In this work the analytical model in [86] is used to find the capacity of an IEEE 802.11 MAC protocol and network load conditions in order to optimally tune the back-off algorithm. Our algorithm estimates the collision cost, idle slots and successful transmission. We assume that there are altogether *n* active satellite nodes competing for the use of the shared channel in an IEEE 802.11 Space WLAN. Each of these nodes uses an optimum fixed CW. Our objective is to find the optimum value for CW_{opt} , which maximizes the channel throughput of the IEEE 802.11 Space WLAN. Please note that the amount of satellite nodes in a constellation or formation is always known from the design stage to implementation unlike terrestrial networks where mobile nodes can join the network any time – increasing the network load¹⁵.

¹⁵ However it is possible for later satellites to be launched to join the constellation, but it will always be known before implementation.

In [86] an optimum CW_{opt} is derived, which provides maximum throughput for a given number of nodes or users in the network as follows;

$$CW_{opt} = n\sqrt{2T_c}$$
(5.4)

where T_c is the total time spent during a collision and *n* is the number of stations contending for the medium.Essentially, the four-way protocol in IEEE 802.11 using omni-directional antenna transmission requires the RTS/CTS handshake to resolve the so-called hidden node problem. Therefore the value of T_c is calculated for RTS collisions as:

$$T_c = RTS _ DuRATION + DIFS + \Pr opagationDelayTime$$
(5.5)

The event probabilities derived by Bianchi [86] are used to find the success ratio, n_o/n_s in the proposed algorithm. In [86], τ is the probability that a station transmits in a randomly chosen slot time, obtained as

$$\tau = \frac{2(1-2P)}{(1-2P)(CW_{\min}+1) + PCW_{\min}(1-(2P)^m)}$$
(5.6)

where *m* is the superscript of the maximum value 2^m for the size of the back-off window, P is the probability and CW_{min} is the minimum back-off window size.

If we consider a condition were there is no exponential back-off then m = 0, hence the probability of τ will be independent of P [86], and Equation (5.6) becomes a much simpler dependency on the constant back-off window given by:

$$\tau = \frac{2}{CW+1} \tag{5.7}$$

The probability, P_c , that a transmitted packet encounters a collision, is found as

 $P_c = 1 - (1 - \tau)^{n-1} \tag{5.8}$

 P_i is the probability that a slot will be left idle, given by

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$$P_i = (1 - \tau)^n \tag{5.9}$$

 P_{tr} is the probability that at least one transmission occurs in a slot time, given by

$$P_{lr} = 1 - (1 - \tau)^n \tag{5.10}$$

 P_s , the probability that exactly one station transmits, in other words, the probability of successful transmission is given by

$$P_{s} = \frac{n\tau(1-\tau)^{n-1}}{P_{nr}} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^{n}}$$
(5.11)

Once τ is known, the throughput, S, of the system is obtained by calculating the average time spent transmitting payload data in a slot, divided by the average length of the slot as follows:

$$S = \frac{P_{s}P_{tr}E_{P}}{(1 - P_{tr})\sigma + P_{tr}P_{s}T_{s} + P_{tr}(1 - P_{s})T_{c}}$$
(5.12)

Therefore the throughput, S, can be given as

$$S = \frac{E_p n \tau (1 - \tau)^{n-1}}{\sigma (1 - \tau)^n + T_s n \tau (1 - \tau)^{n-1} + (1 - (1 - \tau)^n - n \tau (1 - \tau)^{n-1}) T_c}$$
(5.13)

where E_p is the time spent transmitting the payload data, σ is the time spent when the medium is idle, T_s is the time spent during a successful transmission as depicted in Figure 5.8. The Success Ratio (SR) can now be found as

Success Ratio =
$$\frac{n_c}{n_s} = \frac{Number of \ collided \ packets}{Number of \ successful \ packets} = \frac{P_c}{P_s}$$
 (5.14)

Therefore SR is given as





where n is the number of the active stations.

The optimum CW_{min} , CW_{opt} , for networks of different sizes is obtained through simulations under saturation conditions as shown in Figure 5.9. For this purpose, the effect of CW_{min} on the normalized throughput percentage performance of the omni-directional IEEE 802.11b is analysed. CW_{min} is set to 31, 63, 127, 255, 511 and 1023 respectively and the throughput performance is investigated. Node parameters¹⁶ for throughput calculations are shown in Table 5.2.

	Table	e 5.2 Parameter values for the modeling and simulation
CWmin	31	L 4000 μ s = 1000 bytes @ 2 Mbps
σ	20 µs	T_s 402 µs = RTS-Duration + DIFS+ Propagation delay
		T_c 402 µs = RTS-Duration + Propagation delay + CTSTimeout
SIFS	10 µs	DIFS $50 \ \mu s = 2 \ \sigma + SIFS$
δ	2 µs	RTS Header + 20 bytes @ 1 Mbps

As seen in Figure 5.9, for a network size of 10 nodes, the maximum throughput, *S*, is reached when the CW_{min} is 63 so the $CW_{opt} = 63$. For a network size of 20 nodes, the maximum throughput is reached when the CW_{min} is 127, i.e $CW_{opt} = 127$. For a network size of 40 nodes, the maximum throughput is reached when the CW_{min} is 255, i.e $CW_{opt} = 255$,

¹⁶ Note that the IEEE 802.11 standards do not specify a length for CTSTimeout and ACKTimeout. We choose Tc = Ts, following the spirit of the IEEE 802.11 standard.

etc.. When we plug these optimum values for CW_{min} in Equation (5.15), for the network with 10 nodes, the success ratio is 0.287, for the network of 20 nodes, $SR_{opt} = 0.301$ and for network of 40 nodes, $SR_{opt} = 0.308$, etc..

Based on Figure 5.9 it can be concluded that the optimum CW_{min} is a complex function of the traffic and the network size and the throughput performance is relatively sensitive to adjustments in CW_{min} .



Figure 5.9 Throughput variation with minimum contention window as a function of the number of nodes

Figure 5.10, shows the probabilities of the slot being in an idle state, having a successful transmission and with a packet collision (P_i , P_s , P_c) when CW_{min} is set to CW_{opt}. As evident from Figure 5.10, P_i and P_s decay exponentially as the number of nodes, n, increases; but these probabilities are significant if the number of nodes is small. The probability of collision, P_c , is also increasing exponentially with increasing the number of nodes. On the other hand, an increase in the number of nodes decreases the probability of successful transmission because of the increased probability of collision.

In Figure 5.11 the success ratio between the number of collided packets and the number of successful packets expressed by Equation (5.15) is represented as a function of n. Interestingly, the SR_{opt} curve varies between the values of 0.23 to 0.31 for different values of n. It can be seen from Figure 5.11 that SR_{opt} can be varied between 0.23 and 0.31 to find the optimum CW that optimizes the throughput for both different channel conditions and network sizes.

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Pc, Pi, Ps versus n with CW = 63



Figure 5.10 Probabilities of the slot time being in an idle state, or in a successful state or in a collision state



Figure 5.11 Success Ratio vs number of nodes

In our proposed scheme, the optimal success ratio is obtained by finding the ratio between the number of collided packets and the number of successful packets. Relating this success ratio to the optimal CW, the nodes can adjust their CW_{min} values so as to operate at optimal conditions. The instantaneous CW_{min} values will depend on the number of contenting nodes over a specific time period, T_s . Hence, the optimum success ratio, SR_{opt} , will depend on the number of collided packets, n_{co} (by counting re-transmissions via carrier sensing) and the number of successful packets delivered, n_s , (by counting acknowledgements).

The proposed dynamic CW adaptation uses an algorithm to get the optimum success ratio in order to adapt the CW_{min} , as shown below.

```
Initialise CW_{min} = 31;

Measure average n_c and average n_s over Ts seconds;

SR = n_c/n_s

Probability_to_Transfer = 1-SR

Transfer_Threshold= 0.23

if Probability_to_Transfer <Transfer_Threshold

CW_{min}=CW_{min}/2;

else

CW_{min}=CW_{min}*2 + 1;

Transfer packet

Initialise Nc, Ns and Backoff_Times_Counter again

Set n_c = 0;

Set n_s = 0;

Set Backoff_Times_Counter=0;
```

5.4.2.2 Adaptive MAC Protocol Implementation in OPNET

WLAN models are part of the standard OPNET [55] modeler 11.0 library. The OPNET WLAN models include: the work stations in Figure 5.11 consist of packet source for packet generation, the sink module for statistical collection and packet destroy; the MAC interface module acting as a primitive to transfer the packet and control attributes to and from the upper layers emulating the Address Resolution Protocol (ARP); and a receiver/transmitter pair. The MAC protocol supports all the functions of IEEE 802.11 such as DCF, which is based on the CSMA/CA and PCF used for the infrastructure mode, as shown in Figures 5.12 (a) & (b).



Figure 5.12 (a) WLAN Station



Figure 5.12(b) OPNET node model of WLAN Station

Figure 5.12 OPNET model of a) WLAN station b) Node of WLAN

The MAC interface process node illustrated in Figure 5.13 shows the init state, which initializes the state variables, used by the model and registers this process as "arp" (address resolution protocol) so that the lower layer MAC can connect to it



Figure 5.13 MAC process interface between the MAC and the upper layers

. The second initialization init2 schedules a self-interrupt to wait for the WLAN MAC process to finalize the MAC address resolution and registration. The wait state obtains the MAC layer information for the local MAC process from the model wide registry such the source and destination addresses. The idle state sets an interrupt for packets arriving for the MAC destined for the node or from the application layer destined for some other nodes. The application state handles packets arriving from the upper layers (source) such as checking for the destination address or randomly generating one. The MAC state handles packets arriving from the MAC state handles packets arriving from the to the sink.

The MAC process node in Figure 5.14 contains all the required functions defined in the 802.11a/b/g standard.



Figure 5.14 The MAC showing both the PCF and DCF modes of operation

The MAC process supports all the DCF and PCF and all the physical layers and their data rates are defined. The MAC process has many transition states and executes appropriate functions. In the *init-state*, all the state attributes and MAC-auto-addressing are initialized, and the WLAN process registration is completed. In the *BSS_init* state, MAC-auto-addressing is completed, network configuration is validated and for the PCF modes, a list of CF-pollable nodes is formed. The state is used as a base station for access point for nodes using the PCF function. In the *IDLE* state, the transmission buffer is emptied and it waits for appropriate interrupts. In the *DEFER* state, receiver status and network allocation vector (NAV) is checked, if busy, it waits until it gets idle and if idle, it waits for inter-frame space time interval (SIFS, PIFS, DIFS or EIFS) before advancing to the next state.

In the *BACK-OFF* state, it waits for the completion of the back-off period and if the backoff is suspended, it computes the remaining back-off duration. In the *TRANSMIT* state, it transmits data/control packets. In the *FRM-END* state, it detects collision if any packet is received during transmission. In the *WAIT-FOR-RESPONSE* state, it waits for the response message until the expected ACK or any type of message is received, or ACK-waiting timer expires. The key functions used to perform operations in the states are given in appendix C. We have implemented the adaptive back-off mechanism and integrated it into the WLAN-MAC process model as shown in Figure 5.15. Three states, *SR-TEST*, *SR_BACKOFF* and *SR_SATISFIED* are inserted into the process model. We have modified states *IDLE*, *DEFER*, *BKOFF_NEEDED*, *BACKOFF* and *TRANSMIT*.



Figure 5.15 The proposed enhanced-WLAN MAC process

The additional pseudo code for states *BACKOFF*, *SR_BACKOFF*, *SR_TEST*, and *BKOFF NEEDED* are given below.

BACKOFF state: The system monitors the channel and keeps track of collisions and retransmissions in terms of time slots.

SR_BACKOFF state:

If Current Contention Window < CW_{min}

Current Contention Window = $CW_{min}/2$

Else

Curent Contention Window = Current_Contention_Window * 2 +1

If Current_Contention_Window > CW_{max}

else

 $Current_Contention_Window = CW_{max}$

Backoff_Time = random_uniform(Current_Contention_Window) Go to BACKOFF state.

SR_TEST State:

SR = Number of collided Packets/Number of Successful Packets Possibility_to_Transfer = 1- SR Transfer Threshold = 0.23 If Possibility_to_Transfer < Transfer_threshold Then

Go to SR_BACKOFF state

Else

Transfer packets

BKOFF_NEEDED state:

Set number of collisions $(n_c) = 0$ Set number of successful transmissions $(n_s) = 0$ Set Backoff times counter = 0

5.5 Evaluation of the Proposed Space-Aware MAC Framework

Having determined the optimal SR around 0.23 to 0.31, we have designed an algorithm that calculates success ratio dynamically in each node and adapts the CW_{min} accordingly. In this way CW_{min} approaches CW_{opt} and eventually SR approaches SR_{opt} . In this evaluation, we considered two performance matrices': throughput and MAC delay. We performed our simulation using the OPNET simulation package. Each run is executed for 90 seconds of simulation time, and models a network of 20 nodes placed randomly in a 10 km X 10 km area.

The propagation model is free space. The transmission rate is 2 Mbps, and the channel is saturated using a constant bit rate - each node has a packet to transmit each time. Figure 5.16

shows the total throughput as a function of simulation time for both our enhanced scheme and the DCF mode of IEEE 802.11. The total throughput/capacity is defined here as the total number of packets actually delivered to their respective destinations in the whole network for a given load during the simulation time. As it can be seen, the throughput in our scheme outperforms the DCF mode defined in the IEEE 802.11 standard.



Figure 5.16 Throughput comparison of the Enhanced IEEE 802.11 vs. the Standard

Figure 5.17 depicts the average MAC-delay incurred for a packet for both schemes. The MAC-delay of a node is the latency involved between the instance at which a packet comes to the head of the node's transmission queue and the end of the packet transmission. As the load increases, there would be an increase in contention, and hence the MAC delay tends to increase in any MAC scheme. However, as shown in Figure 5.17, in our scheme this increase is large as compared to the original DCF mode, which depends on the link bandwidth and CPF repetition interval.

In the case of the original MAC based on DCF, the MAC delay tends to increase significantly with time, which can be attributed to factors such as increased collision rate, and hence increased retransmission attempts and extended BEB delay.

These results show that maintaining the success ratio around 0.2 and adapting the window size accordingly provides the best throughput performance in the network.

Chapter 5 Adaptation of the IEEE 802.11 Medium Access Control Scheme



Figure 5.17 MAC delay comparison of the Enhanced IEEE 802.11 vs. the Standard

5.6 Summary

This chapter describes the design and validation of a Space-Aware MAC in an effort to support high throughput and appropriate QoS in satellite networks. First the MAC design in wireless networks in general and mobile ad hoc networks in particular is examined. The need for research on optimization of the IEEE 802.11 MAC for LEO ISL networks is justified. A review of the state-of-art of MAC protocols is carried out which shows that existing solutions have flaws, and not designed for space networks, and hence cannot be directly applied for LEO satellite communications without modifications. This motivates and justifies our effort to make the IEEE 802.11 MAC Space-Aware, so that it can scale up to the LEO channel conditions.

The proposed protocol makes use of the adaptive contention window concept based on the DCF mode of the IEEE 802.11 standard. This mechanism enables the nodes to compute optimum CW_{min} by using the ratio of the number of collided slots and the successful slots called the success ratio. Simulation results confirm the performance improvement (throughput, MAC delay) of our scheme. In addition, our proposed approach leads to fewer collisions and hence minimizes the need for re-transmission. This fact will in time conserve scarce satellite resources such as battery power and bandwidth on board the spacecraft. The MAC functionality of a node is adaptive and LEO-network-aware depending on the relative mobility pattern of satellite nodes. A major advantage of this scheme is that it is based on the IEEE 802.11 MAC which can be easily integrated into existing terrestrial COTS for space applications.

Chapter 6. Smart-WLAN for Space

Although directional antennas have been used in mobile communications systems for quite a long time, realistic applications of directional or smart antennas in wireless ad hoc network have just emerged in recent years [76, 77]. Directional antennas provide numerous benefits, such as higher gains, increased transmission range and low interference. Wireless medium access schemes play a crucial role in ensuring the efficient and fair sharing of wireless resources. Previous research work on mechanisms at the wireless medium access layer by using directional transmission has assumed equal transmission range when using directional and omni-directional beamforms [76, 77, 78, 79]. The new features of a MAC with directional antennas can cause not only proximity-dependent carrier sensing problems, which have appeared in omni-directional wireless networks, but also affect novel issues related to why directional antennas are used in the first place. Increased capacity (range, and throughput), interference, proximity-dependent carrier sensing problems (hidden, exposed node problems) and support for mobility are the widely used metrics to compare MAC protocols with directional antennas. Given that there are different metrics available to compare MAC protocols with directional antennas proposed in the literature, this thesis is mainly interested in the MAC's ability to support some mobility with increasing ISL range. Some of the requirements of smart antennas for ISL connectivity are outlined in section 6.1. The state of the art in integrating smart antennas with IEEE 802.11 is presented in detail in section 6.2. Justifications for integrating smart antennas with 802.11 are provided in section 6.3. In sections 6.4 and 6.5 antenna modelling in OPNET is described in detail. Section 6.6 describes the switched beam selection technique used. The basic operation of the proposed space-aware directional 802.11 protocol is described in detail in section 6.7. Finally performance evaluations by both analysis and simulation of the proposed protocol are presented in section 6.8.

6.1 Introduction to Space-Aware Directional IEEE 802.11 Protocol

Directional antennas are used to improve the gain on a per-direction basis in wireless communications. The integration of smart antennas with wireless standards to increase

capacity and range while minimizing interference in ISL networks is investigated in this chapter. The main requirements for smart antennas in ISL applications are [58];

- Coverage extension: increased capacity, range and minimum interference between satellites.
- Reduced power requirements as compared to omni-directional antennas.
- Beam agility (gain and directivity) in elevation and azimuth directions to track and access neighbor satellites within the LEO ISL system.
- Beam steering and nulling to minimize interference between ISLs in a predictable but variant LEO geometry.
- Independent transmit and receive directions using array antennas with different power, beamforming and beam agility characteristics to satisfy full duplex communications and maximize ISL network flexibility.

In this section we proposed a new Space-aware 802.11 protocol that takes into consideration some of the requirements, and works in conjunction with location and position finding strategy combined with the predictable and periodic nature of LEO satellites. Our novel protocol architecture is based on the existing IEEE 802.11 standard, and thus can be relatively integrated into the existing system. It is based on switched beams, that is adaptive and LEO network-aware depending on the type of ISL and relative mobility of the satellite nodes. The main motivation behind this idea in essence is three fold: i) it enables capacity increase of the IEEE 802.11 protocol – which is important for LEO networks to provide better link connectivity; ii) it enables spatial division multiple access for higher throughput and iii) it enables minimization of interference between satellite nodes by using alternate beam switching. Our strategy enables improved connectivity between two satellites through a beam selection algorithm, under the control of the MAC protocol. Simulation and analytical results confirm the performance improvement of our strategy.

Our proposed protocol is targeted at satellite constellations and formation flying systems, in LEO satellite networks using ISL. As mentioned before, the DCF mode of the IEEE 802.11 MAC sub-layer is used in these LEO ISL network scenarios. Although the PCF can be used and does require a centralised node, we describe how this can be used in conjunction with DCF in satellite formations, as future work.

6.2 WLAN with Smart Antennas

With the quick emergence of wireless mesh network solutions for broadband wireless connectivity, the physical layer technologies are making remarkable progress allowing higher bandwidth and longer distance. The IEEE 802.11 standard is designed for omini-directional mode of transmission with a maximum distance of a few hundred meters. As a consequence, there are many technical challenges for adopting IEEE 802.11 with smart antennas and outdoor environments.

