FACULTY OF ENGINEERING AND TECHNOLOGY

MASTER IN COMPUTING

# OPTIMIZED ROUTING ALGORITHM IN LOW EARTH ORBIT SATELLITE NETWORKS

Izzat S.Ghaith

Supervised by:

Dr. Mohammad Hussein

Date: August-2020

كلية الهندسة
برنامج الماجستير في الحوسبة

# OPTIMIZED ROUTING ALGORITHMIN LOW EARTH ORBIT SATELLITE NETWORKS

## تحسين خوارزمية التوجيه في شبكات الأقمار الصناعية ذات المدار الأرضي المنخفض


إعداد

عزت سمير غيث


لجنة الأشراف

د. محمد حسين (رئيسا)

د. أياد طومار (عضو)

د. واصل غانم (عضو)

This Thesis was submitted in partial fulfillment of the requirements for the Master’s degree in Computing From the Faculty of Engineering at Birzeit University, Palestine.

August 2020


قل إن صلاتي ونسكي ومحياي ومماتي لله رب العالمين

ACKNOWLEDGEMENTS

I cannot express enough thanks to my University for their continued support and encouragement: Dr. Mohammad Hussein, and all Master of Computing stuff. I offer my sincere appreciation for the learning opportunities provided by my committee.

My completion of this degree could not have been accomplished without the support of my Father and Mother and all my family. The countless times you kept supporting me.

Finally, to my caring, loving, and supportive wife, Majd: my deepest gratitude. Your encouragement when the times got rough are much appreciated and noted. It was a great comfort and relief to know that you were willing to provide management of our household activities while I completed my work. My heartfelt thanks.

*أنا أحكي عن الحرية التي لا مقابل لها، الحرية التي هي نفسها المقابل.*
*" غسان كنفاني "*

# المستخلص


تعدّ الأقمار الصناعيّة واحدة من أهمّ منجزات الثورات التكنولوجيّة في هذا العالم، لما لها من فائدة كبيرة في هذا العالم، وقد أثرت كثيراً في أعمال الإنسان، والمنظّمات، وأنظمة الاتصالات. ولتلبية النمو الهائل في الطلب على خدمات الوسائط المتعددة على الأجهزة النقالة ودعم الاتصال في أي مكان على سطح الكرة الأرضية، اجتذب تطوير أنظمة النطاق العريض الكثير من الاهتمام في الأوساط الصناعية والأكاديمية على حد سواء. ومن المتوقع ان تؤدي الشبكات الساتلية عموما وشبكات السواتل الموجودة في المدار الأرضي المنخفض دورا أساسيا في نر هذه النظم. ومع ذلك، فأن مجموعة الأقمار الصناعية الموجودة في المدار الأرضي المنخفض (LEO) مثل (Iridium) و (Iridium-Next) مكلفة للغاية بطريقة نشرها وصيانتها. ونتيجة لذلك، فان تطوير طرق لتقليل التكليف في وضع السواتل بمدارتها وتقليل اعمال الصيانة برز كتحد كبير للباحثين والمهندسين على حد سواء. والملاحظة الرئيسية في هذه الأطروحة هي أنه يمكن للمرء زيادة عمر خدمة الأقمار الصناعية بشكل كبير من خلال إدارة عمق التفريغ (DoD) في بطارياتهم. يمكن للأقمار الصناعية في مجموعات المدار الأرضي المنخفض أن تقضي حوالي 30٪ من وقتها تحت منطقة الظل، وهو الوقت الذي يتم فيه تشغيلها بواسطة البطاريات. أثناء إعادة شحن البطاريات بالطاقة الشمسية، يؤثر عمق التفريغ الذي تصل إليه أثناء الكسوف بشكل كبير على حياتها، وبالتالي على عمر خدمة القمر الصناعي نفسه. بالنسبة للبطاريات مثل تلك التي تعمل بخطوط Iridium وIridium-Next، فإن زيادة بنسبة 15٪ في (DoD) يمكن أن تقلل عمليا من عمر الخدمة بمقدار النصف. في الجزء الرئيسي من هذه الأطروحة، نقترح تقنيات مختلفة لتقليل عمق تفريغ البطارية في مجموعات المدار الأرضي المنخفض. بفضل الطبيعة الموحدة والمتسقة للغاية لهذه الأبراج، حيث انه يوجد هناك العديد من المسارات بين أي قمرين صناعيين، مما يفتح إمكانية اختيار المسار لتوجيه البيانات بناءً على مستويات البطارية.

في هذا السياق ونحن نركز على توجيه البيانات أولا، نقدم مقياس التوجيه الجديد الذي اعطيناه اسم (NROM)، والذي يحاول تحقيق التوازن بين الأداء في حركة توجيه البيانات وأداره الطاقة في البطاريات التي تعمل على السواتل. النهج الأساسي الذي قمنا باتباعه في هذه الاطروحة هو الاستفادة قدر الإمكان من القطاعية لتلك السواتل بحيث يتم توجيه البيانات لتلك السواتل الموجودة بالمنطقة المقابلة للشمس و بالتالي تكون السواتل تعمل على الطاقة الممتصة من الألواح الشمسية و تجنب السواتل الموجودة بمنطقة الظل , حيث ان تلك السواتل تكون في حينها تعمل على الطاقة المخزنة بالبطاريات, و بالتالي الحد من معدل عمق التفريغ بالبطاريات, تتم كل هذه العملية مع الاخذ بعين الاعتبار عدم تأثر أداء كوكبة السواتل على توجيه البيانات .باستخدام واقعية السواتل في المدار الأرضي المنخفض و طريقة بناء شبكاتها و طوبولوجيها و طريقة توجيه البيانات فيها يظهر ان المقياس (NROM) يمكن ان يزيد عمر البطارية 75% و 100% على التوالي .

في هذه الأطروحة، ندرس الأقمار الصناعية، وكيف تعمل وما هي أهم ملامحها، أيضا، نعرض أنواع الأقمار الصناعية ومداراتها حول الأرض. وبما أن هناك، من حيث المبدأ، ثلاث مدارات تكون فيها السواتل ذاتية - الدوران حول الأرض. حيث تم اشتقاق ثلاث إصدارات من مقياس NROM. حتى نتمكن من خلال هذه التعديلات من اختبار تأثير توجيه البيانات على البطارية. حيث تم عمل عدة سناريوهات واختبارات على مدى فاعلية هذه المقياس، ومن خلال النتائج التي تم تحصيلها تبين ان هنالك نتائج مبشرة وانه من خلال إدارة عمليات عمق التفريغ في البطارية يمكن ان تضاعف من عمر الساتل الفضاء .

# Abstract

*To meet the massive growth in demand for multimedia services on mobile devices and to support connectivity anywhere on the planet, the development of broadband systems everywhere has attracted a lot of attention from academia and industry alike. It is expected that satellite networks in general and the Low-Earth Orbit (LEO) constellations in particular will play a fundamental role in the deployment of these systems. However, LEO satellite groups such as Iridium or Iridium-NEXT are too expensive to deploy and maintain. As a result, extending their terms of service has emerged as a major challenge in research and engineering. The main the key observation in this thesis is that one can significantly increase the service life of the satellites by managing the Depth of Discharge (DoD) of their batteries. Satellites in low earth orbit groups can spend about 30% of their time under the shadow area, which is the time they are powered by the batteries. While the batteries are recharged with solar energy, the depth of discharge they reach during the eclipse greatly affects their lives, and accordingly, the service life of the satellite itself. For batteries such as the one that strengthens Iridium lines and Iridium-Next satellites, a 15% increase for DoD can practically cut its service life by half. In the main part of this thesis, we suggest different techniques to reduce battery depth of discharge in LEO groups. Thanks to the highly uniform and consistent nature of these constellations, there are many paths between any two satellites, which opens up the possibility of choosing the path to route data based on battery levels.*
*In this context, we focus first on Data routing and suggest new routing metrics -NROM- that attempt to balance the performance and "power management" of the battery. Our primary approach is to take advantage of the segmental motion of the satellites in favour of directing traffic through the sun-exposed satellites instead of those obscured, thereby reducing the average battery discharge - all without taking a major penalty of performance. Using realistic LEO topology and traffic requests, we show that NROM metric can increase battery life by up to 75% and 100%, respectively. In this thesis, we study satellites, how they operate and what are their most important features, also, we show the types of satellites and their orbits around the earth. Since there are, in principle, three orbits in which the satellites are located around the Earth. As we have derived three versions from the NROM metric. So that through these adjustments we can test the effect of the battery as we wanted to route the data without looking at the location of the satellite, so that in this case we look at the sensitivity of the data and the need to connect it to the final destination without looking at any other considerations, or that we need to reduce the use of the battery and thus information can pass between the satellites facing the sun and therefore not using the satellites in the shadow area, or it is possible to equate between these two cases. By using realistic LEO topology and traffic requests, we show that NROM metric can increase battery life. Thus, the satellite's lifespan has been doubled, or increased by three quarters of its default life.*

# Contents

# List of Figures

# List of Tables

# List of Abbreviations

**LEO** Low Earth Orbit Satellite.

**MEO** Medium Earth Orbit Satellite.

**GEO** Geostationary Equatorial Orbit.

**RAAN** Right Ascension of the Ascending Node.

**QoS** Quality of Service.

**MAC** Multiple Access Control.

**DAMA** Demand Assignment Multiple Access.

**CDMA** Code Division Multiple Access.

**TDMA** Time Division Multiple Access

**FDMA** Frequency Division Multiple Access.

**NGI** Next-Generation of the Internet.

**ISL** Inter-Satellite Link.

**ISLs** Inter-Satellite Links.

**MAC** Multiple Access Control.

**DoD** Depth of Discharge.

**DSP** Dijkstra's Shortest Path.

**WSN** wireless sensor network.

**IP** Internet Protocol.

**RTP** Real Time Transport Protocol.

**MLU** Maximum Link Utilization.

**NGI** Next-Generation Internet.

**OSPF** Open Shortest Path First.

**QoS** Quality of Service.

**RIP** Routing Information Protocol.

**TCP** Transmission Control Protocol.

**UDP** User Datagram Protocol.

**VN** Virtual Node.

**VT** Virtual Topology.

**OBP** On-board Processing.

**UDL** Unidirectional links.

**SOC** State of charge.

**REAR** Reliable Energy-aware Routing.

**MRPC** Maximum Residual Packet Capacity.

**UDL** User's uniDirectional Link.

**IETF** Internet Engineering Task Force.

**ToS** Terms of Service.

**RSVP** Resource Reservation Protocol.

**FIFO** First-In First-Out.

# Chapter 1

# Introduction

## Contents



A Low Earth Orbit satellite (LEO) system generally refers to a large-scale satellite system composed of multiple satellites capable of real-time information processing, wherein the distribution of satellites is called a satellite constellation. LEO satellites are mainly used for military target detection, and these satellites are natural to obtain high-resolution images of targets; LEO satellites are also used for mobile phone communication. The low orbital altitude of the satellite makes the transmission delay short and the path loss small. A communication system composed of multiple satellites can achieve exact global coverage. Cellular communication, multiple access, spot beam, frequency reuse, and other technologies also provide technical support for LEO satellite mobile communications. LEO satellites are the latest and most promising satellite mobile communications systems [4].
The LEO satellite constellation consists of multiple satellites in multiple orbits. Because LEO satellites and Earth are not synchronized, the constellations are continually changing, and relative positions of the satellites are always changing. In order to facilitate the management and real-time communication of multi-star systems, satellites must be connected not only to ground terminals and gateway stations but also to satellites themselves. Of course, such connections can be connected via terrestrial links or through inter-satellite links. The general constellation has multiple satellite orbits for coordination and real-time communication between satellites; there are inter-orbital links between satellites in different orbits [5, 6].

## 1.1 Communications Satellites

Communications satellites are mainly used to transmit radio waves from one place on the ground to another, where the signal is received from an earth station and amplifies it to have enough energy for re-transmission. It reflects it to the ground station somewhere on Earth, where this signal can transmit anything that radio waves can transmit from phone calls, Internet data to radio and TV broadcasts. Communications satellites mainly overcome the problems of transmitting radio waves that are broadcast straight around our curved planet (continental signals), and they are also useful for communication within remote areas where wired and wireless communications cannot reach. To make a call over conventional landlines (wired phones), we need a complex network of wires and switches to complete a full circuit from the transmitter to the receiver. When we use mobile phones, we can talk from anywhere by using a service signal. While using the satellite phone, we are entirely free from any infrastructure, and we have geographical freedom of making calls and instant massaging too. Communications satellites are "space mirrors" that help us to reflect radio signals, television, Internet data, and other types of information from one side of on Earth to the other. A geostationary communication satellite can cover approximately 40 % of the Earth's surface, enabling any ground, sea, and air communication stations in the coverage area to communicate with each other at the same time. Three geostationary communication satellites distributed at equal intervals over the equator can achieve global communications except for parts of the poles. The communication satellite is one of the earliest and most widely used satellites in the world. Many countries, such as the United States, the former Soviet Union / Russia, and China, have launched communication satellites. When the satellite receives the weak radio signal from one ground station, it will automatically turn it into a high-power signal, and then send it to another ground station, or transmit it to another communication satellite, and then send it to the Earth. On the ground station on one side, we received a signal from far away. Communication satellites generally use geostationary orbit, which is located 35786 kilometres above the Earth's equator. In this orbit, satellite rotates around Earth from west to east at a speed of 3075 meters per second, and the time around Earth is 23 hours, 56 minutes and 4 seconds, which is the same as the time of the Earth's rotation. Therefore, from the ground, the satellite image hangs in the sky, making the work of the ground receiving station much more convenient. The antenna of the receiving station can be fixedly aimed at the satellite and communicate uninterrupted day and night. It does not have to "shake" around like moving satellites, making the communication time intermittent. The communication satellite has undertaken all intercontinental communication services and television transmission [7].

## 1.2 LEO Communication Systems

There are currently eight large companies with LEO satellite programs. One of the most representative of the LEO satellite mobile communication system is the Iridium and the Globalstar systems. The Iridium system is a solution proposed by Motorola of the United States to realize global satellite mobile communication using LEO satellite groups [8]. The Iridium system's original design is composed of 77 small Intel-legend satellites, which are evenly distributed on seven orbital planes 785 KM above the ground, forming a global connection network through microwave links. Because it has an equivalent similarity to the outer electron distribution of helium atoms, it is called the Iridium system. To reduce investment intensity, simplify the structure, and enhance the competitiveness with other LEO systems, Motorola reduced its satellite number to 66 and the orbital plane to 6 circular polar orbits. The satellite in each polar orbit is still 11. The height of the track changed to 765 Km, the diameter of the satellite is 1.2 m, the height is 2.3 m, the weight is 386.2Kg, and the life is five years (up to 8 years) [9]. The Iridium system consists mainly of the following components: satellite constellation and ground control facilities, gateway stations, and user terminals (voice, data, fax). Each star can provide 48 (originally designed 37) spot beams, each with an average of 80 channels, and each star can provide 3840 full-duplex circuit channels. Each satellite uses the interstellar cross-link as a means of networking, including two links of forwarding and backward views connecting two adjacent satellites in the same orbital plane, and two links to satellites in different orbits. The system has the function of space exchange and routing. The system adopts an "inverted" cell structure. The multi-beam projected by each satellite forms 48 cells on the surface of the Earth. Each cell has a diameter of about 667Km. The total coverage is about 4000Km. There are 2150 cells in the world. The system uses seven-cell frequency reuse mode, any two cells using the same frequency are separated by two buffer cells, which can further improve the spectrum resources, so that each channel can be reused 200 times in the world [10].

The basic structure and necessary processing of the Iridium system are on the satellite, and the cell swept across the surface of the Earth as it rotates. The system's handover is that the cell moves across the user rather than the user crossing the cell, which is different from the land mobile communication system. The Globalstar system was a LEO satellite mobile communication system proposed by the US LQSS (Loral Qualcomm Satellite Service). The Globalstar system and the Iridium system are different in structural design and technology. Its role is to ensure that any user on the world can access the ground public network through the system, the connection interface located at the gateway. The Globalstar system's fundamental design idea is to use LEO satellites to form a global mobile communication satellite system. Provide voice, data, or fax, radiolocation services to the world. It is an extension of terrestrial cellular mobile communication systems and other mobile communication systems with interoperability with these systems. It is also a wireless telephone system similar to a cordless telephone, but its range of services is not limited. The same handset can establish reliable, rapid, and economical communication with users anywhere and anytime. The Globalstar system uses a low-cost, highly reliable system design [11].

## 1.3 Problem Statement

In our work, we take care of energy consumption in LEO satellites and the quality of service. A routing protocol that, in addition to the performance, is sensitive to the Quality of Service (QoS) and energy consumption of eclipsed nodes, can reduce the depth of discharge with the attention to the quality of information being exchanged and, thus, significantly increases the lifetime of the batteries and decreases the latency of sensitive information being routed. Mainly analyses the QoS requirements of satellite network service quality that meets the needs of increasing the satellite lifetime, its data routing quality, and provides support for the design and construction of satellite networks data route that meets the needs of LEO constellation. Firstly, its analysis the characteristics of the structure and operation structure of the satellite network and then analysis the key indicators of the QoS of the satellite network service quality, delay, and latency, which meets the requirements of users and mission applications, including analysing the causes and classifications of the satellites. The importance of reducing the use of LEO when it is in the shadow area is beneficial on the LEO Grid system, as they reduce the use of batteries and adjust the data paths to be directed to the satellites located in the solar charging area. By working on the construction of this algorithm, we will answer these questions.

Main Research Questions:

1. Can we extend the service life of LEO satellite by re-routing the data to the satellites exposed to the sun on opposite to eclipsed satellites ?

2. How to implement the data quality of service over this optimized routing ?

3. By how much we can extend the service life of the LEO satellite ?

## 1.4 Thesis Contribution

To meet the exponential growth in demand for multimedia services on mobile devices and to support connectivity anywhere on the planet, the development of ubiquitous broadband systems has attracted much interest from academia and industry. Satellite networks in general and Low Earth Orbit (LEO) satellite constellations, in particular, are expected to play an essential role in the deployment of such systems. However, LEO satellite constellations like Iridium or Iridium-NEXT are extremely expensive to deploy and maintain. As a result, extending their service lifetime has emerged as a crucial research and engineering challenge. The crucial observation in this thesis is that one can significantly increase the satellite service life by managing the Depth of Discharge (DoD) of its batteries. Satellites in LEO constellations can spend over 30 % of their time under the earth's umbra, a time during which batteries power them. While the batteries are recharged by solar energy, the depth of discharge they reach during eclipse significantly affects their lifetime – and by extension, the service life of the satellites themselves. For batteries of the type that power Iridium and Iridium-NEXT satellites, a 15 % increase to the DoD can practically cut their service life in half.

## 1.5 Thesis Organization

The remainder of this thesis is organized as follows:
Chapter two reviews the essential features of satellite power systems. In this chapter, we clarify what these satellites contain from the energy systems and the type of energy systems in satellites. We have also studied the efficiency of energy systems and the charging and discharging processes of batteries operating on these satellites. As for the third chapter of this thesis, we turn to how to build LEO Satellite Network Architecture and the importance of satellites for communication systems, and in this chapter, we explain the network protocols used in these systems, such as the routing layer and the transport layer. We also clarify the mechanism of work in green networks and offer the principle of activating the quality of service in wireless networks. The fourth chapter clarifies the mechanism of work of the quality of service and its advantages, as we explain how the mechanism of guidance for quality of service works. Moreover, we clarify the problems that this mechanism faces when entering the satellite network. Chapter Five presents the Experimental and Evaluation Results and explains how to increase service life satellites using the principle of data routing based on the quality of service so that we introduce a new work mechanism called NROM. In the last, we present a conclusion summary and future work.

# Chapter 2

# Energy Efficiency with LEO Satellites

## Contents



This chapter deals with one of the most important topics related to satellites in low earth orbit: the power supply and how to operate those satellites in outer space. Where we begin by summarizing the energy systems that occupy those satellites and their most essential components where they depend on two energy sources: the batteries for vital operations when the satellite is in the shadow area, and solar energy via solar panels when the satellite is in the area opposite the sun. Then we go to an essential part of the energy files in the satellites, which is the efficiency of those systems in low earth orbit, and then we present the rate of discharge of batteries, which is known as depth of discharge (DoD) used by those satellites. By the end of this chapter, we will also summarize, how the eclipse time is calculated for the satellites in low earth orbit, and finally we will show how space satellites are operated and how to rotate energy during the two phases of the satellite, which, as mentioned earlier, the shadow phase and the sun's face stage. Then, we study the entry/exit positions and times through the earth shadow for LEO satellites.

## 2.1 Satellites Energy Systems

We know that there is a lot of space debris in Low-Earth orbit. The causes of these space debris are different. Many of them are large satellites that have failed. Many satellites fail because their energy systems have reached the end of their life. After all, it failed the mission assigned to it or reached the end of its service life. So, we know that energy systems are a life and death element for Satellites. Because most of the equipment on the Satellites need electricity to power their vital operation, so there is another aspect of life and death that is related to the life of the satellite. We know that a satellite's life is determined in general by the amount of propellant carried and the life of the energy system. Especially the energy system has the characteristic of fading over time, so carrying out some optimized designs in conjunction with the mission of the satellites itself can make the satellites extend life, such as the management of battery packs. This reason is the same as our good power consumption determines the battery life of the mobile phone, except that the mobile phone battery can immediately replace, but the cost of the battery on the satellites is prohibitive [12].

The design of the power supply system also determines the capabilities of the satellite. For example, there are many stand-alone instruments on the satellite. These stand-alone instruments cannot work unlimited. Because of limited energy, each orbit can only allow the main load to work for a limited time, especially those that consume power Powerful instrument. Furthermore, if the energy system can have sufficient energy, these instruments can do more work and exert higher value. Especially for satellites with huge energy demand like Synthetic-aperture radar (SAR), a powerful energy system is an essential basis for its ability to function. Finally, to be more specific, the energy system's design determines the Quality of the satellite, this is because the instruments on the satellite not only require power consumption, but they also require stability, reliability, safety, and many other aspects. These also affect the effectiveness of satellite missions from another aspect [13].

## 2.2 Components of Satellites Energy System

The current satellites have chosen the standard configuration of solar panels plus battery packs. This configuration accounts for more than 90% of spacecraft. Here, solar windsurfing belongs to the energy acquisition part, which can also be called a power generation device. Means of energy access also include chemical and emissive energy. Solar windsurfing belongs to external energy, and external energy receives an environmental impact. Therefore, the design of panels varies greatly depending on the orbit and the lighting. Like chemical energy and nuclear energy, they belong to the internal energy power generation device. Early satellites and some small satellites with low lifespans (such as cubic stars) used chemical batteries, which accounted for about 5% of the entire spacecraft. Energy storage equipment generally serves the form of external energy, such as solar panels. This is because the state of the solar panels board's output energy has also changed due to the consistent change in lighting conditions on satellite orbits [14].

The consideration of smooth power consumption requires a battery pack. Save so many times and makeup when energy is not enough. For the use of solar panels and battery packs, we have described its changing characteristics, so we need to take some control measures to achieve a standard use requirement—for example, power bus regulation, battery pack charge, and discharge control overcharge protection. Let us focus on the standard configuration today. The standard configuration that accounts for more than 90 % is the converge of today's design. The design of this energy system affects the satellite's capabilities and dramatically affects the satellite's configuration. For solar panels, the first task is to transform as much energy can be generated. We know that the conversion efficiency of solar cell arrays is fixed, and the development speed is not very fast, so the solar energy sources that reach the earth are fixed at about 1,300 watts. Therefore, the solar panel hopes to shine as much sun as possible, which is equivalent to the most significant direct exposure to the sun and the longest exposure time. However, the reality is different. This ideal state is very different. The main thing is that the angle of incidence of the sun is awkward to guarantee. So, the satellite should adopt attitude adjustment or install SADA (solar windsurfing drive) to face the sun as sunflower does. However, it is still inevitable that satellites will always enter the shadow. Then, the power controller's design is based on the characteristics of the shadow, frequency, and time. This can optimize the energy use on the one hand and extend the satellite's service life as much as possible. Simultaneously, the series-parallel relationship of the solar cell array affects the output voltage and current. Moreover, solar cell arrays also have firm temperature characteristics; that is, they are sensitive to temperature. Due to the radiation environment on the orbit, the solar array will also gradually degrade over time, and a sufficient margin must be left in consideration to the service life when designing [15].