Smart antennas offer a variety of potential benefits for wireless communication systems. In particular, it can improve spatial reuse, transmission range and hence network capacity. The integration of the physical layer and the medium access control schemes has been addressed with respect to mobile ad hoc networks where nodes are equipped with smart agile directional antennas [76, 77, 78, 79]; however, space applications have not been targeted yet. The argument behind these proposals is that the current protocols using omni-directional RTS and CTS can waste wireless bandwidth by reserving the wireless medium over larger areas than actually required. The assumption made is in most of these proposals is that the transmission could be made in either omni-directional or directional way while the reception is omnidirectional only. CTS frames are always transmitted omni-directionally, while RTS could be transmitted directionally or omni-directionally. The use of directional RTS can increase spatial reuse while using omni-directional RTS can reduce the chance of CTS and/or ACK collision. So in these techniques there is a trade-off between spatial reuse and collision. In general, the use of directional antennas leads to high spatial reuse since data and ACK are transmitted directionally, thus reducing interference regions. One strong assumption made in [76] is that each node knows exactly the location of other nodes by using location information derived from the physical layer parameters using GPS signal. Considering the problem of locating and tracking down mobile nodes in wireless networks, another MAC has been proposed in [77] that does not require additional hardware to identify the directions of specific nodes. The following sub-sections describe some of the research work carried out in extending IEEE 802.11 for long range.

6.2.1 MAC Protocols with Switched Beam Antennas

In single beam systems, nodes are equipped with a switched beam system and they choose on the predefined beams based on a beam selection criterion. A directional antenna can

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transmit over a small angle and several directional antennas can be used to cover all directions e.g. four antennas with 90° aperture. Based on location finding the sender may select the appropriate directional antenna to communicate with a receiver. Location finding can be (a) a Global Positioning System (GPS) [76], or (b) a Direction-Of-Arrival (DOA) method, or (c) a node may inform its location information to its neighbours periodically using beacons [95].

In [76] the Directional MAC (D-MAC) protocol has been proposed, where RTS packets are exchanged directionally and the data packets are also sent directionally. In this proposal, it is assumed that every node knows its neighbours' location. As defined in IEEE 802.11, if node X is aware of an on-going transmission between two other two nodes (due to receipt of RTS or CTS from other nodes), it will defer transmission. It will not participate in a transfer itself, while the transfer between two nodes is in progress. The directional MAC protocol applies the same principle, but on a per-antenna basis, i.e., DMAC performs carrier sensing on a per-antenna basis. If antenna T at node X has received an RTS or CTS related to an ongoing transfer between two other nodes, then node X will not transmit anything using antenna Tuntil that transfer is completed. Antenna T is put into 'blocked' state for the duration of the transfer. The duration of the transfer is defined in the RTS and CTS packets; therefore, each node can determine when a blocked antenna should become unblocked. RTS packets are sent in omni mode if none of the directional antennas are blocked, and are sent directionally if and only if none of the directional antennas are blocked. However, CTS packets should always be sent in omni mode. However, after the channel is reserved between 2 nodes, data is sent directionally.

The protocol proposed in [76] has a better throughput performance than the IEEE 802.11 where in some of their simulation scenarios, the throughput is doubled. In the DMAC protocol, the location information is included in the RTS/CTS messages, where nodes get their own positions using GPS.

In [77], a MAC protocol is proposed for single beam directional antennas, where the location information is obtained by DOA. This algorithm depends on selecting the antenna on which the maximum power has been received. All nodes are equipped with directional antennas. The nodes exchange RTS and CTS packets in omni-directional mode and the power and direction information is extracted from the RTS/CTS messages. The antenna selector compares the received signal power at the antennas and chooses the antenna with maximum power. Then, the receiving node replies by a CTS packet in omni-directional mode. This time the sender node selects its best antenna similarly, as shown in Figure 6.1.

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Figure 6.1 Operation of the DOA based MAC [20]

After RTS/CTS exchange, the data packet is sent and captured with the selected directional antennas. Simulation results in [77] show that, the peak throughput nearly doubles when 180 degrees directional antennas (2 beam sectors) are used in place of omni-directional ones. On the other hand when the number of directional antennas per node is increased beyond 2, the incremental improvement of throughput is less pronounced. For example with 4 directional antennas the improvement is 2.5 or 3 times over the omni-directional mode.

In [104] sector antenna directivity by dividing the channel is proposed, which is named as "Directional CSMA/CA (D-CSMA)". In this proposal many nodes can transmit their packets simultaneously making the channel usage efficient. The nodes adjust their NAVs in each sectored antenna. Even with one available sector in a node, when a packet arrives, a node can transmit its own packets by the available sectors left after sensing and contending for the channel. In Figure 6.2, the meshed sector is the adjusted NAV.



Figure 6.2 System image of D-CSMA [104]

After the handshaking between STA1 and STA2, STA3 can transmit data to STA4 by using the available antenna. Hence, there is a case when STA1 can share the same channel with STA3 at the same time.

There is a major drawback in the proposed protocols of [77] and [104]. Deafness problems occur when a node attempts to transmit to another node that is already busy in a direction that cannot be detected by the attempting station. Successful collisions and re-transmissions occur and the throughput gained from directional transmission is substantially reduced.

In [105, 106] proposals are made to solve the deafness problem by using a tone directional MAC (Toned MAC) algorithm. They suggested using some portion of the frequency (in-band signalling) as a control channel in the same band of wireless local network to warn the surrounding nodes. Surely, this will need a new regulation in the ISM band used by WLAN to implement their proposal.

In [107], Korakis et al proposed to steer RTS beams and send data in different directions sequentially. This requires time delays to finish steering and establishing links. During steering interval all nodes in the network are required to remain silent, thus waste of network capacity. Furthermore, the exchanged RTS and CTS messages in [107] do not allow the other nodes to start communication immediately after start-up.

The next subsection considers MAC protocols proposed for adaptive beamforming systems.

6.2.2 MAC Protocols with Adaptive Beamforming Systems

Adaptive beamformers rely on algorithms that can steer the main lobe of the antenna beam in the direction of the desired user and simultaneously place nulls in the direction of interferers. The trade-off in the beamforming systems is the effect of the length of the training sequence. Popular beamforming algorithms like LMS, RLS use a training sequence to obtain the desired beam pattern, while blind beamforming methods such as the CMA do not impose such requirement. Please refer to appendix E for adaptive antenna algorithms.

Single user beamformers allow nodes to change the direction of their single beam pattern to the signal of interest more accurately than a single switched beam system. Larger Short Interframe Time Space (SIFS) time (the shortest time interval between frames) or longer RTS/CTS packet sizes have been proposed to allow more time for antenna adaptation [108].

In [109], a MAC layer protocol is proposed for ad hoc networks with nodes that are equipped with smart antennas using a single user beamformer. In the proposed protocol, training packets are exchanged after the successful reception of RTS and CTS packets. As shown in Figure 6.3, the transmitter and receiver exchange training sequences, TXTRN and RXTRN, which are used at both ends to adjust the antenna weights. Then data packets are transferred to the destination node directionally. After the transmission ends, the antennas are set back to omni directional mode.


Figure 6.3 MAC timing diagram for an adaptive beam antenna integration [26]

It is also important to note that, the Network Allocation Vector covers until the end of TXTRN packet for neighbours in omni directional mode. On the other hand, network throughput drops and the packet delay increases rapidly with increasing the training packet size. Furthermore training periods greater than 20% of payload reduce the throughput considerably while training periods lower than 6% of the payload increase the throughput by three times as compared to the systems where isotropic antennas are used instead of smart antennas [109].

In [108] beam forming in PCF based access is proposed by Acampora et al, which involves a pilot tone from each remote user to allow the base station to continuously adjust the weighting coefficients. In [108] frames of fixed length are assumed. Each remote node is polled exactly once in every frame where there is a polling segment and a data segment.

6.3 The Need for Integration of Smart Antennas with IEEE 802.11 for Space Applications

As discussed in section 6.2 there have been efforts to increase the range of IEEE 802.11 via employing smart antennas for data transmission, however, the proposed mechanisms assume the use of an omni-directional mode of transmission for at least one control frame, which could not provide better capacity in LEO networks. In addition, almost all schemes tend to not take mobility of nodes into consideration. Without considering mobility, which is the main source of uncertainty in LEO satellite networks using ISLs, the direct applicability of these schemes in relatively volatile LEO networks is questionable.

The need for integration of smart antennas with IEEE 802.11 for LEO ISL communications can be justified by examining two categories of issues: (a) issues related to the outdoor, longer distance use of 802.11, which it was not designed for. (b) more generic issues related to the design of physical and MAC layer protocol for space use. We start our discussion with the physical layer and then move up the MAC layer subsequently.

6.3.1 Physical Layer Issues

6.3.1.1 Empirical Path Loss Models

The first challenge we face is to figure out how far IEEE 802.11 transmissions would go. Range is a function of effective transmitter power, path loss, receiver antenna gain, and receiver sensitivity. Receiver sensitivity for most of the commercial products is about -85 to -90 dBm while transmit power is about 15-20 dBm. Some products provide external connectors to which high gain antennas can be attached. The power received by an antenna that is separated from a transmitter antenna by a distance d in free space is given by the Friis free space equation, the model used in OPNET.

$$P_{r}(d) = \frac{P_{t}G_{t}G_{r}\lambda^{2}}{(4\pi)^{2}d^{2}} = P_{o}\left(\frac{\lambda}{4\pi d}\right)^{2}$$
(6.1)

Where $P_r(d)$ = received power, which is a function of d, P_t = transmitted power, $P_0 = P_t G_t G_r$, G_t = transmitter antenna gain, G_r = receiver antenna gain, d = transmitter to receiver separation in meters, and λ = wavelength in meters.

The Free space gain is defined as

$$PL_{FS} = 20\log\left(\frac{4\pi d}{\lambda}\right) (dB)$$
(6.2)

where P_{LFS} is the free space path loss and usually expressed in decibels.

However, additional channel conditions would be applicable in space conditions such as trospospheric conditions, drag, temperature variations, propagation delay variations between satellites, etc. Antenna angular variations due to high satellite mobility can be another reason because of which signal strength fluctuation can happen at the receiver. The next challenge is to estimate how much area can be lit up by a single transmitter, for last-hop access. Our aim is to increase the range and coverage area of IEEE 802.11 transmission/reception in space conditions using smart antennas. In these cases, if a given area (number of satellites) can be lit up with fewer transmitters, overall the system cost can be reduced.

6.3.1.2 IEEE 802.11 Physical Performance for Outdoor Use

Satellite constellations have a time varying network topology. Given that ISL are formed between two satellites that are moving at very high velocities with respect to each other and Earth, the network topology can change rapidly but in a periodic and predictable way. This dynamic nature of LEO satellite ISL coupled with poor channel conditions and interference may cause excessive link failures. As a result of the time varying nature, satellites may face a change of topology and connection during a session.

The IEEE 802.11 PHY has been designed to operate under indoor channel conditions where the Root Mean Square (RMS) delay spread is of the order of 100 ns. Delay spreads of 1 microsecond or more, which is linked to long-distance outdoor scenarios can cause severe multipath loss Equalizers built in current IEEE 802.11 radio chip-sets are not designed to cope with such high delay spread channels. Adding equalizers would potentially solve such problems. However, the above problem does not surface in space communication and long-distance links since they are almost free from multipath loss. Satellite antennas mounted above the ground surface ensures that there is no Freznel zone between two satellites.

6.3.1.3 **Power Efficiency**

Power in LEO network is critical. Satellites are energy-constrained operated, with a limited battery life and rely on solar energy, power conservation is a critical design criterion. The use of radio for communications can significantly affect battery life. On the other hand, satellite transmit power should be optimal so as to sustain the highest possible data rate, while keeping the adverse interference effect on the other neighbouring concurrent transmissions minimal from other satellites. Wireless devices on board should offer advanced power management support to maximise battery life.

6.3.2 MAC Layer Issues

The IEEE 802.11 MAC is designed for operation when a small number of users share a channel in an indoor setting. First, the value for the ACK timeout is too small to work over long-distance links (Packet propagation delay over 15 km is 50 μ s). Similarly, in the IEEE 802.11 contention-based MAC, the contention slot-time requires adaptation to long range (default slot-time value is 20 μ s). Furthermore, the case of a node with directional antennas is the classic case of hidden nodes. Bandwidth and capacity are constrained, since LEO satellites are limited by size, power and processing power, Inter-satellite links will continue to have significantly lower capacity than wired (terrestrial) networks and hence congestion and asymmetric links can be more problematic.

6.4 Antenna Model

In our work the beam patterns are predefined and fixed according to the radiation pattern of the directional antennas used. An antenna pattern defines the gain on a per-direction basis. Directional antennas in wireless systems are designed to concentrate high gains within a concise region. In the event that the communicating nodes are stationary, the antenna can be pointed in a direction to achieve maximum gain. On the other hand systems that contain mobile components, it might be of interest to either alter the antenna pointing direction or switch the beams periodically to maximise the gain.

6.4.1 Antenna Pattern Usage

The antenna model consists of a set of gain value that varies as a function of the direction in three dimensions. Physically, an antenna can be thought of as a three-dimensional object whose shape indicates the relative magnitude of gain in each direction. The simplest case is the sphere, which represents an antenna pattern known as isotropic, which radiates power equally in all directions. Its gain is zero dB at all points as shown in Figure 6.4.



Figure 6.4 Isotropic antenna pattern

Because the antenna pattern map gains in all directions in a three dimensional space, it can be represented as a function of two angle variables called θ and ϕ (theta and phi). As shown in Figure 6.5, the angle ϕ varies from 0 to 180 degrees and the variable, θ varies from 0 to 360 degrees. Together they can uniquely specify all directions in terms of vectors departing from the centre of the pattern.



Figure 6.5 Antenna pattern representation in OPNET

OPNET offers the ability to define antenna patterns using the antenna pattern editor. Figure 6.6 shows the antenna module and its associated attributes.

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Radio transmitter	Allow packet to be sent outside of the node's boundary via radio link	
Radio receiver	Allow packet to be received from other nodes via radio link.	
Antenna	Optionally can be used to exchange packet with other nodes, when antenna directionality or gain need to be modeled.	

Attribute	Value	-
name	ant	1
pattern	cone	
pointing ref. phi	0.0	
pointing ref. theta	180	
target latitude	0.0	
target longitude	0.0	
target altitude	0.0	
icon name	antenna	
Extended Attrs.		*
Extended Attrs.	1 Objects	

Figure 6.6 Antenna model attributes in OPNET

The pattern editor is associated with both the radio transmitter and receiver to provide gain using an antenna module in the node editor. This module provides an attribute called "pattern" that allows for the specification of the pattern. A reference point on the antenna pattern is required for pointing the antennas pattern and aiming the antenna pattern are attributes of the OPNET model, they can be accessed and changed during simulation. Phenomena like an antenna tracking a target or the rotation of an antenna can be incorporated. There exist two more attributes of the antenna module that define this pointing direction. These attributes are called ref.phi and ref.theta. Three more attributes are defined for target location for which the antenna pointing reference can be pointed. These attribute are called target latitude, target longitude and target altitude. The attributes can be accessed-using kernel procedures like op ima obj pos get () to attain a location of a mobile node and op ima obj attr set () to dynamically change the value of an attribute like target latitude, or pointing reference. In OPNET, to get location information of nodes, we need its object ID. All nodes register these IDs in a global array that is accessible to all process nodes. We use a process model called the pointing processor which can retrieve the node object ID of other nodes from global array by using kernel procedure op ima obj pos get () and update the node antenna's target location.

6.4.2 Smart-WLAN Antenna Model

The performance of the directional antennas is quantified by the directivity of the main beam, i.e. its beamwidth. Beamwidth can be specified between half power points, half-power beanwidth (HPBW), or the beamwidth between first nulls (BWFN). As illustrated in Figure 6.7. The second performance measure is the beam selectivity, which measure the gain in out of beam directions. The specific patterns can be quite complex and will depend on the specific design of the antenna. In our simulations in OPNET we use a more generic model called the beam and ball which is illustrated in Figure 6.7. It accurately models the characteristics of a main beam but blurs the variation of the sidelobes as a single gain in all directions. This model is very generic but provides a computational simple model to access gain in all directions. The calculation occurs in two steps. First, the angle between the main beam and the direction of a receiver is determined and then this angle is used to access the gain. Let u be the unit vector that points in the direction of the main beam. Let r be the unit vector towards the receiver. The vector r can be determined by using

$$r = \frac{z - s}{|z - s|} \tag{6.3}$$

Where s and z are the coordinates of the source and destination locations provided by a DOA algorithm or GPS. The angle between these directions, θ can be calculated by using the inner product

$$\theta = ar\cos(u^T r) \tag{6.4}$$

And the gain is calculated using

$$g = \begin{vmatrix} g_{mb} \frac{\sin(\theta)}{\theta} & \theta \le \frac{BWFN}{2} \\ g_{mb} - g_{oob} & \theta > \frac{BWFN}{2} \end{vmatrix}$$
(6.5)

Where g_{mb} is the maximum gain in the mainbeam direction and g_{oob} is the difference in gain from the mainbeam in the ball directions. In the beam and ball model g_{oob} =MSLL (Maximum sidelobe level)



Figure 6.7 An illustration of a beam and ball model

The beams illustrated in Figure 6.8 show ideal and realistic cases. Consider two patterns: the first antenna pattern assumed to have an ideal shape with full reception in the desired direction and rejection in other directions. The second figure considers a more realistic case with side lobes having a 20dBi of directional gain with a 90° half beam width and about 40dB front to back ratio. For modelling this antenna, we use



(a) Ideal pattern

(b) Real pattern

Figure 6.8 illustration of a) Ideal and b) Realistic antenna beams

real patterns as specified in commercial devices. We then put together four beams as shown in Figure 6.9 for both the ideal and realistic cases. Using these four beams in the antenna model we can cover all four different directions: North-East (*NE*), North-West (*NW*), South-East

(*SE*) and South-West (*SW*). We assume that each satellite node uses all four individual beams in order to cover all four directions and switch between beams as directed by the MAC protocol. In this thesis, we modelled antenna patterns using the pattern editor of OPNET and we designed a beam selection algorithm that directs the beams in specific directions as dictated by the MAC. The assumption is that there must be some difference between power levels or BER of the two simultaneously arriving packets in order to capture the more powerful packet from one beam and to avoid beam falsing. As the normal rejection ratio ranges from 1 to 20 dB [36], we used 20 dB as a rejection threshold in our physical model.



(a) Ideal Beams

(b) Realistic beams



As illustrated in the ideal beams in Figure 6.9, the four perfect antenna beams cause overlap regions of total 2° at the beam edges. These overlap regions are blind angles where packet reception, i.e. capture can be very difficult. Using these models in OPNET, we experiment with packet capture events by keeping one of the nodes fixed and the other rotating around the fixed node, we then measure the effective aperture of the ideal antenna pattern. As illustrated in Figure 6.10(a) the packet capture is function of the angle of arrival ranging from 0 to 180 degrees. This experiment proved that the effective aperture of the ideal antenna is 88°. Hence, two nodes within 88° with respect to each other can communicate, otherwise the packet will be lost.



6.10(a) Packet capture of ideal pattern vs. angle



6.10 (b) Packet capture of real pattern vs. angle



As shown in Figure 6.10(b) for the realistic beam, there are overlapping regions between beams. The same experiment is repeated for the realistic beam and the effective aperture per beam is measured as 70° . These experiments show that the orientation and position of satellite nodes with respect to each other is important for successful packet capturing with directional antennas.

In our scenarios, we assume that satellite nodes are deployed in such a way that they face each other from a non-blind angle. In LEO satellite networks, both the azimuth and elevation angles are predictable and periodic. In our model, LEO satellite networks with known orientations and positions are simulated in STK and then used in OPNET to design our antenna beam patterns for protocol analysis as shown in Figure 6.11.





Figure 6.11 An illustration of antenna beam pattern in OPNET

The beam selection is described in section 6.6. Satellite nodes can monitor the signal level on all beams, and choose the best beam. The best beam is defined as the beam over which a node gets the highest SNR.

6.5 Switched Beam Antenna Selection

One of the most important tasks of designing a switched-beam array system is to develop an efficient scheme for beam selection, in such a way that a node can quickly and efficiently switch on to the correct beam, which covers the area where the target node belongs. The signal transmitted from every node is received through each of the predefined narrow beams at the destination node. Thus, the destination node must be able to determine which of the preset beams should be selected, in order to extract the individual signal. The primary factor that determines the performance of the smart antenna is the accuracy of the beam pattern that is provided by the weight vector. Another important factor is the speed of obtaining the beam pattern, especially for adaptive array systems, because the weight vector has to be computed for every snap shot of the input signal. This means that the new beam pattern formed, is from the datum of the previous received signal and the target might have moved to a new location resulting in mis-tracking. However this problem of the beam forming speed does not seem to be that serious for switching beam arrays, since the beam selection can be done fast enough to decide which beam the target belongs before the target moves to a different beam. Although adaptive beamformers have a high degree of directional control but that is at the expense of high cost and complex hardware. On the other hand, switched fixed beams using phased arrays of antenna elements offer a more cost effective solution, but are less controllable and are less optimized.