## 2.3 Power Supply Used on Satellites

Energy is indispensable for satellites. Many electronic devices on satellites need electricity. Power failures cause many malfunctioning satellites. Satellite power supplies are used in satellites to generate, transform, and store electrical energy, and are composed of devices such as electrical energy storage, power supply voltage conversion, power generation, and power supply regulation. With the development of satellite technology, the power supply energy has also been continuously improved and has increased from the first dozens of watts to more than ten kilowatts.

Satellite power sources include chemical power, nuclear power, and solar battery power. Moreover, the inexhaustible energy source is solar energy, so most satellites currently use solar cells. This battery uses the photoelectric effect of semiconductor materials and can work for years or even decades. Early satellites had a small area because solar cells were attached to satellites' surface, and their power generation was not high. Tens of thousands of solar cells are now attached to large panels, and the entire solar panel installed outside the satellite. The power generation has been dramatically expanded.

Nowadays, gallium arsenide is widely used. Unlike the first solar cells made of semiconductor silicon, the photoelectric conversion efficiency is high. To further increase the number of solar cells, medium and large satellites often use solar wings connected by several solar panels.

Because the rocket could not fit too much, the solar wing folded during launch, and the rocket separated from the satellite and then unfolded. The solar wing on many satellites uses advanced technology. To make the solar wing always face the sun to obtain the maximum electrical energy: one equipped with a driving mechanism that rotates with the solar wing; the other is the use of a solar sensor to control the rotation of the driving mechanism. The solar wing used to capture the sun's position, provide sufficient energy for the satellite, and make the sunlight as perpendicular to the solar wing as much as possible [16].

## 2.4 Energy Efficiency in LEO Satellite Constellations

These types of space satellites rely on solar panels and rechargeable batteries as both are an energy source and energy storage. These are two sources of energy that complement one another during two uncertain stages. The first stage when the satellite revolves around its orbit and is facing the sun, the solar panels convert the sunlight it absorbs into electrical energy to carry out the vital operations of the satellite, While the remaining energy will be stored for later use. In the second stage, when the satellite is in shadow, it uses the batteries' stored energy to operate the satellite equipment. As for satellite constellation such as Iridium, the satellite spends about 30% of its rotation around the orbit in the shadow region. Also, it is difficult to replace the batteries of the satellite, Increasing the lifetime of the batteries inevitably leads to an increase in the lifetime of the satellite itself [17, 18].

The dominant element that determines battery life is the Depth of battery Discharge (DoD). For nickel-hydrogen batteries, as these types of batteries operating in current satellites of the Iridium constellation. Studies have shown that when the Depth of Discharge (DoD) is reduced by 15%, this doubles the battery lifetime. Also, lithium-ion batteries are similar in attitude where this type of batteries will operate and power Iridium NEXT constellation satellites [19, 20].

The LEO constellations have a uniform and symmetric nature, including uniformity and consistency. This ensures that these will be minimum paths between two nodes, so there will be several options for transferring data between two nodes. Therefore, the choice of routes of data transfer between the constellation of space satellites will affect the age of these satellites. Therefore, much effort has been made to design a protocol for data routes in LEO constellations [21, 22].

Unfortunately, all these protocols aim to speed the transmission of data and improve data routes' performance regardless of the use of energy in these satellite constellations. The underlying assumption is that space satellites operate on solar energy and batteries and are recharged by solar energy so that a routing protocol concerned with energy usage is a secondary option for such protocols. For this, designing a protocol for data route in LEO constellation that is concerned with energy consumption's and its essential characteristics associated with performance reduces the amount of battery discharge, increasing in battery lifetime, thus increasing the lifetime of the satellite [23].

## 2.5 Powering LEO Satellites

Each space satellite needs electrical energy to perform its tasks as well as to cover its vital processes. Therefore, it is natural for satellites to have solar panels in addition to recharging batteries [24]. So each satellite has a renewable energy source as well as a source of energy storage for use when necessary, especially when the satellite is in the shadow area, the satellite uses its stored energy to carry out vital tasks, and when it is in the sunny area, it uses solar energy directly, so that the two processes are complementary to each other. When the satellite is exposed to the sun, it uses the energy to operate various equipment in satellites and the exceeded energy stored inside batteries. Figure 2.1 shows LEO satellites in his orbit around the earth and how they enter the shadowed area where the satellites operated by rechargeable batteries. Because of periodicity, that process of charging and discharging batteries leads to shortening battery lifetime, and thus the age of satellites as well [25]. In contrast, GEO satellites enter the shadow region two near-equinox periods a year (March, September) and the total time these satellites stay in the shaded area is not more than 72 minutes a day, which means not more 5% a day of the total orbit time. On the other hand, LEO Satellites revolve around earth once every 100 minutes, which means that these satellites spend 35% of their rotation in the shadow region [26, 27]. Researchers are excited when the satellites are in the shadow region when they rotate around the earth to study new ways to preserve the age of these satellites, such as reduce the reliability of the satellite on batteries and the sizing of the solar panel, and thermal control requirements.

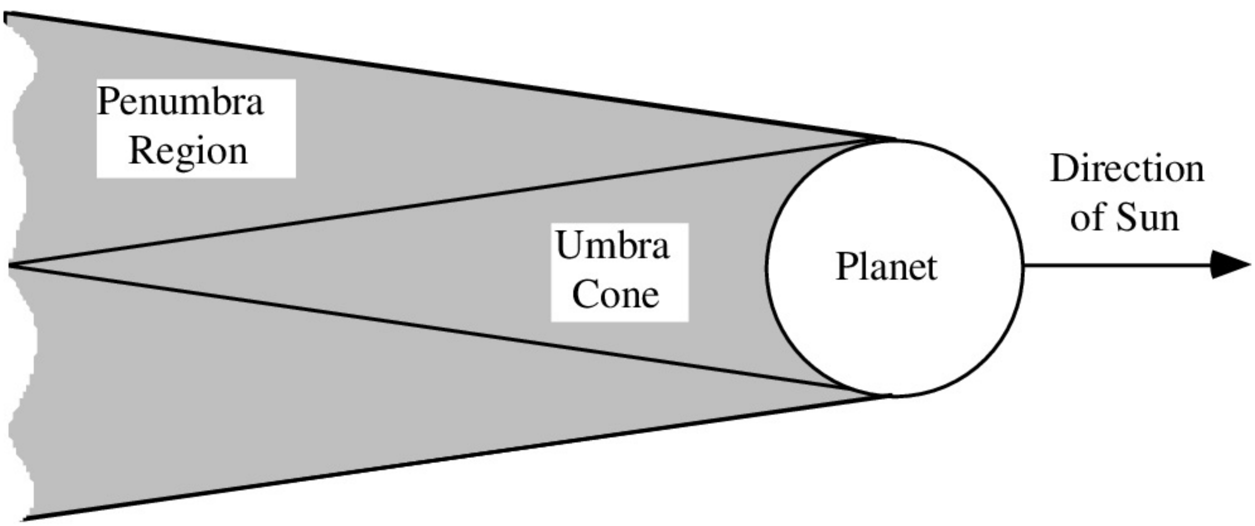


Figure 2.1: LEO Satellite in umbra [1].

## 2.6 Depth of Discharge (DoD)

Most solar batteries need to maintain some charge at all times because of their chemical composition. If it uses 100% of battery, it will shorten their useful life dramatically and feel the depth of discharge of the battery the amount of battery capacity used. Most manufacturers determine their maximum performance. For example, if a 10-kilowatt-hour battery contains a 90 percent discharge depth, no more than 9 kilowatt-hours of the battery should be used before it is recharged. In general, Depth of Discharge (DoD) refers to the percentage of the rated capacity taken from the battery. The discharge depth of shallow-cycle batteries should not exceed 25%, and deep-cycle batteries can discharge 80% of their power [28]. Because the battery life is affected by the average charge state of the battery, we must coordinate the relationship between the battery's cycle depth and capacity when designing a system. The discharge depth of a cell or battery is measured by the amount of charge released. It is expressed in the form of (A·h). DoD can also be expressed as a percentage. Lead-acid batteries usually express their DoD as a percentage. It is more useful to express DoD in the form of (A·h) so that the combination of state of charge (SOC) (expressed as a percentage) and DoD (expressed as A.h) can convey more information than both indicators are expressed as a percentage. This is obvious for a battery whose actual capacity is more significant than its nominal capacity (for example, nominally 100 (A.h), actually 105(A.h)). When a battery with a rated capacity of 100(A.h) discharges 100(A.h), the SOC will become 0. At this time, the DoD of the battery can be expressed as (100) or 100(A.h). However, if it wants to release the full charge of the battery, the battery SOC is still only 0 (because the SOC cannot be negative), and the battery DoD marked as a percentage can only be 100% (because of the DoD marked as a percentage) cannot be higher than 100%. However, if expressed in (A.h), the DOD will become the correct 105(A.h). Knowing the DOD of the battery is 105(A.h) is more useful than knowing that it reaches 100% because even if the DoD of the battery reaches 100%, it can still release electricity from it. Another critical reason to express DoD with (A.h) is that the discharge depth of a battery is independent of its discharge rate.

## 2.7 LEO Network Model

Let us assume that the LEO satellite grid constellation consists of several polar orbits that are evenly separated, let us consider that the number of these polar orbits is N and the angular separation of these orbits is (180°/N), and the planes $p_1$,$p_2$,..,$p_N$ which cross each other over the pole areas and each orbit has M evenly separated satellites (angular separation of 360°/M). [29] In this thesis, we assume that each satellite, $s_{i:j}$ (the jth satellite on the ith plane), in the constellation has Inter-Satellite Links (ISLs) with its four neighbouring satellites: two intra-plane (La) ISLs connecting to vertically adjacent satellites in the same plane, $s_{i:j\pm1}$, and two inter-plane (Le) ISLs connecting to the closest neighbouring satellites in the adjacent planes, $s_{i:j\pm1}$. As shown in Fig. 2.1, these ISLs form a mesh network with a seam between the first plane $p_1$ and last plane $p_N$, where satellites in planes along the seams rotate in opposite directions. On the identical plane, all satellites move in the equivalent round direction. The intra-plane ISLs are preserved at all intervals, and their lengths are static and can be calculated as noted in. [30] :

$$L_a = \bar{2}R\sqrt{1 - \ cos(360° \frac{1}{M})} \quad (2.1)$$

Among the planes, the ISL between the planes only works outside the pole area and its length. The movements of the satellites change over time. [30]:

$$L_e = \bar{2}R\sqrt{1 - \ cos(360° \frac{1}{2N}) \ cos(lat)} \quad (2.2)$$

Where R is the radius of the plane and lat stands for the latitude at which the interplane Inter- Satellite Link (ISL) resides. The Propagation delay can be computed using equations (2.1) and (2.2).Let $L(S_{isis}, S_{id\ jd})$ be the length of ISL between satellite $S_{is;js}$ and satellite $S_{id;jd}$. The propagation delay of a multi-hop path can be computed as follows:

$$T_p = \frac{\sum_{j=1}^{h(p)} L(S_{isjs}, S_{idjd})}{V} \quad (2.3)$$

Where $h_p$ is the number of hops on a specific path and V is the speed of light.

## 2.8 LEO Satellite Eclipse Time

We have made a quick review of the material of the book [31], which can determine accurately and at what time the satellite is in the shadow region during its rotation, if the answer is yes, calculating on how long the satellite will be in the shadow region. We will use this information to build routing metrics module in the satellite network grid so that satellites in the shadowed area will be avoided, and instead, the data packets will be forwarded to the satellites that orbiting in the solar zone. When building this routing metric, we will consider the Quality of service (QoS). We can compute the exact location of the space satellite by using its orbital parameter. By using Kepler model we need their parameters, we can determine the shadow condition of the earth space satellite: The orbital inclination dented by the symbol $i$, the orbital size, and the and the right ascension of the ascending node (RAAN), denoted by $\Omega$ (Omega). The angle between the equatorial plane and the orbit plane is the orbit inclination, on the other hand, RAAN is the angle measured from the vernal equinox along the earth equator to the point at which the satellite ascends from south to north. With all this information, we can make accurate calculations of any available satellite in the group about the time it enters and exits the shadow (umbra) area [32–34].

This space satellite orbits around the earth 14 times during the 24 hours, so that the satellite needs about 100 minutes to complete its rotation around the earth, of which about 36 minutes is in the shadow region. Figure 2.2 shows the 24 hour analysis of LEO satellite rotation periods in the sun and under shadow .

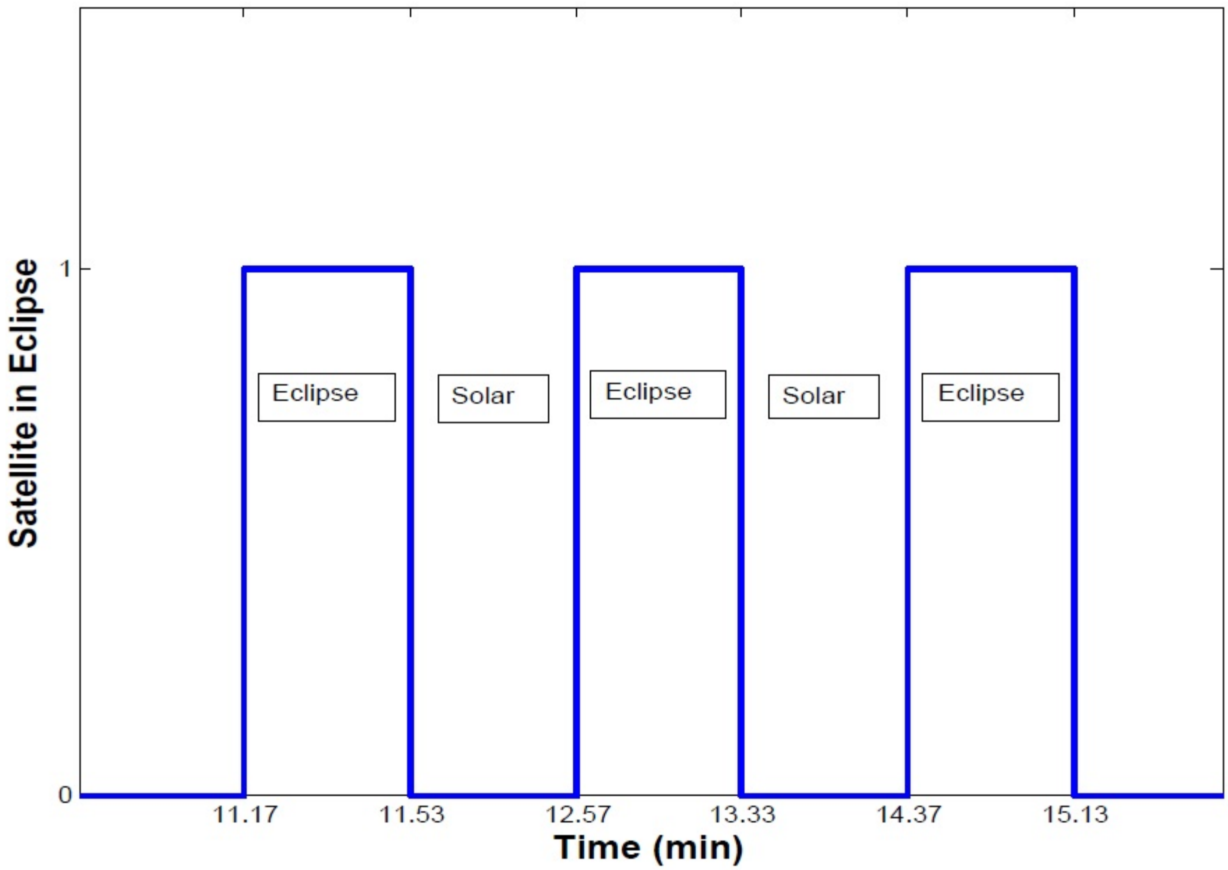


Figure 2.2: The analysis is for 24 hours, but for clarity of presentation, only a few hours are depicted.

### 2.8.1 Computing Eclipse Time for LEO Satellite

The movement of satellites in orbits is subject to the three Kepler laws of planetary motion between any two objects in space in the presence of gravity with modifications and redefinitions that Newton made on these laws in 1665 [35].

1. Kepler's First Law: The shape of the path followed by satellite around Earth is an ellipse, with the planet earth being the center of the mass in one of the ellipses. The size of the ellipse depends on both the satellite's mass and its angular velocity.

2. Kepler's Second Law: The line between the satellite and the planet crosses equal areas during equal times.

3. Kepler's Third Law: The orbital time square of the orbit is proportional to the average distance between the two objects.

We have coded the algorithm in a MATLAB script, and in Figure 2.3, we illustrate how the script works for a particular Iridium satellite. Based on data publicly available [17], we use

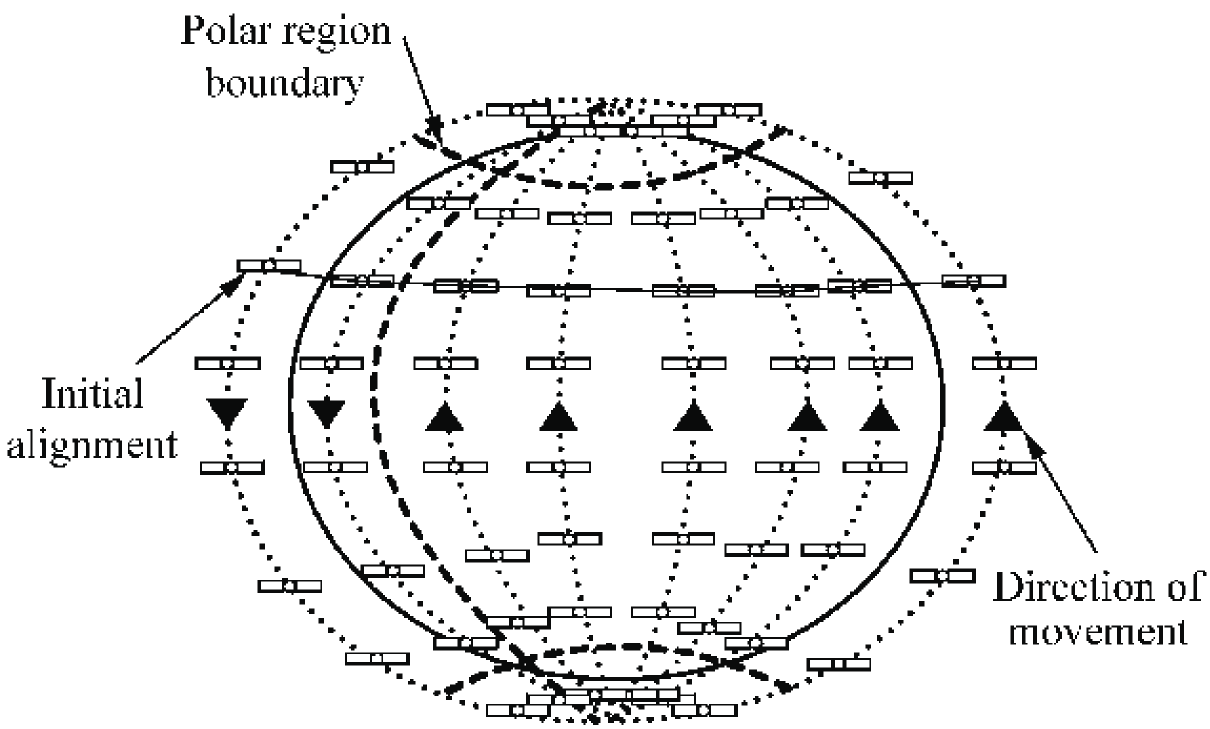


Figure 2.3: LEO Satellite Network Model [2] .

the following parameters:

1. Altitude 780 kilometres

2. Orbit inclination 86.4$\circ$

3. Eccentricity zero

4. RAAN 235.47$\circ$

5. Argument of perigee zero

The analysis begins on September 1st, 2013, at 11:00:00 UTC and is carried out for a 24h period. For clarity, only a few hours are depicted in Figure 2.3. We observed that an Iridium satellite performs a full circle around the Earth in around 100 minutes and spends about 36 minutes in the Earth's umbra. Considering the significant portion of time, the satellite is eclipsed, the battery operation and life are essential to the service life of the satellite itself.

# Chapter 3

# Networking with LEO Satellite

## Contents



This chapter of the thesis introduces the fundamental principles for the formation of networks in satellites. First, we explain the importance of satellites in communications and how to develop the communications sector. We believe it will be an essential part of the internet infrastructure over the coming years. Then we come up with a topic of great importance: how to build networks for satellites in the low Earth orbit, then review the energy routing protocols, transport, and MAC on these satellites, where we explain them and demonstrate how they were created and how they were used. Then we explain the basics of green network strategies, especially in terrestrial wireless networks, later we explain the energy-saving routing protocol in wireless networks in particular. Finally, we conclude with a simple explanation of the analysis of the problem of service quality orientation in the LEO satellite network and how to work on finding a Metric for data routing that works on the principle of quality of service.

## 3.1 The Importance of Satellites for Telecommunication Systems

Satellite communication refers to the use of satellites as relay stations to forward or reflect radio waves to achieve communication between two or more earth stations or between earth stations and spacecraft. Satellites used in communication systems can have different operational orbits, while systems of different orbital satellites have significant differences in network structure, communication methods, service scope, and system investment [36]. In other words, satellite communications are communications between satellites, including radio stations in the ground, water, and atmosphere, using satellites as relay stations.

The broadband LEO constellation satellite communication system is one of the important developments of hot spots in the field of satellite communication. The traditional GEO satellite network has large propagation delay, high propagation loss, weak on-board processing capability, small network throughput, and high communication cost. They are mainly used as an extension and supplement to the terrestrial communication network. The use of GEO satellites to build a globally oriented, economically competitive broadband satellite communications system is complicated under current technical conditions like mobile communication and other communication methods. Satellite communication has the following characteristics:

1. The satellite communication coverage area is large, and the communication distance is long. Because the satellite is far from the ground, a geosynchronous satellite can cover 1/3 of the Earth's surface. Therefore, global communication beyond the poles can be accomplished by using three properly distributed geosynchronous satellites. Satellite communications are the main means of long-distance transoceanic telephony and television broadcasting [37].

2. Satellite communication has a multiple access function. This means that all earth stations in the area covered by the satellite can use the same satellite to communicate with each other [27].

3. The satellite communication band is wide and has a large capacity. Satellite communication uses the microwave frequency band, and multiple transponders can be installed on each satellite, so the communication capacity is large [38].

4. Satellite communication is flexible. The establishment of earth stations is not restricted by geographical conditions and can be built in remote areas, islands, cars, planes, and ships [38].

5. Satellite communication quality is good, and reliability is high. The radio waves of satellite communication mainly propagate in free space, with low noise and good communication quality. In terms of reliability, the normal operation rate of satellite communication is over 99.8% [39].

6. The cost of satellite communications is independent of distance. The construction investment and maintenance costs of terrestrial microwave relay systems or cable carrier systems increase with distance, and satellite communication does not require line investment between earth stations and satellite transponders. Therefore, the cost is independent of distance [38].

## 3.2 LEO Satellite Network Architecture

Inmarsat was the first satellite to be put in the geostationary orbit, and this sat was a single sat used for communication, it was an excellent example of using successful GEO satellite for telecommunication . GEO satellites used for many successful commercial services such as weather forecasting, TV broadcasting, and long-distance communications [10, 40].