A smart antenna steering algorithm operates in response to different functions monitored by the MAC layer. One function is when the MAC layer indicates that the node has received D-RTS or D-CTS packets and in response, the antenna algorithm stores the index of the currently selected antenna and selects the best beam based on a set of criteria. Satellite nodes are equipped with a smart antenna as well as an antenna steering algorithm that enables the antenna to switch electronically to a particular directional antenna beam. Signal quality information, such as a Received Signal Strength Indicator (RSSI) or a SNR¹⁷ is typically used to determine or steer a preferred directional antenna beam. However it is difficult to accurately measure signal quality information when the received signal includes undistorted signals plus random noise. In addition, the signal may be distorted and directional interference may be added in the received signal. Consequently, signal information alone may always not be a reliable indicator of the quality of the radio link. This is especially true in radio environments that are particularly rich with interference coming from other satellite nodes and ground stations or other types of noise and interference sources. However, the use of link quality metrics (LQM) such as Frame Error Rate (FER) as an alternative to (or a combination of) RSSI is beyond the scope of this thesis.

In view of the forgoing background, it is therefore an objective of this research to provide a simple antenna steering algorithm that response to functions performed by the MAC layer of the satellite node affecting the radio link. Typically the signal quality metric (SQM) that is most readily available from the physical layer is the RSSI which is measured at the PLCP header for each packet RSSI is used as the metric for the antenna steering algorithm, and is then provided to the SQM module by the MAC layer as shown Figure 6.12. The RSSI will hold for both reception and transmission, although to a lesser degree, since in the IEEE 802.11 WLAN the wireless physical channel is a shared media. The wrong beam determination can occur, for example, when the scan indicates a better main beam having an RSSI that exceeds the RSSI of the current main beam by a signal drop threshold (e.g. some dB value).

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¹⁷ A beam selection algorithm based on maximum SNR is given in Appendix F.



Figure 6.12 Transceiver architecture of Directional MAC protocol using switched beams

There are a number of ways to calculate the RSSI lower control limit. The one used in this thesis, is to use both a mean of RSSI and two times the standard deviation or 2σ . The RSSI lower control limit is given as follows:

$$\overline{RSSI} = \frac{1}{Q} \sum_{i=0}^{N-1} RSSI_i$$
(6.6)

where Q = RSSI window size in frames, and σ_s is

$$\sigma_{s} = \sqrt{\frac{1}{Q} \sum_{i=0}^{N-1} (RSSI_{i} - RSSI)^{2}}$$
(6.7)

Where $RSSI_i$ is the RSSI value reported for frame *i* and the *N*-*I*th frame is the most recent frame.

6.6 Space-Aware Directional WLAN Protocol Description

The smart antenna technology is directed at having the ability to change the radio beam transmission and reception to suit the medium within which the radio communication systems operate, providing relatively high gain without adding excessive cost or system complexity. However, the deployment of smart antennas for use in wireless communications creates new problems such as node deafness, hidden node problems, and difficulty in determining locations of neighbouring nodes. Although the use of directional antennas has received attention fairly recently, there are a number of interesting studies on designing a suitable MAC protocol to try to address the problems above [76, 77]. Most of the studies propose protocols that do not deal effectively with the problem of hidden nodes due to asymmetry in gain; they do not incorporate any functionality to inform a sender's and/or receiver's directional neighbours (the neighbours that are beyond the omni-directional radial range) of the intended transmission. All of these studies assume at least one omni-directional or directional control packet transmission or reception. Any omni-directional transmission in the IEEE 802.11 handshaking frame will limit the directional coverage range to the omnidirectional range as the maximum distance between two nodes is defined by the smaller coverage range of the four handshake frames [107]. Assume RTS is transmitted omni directionally while the other three frames (CTS, DATA, and ACK) are transmitted directionally. Then the directional modes transmissions must reduce their transmission energy, to cover no more than the coverage area of the RTS. This clearly constitutes a disadvantage of the mentioned MAC protocols as in this way they do not exploit one of the main features of the directional transmission, the increase of the coverage range.

However, in this section, we propose a protocol based on the concept of IEEE 802.11 protocol, using two modes of transmission: directional and omni-directional. A directional antenna is used to transmit over smaller angles (e.g., 90 degrees), and four directional antennas are used to cover all directions. Therefore, satellite nodes can transmit and receive in omni-directional mode using all the directional antennas, if and only if none are blocked, as will be explained section 6.6.3.

Nevertheless, it uses only directional transmissions, increasing in that way the coverage area. Moreover, the transmitter informs the neighbors about the intended transmission to defer their transmissions by using all the four directional beams. Finally, our proposal assumes a priori information about neighbor satellite's locations using the GPS. It provides a simple scheme for recording and maintenance of neighbours' location by maintaining a MAC table.

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The following are a number of assumptions made in this thesis regarding the satellite network architecture, satellite node capacity, communications parameters, and the network traffic of the considered LEO network with ISLs:

- Satellite nodes are at least equipped with four ISLs: a MAC, and four transceivers for communication with four neighbouring satellites.
- It is assumed that satellite nodes are identified by fixed identities (IDs) (for example, based on IP addresses)
- All the satellite nodes in the constellation are identical and have equal capabilities unless explicitly mentioned. This means that all satellites are equipped with identical communication devices and capable of performing functions from a common set of networking services. However, all nodes may not necessarily perform the same function at the same time.

In this section the basic protocol operation will be discussed and the required elements of the protocol are given in detail.

6.6.1 Medium Access Table

In our proposed protocol, every satellite node uses a medium access table to keep the locations of neighboring nodes. The fields of the tables are created for each neighbor in every node. The nodes get information about communication around them both through packets and through the carrier sensing mechanisms to fill the appropriate fields of the MAC table. For example, the neighbour's address field is filled by getting packets from neighbours. The MAC table and meanings of the fields are shown in Figure 6.13. The need for such tables was proposed in [107] but we have improved on that approach by adding new table entries in order to overcome the problems of interference in LEO ISL networks.

Me	Neighbour's	My Beams	Neighbour's	E	Beam blo	cking	
	address		Beam	Beam 0	Beam 1	Beam 2	Beam 3

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<u>Field</u>	Meaning
Me	: Who am I?
Neighbour's Address	: Who is in the range of me?
My Beam	: My best beam to communicate with the neighbour in the list
Neighbour's beam	: Neighbour's best antenna and beam to communicate with me
Beam Blocking	: Which beams should I block?
	Figure 6.13 The MAC Table

6.6.2 Packet Formats

In IEEE 802.11, the optional RTS and CTS packets are normally used to inform other nodes about intending packet exchange between nodes to reserve the medium for a limited time by setting their NAV. In our proposed protocol, these packets are not only used to reserve the medium but also to give the best beams to communicate with neighbours. For this reason we have added new fields to these packets.

The format of the modified RTS, called Directional-RTS (D-RTS), is shown in Figure 6.14. In addition to the existing fields of the RTS, the D-RTS has an extra "Transmitter Beam Number" field.

Octets:	2		2	1	6	6	4
				Transmitter	Transmitter	Receiver	
	0	ol	ion	Beam	Address	Address	
	Frame	Contr	Durat	Number			FCS

Field	Meaning
Duration	: Duration of the communication to set NAV
Transmitter beam number	: The beam number of the source signal
Receiver Address	: destination node address of the packet
Transmitter Address	: Source node of the packet
	Figure 6.14 D-RTS Frame Format

In addition to the existing fields of the CTS frame, Directional-CTS (D-CTS) packet has a "Transmitter's Best Beam Number" and "Receiver's Best Beam Number" fields added as shown in Figure 6.15

			a Julia	Transmitter	Receiver	Transmitter's	Receiver's	
a	,	lo	ion	address	address	Best beam	Best beam	
Frame	TIMT T	Contr	Durat			number	number	FCS

<u>r ieiu</u>	wiedning
Duration	: Duration of the communication to set NAV
Receiver Address	: destination node address of the packet
Transmitter Address	: Source node of the packet
Transmitter's best beam number	: Transmitter will send packets over this beam
Receiver's best beam number	: Receiver will accept packets over this beam

Figure 6.15 D_CTS Frame Format

6.6.3 Basic Protocol Operation

The D-RTS/D-CTS signals are used for collision avoidance between nodes before and after beamforming. In Figure 6.16, the MAC timing for the switched beamforming is shown.



Figure 6.16 The Proposed D-MAC Timing Scheme for switched beams

The antenna controller shown in Figure 6.17 selects the best transmit and receive antenna beam patterns in accordance with the commands obtained from the MAC sub-layer. While forming the transmit beam the controller needs to know the value of the desired angle of

transmission with respect to the antenna axis. In both transmit and receive beamforming the antenna can operate in two fundamental modes: omni-directional (using four directional beams) and directional. The omni-mode is used during handshaking and beamforming, while the directional mode is used during data transfer. We now describe the basic operation of our proposed protocol using the example scenario given in Figure 6.18.



Figure 6.17 Modeling of a wireless node of a Switched beam antenna system in OPNET

Suppose Satellite node S_{22} wants to transmit a packet to satellite node S_{21} in the same orbital plane using the Intra-Satellite link. Node S_{22} sends a D-RTS packet in every direction. After getting a packet from node S_{22} to node S_{21} and decapsulating it, every surrounding node will be aware of packet exchange between nodes S_{22} and node S_{21} . Each satellite reads the receiver address and if a node is the destination, it marks the maximum power received beam, which is in the direction of the source node, to be used for data exchange.

The nodes other than the destination node block their own beam at that direction (signal direction obtained from received beam) so as not to interfere with the data exchange between nodes S_{22} and S_{21} . After getting the D-CTS packet from node S_{21} , a node may remove the blocking condition on its beam in the direction of node S_{22} , if that beam does not interfere with S_{22} and S_{21} 's communication. While blocking the beams, a timer is set after reading the duration field of the received D-RTS packet.



Figure 6.18 Simple topology of a LEO satellite constellation using switched beams

This is called Directional Network Allocation Vector (D-NAV) in [76], which in fact is similar to the NAV of IEEE 802.11 but this time, for a specific direction. The beams are released after this timer expires. After getting the D-RTS[2, S_{22}, S_{21}] packet, node S_{21} records the name of the node in its neighbour list, the index number of its receiver's best beam (beam numbered as 4 in Figure 6.18), which is to be used during communication between the two nodes. Node S_{21} also determines its best beam in the direction of node S_{22} , and records it in the appropriate field in its list. The best beam is defined as the beam over which a node gets a

signal with maximum SNR value. In this case, since the destination is node S_{22} , itself, it blocks all the beams except the best beam (beam 4).

Now, let us consider the other nodes in the scenario. Satellite node S_{12} gets the D-RTS $[3,S_{22}S_{12}]$ packet from S_{22} , and encapsulates it and record node S_{22} into its neighbours list while noting beam number of node S_{22} under neighbour's beam field and the best beam of itself in the direction of node S_{22} , which is the beam with the best reception with respect to node S_{22} . Node S_{12} also marks "yes" to blocking field in that direction not to cause packet collision at node S_{22} . Table 6.1 shows the configuration of the table at each node, after the D-RTS packet is received from node S_{22} .

Me	Neighbour's	My Beam	Ncighbour's		Blocking		
	Address		Bcam	Beam 1	Beam 2	Beam 3	Beam 4
S ₂₂	S ₂₁	2	4	Yes	No	Yes	Yes
S ₂₁	S22	4	2	Yes	Yes	Yes	No
S ₁₂	S ₂₂	1	3	Yes	No	No	No
S ₂₃	S ₂₂	2	4	No	Yes	No	No
S ₃₂	S22	3	1	No	No	Yes	No
							1

Table 6.1 Complete list after getting D-RTS from Node S22

Table 6.2 shows the configuration of the table at each node, after the D-CTS packet is received from node S_{21} .

Table 6.2 Complete list after getting D-CTS from Node

Me	Neighbour's	My Beam	Neighbour's		Blocki	ng	
	Address		Beam	Beam 1	Beam 2	Beam 3	Beam 4
S ₂₁	S ₂₂	4	2	Yes	Yes	Yes	No
S ₂₂	S ₂₁	2	4	Yes	No	Yes	Yes
S ₁₁	S ₂₁	1	3	Yes	No	No	No
S ₃₁	S ₂₁	3	1	No	No	Yes	No

After D-RTS/D-CTS handshake, node S_{22} sends the data over its second beam to node S_{21} 's fourth beam. Other nodes are also allowed to communicate with each other by sending new D-RTS packets over unblocked beams which will interfere with communication between nodes S_{22} and S_{21} . Therefore, if antennas and medium are available, a node can communicate with another node without interfering with the ongoing transmission. This is called Spatial Division Multiple Access (SDMA). The network throughput is doubled where two data streams exist in the same basic structure set of nodes simultaneously.

6.7 Evaluation of the Proposed Smart-WLAN Framework

6.7.1 Throughput Analysis

In this sub-section the maximum throughput of IEEE 802.11 obtained by a single station is calculated. The obtained result is then compared against that of our proposed four beam sector scheme. This analysis demonstrates the capacity (throughout) increase of our proposed directional MAC scheme. We define the upper limit of the throughput that can be achieved in the IEEE 802.11 network as its Maximum Theoretical Throughput (MTT). Since IEEE 802.11 is defined from the physical to the MAC layer in the OSI model, we are interested in the actual throughput provided by the MAC layer. Therefore, we can define the MTT of IEEE 802.11 as the maximum amount of MAC Service Data Units (MSDU) that can be transmitted in a time unit. Typical encapsulation between the application and IEEE 802.11 is the Transmission Control Protocol (TCP) and the User Datagram Protocol (UDP) over the Internet protocol (IP), and over Logical Link Control (LLC). The higher the layer, the lower the maximum throughput of the layer, as overhead accumulates at each layer. In addition, the maximum throughput at the application layer can be further affected by the dynamics of the TCP. The effect of upper layers such TCP on the throughput is out of scope of this thesis. The maximum throughput observed by an application layer is described by the following equation when no fragmentation is used at the lower layers.

$$MTT_{APP} = \frac{\Gamma}{Y + \Gamma} \times MTT_{802.11}(bps)$$

(6.8)

Where MTT_{APP} is the MTT of the application layer, Y is the total overhead above MAC layer, Γ is the application datagram size and MTT_{802.11} is the MTT of the 802.11 MAC layer. In the rest of the thesis, the term MTT is refers to the MTT of the 802.11 MAC layer (MTT_{802.11}), unless explicitly mentioned to the contrary.

In order to calculate the MTT, we first convert all the overheads at each sublayer into a common unit-time. To obtain the MTT, we will divide the MAC SDU by the time it takes to transmit it.

$$MTT = \frac{MSDU \ size}{Delay \ per \ MSDU}$$

Figure 6.19 shows the total communication sequence in order to send a data packet successfully by the use of RTS/CTS mechanism as specified in 802.11 standard [8].



Figure 6.19 RTS/CTS handshake with omni-directional antenna

The total delay is calculated as a summation of all the delay components in Figure 6.19 as follows:

 $\begin{aligned} Delay \ per \ MSDU &= (T_{RTS} + T_{SIFS} + \tau_{\Pr op} + T_{CTS} + T_{SIFS} + \tau_{\Pr op} + T_{data} + T_{SIF} + \tau_{\Pr op} + T_{ACK} + \tau_{\Pr op} \\ &+ T_{DIFS} + \left(\frac{CW_{\min} * T_{Slot}}{2}\right) \quad \big) \times 10^{-6} s \end{aligned}$

(6.9)

The total delay per MSDU can be simplified to a function of the MSDU size in bytes, x as:

$$Delay \ per \ MSDU(x) = (bx+c) \times 10^{-6} s \tag{6.10}$$

Where b and c are delay parameters associated with data and control signals respectively.

MTT can be found simply be dividing the number of bits in MSDU (8x) by the total delay in Equation (6.9).

$$MTT(x) = \frac{8x}{bx+c} \times 10^6 \tag{6.11}$$

As can be observed from Equation (6.11) when the MSDU size tends to infinity, the MTT is bounded by:

$$\lim_{x \to \infty} MTT(x) = \frac{8}{b} \times 10^6 \, bps \tag{6.12}$$

Also as the data rate tends to infinity, the parameter b in Equation (6.12) tends to zero:

$$\lim_{b \to 0, c \to c'} MTT(x) = \frac{8x}{c'} \times 10^6 \, bps \tag{6.13}$$

Where c' is the sum of all the delay components that are not affected by the data rate.

The data frames in 802.11 are transmitted by the data rate and control frame are transmitted by the control rate. Control frames such as RTS, CTS and ACK are always transmitted at 1 Mbps for backward compatibility. The contention window size does not increase exponentially since there are no collisions. Thus, CW is always equal to the minimum contention window size (CW_{min}), which varies with different spread spectrum technologies.

If we assume that all packets are sent at the link rate of 2 Mbps with zero BER and no losses due to collision. The specifications for IEEE 802.11b are given Table 6.3

Tpreamble	144 µs
T _{phyheader}	48 µs
CW _{min}	31
T _{slot}	20 µs
T _{SIFS}	10 µs
T _{DIFS} =2*T _{slot} +T _{SIFS}	50 µs
τ_{prop} (maximum propagation delay)	l μs

Table 6.3 IEEE 802.11b Specific Parameters

The data transmission delay, T_{data} , the ACK transmission delay, T_{ack} , the RTS transmission delay, T_{rts} and the CTS transmission delay, T_{cts} , are expressed as follows:

$$T_{data} = T_{preamble} + T_{Phyheader} + \frac{(34 + L_{data}) * 8}{(2 * 10^6)}$$
(6.14)

$$T_{RTS} = T_{Pr \ eamble} + T_{Phyheader} + \frac{20*8}{(2*10^6)}$$
(6.15)

$$T_{ack} = T_{Pr\,eamble} + T_{Phyheader} + \frac{14*8}{(2*10^6)}$$
(6.16)

$$T_{CTS} = T_{Pr\,eamble} + T_{Phyheader} + \frac{14*8}{(2*10^6)}$$
(6.18)

Then the total access delay from Figure 6.19 for omni direction transmission is given as

$$Cycle \ Time_{802.11} = (T_{RTS} + 3*T_{SIFS} + 4*\tau_{Prop} + T_{CTS} + T_{data} + T_{ACK} + T_{DIFS} + \left(\frac{CW_{\min}*T_{Slot}}{2}\right)) \times 10^{-6} s$$
(6.19)

therefore the maximum throughput can be calculated as

$$MTT_{Ommi} = \frac{8 * L_{data}}{cycle Time_{802.11}}$$

$$= 1.830 Mbps$$
(6.20)

The value obtained through Equation (6.20) verifies the boundary condition for the IEEE 802.11 omni-directional performance. We then analyse analytically the throughput of the proposed MAC with a switched beam antenna and compare it with the IEEE 802.11 throughput for 2 Mbps link rate. Figure 6.20 shows the total communication sequence in order to send simultaneous data packets successfully by the use of D-RTS/D-CTS mechanism in two sectors.





We introduce a new interframe timing parameter called T_{DEFER} at the end and beginning of each SDMA (sector) period to inform surrounding nodes in order to prevent deafness Although this new timing delay will increase the MAC delay and hence downgrade the throughput, it is important to prevent deafness and avoid packet collision. The MTT_{D-MAC} is now given as:

$$MTT_{D-MAC} = \frac{8 * L_{data}}{Cycle \ Time_{802.11} + T_{Defer}} \times 10^6 s \tag{6.21}$$

We substitute the value of equation (6.19) in equation (6.21) and obtain the following:

$$MTT_{D-MAC} = \frac{8 * L_{data}}{Cycle \ Time_{802.11} + T_{D-RTS} + T_{SIFS} + \tau_{Prop} + T_{D-CTS} + T_{DIFS} + \left(\frac{CW_{min} * T_{Slot}}{2}\right) \times 10^6 s$$
$$= \frac{8 * 4095}{17900 + 901} \times 10^6 s$$
$$= 1.742 \ Mbps$$

Therefore the MTT_{D-MAC} network throughput to send data simultaneously by the use of RTS/CTS mechanism in two sectors will be $2*MTT_{D-MAC} = 3.484 Mbps$. The D-MAC outperforms omni-directional IEEE 802.11 by 52%. The throughput performance of the network will depend on the network topology, because the SDMA conditions occur when there is an additional diagonal path which should not interfere with the ongoing communication. Furthermore, the effect of packet size on throughput must also be considered. In fact, every packet carries a header. Each header has a pre-defined length and this length may become comparable with the length of the actual data carried by that packet if the packet is too small.