Table 3.1: Main LEO Satellite Constellations

| Organization | System | Altitude (kms) | Min. Elvation Angle | ISLs | No. of Satellites | Coverage (%) |
|---|---|---|---|---|---|---|
| Teledesic Co. | Teledesic | 1375 | 40 | Yes | 288 | 100 |
| Motorola | Iridium | 780 | 8.2 | Yes | 66 | 100 |
| Global Star Co. | Global Star | 1406 | 10 | Yes | 48 | 83 |
| Japan NiCT | NeLS | 1200 | 20 | Yes | 120 | 79 |
| Motorola | Celestri | 1400 | 16 | Yes | 63 | 73 |
| Alcatel | Skybridge | 1469 | 10 | No | 80 | 86 |

Since the beginning of the '80s GEO-satellite has been successful in providing many services such as television broadcasting, long-distance communications, and weather forecasting, but because of the distance of those satellites which results in high propagation delay, this leads the experts to switch to another alternative where the connection speed is higher with lower propagation delay. The alternative was LEO Satellites, which gives higher throughput with lower power consumption demand. Table 3.1 shows the main LEO Satellite constellations with main features that identify each constellation system. Besides, the constellation of LEO satellites is designed to cover the entire globe evenly, even if the amount of data transferred to the world is not homogeneous or equal. Satellite communication is an essential achievement in modern communication technology. It developed based on terrestrial microwave communication and space technology. Compared with cable communication, microwave relay communication, optical fibre communication [41].

According to the altitude of the satellite orbit, the communication satellite can be divided into low earth orbit communication satellite (LEO), medium-orbit communication satellite (MEO), and high-altitude geosynchronous communication satellite (GEO). The LEO satellite orbit has a height of 500km to 2000 km, the MEO satellite orbit has an altitude of 2000 km to 36000 km, and the GEO satellite orbit has an elevation of 36,000 km. LEO satellite communications are the most popular: on the one hand, LEO satellites have low orbital heights, resulting in short transmission delays and low path loss. Constellations of multiple satellites can achieve exact global coverage. Technologies such as communication, multiple access, spot beam, and frequency reuse also provide technical support for LEO satellite mobile communications. Therefore, the LEO system is considered as one of the most promising satellite mobile communication technologies [27, 42]. LEO satellite communication systems also have inherent shortcomings, such as a large number of satellites, which leads to problems like ground control, maintenance systems, technical bottlenecks problems, call quality, data transmission rate, and cost of use. With the rapid development of communication technology and microelectronics technology in the past two decades, the signal processing capability and communication bandwidth of communication systems have been continuously improved. From the current use of LEO satellite communication systems such as the second generation of Iridium and Global Star, the technical problems of high drop rate that plagued the early comet system have been effectively solved, which has cleared the way for the popularization of LEO satellite communications [43, 44].

## 3.3 MAC, Routing and Transport Protocols for LEO Constellations

Satellite communication networks have unique functions in communication, navigation, resource detection, environment, and disaster monitoring, and can be used as a supplement to ground networks and as a disaster recovery backup method. LEO satellites have low latency, short development cycles, new technology, and low cost. They can perform spatial tasks in the form of a LEO constellation network. The routing problem is essential in the space network, which is of great significance for improving the timeliness and reliability of data transmission. The LEO constellation network has the characteristics of dynamic topology changes, limited node storage, and computing capabilities, extended inter-satellite link transmission, and uneven distribution of bearer data traffic, making its routing technology face new challenges [45, 46].

### 3.3.1 Multiple Access Control (MAC)

This protocol is designed to regulate the transmission of the packets or resend damaged packages. This protocol also resolves the collisions during contention periods among stations. Additionally, the long broadcast delay of the earth-satellite link and the massive number of user's stations distributed within the satellite footprint execute severe demands

and limitations on MAC protocols that can be engaged in a satellite grid network. The Protocol of Medium Access Control (MAC) has been classified into three groups or categories. Demand assignments, random, and fixed. In the following sections, we will present some MAC protocols used to reduce energy consumption in a single satellite [47, 48]. In the fixed assignment protocols, the channel bandwidth allocation is static when allocated to another station; this allocation is also independent of other station activities. The fixed allocation system consists of three different allocation systems: Code Division Multiple Access abbreviated as (CDMA), Time Division Multiple Access (TDMA), and Frequency Division Multiple Access (FDMA).
TDMA is a technology for providing digital wireless service using TDM. This technique divides radio frequency into time segments, then assigns those parts to multiple calls. In this way, one frequency can support multiple concurrent data channels. The GSM digital cellular system uses TDMA technology. Because TDMA is one of the oldest digital cell technologies, it is also the least developed digital technology, partly because it lacks flexibility compared to other technologies [49, 50].
CDMA is a digital cellular technology that uses distributed spectrum methods. CDMA does not allocate a specific frequency per user, unlike competing systems such as GSM using TDMA, which use each available spectrum channel as a whole. Individual conversations encoded in a numeric sequence that appears to be random. Many conversations are made simultaneously by sending all connections in groups of bits and bits mixed, with each group encodes with a particular connection with a different code. Each connection can be reassembled in the correct order at the other end, using unique symbols associated with specific sets of bits. CDMA is considered as the latest digital technology for mobile phones.
Frequency division multiplexing (FDM) refers to a technique in which the carrier bandwidth is divided into multiple sub-channels of different frequency bands, and each sub-channel can transmit a signal in parallel. Under frequency division multiplexing technology, multiple users can share a physical communication channel; the process is frequency division multiple access multiplexing (FDMA) [49, 51].

### 3.3.2 Routing

The advantages of LEO satellites with On-Board Processing (OBP) and ISL capabilities are short-latency and seamless connectivity, which is very attractive for the Internet in space. In this type of network, the main technical problem is the complex dynamic routing caused by the satellite's motion. Although the constellation topology changes frequently, the orbit of the satellite is very strict and, therefore, periodic and predictable [52, 53]. Some commonly used dynamic routing mechanisms on the Internet, such as distance vector and link-state algorithms, cannot be used directly in constellation routing. This is because the topology of the constellation often changes, which leads to huge overhead. The following introduces two new concepts for dynamic constellations: discrete-time dynamic virtual topology routing [54, 55]. The purpose of the VT strategy is to hide topology changes from routing protocols. The virtual topology consists of virtual nodes (VN), which overlap the constellation's physical topology. Even if the satellite passes through the sky, the virtual topology remains the same. Each VN maintains state information, including routing tables and user information within the coverage area. At a specific time, the VN is represented by a particular satellite. When a satellite disappears into the horizon, VN is represented by another satellite passing above, and the state information transmitted from the first satellite to the second satellite. The routing decision is based on the virtual topology, and the protocol does not pay attention to the dynamic constellation distribution hidden in the state transfer [55, 56]. The network transmission rate is rapidly increasing. While experiencing excellent communication services, users have put forward more demands for service differentiation and service quality. Since the coverage area of terrestrial mobile communication equipment is greatly affected by ground environment factors, the traditional terrestrial mobile communication network cannot meet users' communication needs in remote areas or flat natural areas. Satellite communication systems cover a wide range of areas and not limited by ground environmental factors. They can cover the blind areas of terrestrial communication systems and widely used in defence, security, navigation, commerce, disaster prevention, and other fields. The static update algorithm periodically called by the satellite node and is mainly used to adapt to the regular link state change. The location information of the node itself and the distribution law of the satellites in the constellation, the location distribution of other satellites is derived, the topology of the network predicted, and the link-state information saved in the link-state database. The dynamic update algorithm mainly deals with sudden link failures and the update mechanism based on the detection of Hello packets. According to the result of the static prediction algorithm, the marked communicable link is periodically fault-detected, and the flooding of the link-state update packet used to notify the fault and the fault recovery. When the link status is updated, the shortest path algorithm is used for route calculation [57, 58].

The primary purpose of the third layer equipment is to complete the routing process. This process requires the completion of two primary tasks. The first is to obtain information describing the network topology, called routing information. The second is to understand and analyse the information. Calculate the best path for each possible destination. Add it to the routing table, help guide the routing decision for each packet individually, and the routing decision is to specify the port through which the data packet will be pushed. This decision depends on the information in the routing table [53]. Routing protocols are a source of routing information, and secure this information for third-tier devices, along with static routing and directly connected networks. Besides, the routing protocols analyse the information and choose the best path for each destination. The path is then added to the routing table, regarding its source, that is, a routing protocol adds it. The working node at the third layer's level contains the information needed to fill its routing table in three ways. The first is direct communication with the networks. The second is the manual routing, in which the network administrator manually fills the routing table, either using commands for the router operating system or graphical interface. The third is the Dynamic Routing, where one or more routing protocols automatically fill the routing table. After the routing protocol transfers the information associated with routing between routers, which may be full routing tables or topology information needs further processing, a set of rules that governs how to handle this information. These rules are called the routing algorithm. Each protocol has a unique routing algorithm. This algorithm identifies how the protocol understands the network topology and how it deals with it, and the cost of the path. Thus, it determines the mechanism for selecting the best path, and the most famous algorithms adopted by the routing protocols are the Ford-Blemn algorithm and the Dijkstra algorithm [52, 59]. Some router operating systems support the use of more than one routing protocol at the same time, and this confusion is caused by the different cost of the path in each. For example, the best path for a protocol may be the path with the lowest weight. Also, some protocols deal with weights of the rank of millions, other tens, and only hundreds, in which case the administrative distance is used, a numerical value that can be set and given to the routing protocol. If two paths are obtained from a protocol in different orientations, not weights are compared with each other because they are caused by different protocols but choose its path guidance weightless the owner of the supervisory protocol [30, 60]. The characteristics of routing protocols differ from each other: how to avoid loops, how to choose the best paths, the meaning of weight or cost, and the time required to perform recalculation when a change in topology occurs, as well as scalability.

### 3.3.3 Transport

The satellite communication protocol is the Application of the TCP/IP protocol in satellite communication. The satellite communication network's primary function is to support the packet transmission services of the layers below the network layer. Channel characteristics such as code rate have a substantial impact on the TCP protocol on the terminal device. The TCP/IP protocol is a protocol stack that contains the main network layer functions, all transport layer functions, and a part of the session layer functions; it relies on the lower layer media access layer, data link layer, and physical layer protocol. Point-to-point packet transmission capability; it provides end-to-end data block transmission services up to the upper layer application protocol through a standard service interface (socket), which can be connection-oriented reliable transmission (TCP) or packet-oriented Non-reliable transport (UDP). TCP also completes some of the functions of the session layer, supporting the establishment, maintenance, and teardown of end-to-end connections [61–63]. In summary, the TCP/IP protocol masks the details of data transfer between different types of networks and the differences in system hardware and software between different data terminal devices. Using the definition of each layer protocol in OSI, the main functions of TCP/IP can be explained more concisely:

1. IP layer protocol, which implements the addressing, routing, and forwarding functions of the network layer, and forwards data packets from the source data device to the destination device, facing only independent messages, not facing the connection, and supporting the message. Decomposition and reorganization does not guarantee the reliability of message transmission and the order between messages [64].

2. TCP layer protocol, which realizes reliable data block transfer between source data

device and destination data device, supports data splitting, compressing data, error control (error detection and correction), sequence control, traffic, and congestion control. The transport layer creates communication channels to transmit data between hosts, in isolation from the real network structure and distribution. The application layer uses these channels. This layer includes error control, segmentation, flow control, congestion control, and service addressing using port numbers. Communication channels created in this layer can be classified into two types: channels that require connection configuration, TCP establishes this type of channel and channels that do not fit the connection configuration, such as those created by the UDP [65–67].