6.7.2 Simulation Results

In order to evaluate the effect of the LEO ISL variance on the Quality of Service (QoS), parameters such as the carrier-to- noise (C/N), energy-to-noise (Eb/No) and bit error rate (BER) were estimated.

Three cases were modelled – when the satellites are in the same plane, in different planes and in cross-seam as shown in Figure 6.21.

A smart antenna simulation environment was implemented using Matlab and imported to the STK simulation tool for physical layer analysis. The transmit power is kept at 30 dBm, with 0 dBi for the omni-directional antenna and 16 dB gain using the proposed smart antenna in section 6.6. The transmission rate is 2 Mbps using the BPSK modulation scheme.



Figure 6.21 a) Omni-directional (broadcast) mode during handshaking using control frames b) Data transmission after handshaking in STK

Figure 6.22 shows an exponential decrease in E_b/N_o with increasing range between satellites in different orbit planes but with a 16 dB gain using the smart antenna. In Figure 6.23, both antennas experience low BER at the poles, but it starts to increase exponentially towards the equator at certain latitudes for the omni-directional antenna as the ISL range increases. The BER is constant throughout the orbit period for the smart antenna.



Figure 6.22 Inter-orbit plane range variation with Eb/No

The antenna angular variation required to track and maintain the cross link between satellites depends on network topology parameters such as the angle between planes and the amount of satellites in a constellation.



Figure 6.23 Inter-orbit plane range variation with BER

It can be seen from Figure 6.24 that in cross-seam, E_b/N_o is decreasing exponentially is lowest near the poles where the satellites are visible at certain latitudes. From the simulation results shown in Figure 6.24, we observe that there is a 17 dB gain when smart antennas are used as compared to omni-directional antennas.



Figure 6.24 Eb/No with Cross-seam length variations





Figure 6.25 BER with Cross-seam length variations

The BER comparison in Figure 6.25 shows that smart antenna can be used for cross seam communications when two satellites are visible at certain latitudes. However, to form smaller main lobes and better gain, more antenna elements will be needed, which will lead to an increased hardware cost and tracking requirements. The result shows that with the use of smart antennas the IEEE 802.11 ranges could be increased from 1 km to 5,000 km for ISL communication without much modification to the standard.

6.8 Summary

In this chapter we proposed a new MAC protocol, Smart WLAN using switched beam antennas and validate a space-aware MAC in an effort to support high capacity (increased range and throughput) with minimum interference. Existing work found in the literature cannot scale up to LEO ISL network range and dynamics, which justifies the research effort to make the MAC space-aware. The proposed scheme makes use of directional antenna integrated with IEEE 802.11 based on the DCF mode for the first time in LEO ISL networks.

Directional RTS/CTS messages are used to construct a MAC table to track the location of not only the destination nodes but also all communicating neigbours. We prove that Smart_WLAN introduces SDMA capability into the wireless ad hoc network by performing physical and carrier sensing in a directional sense. This is verified analytically and by simulations. Our results promise significant enhancements over omni-directional IEEE 802.11, with throughput gains 52-80%. Our conclusion was that if small packets are concatenated into longer packets, the performance of the system increases because of achieving SDMA.

The contributions of Smart WLAN protocol can be summarised as follows: (1) a medium access table is constructed for location determination and update of locations of neigbouring nodes is performed. (2) SDMA support is accomplished leading to increased throughput. (3) Deafness is prevented through defer bits that are sent at the end of SDMA period (sector) until the end of the continuing data packet to inform surrounding nodes.

Chapter 7. Case Study: Space-WLAN for Satellite Formations in LEO

This chapter presents the results of a case study which is carried out to evaluate and validate the proposed Space-Aware WLAN. Satellite formation flying scenarios in LEO are used in this case study. The chapter is organized as follows: in section 7.1, an introduction to satellite formation flying is presented. A simple concept of formation design using a regular constellation of polar orbits is presented in section 7.2. The network model used in these formation scenarios is presented in section 7.3. In section 7.4 a step-by-step approach is taken to optimize key physical and MAC layer parameters in our effort to make IEEE 802.11 scalable to LEO networks using the proposed schemes and concepts in previous chapters. Section 7.5 summaries the chapter.

7.1 Introduction to Formation Flying

Formation flying will vastly increase the capacity of small satellite missions as the technology matures, but there are severe challenges for subsystems. The most demanding task will be to implement effective control and maintain satellites in close formation for the duration of the mission. The main subsystems that will determine the constraints on formations are the propulsion subsystem, the communication subsystem and the lifetime of the formation.

Formation flying of multiple spacecraft to replace a single large satellite will be an enabling technology for a number of future missions [7, 11]. Potential applications include synthesis of large apertures, allowing each satellite in the cluster to communicate with each other using ISLs and to share the processing, communication and payload as an aggregate thus forming a large 'Virtual satellite' in space. The satellites in cluster will have an almost unlimited effective aperture since the separation between the satellites is varying from apogee to perigee in orbit. The cluster architecture is highly adaptive since neither geometry nor number of satellites in the cluster is fixed. The cluster configuration can be adapted to suit the needs of an emerging mission. Furthermore, these satellites can be mass-produced and deployed in phases over a number of years, which will lower the production cost, while providing acceptable levels of performance.

Inter-satellite networking in general distributed spacecraft missions, including formation flying were investigated in [110]. Based on a survey of many proposed space missions, requirements and protocols were identified. Protocols under consideration were IEEE 802.11, 802.15.1/Bluetooth, IEEE 802.16/WiMAX, HomeRF and CCSDS-Proximity-1.

Related research studies for ISL communications protocols for LEO networks have been presented in [111, 112, 113]. Considerations of file transfer between spacecraft in a formation using TCP/IP were analyzed and simulation results were presented. Comparison of SAFE and FTP file delivery among spacecraft in a circular formation is given in [111] using either ATM or 802.11. In [113], ISL networks were modeled using either wireless IEEE 1394 or IEEE 802.11 in a formation with the FTP protocol transferred between spacecraft and ground. The assumption in some of these studies are static networks in which the spacecraft where in formation. In our work, we emphasize the dynamics of LEO missions as it evolves through phases that pose significantly different communication constraints on the IEEE 802.11 protocol. In all the related research studies conducted on IEEE 802.11 for ISL none has investigated how to optimize the physical and MAC layer parameters to scale up to LEO range and dynamics.

As might be expected, perturbation effects differ in their significance for LEO satellites from that for satellites at much higher orbits. The two important perturbations of the LEO orbits due to Earth's oblateness are nodal regression and apsidal precession. The line that is common to both the equatorial plane and the orbital plane is called the lines of nodes. This line processes at a rate that is dependent upon the magnitude of the satellite orbit's semi-major axis a, eccentricity e, and inclination i.

In this chapter, the constraints of the IEEE 802.11 protocol are analyzed for two types of formation flying scenarios: the triangular and the circular flower constellation as in [114]. The perturbation effects of placing the circular formation in polar (sun synchronous) and inclined (Frozen) orbits are also investigated. Equatorial LEO formation is not considered in this thesis. Applications in LEO equatorial orbits are rare because of the small coverage area. The introduction of inclination differences in designing equatorial LEO formations will also introduce secular drifts, causing the formation to drift apart.

In sun synchronous orbits the rate of procession is 0.9856 degrees per day, wherein the line of nodes turns around 360 in one year. κ in Equation (3.12) is a secular correction to the mean motion to account for the effect of J_2 . At this specific rate the satellite's orbital plane remains essentially fixed with respect to the sun and also views the Earth below at the same angle. In a sun-synchronous orbit, the satellite passes over the same part of the Earth at roughly the same local time each day. This makes communication and various forms of data collection such as remote sensing very convenient. For example, a satellite in a sun-synchronous orbit could measure the air quality of London, UK at noon every day.

The Flower Constellations [114] are used to design the formations in this case study. The Flower Constellations are suitable for formation flying in LEO since the satellites in the formation are using almost the same orbital parameters, thus experiencing the same perturbations. Each satellite in the formations has the same inclination *i*, eccentricity *e*, angle of perigee *w* and semi-major axis *a*. Using these initial orbital parameters a pair of right ascension of the ascending node (RAAN) and the eccentric anomaly, *v*, is computed for each satellite. By using the critical inclination, the motion of the lines of upsides can also be eliminated [114]. The shape of the Flower Constellations is not rigid and will deform as it approaches apogee and perigee. This deformation can be taken advantage of in ISL applications since they form an intra-orbit plane at the poles thus having minimal variations in propagation delay, Doppler shift, Az and EL.

7.2 Satellite Formation Design in LEO

In order to achieve a considerable reduction of complex equipment required on the ground in connection with the accurate calculation of the exact position of each individual satellite in a formation, the exact position of a central master satellite of a sub-group of the formation has to be determined. This calculation can be performed autonomously on board each satellite by means of GPS. Then the exact position of all the other satellites in the same formation is determined in reference to the master satellite using ISLs.

To ensure that the LEO constellation provides the desired coverage, the satellites must maintain their assigned orbits in the constellation. It is therefore important to create a formation-keeping method to reduce the long deviations and delta V $(\Delta V)^{18}$ during the working phase of an established satellite network. The formation-keeping ΔV is governed mainly be the physical size of the formation and the uncertainties in relative positions and velocities [125]. Another important aspect of formation keeping in real time LEO networks is to operate with fixed phase between the planes, which assures that the satellites of the same formation always remain in the same relation to each other.

¹⁸ ΔV is used as an indicator of how much fuel is required to carry out an orbital maneuver i.e. to change from one trajectory to another.

Generally, any formation shape can be form using this method, in which all orbits are at the same orbital altitude, in most cases at a defined fixed angular offset in respect to each other. In this sense, the linkage between individual satellites of a ring constellation and individual satellites of adjacent satellites of other ring constellations can be considered to be a "Formation". This brings the advantage that, in addition to actual communication purposes, the realization of very inexpensive, permanent, constantly updated information regarding the respective course of all satellites possible. This information can be used to maintain an exact phase between the planes of all the satellites in the formation.

As shown in Figure 7.1 (a) six orbits are created by orbital planes P1 to P6 using the star constellation explained in chapter 2. Several satellites can move one after another in each plane at approximately even spacing's. Many formation solutions are possible in this way: Satellites 1 and 2 in orbit P1, satellites 3, 4 and 5 in orbit plane P2, etc. The satellites 1, 2, 3, 4, 5, 7 and 8 are individually represented in Figure 7.1 (b). The satellite 4, which is in the central position, is selected as the master satellite so that is connected, respectively bidirectional, via Earth links with the ground station and via ISLs with other satellites in the formation. Therefore satellite 1,2,3,5,6,7 and 8 form a first ring constellation; satellites 6,7,8,9,10 and 12 form a triangular formation and finally satellites 9,10,11,13,14 and 15 form the second ring formation.

When using ISLs continuously, the Master satellite can be used to support computational requirements in order to achieve considerable reduction in outlay required on the ground in connection with the accurate calculation of the exact position of each satellite in the formation. In order to achieve this goal, the orbital position of the master satellite is determined by means of GPS and then the exact position of other satellites are determined from range and pointing data by means of ISLs. Since the master satellite is always in contact with the ground stations, any required information about the other satellites is always available, by forming suitable ISL routes even if the satellite of interest is not within sight. Even if the master satellite of the formation fails, a new master can be chosen from one of the adjacent satellites. An inherent redundancy of the satellite networks results because each satellite is connected by more than one ISL with other adjacent satellites. Therefore, an exact position determination of all satellites in the formation is made possible in an excellent manner by means of the ring-overlapping continuous connection of all the satellites of the formation.

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7.3 Formation Flying Network Model

In this case study, the constraints of the IEEE 802.11b protocol are analyzed for formation flying using two types of Flower Constellations scenarios. The triangular and circular flower constellation formations [114] are slightly modified to include a Master-Slave configuration [115]. A master satellite at the centre of the formations will act as the Access Point as implemented in terrestrial WLAN with the Slave Satellites surrounding it, acting as mobile nodes. The DCF mode is used in these scenarios to provide robust random access functionality during operational phases such as initial deployment, deformation and reformation, and reconfiguration to new formations, etc. The need for collision avoidance using the CSMA/CA during these unstable formation phases is necessary. In our future formation work, the PCF mode will be used when the satellites are in coarse or precision formation. The PCF mode will provide higher throughput when higher traffic loads and quality of service are required.

Figure 7.2 illustrates the triangular formation shape created with a desired base of 1000 km and a height of 500 km.



Figure 7.2 STK animation of the OPNET simulation for the Triangular & Circular Formations

As the formation approaches the apogee and perigee, it collapses into a line before reforming again. However, since the formation is non-symmetric, the shape inverts as it crosses from one side of the globe to the other.

The circular formation shape in Figure 7.2 is also created with a base radius of 1000 km. There is also formation and deformation of shape as the satellites approach the perigee and apogee but it does not invert per se, as in the case of the triangular formation as illustrated in Figures 7.3 and 7.4.



Figure 7.3 Deformation for the circular formation in STK



Figure 7.4 Reformation of the circular formation in STK

Dynamic simulation analyses in STK are conducted to estimate the expected levels of variations in propagation loss, Doppler shift and angular between the master satellite and a slave satellite in the formations. The results presented in Figure 7.5, a Doppler shift of 100 KHz and a 20 dB loss is experienced between the master satellite and one of the slave satellites. Figure 7.6 show minimal variations in range, azimuth and elevation values for the triangular formation.




Figure 7. 5 Triangular range variations with propagation loss and frequency Doppler shift



Figure 7.6 Triangular formation ISL length, AZ and EL angle variations as a function of the orbital period

The simulation results for the circular formation, presented in Figure 7.7, show a Doppler shift of 50 KHz is experienced with 17 dBs variation in propagation loss, but these values are well within the mobility specifications of the IEEE 802.11 [81]. In Figure 7.8, shows 620 km and 100 degrees variation in range and azimuth values are experienced respectively between the master satellite and a slave satellite as they move in orbit from the equator to the poles.

Another formation scenario is created to investigate the effect of perturbation by placing the circular formation in a frozen orbit. A frozen orbit is characterized by the absence of longtime changes of orbital eccentricity and argument of perigee. Frozen orbits maintain almost constant altitude over any particular point on the Earth's surface.



Figure 7.7 Circular range variations with propagation loss and frequency Doppler shift



Figure 7.8 Circular formation ISL length, AZ and EL angle variations as a function of the orbital period

The effect of J_2 can be mitigated by the appropriate choice of design parameters. By choosing the critical inclination of 63.4 degrees (Frozen orbits), the term $(4-5\sin^2 I_0)$ in (3.12) cancels out, and the parameters of the orbit remain almost constant over time, thus requiring a minimum of fuel for station keeping. Keeping the orbital inclination equal to critical inclination also minimizes apsidal drift and eccentricity variation, thus less variation of ISL length between satellites. Similar simulation experiments as in triangular and circular

formations using polar orbits were carried out for the Circular formation using the frozen orbit, as a result of which a Doppler shift of only 10 KHz is experienced as compared to 50 KHz in the synchronous orbit.

This result indicates that there is a minimal variation in the azimuth angle as compared to the sun synchronous orbit. In conclusion, the result shows that the slave-satellites are more closely locked to the master-satellite in frozen orbits as compared to the synchronous.

7.4 Adaptation of the IEEE 802.11 Standard for Formation Flying

7.4.1 Scenarios and Settings

The tight limitations on increased distance in WLAN for outdoor applications due to DIFS, Slot Time and AckTimeOut timing parameters and the adverse effect on ISL distance between satellite nodes of more than 15 Km were analyzed in section 3.2. The SIFS, DIFS and PIFS timing requirements for both the DCF and PCF operations are clearly defined in the standard but the most stringent requirement is that the ACK has to be received within SIFS interval (10 µS) after packet transmission for IEEE 802.11b outdoor networks. This is because the AckTimOut period, which is usually chosen to be larger than the SIFS value, is set just after a transmission of a packet, and as long as the ACK is received before the timeout expires, the MAC works properly. Typically there is no consequence if the ACK is received later than the SIFS value, however, stations whose expected ACK is lost due to collision cannot remain synchronized with other stations and avoid collision while waiting for the DIFS duration. If the standard is used for ISL applications, the distance is expected to be longer than that in terrestrial WLAN. To avoid time-out expiration of the IEEE 802.11 parameters, the DIFS, the SlotTime and AckTimeOut values must be computed according to the predefined maximum distance between satellite nodes. However a high value for these timing parameters will lead to useless delays and a waste of channel capacity. The solution is to determine the optimum timing values, which will be strongly affected by formation topology and ISL variance between satellites.

We simulated the formation flying scenarios in Figure 7.2 with a data rate of 2 Mbps between the master and the slave satellites. During simulations, the media access delay in the master satellite node is evaluated. The MAC delay is the sum of the queue delay and the contention delays of the data packets received by the WLAN MAC layer from the higher layer as given by Equation (3.29). For each packet, the delay is recorded when the packet is sent to the physical layer for the first time [55]. Given that the main focus of our work is on both the physical and MAC layers of IEEE 802.11b, the mode of operation of the satellites is assumed to be DSSS in the physical layer and DCF in the MAC sub-layer, until stated otherwise.

7.4.1.1 Selection of Optimum IFS Values

The first set of simulation scenarios are designed to demonstrate the effect of Slot Time and SIFS on the IEEE 802.11 performance in the Triangular formation. The triangular formation is chosen in some of these scenarios because the azimuth and the range variations are smaller compared to the circular formation.

The DSSS is used as the physical layer for all the scenarios with a data rate of 2 Mbps. The minimum and maximum contention windows are set to 15 and 1023 slots respectively with a buffer size of 256 Kbits. In these scenarios, AckTimeOut is selected to be twice the max propagation delay between two nodes. Using these initial physical parameters as given in Table 7.1, SIFS and SlotTime values are selected for each scenario.

Table 7.1	Slot Time and SIFS	parameters for three simulation scenarios using the triangular f	ormation
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	Scenario1	Scenario2	Scenario3
Phy. Characteristic	DSSS	DSSS	DSSS
Slot Time (ms)	2	12	8
SIFs (ms)	1	6	4
CWmin	15	15	15
CWmax	1023	1023 ~	1023
WLAN (Mbps)	2	2	2
WLAN Buffer Size (kbits)	256	256	256

As shown in Figure 7.9, Scenario 2 (SIFS of 6 ms and SlotTime value of 12 ms) is found to be closest to the optimum values for SIFS_{opt} and SlotTime_{opt} for this network; hence it has the lowest MAC delay. The results show that the network topology determines the optimum SlotTime and SIFS values. The optimum SlotTime and SIFS time values can decrease the average MAC delay, hence improving the WLAN throughput performance in space.

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Figure 7.9 Average MAC delay as a function of Slot Time and SIFS

7.4.1.2 Selection of Optimum CW Values

The second set of simulation scenarios are designed to demonstrate the effect of the minimum contention window on the MAC delay in the Triangular formation. Parameters for the three scenarios are given in Table 7.2. The SIFS_{opt} and SlotTime_{opt} values of 6 ms and 12 ms found in the previous simulations are used and the CWmin value is varied to find the optimum, CWmin_{opt}. The same physical layer parameters are used as in the simulations in section 8.5.1.1. The CW_{min} value is varied for the four scenarios as 7, 15, 31, and 63 respectively, although 31 to 1023 is defined in the IEEE 802.11b standard.

 Table 7.2
 Parameters for Minimum Contention Window for three simulation scenarios using the triangular formation

	Scenario 4	Scenario 5	Scenario 6	Scenario7
Phy. Characteristic	DSSS	DSSS	DSSS	DSSS
Slot Time (ms)	12	12	12	12
SIFs (ms)	6	6	6	6
CWmin	7	15	31	63
CWmax	1023	1023	1023	1023
WLAN (Mbps)	2	2	2	2
WLAN Buffer Size (kbits)	256	256	256	256

Figure 7.10 shows that the lowest MAC delay occurs for scenario 2 with CWmin_{opt} of 15. This shows that low MAC delays could be achieved and maintained by setting the CWmin to optimum values for lightly or heavily saturated networks.



Figure 7.10 Average MAC delay as a function of minimum contention window

7.4.1.3 Adaptive vs. Standard Minimum Contention Window

This third set of simulation scenarios are designed to demonstrate the effectiveness of the proposed adaptive algorithm for the minimum contention window explained in section 5.4.2, as compared with the BEB algorithm defined in the IEEE 802.11 standard [8]. Similar simulation experiments as in 7.4.1.1. & 7.4.1.2 were carried out for the Circular formation, as a result of which optimum values for SlotTime, SIFS and CW_{min} of 2 ms, 1 ms and 15, respectively, were obtained.

In order to compare the proposed enhanced contention window scheme against the IEEE 802.11 standard using the triangular formation, the throughput is used as the performance metric. The two types of formation flying scenarios with the optimum values were simulated in OPNET. Figure 7.11 presents the throughput achieved by the two contention schemes using the DSSS physical layer with 2 Mbps data rate. It is clearly apparent that the adaptive minimum contention scheme outperforms the standard scheme achieving a higher throughout.

The Triangular (asymmetric) formation has a slightly higher throughput as compared to the circular (symmetric) formation as given in Figure 7.11. This is due to lower angular variations experienced by the triangular formation, hence less antenna pointing error.





Figure 7.11 Throughput of the Adaptive WLAN versus the standard IEEE 802.11

7.4.1.4 Effect of Formation Shape on Throughput

This fourth set of simulation scenarios are designed to demonstrate the effect of formation design parameters on the throughput of the enhanced MAC by including the frozen orbit. Similar simulation experiments as in sections 7.4.1.1. & 7.4.1.2 were carried out for the Circular formation in frozen orbit, as a result of which optimum values for SlotTime, SIFS and CW_{min} of 2 ms, 1 ms and 15 ms, respectively, were obtained. The circular formation using the frozen orbit also has a better throughput than the sun-synchronous orbit due to minimum variation in ISL length and less Doppler shift as shown in Figure 7.12.



Figure 7.12 The effect of formation shape on throughput

7.4.1.5 Effect of Bit Error Rate on Throughput

The fifth set of simulation scenarios are designed to demonstrate the effect of BER on throughput by the introducing errors into the IEEE 802.11 wireless network using the triangular formation. We employed simulation scenarios with BER threshold values of error free (none), 1E-4, 1E-5 and 1E-6 respectively. During simulations, the throughput of the master-satellite is recorded for analysis.



Figure 7.13 The effect of BER variation on the Space-WLAN throughput in the triangular formation

The simulation results in Figure 7.13 indicate that low BER of 1E-5 has no significant effect on the throughput. There is significant degradation of the WLAN performance in the triangular formation with media error rate higher than 1E-4, thus the need for packet fragmentation techniques to improve the performance when BER is high. The use of forward error correction and equalization techniques defined IEEE 802.11 can be used to improve the BER performance in high BER conditions.

7.5 Summary

In this chapter we have presented the design and performance of a complete physical and MAC framework in 802.11 for LEO formations using the proposed Space-Aware WLAN in chapters 4, 5 and 6. A simple concept of formation design using regular orbits with the flower constellation as the basis is presented. This concept is used to create a master-slave configuration. This network model although basic serves the purpose of a testing vehicle for the proposed method. The results in indicate that the tuning the IEEE 802.11 physical layer

characteristics, such as slot time, SIFS, and minimum contention window to optimum values, can greatly improve the performance of IEEE 802.11 in space for ISL applications.

The analytical and simulation results presented in this chapter confirm that adaptive algorithms are needed in both the physical and MAC schemes to account for the LEO variance in satellite formations. The proposed adaptive IEEE 802.11 MAC scheme in subsection 5.4.2 combined with smart antennas will allow achieving seamless connectivity between spacecraft in a changing LEO topology. The use of high-gain and agile antennas with the integration of the new timing scheme in the MAC-layer will enable finding and tracking-over-time of every in-range neighbor satellite with minimal interference while maximizing gains towards target satellites.

Chapter 8. Conclusions

8.1 **Contributions of the Thesis**

The research presented in this thesis examines the optimization of several physical and MAC layer mechanisms of the IEEE 802.11 protocol for adaptive communications in satellite networks using inter-satellite links. The ideas originated by the research pave the way towards a Space-Aware WLAN and can significantly improve the performance of the IEEE 802.11 protocol for space applications. There are presently very few solutions to a given LEO network design problem using inter-satellite links. Our design concept is to develop LEO networks with techniques and technologies already in use in the terrestrial wireless environment (COTS). By doing so, we will be able to reduce cost, deployment and risk. Our research work in this thesis made an attempt to evaluate and optimize key building blocks of the proposed Space-Aware 802.11 framework either mathematically or by simulation or using both techniques for the first time.

Given that maintaining connectivity in LEO networks using inter-satellite links is a challenging task and wireless networks are prone to high BER and interference, the optimal design of LEO satellite network will depend on several objective functions to be minimized such as changes of azimuth angle with time, elevation angle with time and ISL distance with time. In this respect, the effects of LEO ISL variance on the communication parameters are investigated - in order to devise a meaningful communication framework. The integration of smart antennas with IEEE 802.11 is made in order to increase the range and capacity of IEEE 802.11 for ISL applications. The IEEE 802.11 physical layer parameters are re-defined for ISL length. Finally, the MAC layer is optimised for ISL variance – in order to improve optimum throughput possible in such networks. In this thesis, a systematic approach is being applied at each stage such that each contribution can be used as a building block to arrive at the final proposal for an IEEE 802.11 Space-Aware protocol. Summary of the main contributions to the existing body of knowledge are given below:

• Modelling Inter-Satellite Links between Satellites in LEO: Extensive numerical study of the impact of ISL variance on communication parameters between both directly and indirectly connected satellites is carried out.

The performance of ISL communication is measured by creating simple ISL length models in a LEO satellite network. Communication parameters such as satellite-to-satellite path length, ISL length variations with time and angular velocity requirements for antennas used for links between neigbouring orbital planes are analyzed and verified by simulations.

It is shown that the most important design factors determining ISL length for a given altitude are related to the network skew, the number of orbital planes and the number of satellites. The results show that minimization of antenna angular velocity of satellite antennas used for ISL communication will strongly depend on these factors. It is shown that minimum and maximum rate of change of azimuth, elevation and ISL length variations over the LEO orbit period are very sensitive to changes in design factors such as the phasing between satellites, the number of orbit planes and the number of satellites per orbit plane. It is also shown that changes in ISL length as the satellites move in orbit over time is directly responsible for Doppler shifts in the links. Doppler shift is also directly proportional to the rate of change of the link length, and this rate of change is approximately proportional to the inverse of the number of orbital planes.

Models derived in this thesis are very useful for determining antennas angular variations between satellites as they move in their orbit in a polar constellation.

• Modelling the Effect of J_2 on ISL Length: An analytical model that incorporates the effect of J_2 in to the variation of inter-satellite length as a function of the angle between satellites in different orbital planes is derived. One of the principal requirements of a spacecraft formation is that the component spacecraft does not drift apart from one another. In a fully Keplerian orbit, the only source of drift over multiple orbits is a difference between spacecraft periods, which is equivalent to a difference in spacecraft semimajor axes. The effect of the relative disturbances between spacecraft (e.g., relative drag, J_2) that takes into account separation of orbital planes has been modeled for the first time in this thesis. It is shown that any separation of 10 degrees or more between orbital planes in a constellation introduces ISL variations cause by the J_2 effect. This contribution can be used to initialize a newly deployed formation that is not yet in a J_2 -invariant orbit and to re-initialize a formation that has drifted from its original orbit.

Re-definition of the IEEE 802.11 Physical and MAC Inter-frame Timing Parameter for ISL range. Modification of the IEEE 802.11 physical layer parameters and their impact on the MAC by redefining the inter-frame timing between procedures responsible for range and

medium contention between nodes is investigated. Simulation results in OPNET indicate that tuning of the IEEE 802.11 physical layer characteristics such as slot time and SIFs, and the Minimum Contention Window, can greatly improve the performance of IEEE 802.11 in space for ISLs. The significance of this contribution is that IEEE 802.11 can be extended to much longer range of more than 1,000 km with minimal degradation in throughput.

- Novel MAC Algorithm for ISL Applications. An Adaptive MAC protocol has been proposed that makes use of the adaptive contention window concept based on the DCF of the IEEE 802.11 standard. This mechanism enables the nodes to compute the optimum CW_{min} by using the success ratio to provide better throughput performance in LEO networks. Furthermore the adaptive MAC scheme is based on choosing an appropriate CW-range accordingly to the current LEO network load and the knowledge from continuous network measurements. Besides maintaining fairness among competing satellite nodes, the proposed algorithm shows that high stability in throughput and MAC delay can be achieved in changing LEO conditions. In conclusion, it is confirmed that adaptive algorithms are needed in both the physical and MAC schemes for contention of medium to adapt to ISL variance.
- Novel Smart Antenna Integration with IEEE 802.11: The IEEE 802.11 physical layer and MAC layers are integrated with smart antennas for ISL applications called the Smart-WLAN for satellite networks. Using switched beamforming and position measurement techniques improvements in capacity and throughput are achieved in inter-satellite links in a LEO network. This is verified by relevant simulation results using Matlab, STK and OPNET simulation tools. The use of these smart antenna integration techniques under the function of the MAC layer will enable finding and tracking-over-time of every in-range neighbour satellite with minimal interference while maximizing gains towards target satellites.
- **Demonstration of the Proposed Space-Aware WLAN for a Satellite Network:** A case study is undertaken to validate the proposed Space-Aware WLAN for formation flying using constellation design as the basis with uniform Keplarian orbital parameters. The results show that selection of appropriate orbital parameters and a good formation design can influence the performance of IEEE 802.11 in space applications.

We have examined the effect of the initial contention window size on the performance by employing optimum value compared to the standard proposed value ($CW_{min} = 32$). Results

indicate that adjustment of CW_{min} , SlotTime and AckTimeOut values does considerably improve the performance of IEEE 802.11 in satellite networks.

In conclusion, we propose a Space-Aware IEEE 802.11 framework which consists of an adaptive contention window algorithm, a Smart WLAN employing smart antennas with optimised physical and MAC layer parameters for ISL communication. We concluded that each proposed set achieves better performance on particular metrics and it could be employed to match specific space communication needs.

The results of the study have been included in wireless studies for space applications funded by the European Space Agency (ESA) [123] and the ESPACENET [124] projects.

8.2 Future Work

Potential directions for extension of this work can be two fold: more work on Physical and MAC layer optimization techniques.

It would be interesting if further work can be focused on how a multi-band, multi-carrier and multi-standard radio can be added to the adaptation of transceivers in a coordinated use of spectrum to handle LEO ISL dynamics. The concept of adapting transceivers to different space conditions that can be continuously re-configured such as Software Defined Radios (SDR) should be well studied to identify parameters in which these radios can operate. The deployment of efficient and reconfigurable modulation and coding techniques will be highly desirable in ISL networks. Depending on the conditions the onboard electronics could autonomously configure a receiver/transmitter for short wave communication to ground and into a gigahertz range transceiver for inter-satellite communication. Additionally, support for a multi-protocol with reconfigurable radios and programmable mixed-signal processing will be needed for LEO satellites using ISL to accommodate different channel bandwidths and data rates. This new novel concept, if implemented could facilitate interaction among different constellations, using different protocols. It will be quite challenging to find a "universal" protocol to meet the requirements for all these future missions with different requirements, hence it will be extremely likely that in the next few years these missions will operate with multi-protocols. This design will definitely complement "internet in the sky" were satellites in cluster formations will be able to use a short haul protocols with their own dynamic routing algorithm while able to use border gateway routing protocols for information destined for other clusters in other formations or constellations using long haul protocols.

Future work should also investigate the use of both DCF and PCF modes defined in the 802.11 standard using cross-layer feedback designs for satellite formations. The DCF mode will be used to provide robust random access functionality during operational phases such as initial deployment, deformation and reformation, and reconfiguration to new formations, etc. The need for collision avoidance using the CDMA/CA during these unstable formation phases is necessary. The PCF mode will be used when the satellites are in coarse or precision formation. The PCF mode will provide higher throughput when higher traffic loads and quality of service are required. Interaction between the higher layers and the 802.11 MAC will be accomplished via the Station Management Entity (defined in the 802.11 standard), for enabling/disabling DCF/PCF modes and the optional RTS/CTS to improve the performance when needed most.

In addition to other possible directions of future work identified, it would be interesting if individual features of different IEEE 802.11 supplements (Please refer to Appendix E) such as QoS in 802.11e, high mobility in 802.11p, MIMO technology in 802.11n and mesh networking in 802.11s are incorporated into a single WLAN chip and be evaluated in a preliminary design review for ISL communications [130].

A Satellite network architecture is proposed in [125] which investigates integration of two connection-less protocols such as IEEE 802.11 and SpaceWire [136] to provide a reliable fault tolerant network between and within spacecraft. It is concluded that incorporation of IEEE 802.11 and SpaceWire could potentially allow the seamless interoperability and connectivity between all subsystems as well as other spacecraft in a constellation or cluster. The proposed high-speed IEEE 802.11/SpaceWire architecture will be capable of intermodule and spot beam switching with minimum delay and buffering and is expected to outperform ATM satellite networks.

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APPENDIX A LEO Constellations

Some of the reference constellations considered in this thesis is displayed in Figs. A.1 - A.6. They are shown (approximately) true to scale with respect to each other. Table A.1 lists all relevant constellation parameters of these six constellations at a glance.



Figure A.1 Iridium 6 X 11 LEO Star Constellation



Figure A.2 GlobalStar 8 X 6 LEO delta constellation



Figure A.3 ICO 2 X 5 MEO delta constellation



Figure A.4 M-Star 12 X 5 LEO delta constellation

Appendix A



Figure A.5 LEONET 3 X 5 MEO delta constellation



Figure A.6 Celestri 7 X 9 MEO delta constellation

	Iridium	GlobalStar	ICO	M-Star	Celetri	LEONET
Constellation						
pattern			dal White and	A straight and		
Orbit	Star	Delta	Delta	Delta	Delta	Delta
Classification			Service Services	The second second		
Orbital altitude, h	780	1414	10390	1350	1400	6390
Orbit period, T	100	113.4	6H	112m 4s	113m 7s	3hrs 5m 21s
Inclination, I	86.4	52	45	47	48	54
No. of satellites	66	48	10	72	63	15
in constellation				the second second		
No. of planes	6	8	2	12	7	3
Phasing factor	0	1	0	5	5	1
Planes spacing at equator	31.6/22°	45	180	30	51.43	120
No. of ISLs per satellite	2	None	None	2	2	2
No. of Intra- satellite links per satellite	0-2	None	None	2(T1)/4(T2)	2	2
Type of inter- satellite links	Switched	N/A	N/A	Permanent	Permanent	Permanent
No. of intra- satellite links in constellation	60	None	None	72	63	15
No. of inter- satellite links in constellation	40	None	None	72/144	63	15
No. of ISLs in constellation	106	None	None	144/216	126	30
Minimum Elevation angle	8.2 -	10	10	22	16	20

Table A.1 List of orbital parameters for the satellite constellation

APPENDIX B

Space Geometry and Orbit Mechanics

B.1 Satellite Orbits

B1.1 Basic Orbit Parameters

In the idealized scenario, a satellite orbit will remain constant in space for all times; that is its orientation is sidereal fixed (i.e. fixed with respect to the stars) and independent of the earth's rotation as shown in Figure B1. For the general case of elliptical orbits the position of a satellite in a point in space at any given time is thus completely determined by a set of six orbital parameters: three of them define the orientation of the orbital plane in space, two additional ones define the geometrical shape (parameters of the ellipse, or specifying a circle as a special case) and the last parameter describes the position of the satellite within the plane.



Figure B.1 Satellite orbital parameters

B.1.2 Orientation of the Orbit Plane

The parameters that characterize the orbit Orientation are shown in Figure B.1.

• The right ascension of the ascending node (RAAN) Ω determines the angle between a reference direction and the line of nodes. The reference direction is given by the direction from the earth's center to the sun at vernal equinox. Equivalently, this direction corresponds to the intersection between the equatorial plane and the plane of the ecliptic. The reference direction remains fixed in space.

• The inclination i defines the angle between the orbit plane and the equatorial plane. It is counted positively with respect to the ascending satellite orbit track. The line of intersection between the two planes is called the line of nodes. The ascending node is passed when the satellite enters the northern hemisphere.

• The argument of perigee ω_0 is the angle between the line of nodes and the semi-major axis of the ellipse. This parameter is not relevant in the special case of circular orbits.

B1.3 Geometrical Shape of the Orbit Plane

The shape of the orbit plane is determined by the semimajor axis, a, of the ellipse and the eccentricity, e; restricting to circular orbits now we can just shortly state here that e = 1, and a becomes the radius, r, of the circular orbit planes.

B1.4 Position of the Satellite in the Orbit Plane

Finally, one more parameter is needed to determine the satellite's position. This parameter is the true anomaly, θ_T , position to the argument of perigee, which is not relevant for circular orbits, as we have just said. Therefore, the nodal angular elongation ω is used instead for circular orbits; as shown in Figure 2.5 ω relates the instantaneous satellite position within the plane to the ascending node of the latter.

B1.5 Orbit Period

Essentially based on Newton's law of gravity, the important orbit period, T, can be derived as a function of the radius, r for circular orbits, where μ_g the universal gravitational constant and M_E is is the mass of the earth.

$$T = 2\pi \sqrt{\frac{r^{3}}{\mu_{g}M_{E}}}$$
(B1.1)

B1.5.1 Useful Circular orbits

For a number of reasons, including required number of satellites for earth coverage, free space loss, and propagation delay, the altitude h of the satellites over ground is a crucial parameter for any constellation. Obviously, with $h = r - R_E$., The orbit altitude is related to the orbit period T by

$$h = 3\sqrt{\mu_g M_E \left(\frac{T}{2\pi}\right)^2 - R_E}$$
(B1.2)

Particularly attractive orbit periods are those where T is an integer divisor of a sidereal day T_E (the time of one earth rotation, 23 h 56 min 4.1 s) since in this case the satellite positions reiterate periodically day by day: roughly speaking, when T = 1, 2, 4, 6, 12, 24 h. However, some periods may not be used since the associated altitude falls into the so-called Van Allen belts, which are regions of the ionosphere with high ion concentration, thus reducing the satellite's lifetime. Three regions of operation can be identified:

• Low earth orbits, with altitudes from 500–1500 km above the earth and periods of approximately 2 h,

• Medium earth orbits, with altitudes from 5000–11000 km above the earth and periods of approximately 4–6 h, and the

• Geostationary earth orbit at 35 786 km altitude and a period $T = T_E$.

The GEO orbit is a special geosynchronous orbit, namely the one in the equatorial plane (i = 0), whereas LEO and MEO orbits are also called non-geosynchronous orbits. Finally, Figure B2 illustrates typical orbit types with various inclination angles at a glance. Whereas $i \approx 90^{\circ}$ for polar (or near-polar) orbits, the inclination angle of inclined orbits is usually between 40° and 80°.



Figure B.2 a) LEO in polar and inclined orbit b) MEO in inclined orbit and GEO in equatorial orbit

Due to limited coverage area a satellite can provide, a number of satellites are used to extend the coverage forming a constellation. In non-geostationary satellite constellation, the total instantaneous coverage area consists of the union set of the coverage areas provided by all the single satellites at a given time. Coverage overlapping techniques are used in present constellations to prove continuous coverage to a specified area on Earth- the main objective of designing a constellation system [24, 25, 26].