Satellite communication is primarily a communication sub-net that transmits data, not a service sub-net that produces a data source. The satellite communication network's primary function is to support the packet transmission services of the layers below the network layer, which are directly related to the IP layer protocol and can support the IP layer protocol to form an end-to-end connection. However, the channel characteristics such as delay, rate, and the bit error rate of the end-to-end connection formed may have a substantial impact on the TCP protocol on the terminal device and must be considered in the Application of the TCP protocol in the satellite communication network [67]. Since satellite communication is an inherent feature of the satellite transponder, the satellite communication network has two network structures: a star network and a mesh network. Such a network structure is much simpler than a data network on the ground. Therefore, the main functions of network layer protocol control, such as routing, congestion control, and multipath transmission collision, are not truly reflected in the satellite network. In many cases, such as in a mesh satellite network, the establishment of a satellite link determines the unique path of the data link, neither addressing routing requirements nor resource configuration. At this point, it can cancel the Net/MAC layer. At this time, the IP is "transparent" through the satellite network, and there is no additional protocol overhead. This situation seems to challenge the necessity of the TCP/IP protocol in satellite networks. However, this network form is straightforward in the topology and data services of the satellite network and is limited only in the case of a strict "communication subnet." With the enhancement of satellite network functions, this simple network form is no longer applicable. For example, network management has become an essential part of the satellite communications network [64,66]. From a functional point of view, the network management subsystem belongs to the upper application software, namely Application. It relies on the data transfer service provided by the underlying communication protocol. Now the most common network management protocol is SNMP (Simple Network Management Protocol), and SNMP is based on UDP providing services. In the "transparent" network structure that does not directly support IP protocol, SNMP-like data transmission protocols, and the use of these protocols, the upper-level business cannot be realized, which fundamentally limits the functions and services of the satellite network. This alone is sufficient to illustrate the significance of supporting the TCP/IP protocol in satellite data communication networks. The TCP/IP protocol relies on its extensive software support to overwhelm other communication protocols that may be "technically better" and become the standard for the Internet [63]. UDP is one of the protocols in this layer, an unreliable protocol that provides a data transmission service with the best delivery effort, although it has a mechanism for checking the collective verification, it adopts an insufficient and straightforward algorithm. UDP is an ideal choice for applications that include multimedia streaming such as voice, image, VoIP and other real-time applications where data access to its target is a higher priority than reliability the network [63,64]. Also, this class is the Real-Time Transport Protocol (RTP), which is designed for real-time data transmissions such as audio or video streams. The transport layer, or the interface between hosts, in the Internet model (TCP / IP), corresponds to the fourth layer in the standard communication model (OSI), also called the transport layer [68].

## 3.4 Green Networking Strategies

As far as we know, no method for satellites has been proposed in the literature for reducing energy consumption in LEO satellite networks. So, we review these technologies for Ground networks and GEO satellites developed so far and discussed their applicability to the Earth LEO satellite background.

### 3.4.1 Terrestrial Wireless

Network technologies that save energy can be divided into five categories in a wireless environment. Topology control, data reduction, energy-efficient routing, protocol overload reduction, work cycle, and duty cycling Figure 3.1 illustrates the classification of energy-saving technologies in terrestrial wireless technology.

- Data reduction: This strategy focuses on reducing the quantity of data produced, processed, and sent, thus reducing the amount of energy consumption at the mobile point. There are several strategies to reduce energy in wireless network environments ranging from data compression to data aggregation technology [69].

- Reducing protocol overload: Most of these protocols need control packs to be replaced. Since these packages do not contain data for applications. Therefore, we consider that sending and receiving information leads to indirect costs. Several techniques have been introduced in the literature to reduce indirect costs in algorithmic protocols, such as reducing programming to avoid unimportant transmissions. Furthermore, cross-layer with lower and upper layers to optimize network resources [70].

- Efficient energy routing: This algorithm's main objective is to increase the entire network's age. These algorithms are associated with reducing the total consumption of energy when routing and by increasing the lifetime of each point of the network, which results in an increase in the age of the network in general. Some of these protocols use geographic coordinates for each point to build a practical path towards the target. Others are opportunists, taking advantage of the mobility of the nodes and the transmission characteristics of wireless media improve energy efficiency through the

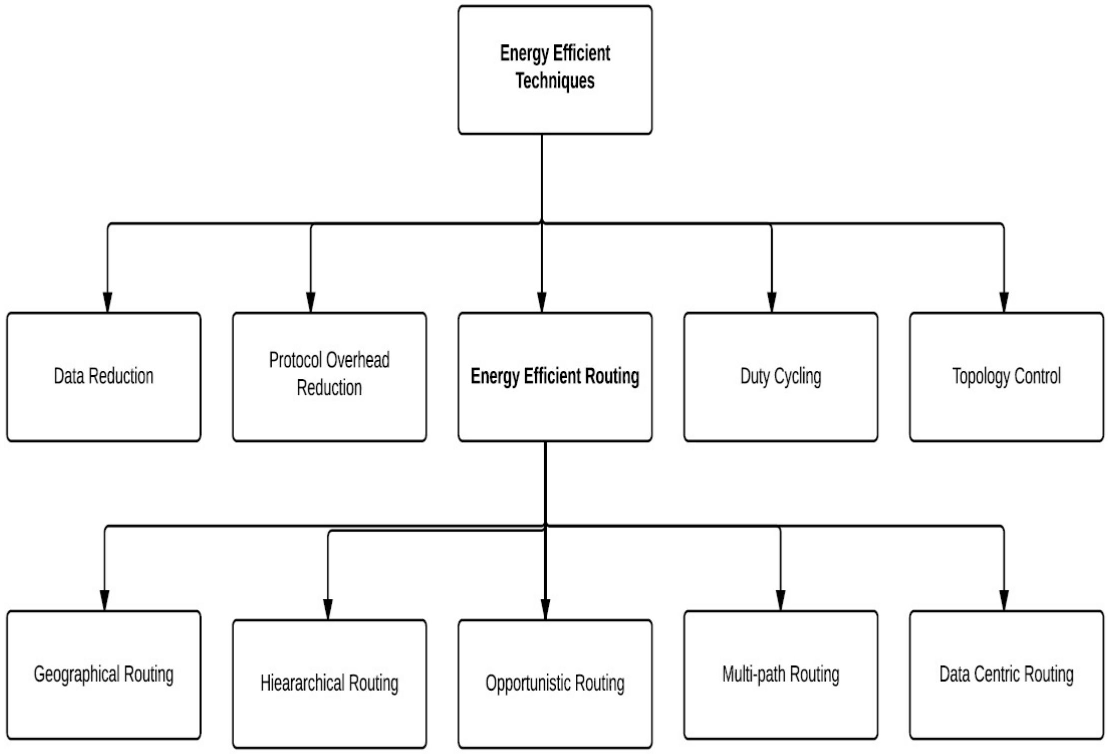


Figure 3.1: Taxonomy of energy efficient techniques in terrestrial wireless

transmission. In this way, the lifetime of the network is maximized. The multipath routing algorithm uses several implement load-balanced routing and increased robustness of routing failures—finally, the data.
Route-centric protocols only send data to the number of nodes of interest to remain useless Transmission [71–75].

- Duty cycling Service period: The service period is the proportion of time the node is running, i.e., each node in the wireless node alternates between an active state and a standby state to save energy, and the average sleep time (many) is longer than the active period. This method can be divided into two technologies. High load cycles focus on disabling redundant nodes for high levels to maintain saved settings in real-time mode to save energy to meet application requirements [76]. Low load cycle is the planned activity of the selected node and active mode to ensure the functionality of the network, i.e., turn off the active node's radio. When does it need to communicate [77].

- Topology Control: Topology Control is designed to adjust the topology of a highly dynamic network to provide better network resource control and improve communication efficiency. It improves energy efficiency by adjusting transmission power while maintaining the network connectivity [78].

## 3.5 Energy Efficient Routing Protocol

The routing protocols at the wireless nodes have the common purpose of effectively utilizing the restricted nodes. Node resource to extend the network life cycle. Various routing technologies are various possible applications that are used depending on the requirements. We propose some representatives applicable to energy-efficient routing in Wireless Sensor Network (WSN) to demonstrate its progress. The section also emphasizes the need for Energy-Aware routing for LEO satellite constellations. Reliable Energy-aware Routing (REAR) provides on-demand routing with Hassanein and Luo [79]. Protocol to verify that each node has enough energy in the selected path: the remaining energy in the node low therefor it is avoided. However, the chosen path does not minimize the required energy when forwarded packet from source to destination. Therefore, the network life cycle is Maximize K. Akkaya et al. An energy-aware QoS routing protocol for WSN is proposed [80]. It finds the lowest cost, limited delay path for real-time data. Link cost used is a function capture the energy reserve of the node, transfer energy, send error rates, and other communications. The extension of the battery life of the parameter wireless sensor network is discussed in [81]. A layered network architecture has been designed, which is a node with renewable energy, the source (shown as the master node) performs most of the messaging tasks. The battery (shown as a secondary node) has fewer communication requirements. The Maximum Residual Packet Capacity (MRPC) protocol is proposed in [82]. Link reliability MRPC depends on the fact that it chooses the path during routing. The minimum transmission energy for reliable communication does not necessarily maximize lifetime on the ad-hoc network. On the other hand, MRPC, identifies not only the node's capacity but also the node's energy level.

Not only battery level but also reliability Specific links Eu and so proposed on [83]. Optimal routing of energy-efficient wireless sensor networks with optimal relay as they investigated the impact of routing and node layout on the network layout. In [84], multi-path routing is formulated as a linear programming problem for the following purposes: Maximize the time required for the first sensor node to lose energy. Source is The packet is sent at a constant rate. Directed Diffusion (DD) Synchronous Broadcasting. In [85] Purposed sensor interest information. Only the nodes of interest respond with gradient messages. Therefore, both have the interest and gradient establish a path between the sink sensor and the sensor of interest.

## 3.6 Analysis of QoS Routing Problem in LEO Satellite Network

To achieve global coverage, a LEO constellation includes at least dozens of LEO satellites. For example, the Iridium constellation consists of 66 satellites with six orbital planes, and each orbital plane contains 11 satellites. Teledesic consists of 288 LEO satellites, divided into 12 tracks, 24 satellites per track surface. There may be multiple service satellites in the same ground area, especially in low latitude areas. The OBP (On-board Processing) on the satellite completes the functions of routing and forwarding data. There is an ISL (Inter-satellite Link) between the satellites. An end-to-end connection may pass through multiple ISLs. We know that LEO satellites are different from GEO (synchronous orbit) satellites. They are in high-speed motion. The coverage area of LEO satellites is also moving on the surface of the Earth. The movement of LEO satellites also leads to the network topology of the entire satellite network to change frequently.

# Chapter 4

# Energy Efficiency with LEO Satellites

## Contents



This chapter explores QoS Routing for Extending Satellite Service Life systems. It discusses and describes the Quality of service mechanism and how to extend service life in LEO satellites. This chapter describes a few basics of each of QoS and how to enhance the routing metric in LEO satellite constellation. This chapter addresses the need to apply the Quality of service in the data routing of satellites, especially those in low earth orbit, as we present the technical problems facing the Quality of service when applied to a constellation of satellites and how to overcome those problems. This chapter also discusses challenges, slips, and future research directions. LEO satellite is the future of communication in the globe. Traditional routing metric algorithms, such as Dijkstra's shortest path algorithm, have been widely used over the last decade for routing data in LEO satellite constellations.

## 4.1 Introduction

With the rapid development of IP services and the growing demand for timely business support, there has been a keen interest in LEO satellite networks. The LEO satellite network provides global coverage for geographically dispersed users, low transmission delay (500 to 2 000 km), and a small transmission delay, even compared to terrestrial wireless networks. The LEO satellite network provides real-time application services to users anywhere [86, 87]. In order to achieve global coverage, a LEO constellation includes at least dozens of LEO satellites. Regularly, to achieve better seamless coverage, there may be multiple service satellites in the same ground area, especially in low latitude areas. The OBP (On-Board Processing) on the satellite completes the functions of routing and forwarding. There is an ISL (Inter-satellite Link) between the satellites. An end-to-end connection may pass through multiple ISLs [88].

We know that LEO satellites are different from GEO (synchronous orbit) satellites. They are in high-speed motion. The coverage area of LEO satellites is also moving on the surface of the Earth. The movement of LEO satellites also leads to the network topology of the entire satellite network that changes frequently. So, what new problems will QoS routing face in this particular network environment?

Which brings new problems to QoS routing. The specific performance is as follows:

1. The high-speed movement of LEO satellites and the dynamic changes in satellite network topology results in frequent switching. On the one hand, due to the attenuation of the communication signal and the shadowing effect of the terrain, reliable transmission between the satellite and the user can be performed only at a considerable elevation angle. The lower orbital height of the LEO satellite and the larger elevation angle determine the satellite's smaller coverage area. At the same time, the LEO satellite is in high-speed motion, and its coverage area is also rushing on the surface of the Earth, which leads to the user terminal may continuously switch from one LEO satellite to another LEO satellite in a connection process which is known as user to sat switch. On the other hand, a multi-hop connection may pass through multiple ISLs, and the movement of the satellite may cause one or several ISLs to be unavailable (for example, the satellite moves to a high latitude region), resulting in satellite-to-satellite switching, so-called Sat-to-Sat switch. Whether it is a User-to-Sat switch or a Sat-to-Sat switch, the established QoS route is unavailable, and an entire (or partial) path must be re-selected. Re-routing requires a long transition delay and may not meet specific QoS's delay requirements, resulting in termination of communication. The signalling overhead and processing load required to reconstruct the route at the same time also waste resources [89].