We consider the general case of elliptical orbits, with circular orbits as a special case, and present the derivation of satellite velocity and orbit period. In the early 17th century Johannes Kepler discovered some important properties of planetary motion that are known since then as Kepler's laws:

• *First law (1602):* the planets move in a plane; the orbits around the sun are ellipses with the sun at one focal point.

• Second law (1605): the line between the sun and a planet sweeps out equal areas in equal intervals of time.

• *Third law (1618):* the ratio between the square of the orbit period T and the cube of the semi-major axis a of the orbit ellipse, T^2/a^3 , is the same for all planets.

These laws can be applied to any two-body system subject to gravitation, and also describes the motion of a satellite around the earth.

B1. Elliptical and Circular Orbits

As shown in Figure B3, the geometry of an elliptical satellite orbit according to Kepler's first law. The satellite orbit has an elliptical shape with the earth at one focal point. The ellipse is defined by two parameters: the semi-major and semi-minor axes a and b. The shape of the ellipse can also be described by the numerical eccentricity.

$$e = \sqrt{1 - \frac{b^2}{a^2}}$$
 with $0 \le e < 1$ (B1.3)



Figure B.3 Parameters of elliptical orbits

With this parameter the distance of the focal points from the ellipse center can be expressed as $e \cdot a$. The distance of the satellite from the earth's center is the radius r. The point of the orbit where r is smallest is called perigee with $r = r_p$. The point with largest r is denoted apogee with $r = r_a$.

From Kepler's second law we can deduce that a satellite moves quickly near perigee and slowly near apogee. According to Figure B3 and using equation B1.3, we can set up the following relations:

$$a = \frac{r_a + r_p}{2}$$

$$e = \frac{r_a - r_p}{r_a + r_p}$$
(B1.4)
(B1.5)
$$r_a = a(1+e)$$
(B1.6)
The angle θ_T between the perigee and the satellite as seen from the earth's center is commonly called the *true anomaly*. It can be used to determine the satellite radius *r* along the elliptical orbit.

$$r = \frac{a(1 - e^2)}{1 - e\cos\theta_T}$$
(B1.7)

The angle between perigee and the satellite with respect to the ellipse center is denoted the *eccentric anomaly E*, which is related to θ_T through

$$\cos\theta_T = \frac{a}{r} (\cos E - e) = \frac{\cos E - e}{1 - e \cos E}$$
(B1.8)

The time t after perigee passing t_p can be related to the eccentric anomaly E through

$$\frac{2\pi}{T}(t-t_p) = E - e\sin E \tag{B1.9}$$

where T is the orbit period of the satellite and the term $2\pi(t - t_p)/T$ is called the *mean* anomaly. Using Eq. B1.8. and Eq. B1.9 the time can be derived as a function $t(\theta)$. However, since the inverse function of Eq. B1.8 cannot be solved, the time behavior of $\theta(t)$ must be determined numerically. The satellite altitude h above the earth's surface is $h = r - R_E$, with R_E being the radius of the earth. Accordingly, the orbit altitude at apogee is $h_a = r_a - R_E$ and the altitude at perigee is $h_p = r_p - R_E$. Actually the earth is not an ideal sphere but exhibits some flattening at the poles. In the following, we will use $R_E = 6$ 378 km representing the mean equatorial radius.

B2. Circular Satellite Orbits

A circular satellite orbit is a special case of an elliptical orbit with zero eccentricity, e = 0. Thus, $a = b = r = r_a = r_p$. The earth is at the center of the circular orbit, and the satellite altitude $h = r - R_E$ is constant. Furthermore, it follows for the time behavior of the true anomaly that

$$\theta(t)=\frac{2\pi t}{T}.$$

B3. Satellite Velocity and Orbit Period

Isaac Newton extended the work of Kepler and in the year 1667 discovered the law of gravity. This law states that two bodies with masses m and M at a distance r attract each other with the gravitational force

$$F_a = G \frac{mN}{r^3} \tag{B1.11}$$

Here, $G = 6.6732 \cdot 10^{-11} \text{Nm}^2/\text{kg}^2$ is the universal gravitation constant. For a satellite orbiting around the earth the mass *m* represents the satellite mass and $M = M_E = 5.9733 \cdot 1024$ kg is the mass of earth. The total mechanical energy consisting of the potential energy and the kinetic energy is constant:

$$\frac{mv^2}{2} - \frac{\mu m}{r} = -\frac{\mu m}{2a} \tag{B1.12}$$

where $\mu = GM_E = 3.986 \cdot 10^{14} \text{ m}^3/\text{s}^2$. Thus, the velocity v of a satellite in an elliptic orbit may be obtained by

$$v = \sqrt{\mu \left(\frac{2}{r} - \frac{1}{a}\right)} \tag{B1.13}$$

which can be simplified for circular orbits $(r \equiv a)$ to

$$v = \sqrt{\frac{\mu}{r}}$$
(B1.14)

Equation B1.14 states that the velocity of satellites in circular orbits is constant, coinciding with Kepler's second law. The orbit period can now be derived as

$$T = \frac{2\pi r}{v} = 2\pi \sqrt{\frac{r^3}{\mu}}$$
(B1.15)

Earth coordinate systems. This for elliptical orbits generalizes to

(B1.10)

$$T = 2\pi \sqrt{\frac{a^3}{\mu}}$$

(B1.16)

according to Kepler's third law.

The orbit mechanics discussed so far are idealized in the sense that they assume a spherical and homogeneous earth, empty space, and the absence of any gravitational forces from sources other than the satellite and the earth. For this ideal scenario the satellite orbit will remain constant for all times.

APPENDIX C

Matlab, OPNET and STK Modelling

This appendix summarizes the simulation modeling work carried out in this thesis. Figure C.1 introduces the Matlab, OPNET Modeler and STK development environments and describes the hierarchical nature in which the satellite IEEE 802.11 model was created. The smart antenna algorithms are implemented in matlab and imported into STK using the Matlab/STK interface. Physical layer analysis is performed in STK such as link budget and antenna and satellite selection strategies, etc. Trajectory and link availability calculations are taken from STK and are provided to the OPNET code through navigation module which simulates a runtime environment for protocol layer analysis. All coordinate translation is performed in STK (OPNET operates solely in an Earth-centered fixed coordinate system). In real implementation, these calculations would be performed by the onboard computer.

C.1 Introduction to the OPNET Modeler

The OPNET Modeler development environment consists of three main editors: 1) Network editor, 2) Node editor, and 3) Process editor. The editors are organized hierarchically, such that modeling in the Network editor uses elements modeled in the Node editor, and in-turn modeling in the Node editor uses elements modeled in the Process editor. Each editor models a different characteristic of behavior; the Network editor captures the network topology in terms of devices, links, sub networks, and geographical context; the Node editor captures the device internal architecture in terms of functional elements and data flows between them; and the Process editor defines the behavior of functional elements (e.g. protocols, algorithms, applications) specified using a Finite State Machine (FSM) and programming language. All editors use a graphical interface in which the user works with objects representing the modeled systems structure and components.



Figure C.1 Simulation Methodology for the Space-WLAN

Appendix C

The network domain allows geographical information to be included in the network model, using latitude/longitude and xy coordinates to physically place nodes at specific locations in the network scenario. OPNET includes a number of regional and world maps that can be overlaid on the network, to give the network scenario an impression of a real-world deployment. OPNET uses the inherent distance between nodes to automatically calculate communication delays and losses. The topology of the communications network is designed within the Network editor. An example network topology (also referred to as a *network scenario*) is shown in Figures C.2 and C.3.





(b)

Figure C.2 Triangular formation in polar orbit a) LEO constellation b) Ground tracks imported from STK into OPNET network scenario

Appendix C





Figure C.3 Circular formation in polar a) Frozen orbit and b) Ground track imported from STK into OPNET network scenario

The communicating devices are called *nodes*, which are created using the Node editor (Figure C.4). Nodes communicate with each other using *links*, which model the physical communications channel. Within a single network scenario, there may be many instances of a node based on the same model. The term *node* is used to refer to a single instantiation of a node model, and the term *node class* is used to refer to the set of nodes having the same model. Nodes contain parameters called *attributes*, which allow the user to customize the

behavior of each instance of a node. Nodes may be designated as either fixed, mobile, or satellite. Fixed nodes remain at the specified location throughout the entire simulation run. Mobile nodes have a predefined trajectory attribute, which specifies the node location relative to time for the entire simulation run. Satellite nodes have a predefined orbit attribute which describes their motion during the simulation run.



Figure C.4 The WLAN node model

The functionality of user defined node modules is specified within the Process editor, using the C/C++ programming language and a Finite State Machine (FSM) framework. An example FSM showing unforced states (red) and forced states (green) is shown in Figure C.5. The FSM describes the set of states that the process may enter, and for each state, the conditions required to leave. Each state has *enter executives* and *exit executives*, which are lines of code that are executed as the state is entered and exited respectively. A state may be either forced or unforced. A forced state causes process execution to execute the enter and exit executives, evaluate transitions, and immediately move to the appropriate next state. An unforced state causes process execution to halt after execution of the enter executives. Process execution resumes upon the next invocation of the process; the exit executives are executed, transitions evaluated, and process execution moves to the appropriate next state. Processes are arranged hierarchically, allowing a process to create and invoke a new instance of a predefined process. The creator is referred to as the *parent* process, and the new process is referred to as the *child* process. Hence a number of processes, referred to as a process group, can execute within a single processor or queue module. The process editor allows the user to specify parameters called *attributes*, which are used once the process is instantiated to customize its behavior.

This facilitates the re-use of process models by eliminating the need to hardcode values, instead allowing values to be set on a per-instance basis at design time and read during simulation runtime. For example, a traffic source model may have an attribute called packet interarrival time, which can be set individually for each instance of the model, allowing the single traffic source process to generate a variety of data rates.



Figure C.5 The Simple packet source and sink process models

APPENDIX D

Multiple Access Schemes

In terrestrial wireless networks, numerous users simultaneously communicate to and through the same receiving point defined as multiple access. Multiple access is employed by allowing users to share the same base station and medium with minimum interference. Multiple access can be assigned into four domains, namely (1) frequency, (2) time, (3) code and (4) space. These four domains produce four different multiple access schemes, namely Frequency division multiple access (FDMA), Time division multiple access (TDMA), Code division multiple access (CDMA) and Space division multiple access (SDMA). Any of these access schemes are adequate in providing increased capacity and spectral efficiency. Since the focus of our work on the PHY layer is on CDMA, we review the IEEE 802.11 with a greater emphasis on the CDMA using the DSSS with BPSK modulation scheme.

D.1 FDMA

FDMA is a technique where individual mobile nodes are allocated individual channels and a unique frequency band within a cell. These channels are created by dividing the finite spectrum of the cell into several smaller bandwidths. A channel is assigned to a mobile user when needed, and during a call and no other user is allowed to use that channel. There are exist some limitations to FDMA, particularly when the channel is idle or not in use and cannot be used by others, thus wasting resources. The channels are narrowband and the need for strict RF filtering is required to mitigate inter channel interference. The number of channels, N_{ch} simultaneously supported by FDMA is given by

$$N_{ch} = \frac{B - 2 \times B_G}{B_{ch}} \tag{D1.1}$$

Where B is the total bandwidth of the frequency spectrum, B_G is the guard band on the edge of the frequency spectrum and B_{ch} is the channel bandwidth.

D.2 TDMA

TDMA is a technique where individual mobile users are allocated individual channels within the cell where each channel is a small time slot. These channels are cyclically repeated over, total number of time slots, N_t . As in FDMA, each user is allocated a channel and no other user is allowed to use that channel. However unlike FDMA, TDMA is discontinuous, meaning that digital data and digital modulation must be used due to the discrete nature of allocating separated time slots. Information is sent in small frames of time slots for each user. The time slot values are small enough that it is not noticeable to the user. The difference between FDMA and TDMA is that for TDMA the same carrier frequency is used by all nodes in the cell. It is the non-overlapping time slots that separate the users. The main advantage of TDMA is that it is possible to allocate any number of time slots to a user are far as delay tolerable. This allows bandwidth in a cell to be supplied on demand by reassigning time slots for users having priority. The number of channels, N_{ch} , simultaneously supported by TDMA is given by

$$N_{ch} = \frac{N_m (B - 2 \times B_G)}{B_G} \tag{D1.2}$$

Where N_m is the maximum number of mobile users allowed in a cell.

D.3 SDMA

SDMA is a technique which allows two or more users to share the same frequency, time and code domains within a cellular group based on their separation within the cell. A particular aspect of SDMA is the ability to divide a cell into different sectorial beams (i.e. 3 sectors – 120 degree beams, 6 sectors – 60 degrees beams, etc). Each sector can then be treated as a new cell; one that serves the same number of users as an ordinary cell. Therefore, if the number of users in a cell is N_{cell} , then the capacity of a cell divided into P_{sector} , sectors is equal to $P_{sector} * N_{cell}$. The ultimate goal of SDMA is high sensitivity reception, by directing high gain beams towards individual mobile users or group of users and steer nulls in the direction of interferers in order to improve signal quality and allow simultaneous transmission between users. Additionally, Spatial Filtering for Interference Reduction (SFIR) is used to reduce the interference in a cellular system by directing beams towards individual users and avoiding areas where there are no users. SDMA also has the ability to provide reuse of common frequencies among different cells. By spatially separating cell with similar carrier

frequencies over large areas and distances, one can reduce the level of co-channel interference and increase capacity.

D.4 CDMA

In CDMA systems, all users transmit in the same frequency band simultaneously. Communication systems following this concept are call spread spectrum (SS) systems. In this transmission technique, the narrow band message signal of the mobile user, m(t), is multiplied by a wideband orthogonal spreading sequence, c(t), whose chip rate is much higher than the data rate, m(t). As a result the bandwidth occupancy is much larger than required. Each code is approximately orthogonal to every other mobile user's code in the cell. Codes and messages from other mobile users are seen as noise in the background of the received signal. Every mobile node shares access to the same frequency and time domains of the cell.

CDMA has a soft capacity limit, as the number of users in the cell is increased, the noise level is increased. Therefore, there is no limit to how many users may exist in a cell as long as the SNR is tolerable. However, with an increasing number of users the overall quality is decreased. CDMA is a very desirable access scheme because of its ability to spread the bandwidth of the message across the finite spectrum of the cell. During transmission a signal power level is comparable to noise floor of the cell making it clandestine and virtually indistinguishable, thus very valuable for multiple satellite networks in LEO. In order to decode the message the receiver must have a priori knowledge of the spreading code of the indented transmitter. Common orthogonal codes include: PN sequence, Walsh and Gold. This access scheme is extremely desirable and shows great promise as the standard for future generations of mobile and satellite communications systems. The capacity, N_{ch}, of a cellular CDMA is given by

$$N_{ch} = 1 + \frac{\frac{W}{R_b}}{\frac{E_b}{N_0}} - \binom{n_{th}}{S}$$

(D1.3)

Where W is the total RF bandwidth, R_b is the baseband information bit rate, E_b/N_0 is the signal-to-noise ratio (SNR), n_{th} is the thermal noise coefficient and S in the desired signal power.

D. 4.1 Spread Spectrum Methods

The use of spread spectrum (SS) link in LEO satellite networks is very desirable as spread spectrum links can provide resistance to international jamming, mask the transmitted signal in the background noise to prevent eavesdropping, provide resistance to degrading and multipath effects on the signal, and also provide range-measuring capability. In order to consider SS method, the following must be satisfied.

- 1) The bandwidth of the transmitted signal s(t) must be much greater than the bandwidth of the message signal m(t).
- The wide bandwidth of s(t) must be caused by an independent modulating waveform c(t) called the spreading signal, and this signal must be known by the receiver in order for the message m(t) to be detected.

Assuming that the spreading signal bandwidth is much greater than the message signal bandwidth, the transmitted signal bandwidth will be approximately equal to the spreading signal bandwidth. The SS signal is:

$$s(t) = \operatorname{Re}\left\{g(t)e^{jw_{c}t}\right\}$$
(D1.4)

Where the complex envelope, g(t), is a function of both m(t) and c(t) given by:

$$g(t) = g_m(t)g_c(t) \tag{D1.5}$$

Where $g_m(t)$ and $g_c(t)$ are complex envelopes of m(t) and c(t) respectively for the usual types of modulation (i.e AM, FM, PM, etc).

The two major types of spread spectrum systems are direct sequence spread spectrum (DSSS) and Frequency Hopping Spread Spectrum (FHSS).There are different aspects available to compare the spread spectrum techniques proposed in the IEEE 802.11 standard. Power, increasing range, delay spread and link connectivity are the widely used to compare PHY layers. Given the fact that there exist four PHY layers in the 802.11 standard but this thesis is mainly interested in the PHY's ability to support high mobility, longer range and Doppler shift and rate of change of Doppler frequency. In this respect, the following sub-section looks at the different PHY layer implementations in 802.11b and compares the different schemes appropriate for LEO ISL networks.

D.4.1.1 Frequency Hopping Spread Spectrum

FHSS is one of the variance of spread spectrum- a technique that enables coexistence of multiple networks in the same area. The 802.11b uses FHSS to minimize interference with

others using the same spectrum. FHSS consist of 79 non-overlapping frequency channels with 1 MHz channel spacing. The transmitter frequency changes in a pseudo random fashion and keep mobile node to run on different frequency hopping patterns. Typically, IEEE 802.11 does 1 MHz jumps every tenth of a second (0.1 Sec). Since the maximum bandwidth for FHSS in 802.11b is 1 MHz, the transmission data that can be carried out at only 1 or 2 Mbps in the 2.4 GHz band. FHSS takes data signal and uses Gaussian frequency shift key to modulate it with a carrier signal that hops from frequency to frequency as a function of time over a wider band of frequencies. FHSS is resistant to multipath fading through the inherent of frequency diversity mechanism. Concerning multipath diversity, currently the FHSS systems employ 2 or 4 level FSK modulation and a 20dB bandwidth of 1 MHz [8]. The narrowband FHSS systems work satisfactorily in environments where delay spread is in the range 100-200 ns [8]. The receiver sensitivity is defined by the standard [8] at least -75dBm and since the transmitting power is 20dBm, we can conclude that FHSS systems satisfy marginally the path loss requirement of 100 dBm. The FHSS frame structure is given in Figure D.1.



Figure D.1 IEEE 802.11 FHSS Frame Structure

D.4.1.2 Direct Sequence Spread Spectrum

The extension of the DSSS system builds on the data rate capability to provide 5.5 and 11 Mbps payload data in addition to the 1 and 2 Mbps data rates provided by FHSS. By the use of RAKE receivers and decision feedback equalizers, the 802.11b systems can obtain multipath diversity. For typical data rates of 2Mbps these DSSS systems can manage delay spread higher than 200 ns [8]. The operating typical range for outdoor environment is only 300 m. The receiver sensitivity to be less than -80dBm at 2Mbps and the BER lower than 10⁵. The maximum allowable output power as measured in accordance with practices specified by the regulatory bodies is 100 mW EIRP (20dBm) for Europe and 1Watt for US. According

to this, 802.11b system shall be able to overcome 100dBm path loss at 2Mbps data rate, providing immunity also for typical fade margin.

In DSSS instead of dividing the frequency into channels as in FHSS, the data signal, m(t), which is a binary digital signal having bandwidth B_m , is multiplied by a pseudo random noise (PN) code, c(t), with a bandwidth B_c , where $B_c \ll B_m$. A PN code is a sequence of -1 and 1 (polar) or 0 and 1 (non-polar) with a specified period named chip period. The following 11chip Baker sequence code is used as the PN code in the IEEE 802.11 standard: +1, -1, +1,+1, -1, +1, +1, +1, -1, -1, [8]. The rate of the chip in the spreading signal, R_{chip} , is greater than the symbol rate, R_m , of the message signal. The effect of the PN code sequence is to spread the transmitted bandwidth by a ratio of 11:1 (spread spectrum). A PN code has noiselike properties. This results in low cross-correlation values among the codes and the difficulty to jam or detect a data message. By spreading the signal symbol with a sequence across the entire bandwidth, bandwidth utilization increases with less power density. The result is a high speed digital stream which is then modulated. The pulse widths of the message signal, m(t), and the spreading signal, c(t), are T_m and T_{chip} , respectively. T_m is referred to as the bit interval and T_{chip} is called the chip interval. With this, we can define the spreading factor, or processing gain of the DSSS system, which is given by:

$$G_c = \frac{R_{chip}}{R_m} = \frac{T_m}{T_{chip}} = \frac{B_s}{2R_m} = 2^r - 1$$

(D1.6)

Where: r is the number of chips in one period of m(t), and $T_m = (2^r - 1)T_{chip}$.

As stated previously, the message signal, m(t), is a binary digital signal with a sequence of symbols, m_k each of which has a period of T_m . We can then define m(t) as:

$$m(t) = \sum_{k=-\infty}^{\infty} m_k \cdot \mu\left(\frac{t - kT_m}{T_m}\right)$$
(D1.7)
When $\mu\left(\frac{t}{T}\right)$ is the unit impulse function given by :

 $\mu\left(\frac{t}{T}\right) = \begin{cases} 1, \ 0 \le t < T \\ 0, \ Otherwise \end{cases}$

Next the message signal, m(t), is multiplied by the spreading signal, c(t), which is of the form:

$$c(t) = \sum_{k=-\infty}^{\infty} \sum_{n=0}^{N-1} c_n \cdot \mu \left(\frac{t - (n - kN)T_c}{T_c} \right) \quad \text{for } |c_n| = 1$$
(D1.8)

Resulting in q(t):

$$q(t) = m(t)c(t)$$

Next q(t) is modulated to a carrier frequency, f_c , by multiplying q(t) by $\cos(\omega_c t)$ producing the transmitted signal, s(t):

$$s(t) = m(t)c(t)\cos(\omega_c t)$$
(D1.9)

Assuming that the wireless channel does not distort the transmitted signal, and the received signal, r(t), is a scaled version of s(t) with added white Gaussian noise, n(t).

$$r(t) = A_c s(t) + n(t) = A_c m(t)c(t)\cos(\omega_c t) + n(t)$$
(D1.10)

The received signal, r(t), is then demodulated by the same carrier scaled by a factor of 2.

$$x(t) = r(t) 2\cos(\omega_c t) = 2A_c m(t)c(t)\cos^2(\omega_c t) + 2n(t)\cos(\omega_c t)$$
(D1.11)

Then, the signal is despread by the same spreading signal, c(t), used in the transmitting stage. There then exist a situation where $c(t)^2 = 1$. This results in:

$$y(t) = 2A_{c}m(t)\cos^{2}(\omega_{c}t) + 2n(t)c(t)\cos(\omega_{c}t)$$
(D1.12)

A low pass filter (LPF) with a cut-off of R_m can be used to extract the message signal from equation (D1.12). A trigonometric identity is performed on equation (D1.12) to return:

$$y(t) = 2A_c m(t) [1 + \cos(2\omega_c t)] + 2n(t)c(t)\cos(\omega_c t)$$
(D1.13)

The LPF is used to discard the higher frequency component centered on $f_c & 2f_c$ resulting in:

$$\hat{m}(t) = A_c m(t)$$
(D1.14)

This results in a received signal that is a scaled version of our original transmitted signal. .

The DSSS physical layer for 802.11 provides 4 different bit rates. As illustrated in Table D.1, each of the 4 data rates employ a different combination of modulation technique and spreading code to achieve the desired symbol rate, and the number of bits per symbol. The basic rates 1 and 2 Mbps, employ a Barker spreading code with a differentially encoded BPSK or QPSK respectively. The receiver can detect the signal coherently or differentially.

Bit Rate (Mbps	Coding Scheme	Modulation Technique	Bits per Symbol
1	Barker sequence (11Chips)	DBPSK	1
2	Barker Sequence (11Chips)	DBPSK	2
5.5	CCK or optional BCC	DQPSK	4
11	CCK or optional BCC	QPSK	8

Table D.1 IEEE 802.11 DSSS modulation techniques and Spreading Codes

In the latter case, it is necessary to lock and track the carrier phase precisely. If the signal is differentially detected, we denote the modulations as DBPSK or DQPSK or else DE-BPSK or DE-QPSK for coherent detection. Tables D.2 and D.3 show the differentially BPSK and QPSK encoder respectively.



Bit input	Phase Change (+jω)
0	0
1	π

The properties of DBPSK using lower rates with longer range and better SNR are of interest in this thesis for LEO ISL applications; hence the BPSK is described in detail.

D.4.1.2.1 BPSK Modulation Scheme

BPSK is a form of digital modulation used in a typical DSSS system given by:

$$s(t) = A_c \cos[\omega_c t + D_p m(t)] \tag{D1.15}$$

Where D_p is the phase deviation of the BPSK signal. The convenience of BPSK signaling is that it can be represented in the form of Double Side Band with Suppressed Carrier (DSB-SC) by performing a trigonometric identity on equation (4.15) to get:

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$$s(t) = A_c \cos(D_p m(t) \cos(\omega_c t) - A_c \sin(D_p m(t)) \sin(\omega_t t))$$
(D1.16)

Using the fact that m(t) can take values of either +/- 1, and that cos(x) and sin(x) are even and odd functions of x, we can reduce the BPSK signal to:

$$s(t) = \underbrace{[A_c \cos[(D_p)]\cos(\omega_c t)] - [A_c \sin[(D_p)]m(t)\sin(\omega_c t)]}_{Pilot \ Carrier \ Term} - \underbrace{[A_c \sin[(D_p)]m(t)\sin(\omega_c t)]}_{Data \ Term}$$
(D1.17)

The amplitude, A_c , of the pilot carrier term is determined by the peak phase deviation $D_p = \Delta \theta$. The digital modulation index, h_m , for digital angle-modulated signal is given by:

$$h_m = \frac{2\Delta\theta}{\pi} \tag{D1.18}$$

Where $2\Delta\theta$ is the maximum phase-to-phase deviation (radians) during the time required to send one symbol, $T_{sym} = T_m$. If D_p is small, then the pilot carrier term has large amplitude. Consequently, a large D_p diminishes the power in the data term, which contains the message signal. The power in the data term needs to be maximized so that there is low probability of error, while maintaining high spectral efficiency. This is achieved when $\sin(D_p)=1 \text{ or } D_p = \Delta\theta = 90^\circ$. This corresponds to the optimum value of $h_m = 1$, where the BPSK signal is given by:

$$s(t) = -A_c m(t) \sin(\omega_c t)$$
(D1.19)

Equation (D.19) Shows that BPSK is equal to DSB-SC for values of peak deviation which maximize the data term, and where m(t) is a polar baseband digital signal. Throughout this thesis, we assume that $h_m = 1$ and the resulting BPSK signal is a shifted form of s(t) given by:

$$s(t) = A_c m(t) \sin(\omega_c t) \tag{D1.20}$$

On the other hand, High Rate-DSSS (HR-DSSS) physical layer, comprising the 5.5 and 11 Mbps rates, employs Complementary Code Keying (CCK) in the 2.4 GHz band. The Length of 8 complementary codes which are used in the 802.11b, can be written as a function of four phase elements $\phi_1, \phi_2, \phi_3, \phi_4$ by:

$$c(\phi_{1},\phi_{2},\phi_{3},\phi_{4}) = e^{j(\phi_{1}+\phi_{2}+\phi_{3}+\phi_{4})}, e^{j(\phi_{1}+\phi_{3}+\phi_{4})}, e^{j(\phi_{1}+\phi_{2}+\phi_{4})}, -e^{j(\phi_{1}+\phi_{4})}, e^{j(\phi_{1}+\phi_{2})}, e^{j(\phi_{1}$$

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For a CCK 11 Mbps modulation the eight binary word $D = d_7 d_6 d_5 d_4 d_3 d_2 d_1 d_0$ are used to encode the phase parameters $\phi_1, \phi_2, \phi_3, \phi_4$. The encoding is based on the differential QPSK modulation. The first debits (d_0, d_1) encode ϕ_1 based on the DQPSK specified in Table D.3.

Bit pattern [di, di+1]	Phase change (+jω)
00	0
01	$\frac{\pi}{2}$
11	π
10	$3\pi/(-\pi/2)$

Table D.3 2 Mbps DQPSK Encoding

Then, the data debits (d_3d_2) , (d_5d_4) and (d_7d_6) encode ϕ_2 , ϕ_3 and ϕ_4 respectively, based on QPSK as specified in Table D.3. For example a data stream of 01100011, we get from Table D.3, $d_0, d_1 = 10$, $\phi_1 = \pi$, $d_3d_2 = 00$, $\phi_2 = 0$, $d_5d_4 = 10$, $\phi_3 = \frac{3\pi}{2} \left(-\frac{\pi}{2}\right)$, and $d_7d_6 = 01$, $\phi_4 = \frac{\pi}{2}$. Finally, using Equation (D1.21), we can find out the codes which should be sent from all possible codes.

DSSS has good auto correction properties, good coding gain and robust against time delays. All the preamble and header of the frame are always transmitted at 1 Mbps rate as defined in the 802.11 standard and the higher data rates if employed are used to modulate the Main protocol data unit (MPDU). The DSSS frame structure is shown in Figure D.2.



Figure D.2 The DSSS Frame Structure

D.5 Orthogonal Frequency Division Multiplexing (OFDM)

The 802.11a operates in the 5 GHz band with data rates up to 54 Mbps and use OFDM to spread the transmitted signal over a wider bandwidth. OFDM is a form of multi-carrier transmission that divides the available spectrum into many carriers, each one modulated by a low rate data stream using Phase Shift Keying (PSK). OFDM is similar to FDM but it is less sensitive to inter-symbol interference (ISI), which is normally a problem for conventional modulation techniques. OFDM allows very efficient frequency re-use (a prerequisite for LEO constellations) since it can be combined with Code Frequency Division Multiplexing (CFDM) transmission, thus providing very high diversity properties using correlation of signals. The only major disadvantages of OFDM are that it requires highly linear power amplifiers, and also requires frame synchronization at the receivers. The following modulation schemes can be supported by 802.11a: BPSK, QPSK, 16QAM, or 64QAM.

D.6. Infra Red

The Infra Red (IR) physical layer offers significant advantages over FHSS and DSSS for it can support higher data rates and use basic properties of the information theory to detect and demodulate signals thus reducing receiver complexity. The major disadvantage of IR for space applications is that it shares the same frequency spectrum with the sun, thus making the use of IR based systems practical only for indoor applications.

APPENDIX E

IEEE 802.11 Protocol Wireless LAN

Although the original concept of wireless LANs has existed since late 1970s, the WLAN technology has been evolving since in late 1990s. Today, it has become a ubiquitous networking technology. The recent development and explosive growth of this technology can be attributed to many factors, for example, technological advances in error correcting codes, modulation techniques, processing power on network interfaces, availability of unlicensed radio spectrum, and the need for wireless connectivity and mobility. There are multiple wireless LAN technologies in present markets, such as, Wi-Fi, Bluetooth, WiMAX, ZigBee etc. All of these technologies operate in the 2.4 GHz ISM (Industrial, Scientific, and Medical) radio spectrum. Wi-Fi technology is based on IEEE 802.11 standard [8] and IEEE 802.11b is the most mature technology to date.

The aim of the IEEE 802.11 standard is to provide wireless connectivity to devices that require a quick installation, such as portable computers, PDAs, or generally mobile devices inside a WLAN. The WiFi WLAN is based on a cellular architecture; each cell is called a Basic Service Set (BSS). A BSS is a set of mobile or fixed WiFi nodes. Access to the transmission medium is controlled by means of a set of rules called a coordination function. WiFi defines a Distributed Coordination Function (DCF) and a Point Coordination Function (PCF), the latter being optional. The MAC protocol used is a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol, the technical name for DCF; it offers only the best effort service. DCF operates on top of the physical layer providing an ordinary asynchronous traffic. The Point Coordination Function, which is an optional support for time bounded services through the use of the contention free mechanism, is built on top of the DCF. The MAC handles acknowledgement in the 802.11 with optional Request-to-sent (RTS) and Clear-to-Send (CTS) handshaking for reliability and hidden node problems. Mobility is also handled in the MAC layer, so handoff between adjacent cells is transparent to layers built

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on top of the 802.11 device. The IEEE 802.11 standard defines MAC procedures for accessing the physical medium, which can be infrared or radio frequency.

Table E.1 summarizes the status of the IEEE 802.11 standard family, including the draft versions and those that are still at tasks group development status.

Standard	Description	Status
IEEE 802.11a	WLAN; up to 54 Mbps; 5 GHz	Approved 1999
IEEE 802.11b	WLAN; up to 11 Mbps; 2.4 GHz	Approved 1999
IEEE 802.11g	WLAN; up to 54 Mbps; 2.4 GHz	Approved 2003
IEEE 802.11e	New Coordination function for QoS	Approved 2005
IEEE 802.11f	IAPP (inter-AP protocol)	Approved 2003
IEEE 802.11i	New encryption standard	Approved 2004
IEEE 802.11n	High Date rate & MIMO physical layer	Ratification 2008
IEEE 802.11p	High Mobility support up to 200km/h	Ratification 2008
IEEE 802.11s	Mesh networking support	Ratification 2008

Table E.1 IEEE 802.11 Standard and Supplements

E.2 IEEE 802.11 Frame Structure

In terms of the OSI reference model, IEEE 802.11 covers the MAC and physical layers. The physical layer is again divided into a PLCP and a PMP sub layer. A protocol data unit (PDU) at each layer is defined as the length of the transmission unit at that layer including the overhead. A service data unit (SDU) is defined as the length of the payload that a particular layer provides to the layer above. Therefore, when a higher layer pushes a user packet down to the MAC layer as a MAC SDU (MSDU), overheads occur at each intermediate layer. A format of the MAC header with the exception of the FCS is shown in Figure E.1. More about the functionality of these control frames can be found in the standard [8]. IEEE 802.11 performs packet encapsulation technique to transmit IP packets as shown in Figure E.2. Figure E.2 shows all headers from the application layer to the PHY layer.







Note that check sum fields are done over the whole packets at the UDP, MAC levels and IP header. In IEEE 802.11 MAC layer, each MPDU packet consists of the following components: a MAC layer, optional IP/UDP/RTP/NAL headers, a variable length information frame body, and a frame check sequence (FCS). All the fields contribute to the MAC overhead for data/fragment frame except the frame body which is 28 octets in total.



Figure E.2 Packet encapculation in IEEE 802.11

The frame of RTS, CTS and ACK packets are shown in Figure E.3 as well. Figure E4 illustrates the PLCP preamble and header formats in IEEE 802.11b. A long and short PLCP is defined in 802.11b. The long PLCP (Figure E.4(a)) includes the High Rate PLCP preamble and the High Rate PLCP header. The PCLP preamble contains the following two fields: synchronization (SYNC) and the start frame delimiter (SFD). The PLCP header contains the following four fields: SIGNAL, SERVICE, LENGTH, and CCITT CRC-16 (CRC). The

PLCP header and preamble must be sent using the basic mode corresponding to 1Mbps and DBPSK modulation in 802.11b. However the short frame format shown in Figure E.4(b) is not compatible with PPDUs used in the classic DSSS PHY layer. The short PLCP header uses the 2 Mbps with DQPSK modulation and a transmitter using the short PLCP can only interoperate with the receivers which are capable of receiving this short PLCP format. However, the short PLCP preamble and header can be used to minimize overhead and thus maximize the network throughput.



Figure E.3 (c): ACK Frame Format

Figure E.3 Control frame formats in IEEE 802.11 a) RTS Frame b) CTS Frame and ACK frame formats



Sent by Basic Mode (1 Mbps, 192 ms)

PLCP preamble (144 bits)

PLCP header (48 bits)





Short PLCP preamble (74 bits) at 1 Mbps

Short PLCP header (48 bits) at 2 Mbps

Figure E.4 (b). Short PLC

Figure E.4 IEEE 802.11 PLCP headers a) Long PCLP b) Short PLCP

APPENDIX F

Smart Antennas

Adaptive antenna systems can be defined as antenna systems that can improve range and system capacity by adapting the antenna pattern and concentrating its radiation to each individual node, through the use of more than one antenna element. As shown in Figure F.1 the general classification of AAS basically consist of two types: Switched Beam systems and Adaptive Array System. The switched beam systems comprises of only basic switching between separate directional antennas or predefined beams of an array, while enabling high directivity and gain. Switched beams can be further sub-divided into two: Single beam and Multi beam directional antennas.



Figure F.1 General classifications of Smart antennas

In single beam directional antenna systems, only one beam is active at a time as shown in Figure F.2(a). No simultaneous transmissions are allowed, since in this system there is only one transceiver. On the other hand, multi beam directional antenna system is an example of a Spatial Division Multiple Access (SDMA) system. Here, each directional antenna beam can be used and thus multiple transmissions are allowed at the same time and frequency. The number of beams is equal to the number of transceivers as shown in Figure F.2(b)



(a) Single beam directional antenna (a) Multi

(a) Multi beam directional antennas

Figure F.2 Operational modes of Switched Beam Antennas

Adaptive array systems on the other hand apply adaptive beamforming where a Direction of Arrival (DOA) algorithm is used to determine the direction of the signal received from a user. By this method, users can be continuously tracked. Also interference detection can be added to the beam forming system so that interference is cancelled by adjusting the radiation pattern with nulls and thus the signal to interference ratio is increased. Clearly, adaptive beam forming is more complex than switched beam systems. There are also two kinds of adaptive beam forming. In the single user beam forming, the antenna is adjusted to track one user and cancel the interference by placing nulls as shown in Figure F.3(a). In this case, a single transceiver is sufficient since only one user is active at a given time. On the other hand, in multi user beam forming in Figure F.3(b), there are different beam patterns, and each beam tracks one user. Therefore, simultaneous transmissions are allowed and SDMA is achieved, as illustrated in Figure F.3 (b).

The concept of smart antennas is introduced in section F.1. Section F.2 describes adaptive algorithms that iteratively approximate the optimum beamforming solution. Section F.3 describes fixed beamformers such as Butler's matrix.

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F.3 (a) Single user tracking F.3 (b) Multi user tracking

Figure F.3 Operational modes of Adaptive Beamforming

F.1 Introduction to Smart Antennas

The limitations in wireless communication systems in capacity and reliability are due to three major impairments: fading, delay spread and co-channel interference [87]. Smart antenna techniques using more than one antenna have been investigated to increase capacity and extend range by overcoming these impairments. Smart antenna techniques can be divided into three processes: space, time and space-time processing. The performance of space processing is determined by multipath fading and co-channel interference and it can be limited by the antenna configuration. On other hand, the performance of time processing is limited by the time resolution which is inversely proportional to the bandwidth of the system and can be determined by the delay spread. The bandwidth of any wireless communication system is the most valuation radio resource. It can be more economical to increase the number of antenna elements to achieve more capacity than increase the bandwidth of the system.

A smart antenna is defined as an antenna system that has circuit elements associated with its radiating elements such that one or more of the antenna properties are controlled by the received system [16]. In these systems, each transmitter located at a certain place has a unique pattern, which is called spatial signature.

Looking at recent antenna technologies used in present wireless broadband systems, it is useful to divide the two: Multiple Input Multiple Output (MIMO) and Adaptive Antenna System (AAS). Both MIMO and AAS are techniques addressing different channel conditions with their own issues. To use MIMO in a highly scattered propagation environment is advantageous, but AAS algorithms may not demonstrate their best performance in such environments. In terms of deployment, MIMO is likely to be used in urban environments to take advantage of uncorrelated scattering, perhaps increasing the system capacity in dense user areas by taking advantage of Spatial Multiplexing (SM). Conversely AAS can be used in Line-of-Sight (LOS) environments where scattering is low and users are sparse, such as LEO ISL applications. In this thesis we are using the AAS to increase the spectral efficiency of the space system to provide capacity and/or coverage gains by means of increased protection against fast fading (function of Doppler shift), thermal noise and multiple access interference. Arrays with omni-directional antennas have larger multiplexing gain and therefore a higher data rate than arrays of smart antennas. However, directional antennas provide larger SNR gains and the use of adaptive data rates will further improve the SNR performance of 802.11 using directional antennas in ISL applications without much modifications of the protocol.

F 1.1 Switched-Beam Antenna System

Switched beam antennas systems (SBSA) can create a group of overlapping beams and together results in omni directional coverage [78, 88, 89, 90, 91, and 92]. The overlapping beams patterns pointing in slightly different directions are presented in Figure F.4.