2. The flow of users on the ground is non-uniformly distributed (time, location). When the satellite is operating along the orbit, the number of users and traffic are changing. This change in user traffic may block some handover calls (due to insufficient remaining resources of the user's unidirectional links( UDL). Simultaneously, the traffic on the

ISL changes with the change of traffic on the user terminal and the uplink connection. So even if there are sufficient resources for the ISL when establishing the connection, congestion may occur over time, blocking the switching call. Besides, even if the user traffic remains unchanged, it will cause load changes of each LEO satellite and traffic changes on the ISL, making some handovers unsuccessful. These blocked handovers make it impossible to further complete QoS routing [58, 90].

3. LEO satellites belong to small satellites, and the storage space, processing capacity, and energy on the satellites are limited. It is unrealistic to maintain and store the link state of the entire network on the satellite. Usually, this part of the work is done on the ground. At the same time, changes in the state of the LEO satellite network are persistent. Thus, the link-state information of the entire network maintained by the ground is also not very accurate, and therefore the QoS routes determined based on this link-state information are not necessarily optimal in the actual network [5, 91].

4. The terrestrial space background noise of the satellite constellation has some interference with the interstellar link. For example, the terrestrial space radiation interference source (mainly the sun, if it is an interstellar laser link, the moon's reflection should also be considered) background interference caused by the interstellar link. This interference may cause some links to fail suddenly and must also be switched [92].

## 4.2 Quality of Service (QoS)

QoS (Quality of Service) is a security mechanism of the network and a technology used to solve network delay and congestion control. Under Normal circumstances, if the network is only used for a specific time-limited application, QoS is not required. According to sender and receiver, many things happen during the transmission of packets from the start point to the endpoint, producing the following problematic results :

1. Packet loss - when a packet arrives at a router and the buffer is full, and this represents a failure sending attempt. The router decides according to the network; to discard a part, do not discard or drop all the packets. Moreover, it is impossible to know in advance that the application at the receiving end must request re transmission at this time, which at the same time may cause a serious delay in the overall transmission.

2. Delay - may need a long time to transfer the data packet to the end because it will be a long queue hysteresis, or the need to use indirect routes to avoid blocking; may be able to find a quick and direct route. In short, the Delay is very difficult to predict [93].

3. Transmission sequence error - when a group of related packets routed through the Internet, different packets may choose different paths, which results in different delay times for each packet. The order in which the last packet arrives at the destination is inconsistent with the rank in which it is sent from the sender. This problem must have a special extra protocol responsible for refreshing out-of-order packets [93].

4. Errors - in some cases, packets may be misrouted, merged, or even destroyed on the way to being transported. In this case, the receiver must be able to detect these conditions and identify them as lost data. Packet, and then request the sender to send another copy of the same packet [93].

## 4.3 QoS Routing Requirements

QoS routing is a routing mechanism that selects paths based on the available resources of the network and the QoS requirements of service flows or a kind of QoS parameters. QoS requirements can be one-dimensional or multi-dimensional parameters. The corresponding QoS routing is called single-dimensional or multi-dimensional QoS parameter routing. The general network process is composed of two parts; one is to select an appropriate route for the forwarded service packet flow for data forwarding according to a particular constraint parameter, and the other is to maintain the information exchange between several points of route forwarding information. QoS routing is also the same process forwarding. QoS routing information with the first representation of control sufficient is to prevent overloading of the network, and then look to meet the QoS requirements of routing wireless network embodiment load balancing; may be based on existing routing algorithms to construct QoS routing IETF defines QoS routing in RFC2386- A Framework for QoS-based Routing in the Internet [94] as follows: QoS routing is a routing mechanism that can perform path calculation based on available network resources and QoS requirements of business flows. As can be seen from the above description of IETF, compared with best-effort routing, QoS routing not only cares about the connectivity of the network but it can meet the effective configuration of the network resources required by the QoS requirements of the service. QoS routing should expand the best-effort routing model from the following three aspects [95,96]:

- First, in order to support multiple service types, QoS routing needs to support the IntServ model, support for IP packet business type (ToS) application needs, source and sink nodes, and Multi-path calculation. The route calculation of some new service applications may require different route measurement parameters, such as bandwidth, cost, cost per hop, Delay, reliability, i.e.
- Second, while providing "better" service performance routing, it is necessary to prevent the service flow from frequently jumping from one route to another "better" route, to avoid unnecessary Delay and jitter caused by route oscillation to the end-user service.
- Third, support optional routing, although this is not necessarily the best or shortest route.

## 4.4 QoS Service Model

When the network is congested, all data streams may be discarded; in order to meet the user's requirements for different applications and different Quality of service, the network

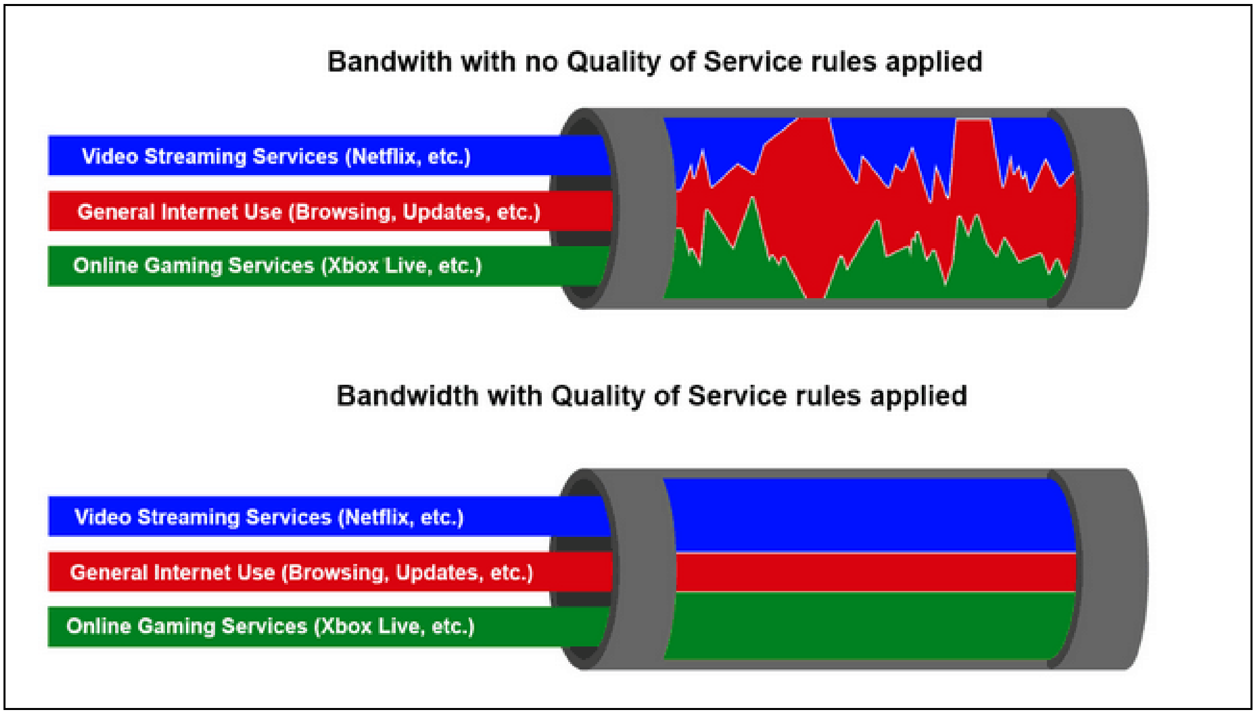


Figure 4.1: Network traffic before and after applying QoS [3].

needs to be able to allocate and schedule resources according to the user's requirements and provide different data streams Quality of Service: for real-time and valuable data reports. Documents are processed first; for ordinary data packets with low real-time performance, lower processing priority is provided and even discarded when the network is congested. Equipment supporting QoS function can provide transmission quality service; for a particular type of data flow, it can be given a certain level of transmission priority to identify its relative importance and use the various priorities provided by the equipment Mechanisms such as forwarding strategies and congestion avoidance and provide special transmission services for these data streams. The network environment configured with QoS increases the predictability of network performance and can effectively allocate network bandwidth and use network resources more reasonably [95, 96]. Generally, QoS provides the following three service models:

1. Best-Effort service (best-effort service model).

2. Integrated service (Integrated Service Model, referred to as Int-Serv).

3. Differentiated service (differentiated service model, referred to as Diff-Serv).

- Best-Effort service model is a single service model and the simplest service model. For the Best-Effort service model, the network tries its best to send packets. However, no guarantee is provided for performance, such as Delay and reliability. The Best-Effort service model is the default service model of the network and is implemented through FIFO queues. It is suitable for most network applications, such as FTP, E-Mail.

- The integrated service: Int-Serv is a comprehensive service model; it can meet a variety of QoS requirements. This model uses the Resource Reservation Protocol (RSVP). RSVP runs on each device from the source to the destination and monitors each flow to prevent it from consuming too many resources. This system can clearly distinguish and guarantee the service quality of each business flow and provide the network with the most fine-grained service quality distinction. However, the Inter-Serv model has high requirements on the device. When the number of data streams in the network is large, the device's storage and processing capabilities will encounter enormous pressure. The Inter-Serv model has poor scalability and is challenging to implement in the Internet core network [97].

- Differentiated Services: DiffServ is a multi-service model that can meet different QoS requirements. Unlike Int-Serv, it does not need to notify the network to reserve resources for each service. Differentiated services are simple to implement and have good scalability [97].

## 4.5 The Position of Common QoS Technology in The Network

QoS guarantee is vital for networks with limited capacity, especially for streaming multimedia applications, such as VoIP and IPTV, because these applications often require a fixed transmission rate and are also sensitive to delay. Network resources are always limited. As long as there is a situation of snatching network resources, there will be requirements for service quality. Service quality is relative to network services. While ensuring the service quality of specific service quality may be damaging the service quality of other services. For example, when the total network bandwidth is fixed, the more bandwidth a specific type of service occupies, the less bandwidth other services can use, which may affect other services. Therefore, network administrators need to plan and allocate network resources reasonably according to the characteristics of various services so that network resources can be used efficiently. In the following points we summarize how the mechanism QoS classifies network traffic [98]

- Traffic classification: A certain rule is used to identify the packets that meet certain characteristics. It is the premise and foundation for differentiated services for network services.

- Traffic policing: Regulate the specific traffic entering or leaving the device. When the traffic exceeds the set value, restrictions, or punishment measures can be taken to protect the network resources from damage. It can act on the inbound and outbound directions of the interface.

- Traffic shaping: A flow control measure that actively adjusts the output rate of flow. It is used to adapt the flow to the network resources that downstream devices can supply to avoid unnecessary packet discarding. It usually acts on the outbound direction of the interface.

- Congestion management: It is how to formulate a resource scheduling strategy when congestion occurs to determine the processing order of packet forwarding, which usually acts on the interface's outbound direction.

- Congestion avoidance: Monitor network resources usage, take the initiative to discard packets when congestion is found to increase and adjust the queue's length to relieve network overload, usually in the outbound direction of the interface.

## 4.6 QoS Functions

The QoS function is designed to ensure the network's efficient operation when it is overloaded or congested. It can specify the traffic's priority and minimize the impact when the connected load is too heavy. Furthermore, it can be applied as follow [99]:

1. Packet Classifier and Marker: Routers on the network boundary use the classifier function to mark packets belonging to a specific communication class according to one or more fields in the TCP/IP packet header then use the marker function to mark the classified traffic. This is done by setting the IP The priority field or differentiated service code point (DSCP) field is implemented [99].

2. Communication rate management: The service provider uses the policing function to measure customer communication entering the network and compare it with the customer's communication profile. At the same time, enterprises accessing the service provider's network may need to use the communication shaping function to measure all their communications and send them out at a constant rate to meet the service provider's control function. The token bucket is a commonly used communication measurement scheme [99].