Figure F.4 A Switched Beam Array Architecture

Switched beams create a number of two-way spatial channels on a single conventional channel in frequency, time and code. Each of these spatial channels has the capability of interference rejection depending on the side lobe level. As mobile nodes move, beam-

switching algorithms for each traffic determine when a particular beam should be selected to maintain the highest quality of service and the beam selection system is updated continuously to get the optimal quality of service. The beam selection algorithm scans the output of each beam and selects the beam with the highest output power or low BER as well as suppresses the interference arriving from directions away from the centre of the active beam.

F 1.2 Digital Beamforming

Adaptive beamforming (ABF) [78, 89, 90, 93, 94] can be described as a marriage between antenna technology and digital signal processing. In comparison with switched-beam antennas and phased array antennas, smoother pattern direction tuning and higher resolution direction finding can be achieved with high-speed DSP and high resolution ADC. A ABF array antenna is shown in Figure F.5.



Figure F.5 Adaptive Beam Array Architecture

The architecture of ABF consist of a down-conversion channel has a low-noise amplifier, a frequency converter, and an ADC. Signals received by individual antenna elements have to be down converted to the base-band, digitized and then are fed into a DSP chip where algorithms are carried out. Fine steering can be achieved by employing high-resolution sampling and quantization in an A/D conversion process. DBF arrays make use of the DOA [78, 93, 94, and 95] information from a desired user and steer a beam maximum towards that user, thus improving upon the capabilities of a switched-beam antenna.

However, the use of high-resolution A/D conversion can result in the dissipation of a substantial amount of DC power. Furthermore, since a ABF antenna needs the same number of A/D converters as the number of antenna elements, the fabrication cost increases with the number of antenna elements. In addition, because the A/D conversion cannot be carried out directly in the RF stage, same amount of power is also consumed at the frequency converters. Due to these reasons, the use of ABF antennas has been restricted to military applications or at the base station for terrestrial wireless communication.

F 1.3 Phased Array Antennas

Phased array antennas have been extensively investigated in [78, 90, 93, and 96] and typical applications are in radar, military scenarios, and satellite communications. The advantages of using Phased array antennas for space-based communications applications are scanning, reconfigurability, weight, and power.

Phased-array antennas consist of a multitude of radiating elements, typically arranged in a rectangular or triangular tessellation. Beam pattern steering of phased array antennas is achieved by implementing phase shift of signals from array elements and keeping the amplitude weights fixed.

Dynamic phased arrays make use of the DOA information from a desired user and steer a beam maximum towards that user, thus improving upon the capabilities of a switched-beam antenna. Tracking is needed to continuously steer the beam towards the desired user. However, the disadvantage of the phased array antenna is the relatively high cost as expensive PIN diodes are used in phase shifters required by beam forming networks.

F 1.4 Parasitic Antennas

To mitigate the disadvantages of the aforementioned systems, adaptive beam forming based on parasitic antennas has been explored [93, 97, and 98]. In this scheme, the active element, which is excited by the transmitted or the received signal sources, is surrounded by a number of parasitic elements, which are not connected to the signal source. In the presence of neighboring elements, each one's performance depends on not only its own current but also the currents on neighboring elements. For resonant elements with no current excitation of their own, there could be a substantial current induced by radiation from another source. The far field radiation pattern is formed by superposition of the radiation of all antenna array

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elements. Thus, changing the radiation of each element it is possible to direct the antenna beam towards desired directions.

F 1.5 Diversity Antennas

Diversity techniques combat against multipath fading and improve channel quality for a given radio spectrum in comparison with that from a single port antenna. Because the correlation among signals from the multiple ports of array antennas undermines the diversity combining performance the challenge of diversity antenna design is how to achieve signal decorrelation, especially at mobile terminals where antenna elements are mounted within small spacing, for a given incident wave distribution scenario. [99, 100]. A flow chart is given in Figure F.6 summarising the applications and benefits of different smart antenna techniques.



Figure F.6 A flow chart showing applications and benefits of different antenna systems

F 2 Fundamental of Smart Antennas

Figure F.7 represents the concept of the smart antenna. The smart antenna can be basically called a set of receiving antennas in a certain topology. The received signals $r_n(t)$ with added noise $n_m(t)$ are multiplied with a weighing factor, w_m^* adjusting the phase and amplitude [78].

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Summing up the weighted signals, results in the output signal, z(t). The concept of a transmitting smart antenna is rather the same, by splitting up the signal between multiple antennas and then multiplying these signals with a factor, which adjusts the phase and amplitude. The signal and weight factors are complex.



Figure F.7 Smart antenna concepts for receiving array system

In other to explain the principle of smart signal processing, a linear array is shown in Figure F.8. Let us consider a plane wave incident on the array from angle (θ, ϕ) relative to the x-axis of the array. The inter-element space i.e. the distance between the antenna elements is given as Δx . The far-field electrical expression of the electrical signal at the m-th element at any time t is given by

$$x_m(t) = r(t) \cdot e^{-j\xi m \Delta x \cos \phi \sin \theta} + n_m(t) \quad m = 1, 2, ..., M - 1$$
(F.1)

Where r(t) are the signal envelope, $\xi = \frac{2\pi}{\lambda}$ is the wave propagation factor and λ denotes the wavelength, given as c/f, where c is the speed of light and f the carrier frequency in Hz. The direction of arrival of the incident wave is (θ, ϕ) with the $n_m(t)$ additive white Gaussian noise (AWGN) at the m-th element.

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Figure F.8 A linear Array Architecture [78]

The output of the array antenna is produced by the inner product of the input signals and weight coefficients determined by adaptive algorithms as

$$z(t) = w^{H} x(t) = \sum_{m=0}^{M-1} w_{m}^{*} [r(t) + n_{m}(t)]$$
(F.2)

Where the superscript H denotes Hemitian transpose operator. The signal data vector can be given as:

$$x(t) = a(\phi, \theta) r(t) + n(t)$$
(F.3)

Where $a(\phi, \theta)$ denotes the Array Factor (AF) vector as

$$a(\phi,\theta) = \left[1, \exp(-j\frac{2\pi}{\lambda}\Delta x \cos\phi\sin\theta), \dots, \exp(-j\frac{2\pi}{\lambda}\Delta x(M-1)\cos\phi\sin\theta)\right]^T \quad (F.4)$$

Where T denotes transpose of a matrix and

$$a_m(\phi,\theta) = e^{-j\xi\,\Delta x_m\cos\phi\sin\theta} \tag{F.5}$$

The array factor is the response of the signal arriving from angle θ , where $x(\phi, \theta)$ and $z(\phi, \theta)$ are the input and output of the beamforming respectively. If we consider ξ and Δx as fixed parameters of the antenna, then the array factor is given by

$$a(\phi,\theta) = \sum_{m=0}^{M-1} w_m e^{-j\xi m\Delta x \cos\phi \sin\theta}$$
(F.6)

If we consider the signal is arriving at the antenna array at an angle ϕ_0 , it is clear that the array response will be maximal by adjusting the phase of the complex weight. Let the complex weight is defined by:

$$w_m = A_m e^{jm\Phi}$$
(F.7)

Where

$$\Phi = \xi \Delta x \cos \phi_0 \tag{F.8}$$

Then the array factor is

$$a(\phi,\theta) = \sum_{m=0}^{M-1} A_m e^{-j(\xi m \Delta x \cos \phi \sin \theta - m\Phi)}$$
(F.9)

Figure F.9 shows the effect of an array response of a linear array with 8 and 16 antenna elements respectively, with the beam steered to the front at ϕ_0 equal to 45 degrees.



Figure F.9 Array Factor with a) 8 elements b) 16 elements with beams steered at $\phi_0 = 45^\circ$

The response is generated by using MATLAB simulations. There are many antenna topologies in which smart antennas can be configured, as circular array or planar arrays.

F 2.1 Switched Beam Selection Based on SNR Maximization

Figure F.10 illustrates the linear array antenna configuration for switched beam forming. The h_i represents the channel between the ith antennas element of a transmit array and receiver.



Figure F.10. Linear array antenna for switched beam forming.

In order to support K fixed switched beams, the transmitting satellite uses E element array antenna and preset K weighting vectors. In order to form switched beam of index k, the transmitting satellite will apply a weighting vector, W_k :

$$W_{k} = \begin{bmatrix} w_{k,1} \\ w_{k,2} \\ w_{k,3} \\ \dots \\ w_{k,E} \end{bmatrix}, k = 1, 2, 3, \dots, K.$$
(F.10)

For a transmit switched beam of index k formed by E element array antenna of the transmitter, the received signal at the receiver side is given by

$$r = \sqrt{\upsilon} H W_k x + n, \tag{F.11}$$

where H is $[h_1, h_2, h_3 \dots h_E]$, r, x, n, υ represent the received signal, transmitted signal, thermal noise and the input SNR, respectively. The transmit pilot signals identifying array
elements must be defined in order to obtain channel measurement vector H. The instantaneous SNR of the received signal at the receiver is denoted by

$$SNR = \upsilon(W_k^H R W_k), \ R = H^H H \tag{F.12}$$

Using the channel measurements and the preset K weighting vectors, the receiver selects the beam which maximizes the received SNR. Therefore the selection is made in such a way that the receiver estimates the SNR for each weighting vector using (F.13) and finds the best beam which gives the best SNR.

 $BeamIndex = \arg\max\left\{ \upsilon(W_k^H R_L^i W_k) \right\}$ (F.13)

$$R_L^i = \iota R_L^{i-1} + (1-\iota)R^i$$

Where R^i and ι represent the i_{th} calculated $H^H H$ in the time sequence and an averaging parameter, respectively. The selected switched beam index at the receiver must inform the transmitter using the feedback channel.

F 2.2 Adaptive Beamforming

In adaptive beamforming [92, 93, 94], complex weights at each element are be used to optimize some property of the received signal. Although, the results does not always give an array pattern having maximum beam in the direction of the desired signal but it does yield the optimal array output signal. Most often this is accomplished by forming nulls in the directions of interferers. Adaptive beamforming is an iterative approximation of optimum beamforming. As illustrated in Figure F.11 a general array with variable element weights is shown.



Figure F.11 An Adaptive Array Antenna System

Adaptive array can be classified into two categories: 1) Non-Blind Adaptive algorithms and 2) Blind Adaptive algorithms. Non-blind algorithms need statistical knowledge of the transmitted signal in order to converge to a weight solution. This is typically accomplished by sending a pilot sequence signal to the receiver to help identify the desired user. On the other hand, Blind algorithms do not need any training signal, hence the term "blind". They attempt to restore some characteristics of the transmitted signal in order to separate it from other users in the surrounding environment. Several of these algorithms are briefly described below in subsections F.2.1.1 and F.2.1.2.

F 2.2.1 Non-Blind Adaptive Beamforming Algorithms

As stated above, non-blind algorithms require a training sequence, d(n), [78] in order to extract the desired signal from the environment. This in itself can be undesirable for during the transmission of the training signal no communication can take place. Additionally, it can be very difficult to statistically estimate the channel conditions to give a reasonable estimate of d(n) needed to accurately adapt to a desired user. With this in mind, the following summarises the basic concept of non-blind adaptive algorithms.

F 2.2.1.1 Least Mean Square Algorithm

The LMS algorithm [78] can be considered to be the most common adaptive algorithm for continues adaptation. This algorithm uses a steepest-descent method and computes the weights vector recursively using the equation

$$w(n+1) = w(n) + \frac{1}{2}\mu_s \left[-\nabla \left(E |e(n)|^2 \right) \right]$$
(F.14)

Where μ_s is the step size parameter and controls the convergence characteristics of the LMS algorithm. $e^2(n)$ is the mean square error between the beamformer output z(n) and the reference signal which is given by,

$$|e(n)|^{2} = \left[d(n) - w^{H}x(n)\right]^{2}$$
(F.15)

In the method of steepest decent the biggest problem is the computation involved in finding the values of r_{sd} and R_{xx} expectation operators in real time. On the other hand, the LMS algorithm simplifies this by using the instantaneous values of the covariance matrices r_{sd} and R_{xx} instead of the their actual values i.e

$$R_{xx}(n) = x(n)x^{H}(n)$$
(F.16)
$$r_{xd}(n) = d^{*}(n)x(n)$$
(F.17)

The weights update can be given by the following equation:

$$w(n+1) = w(n) + \mu x(n) [d^*(n) - x^H(n)w(n)]$$

= w(n) + \mu x(n)e^*(n) (F.18)

Figure F.12 shows the flow chart of computation of complex weight coefficient in the direction-of-arrival algorithm for antenna beam forming using the LMS algorithm.



Figure F.12 A flow chart of an adaptive algorithm for computing the weigth of the LMS tracking system

Therefore the LMS algorithm can be summarized by the following steps:

- 1. Initialize the weight vector w as the first column of an $(M \times M)$ identity matrix. This corresponds to an omni-directional antenna array (or all-pass in filter theory)
- 2. update the weight vector for time sample n+1 by implementing the following:

$$\dot{z}(n) = \vec{w}^{H}(n) \dot{x}(n)$$
$$e(n) = d(n) - z(n)$$

$$\vec{w}(n+1) = \vec{w}(n) - 2\mu \vec{x}(n)e^{*}(n)$$
 (F.19)

Where d(n) is the desired signal and z(n) is the output of the adaptive array. The LMS algorithm initiated with some arbitrary value for the weight vector is seen to converge and stay for

$$0 < \mu_s < \frac{1}{\lambda_{\max}}$$
(F.20)

Where λ_{\max} is the largest eigenvalue of the correlation matrix R_{xx} . The convergence of the algorithm is inversely proportional to the eigenvalue spread of the correlation matrix R_{xx} . When the eigenvalue of R_{xx} are wide spread, convergence is slow. The eigenvalue spread of

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the correlation matrix is estimated by computing the ratio of the largest eigenvalue to the smallest eigenvalue of the matrix. If μ_s is chosen to be very small then the algorithm converges very slowly, but the resulting weight vector will be very accurate, and vice versa for when it is large.

F 2.2.1.2 Recursive Least Squares (RLS) Algorithm

Contrary to LMS algorithm, which uses the steepest descent method to determine the complex weight vector, the RLS algorithm uses the method of least squares. The RLS algorithm [101] estimates the R_{XX} and r_{xd} using the weighted sums so that

$$R_{xx} = \sum_{i=1}^{N} \gamma^{n-1} x(i) x^{H}(i)$$
(F.21)

and

$$r_{xd} = \sum_{i=1}^{N} \gamma^{n-1} d^{*}(i) x(i)$$
(F.22)

The inverse of the covariance matrix can be obtained recursively, and this leads to the update equation:

$$w(n) = w(n-1) + q(n)[d^*(n) - w^H(n-1)x(n)]$$
(F.23)

Where

$$q(n) = \frac{\gamma^{-1} R_{xx}^{-1}(n-1)x(n)}{1 + \gamma^{-1} x^{H}(n) R_{xx}^{-1}(n-1)x(n)}$$
(F.24)

and

$$R_{xx}^{-1}(n) = \gamma^{-1} \Big[R_{xx}^{-1}(n-1) - q(n)x(n)R_{xx}^{-1}(n-1) \Big]$$
(F.25)

The RLS algorithm converges about an order of magnitude faster than the LMS if the SNIR is high but at the cost of increase complexity. It requires an initial estimate of R_{xx}^{-1} and a reference signal.

F 2.2.2 Blind Adaptive Beamforming Algorithm

As stated previously, "blind" adaptive algorithms do not need a training sequence in order to determine the required complex weight vector. In these algorithms, the weights can be updated using any of the methods mentioned above, but the reference signal is obtained by

demodulating z(t). This means that no external reference is required, but convergence is not guaranteed because z(t) may not correspond to d(t).

F.2.2.2.1 Constant Modulus Algorithm (CMA)

The constant modulus algorithm proposed in [78, 101] requires no previous knowledge of the desired signal. Instead the constant or constant amplitude properties of most modulation formats used in wireless communication is exploited. By forcing the received signal to have constant amplitude, CMA recovers the desired signal. The weight update equation is given by $w(n+1) = w(n) = cr(n)e^*(n)$ (F 26)

$$w(n+1) = w(n) - \mu x(n)e(n)$$
 (F.20)

Where

$$e(n) - [1 - |z(n)|^2]z(n)x(n)$$
(F.27)

CMA algorithm can converge to an optimum solution, when it converges, but convergence of this algorithm is not guaranteed because the cost function e is not convex and may have false minima. Additionally, there can be potential problems if there is more than one strong signal, and the algorithm may acquire the wrong signal. This problem could be overcome with additional information about the desired signal. There are variations of CMA that use different cost functions. The Least-Square CMA (LSCMA) is a variation of CMA that uses a direct matrix inversion.

F 2.3 Multiple-Fixed Beam Antennas

An M-by-Z transformation matrix **T** characterizes a fixed beamforming network (BFN) that relates the inputs from the *M*-element array antennas to Z outputs. The relationship between the inputs and outputs of the beamforming network is expressed by [78]

$$z(t) = T^H x(t) \tag{F.28}$$

Typically, the beamforming network produces M outputs from M elements. The M-by-M Beamforming Network Matrix (BFNM) is given by

$$T = \begin{bmatrix} w_0 & w_1 & \dots & w_{M-1} \end{bmatrix}$$

If the transformation matrix T is *M-by-M* with full ranks, then any adaptive array solution can be obtained with the beamforming network.

$$T^{H} = \frac{1}{2} \begin{bmatrix} \frac{(1-j)}{\sqrt{2}} & -1 & \frac{(1+j)}{\sqrt{2}} & -j \\ 1 & \frac{(1-j)}{\sqrt{2}} & -j & \frac{(-1-j)}{\sqrt{2}} \\ \frac{(-1-j)}{\sqrt{2}} & -j & \frac{(1-j)}{\sqrt{2}} & 1 \\ -j & \frac{(1+j)}{\sqrt{2}} & -1 & \frac{(1-j)}{\sqrt{2}} \end{bmatrix}$$

Figure F.13 shows a simple four-by-four beamforming matrix and its corresponding transformation T is given by [78]. It consists of a series of fixed ferrite phase shifters and hybrid junctions operating at RF frequencies to adjust the amplitudes and phase of the received signal at each element. The Butler matrix [89, 91, 102] is capable of simultaneously producing several beams in different angles.



Figure F.13 Butler Matrix implementation of the fixed beamforming network [78]

The value of M determines the location of the fixed beam which is evenly distributed around $\theta = 0^{\circ}$. For a spacing of $\ell = \frac{\lambda}{2}$, the beams are equally spaced over a span of 180°. When $\ell > \frac{\lambda}{2}$, the angular separation of the beams decreases with increasing θ . Figure F.14 shows the individual outputs at ports 1, 2, 3 and 4 for the Butler matrix. Port 1, 2, 3 and 4 corresponds to beam patterns whose main lobe's angular directions are 140°, 105°, 75° and 42° respectively.



Figure F.14 Output of the four port Butler matrix [78]

F 2.4 Diversity Combining

In addition to fixed-beams, phased and adaptive arrays, signals from multiple antennas can be combined to improve performance in fading channels. Three diversity combing methods are depicted in Figure F.15. Selective diversity is the simplest method, as shown in Figure F.15 (a). From a collection of M antennas the branch with the largest signal-to-noise ratio at a time is selected and connected to the receiver. As can be expected, the larger the value of Mantennas the higher the probability of having a higher signal to noise ratio. As shown in Figure F.15 (b), the Maximal ratio combing takes advantage of all the diversity branches of the system. As shown in the configuration, all the M branches are weighted with respect to their instantaneous signal voltage to noise ratios. The branches are then co-phased prior to summing in order to ensure that all branches are added in phase for maximum diversity gain. The summed signals are then used as the received signal. Maximal ratio has advantage over selective diversity but with added complexity. Proper care has to be taken to make sure the signal are co phased correctly and gain coefficients have to constantly updated. A variation of maximal ratio combining is the equal gain combing shown in Figure F.15 (c). In this method the gains of the branches are set to the same value and are not changed thereafter. As with the previous case, all the signals are co phased to give the output.



Figure F.15 Diversity combining techniques a) Selective Diversity b) Maximal-ratio combining and c) Equal-gain combining.