3. Resource allocation: First-in first-out (FIFO) scheduling is a traditional queuing mechanism widely used by current Internet routers and switches. Although first-in-first-out scheduling is simple to deploy, there are some underlying issues in providing QoS. It does not provide a means of prioritizing delay-sensitive communications and moving them to the team's beginning. All communications are treated equally, and there is no concept of communication differentiation or service differentiation. For a scheduling algorithm that provides QoS, at least it can distinguish between different packets in the queue and know each packet's service level. The scheduling algorithm determines which packet in the queue to process next, and the frequency with which a flow packet gets service determines the bandwidth or resources allocated for this flow [99].

4. Congestion avoidance and packet drop strategy: In traditional first-in-first-out queuing technology, queue management is implemented as follows: When the number of packets in the queue reaches the maximum length of the queue, all the arriving packets are discarded. This queue management technique is called a tail drop, and it only sends a congestion signal when the queue is filled. In this case, active queue management is not used to avoid congestion, nor is the queue size reduced to minimize queue delay. Active queue algorithm management allows the router to detect congestion before the queue overflows [99].

5. QoS signalling protocol: RSVP is part of the IETF Intserv architecture that provides end-to-end QoS. It enables applications to put forward quality assurance requirements for each flow to the network. Service parameters are used to quantify these requirements for management control [99].

6. Exchange: The primary function of the router is to quickly and efficiently exchange all input communications to the correct output port and the next-hop address based on the information in the forwarding table. The traditional cache-based forwarding mechanism is efficient, but because it is driven by communication, it has scalability and performance problems, and it will increase cache maintenance and reduce switching performance when the network is unstable. The topology-based forwarding method solves the problems in the cache-based forwarding mechanism by creating a forwarding table that is identical to the router routing table [99].

7. Routing: Traditional routing is based only on the destination, and packets are routed according to the routing table on the shortest path. For some network situations, this seems inflexible. Policy routing is a QoS function that allows users to route based on various grouping parameters that users can configure instead of routing based on the destination. Current routing protocols provide shortest-path routing, which selects routes based on metric values. (such as administrative cost, weight, or number of hops). Packets are transmitted according to the routing table, and nothing is known about the requirements of each flow or the resources available on the route. QoS routing is a routing mechanism that takes into account the QoS requirements of the flow. When selecting a route, it has a precise understanding of the resources available on the network [99].

## 4.7 Routing for Extending LEO Satellites Service Life

In this thesis, we introduce the New Routing Optimize Metric abbreviated as (NROM), aiming to find a balance between performance and battery life in the LEO satellite constellation. We derived three versions of this metric based on adjustments to the values of $\omega_1, \omega_2$, so that through these adjustments, data routing can be tested based on battery usage, Delay sensitive, or a moderate metric balanced between battery consumption and delay-sensitive. As previously mentioned, DoD in batteries has a significant direct and impact on the life of batteries planted in LEO space satellites constellation and therefore has a direct effect on the age of the space satellite. Therefore, our primary orientation is based on a favour for routing data to the satellites facing the sun, and therefore it works during that period over the solar energy, preferring it to satellites that are in the shadow area and that area during that period working on the energy stored in the batteries, and thus we reduce the process of discharging the batteries DoD all this without a significant impact on performance.

## 4.8 NROM: New Routing Optimization Metric

NROM combines the value of battery discharge with its consumption in the satellite constellation and bandwidth management, leading to the production of a new routing metric for low-Earth orbit satellites. The motion of the satellites in the Earth orbit is deterministic. According to the available data on the intended constellation of satellites, the propagation delay can precisely be calculated in advance. The only non-deterministic information is the battery charge level, which must be distributed over the satellite network in a programmed way [100]. Based on the above, we offer a measure of the new metric to increase LEO satellites' service life, where this new metric based on the information available on the constellation of satellites. It is possible to study their locations in detail and to determine whether those satellites were in the shadow area or directly to the sun's rays and on that, it directs information to those satellites that are facing the sun, but if this route cannot manage, it directs them to those satellites where the battery charge is higher than the average. When all the required information is collected, for each space satellite NROM is calculated, the equation is as follows [101]:

$$NROMij(t) = \omega_1 \frac{T_{ij}(t) - T^{max}}{T^{max} - T^{min}} + \omega_2 \frac{S_{ij}(t) - S^{min}}{S^{max} - S^{min}} \tag{4.1}$$

Where $T_{ij}(t)$ is the propagation delay between two satellite i and j at the any given time $t$, and $\omega_1, \omega_2$ are weighting factors where these factors can be tuned on the application needs, for example tuning $\omega_2$ equal to zero will reduce NROM propagation-delay metric . Also, from the equation above $S_t$ represent the time spent by particular satellite in the shadow and can be calculated as shown in section 2.8.1. In this thesis, and based on what was written in literature, we applied three models of service quality to route data in the constellation of satellites to study the extent of their impact on increasing the service life of those satellite constellations. In the following experiments, we will review the results by changing the $\omega_1, \omega_2$ weighting factors values, as follows in the coming sections.

### 4.8.1 Delay Sensitive New Routing Optimization Metric (D-NROM)

For testing delay sensitive, we tuned $\omega_2$ equal to 0. This changes the value of the equation to become pure DSP protocol, as it becomes concerned only with the speed of performance without regard to any other considerations. As it appears in the equation that all the remaining part of the equation is concerned with propagation delay. So, for simplicity, we called it D-NROM. As the performance of the other metrics will be compared to the performance of this metric. The equation will be:

$$D - NROMij(t) = \omega_1 \frac{T_{ij}(t) - T^{max}}{T^{max} - T^{min}} \tag{4.2}$$

### 4.8.2 Battery-New Routing Optimization Metric (B-NROM)

For testing the battery (DoD) we tuned $\omega_1 = 0$. This changes the value of the equation, as it becomes concerned only with battery performance without regard to any other considerations. As it appears in the equation, the remaining part of the equation is concerned with the satellites' time spent in shadow. So, for simplicity, we called it B-NROM. The equation will be:

$$B - NROMij(t) = \omega_2 \frac{S_{ij}(t) - S^{min}}{S^{max} - S^{min}} \tag{4.3}$$

### 4.8.3 Balanced-New Routing Optimization Metric (BL-NROM)

Trying to strike balance between performance and battery consumption, we set $\omega_1$ and $\omega_2$ equal to 0.5. This will lead to explore a balanced NROM over DSP; we called it BL-NROM according to Balanced New Routing Optimization Metric. The equation will be :

$$BL - NROMij(t) = 0.5 \frac{T_{ij}(t) - T^{max}}{T^{max} - T^{min}} + 0.5 \frac{S_{ij}(t) - S^{min}}{S^{max} - S^{min}} \tag{4.4}$$

We then test these NROM metric versions to assess how effective they are on the network's performance in the constellation of satellites. Since these metrics depend on the calibration of several variables, we will try to get the best results and apply them according to the most appropriate use, especially when we recognize the Quality of Service. In the next sections, we will show tests and assessments of these metrics on the constellation network.

# Chapter 5

# Experimental and Evaluation Results

## Contents



In this thesis, we will introduce two new measurement metrics to route data in satellites to reduce the discharge of batteries (DoD) during the passage of the satellite in the eclipse area and thus extending the life of the satellite and the age of the constellation of satellites. This chapter will review the proposed models for information routing operations in the satellite constellation based on the above so that we will study three models of quality of service and their impact on the level of batteries consumption in the satellite, and as is known from the previous chapter. In these tests, we will study the effect of information guidance on the consumption of space satellite batteries, and we will answer several questions:

- First, we will introduce a new routing metric that combines the quality of the service (QoS) and drops all signalling requirements. Instead, it calculates the propagation delay, and the time spent by the satellite in the shadow, both of which can be counted in one routing metric.
- Second, we will use the information available to the general about the Iridium constellation, that the new routing metric can extend the battery life of the LEO satellite.

## 5.1 Routing for Extending LEO Satellites Service Life

In this chapter, we simulate the new NROM routing metric, aiming to find a balance between performance and battery life in the LEO satellite constellation. As previously mentioned, DoD in batteries has a significant direct and impact on the life of batteries planted in LEO space satellites constellation and therefore has a direct effect on the age of the space satellite. Therefore, our primary orientation is based on a favour for routing data to the satellites facing the sun. And therefore, these satellites work during that period over the solar energy, preferring it to satellites in the shadow area. during that period working on the energy stored in the batteries. and thus, reduce the depth of discharging (DoD) process, all this without a significant impact on performance.

## 5.2 Experimental and Evaluation Results

We have used Network simulator (NS2) 2.34 is a simulation platform, and then we evaluated the performance of the NROM metric according to the battery discharge rate, the data delivery rate, average end-to-end delay, and packet delivery ratio. We have applied the three NROM Metric, which represents the QoS Cases over the LEO network.

### 5.2.1 Experimental Setup

**LEO constellation parameters:** Mission started September 1, 2013 at 11:00:00 UTC. Satellite orbit height is 780 km, six orbital planes with an inclination angle of 86° are set, 11 satellites are evenly distributed on each orbital plane, the inter-satellite link bandwidth is 10 Mbit /s, and each satellite has two intra-orbit links and two inter-orbit links, the satellite closes the inter-orbit link between orbits when crossing the polar zone, and no inter-orbit link is provided on both sides of the reverse split. The average length of the data packet is 1000 Bytes, and the data transmission bit rate is selected in the range of 200-1200 Kbit/s. In this scenario, different resource satellites with different data transmission bit rates and different locations are configured. In simulation scenarios where the network load status and transmission path distance are different, the average end-to-end delay and loss rate of the packet is performance evaluation indicators.
**Battery parameters:** To make the simulation as a realistic as possible, the publicly available data on the constellation of the iridium satellites has been used, so that the total battery capacity is 250Wh, the transmitting power is 11 watts, the receiving power is 6 watts, and the nominal operating power is 4 watts and for the idle energy is 3 watts, and the energy in the case Hibernation equals 10% of inert power 0.3 watts.
**Routing protocols :** As is known, any routing metric can be applied to any protocol for data routing, and for ease, the NROM data metric has been applied to the Dijkstra's Shortest Path (DSP).
**Basic for comparison:** We compare NROM to pure Dijkstra's Shortest Path (DSP), for

two reasons.

- DSP remains one of the most popular routing methods for LEO satellite networks.
- Comparing to a protocol that ignores the battery service lifetime helps quantity the potential for improvement and trade-offs involved in switching to protocols that do take the battery life into account.

Table 5.1: Parameters Of Satellite Constellation

| | |
|---|---|
| Number of orbits | 6 |
| Number of satellites pre plane | 11 |
| Satellite altitude | 780 KM |
| Minimum elevation angle | 8.2º |
| Cross-seam ISLs | NO |
| Number of ISLs | 2 Intra-plane +2 inter-plane |
| ISL latitude threshold | ±60º |
| Simulation duration | 6060s |

Table 5.2: Traffic Generator Parameters

| | |
|---|---|
| Terminal Bit Rate (kb/s) | Delay (Ms) |
| ISL queue type | FIFO |
| ISL queue length | 100 Packets |
| ISL bandwidth | 10 Mb/s |
| UDL bandwidth | 15 Mb/s |
| Size of packet | 1000 Bytes |
| "On" period | 0.4 s |
| Bit rate during "On" period | 200-1200 kb/s |
| "Off" period | 0.8 s |

### 5.2.2 Experiment 1: Delay Sensitive Routing

We started simulation tests for testing delay sensitivity, and that is for several reasons, the most important of which is comparing the metrics that we abbreviated in terms of performance with the DSP routing algorithm, which is equivalent to D-NROM in our assumption. Depending on the values in the tables 5.1 and 5.2, the test was started. Table 5.3 and Figure 5.1 shows the results for the simulation; it clearly shows that the more energy it saves, the more delay-sensitive it can achieve. For the D-NROM, you can achieve better results for delay-sensitive values, but this will be at the expense of the satellite's battery and service life.

Table 5.3: Results for Delay Sensitive Routing

| **Terminal bit rate (kb/s)** | **D-NROM** | **BL-NROM** | **B-NROM** |
|---|---|---|---|
| 200 | 69 | 71 | 73 |
| 400 | 71 | 72 | 74 |
| 600 | 75 | 78 | 80 |
| 800 | 77 | 81 | 84 |
| 1000 | 80 | 84 | 89 |
| 1200 | 83 | 89 | 98 |

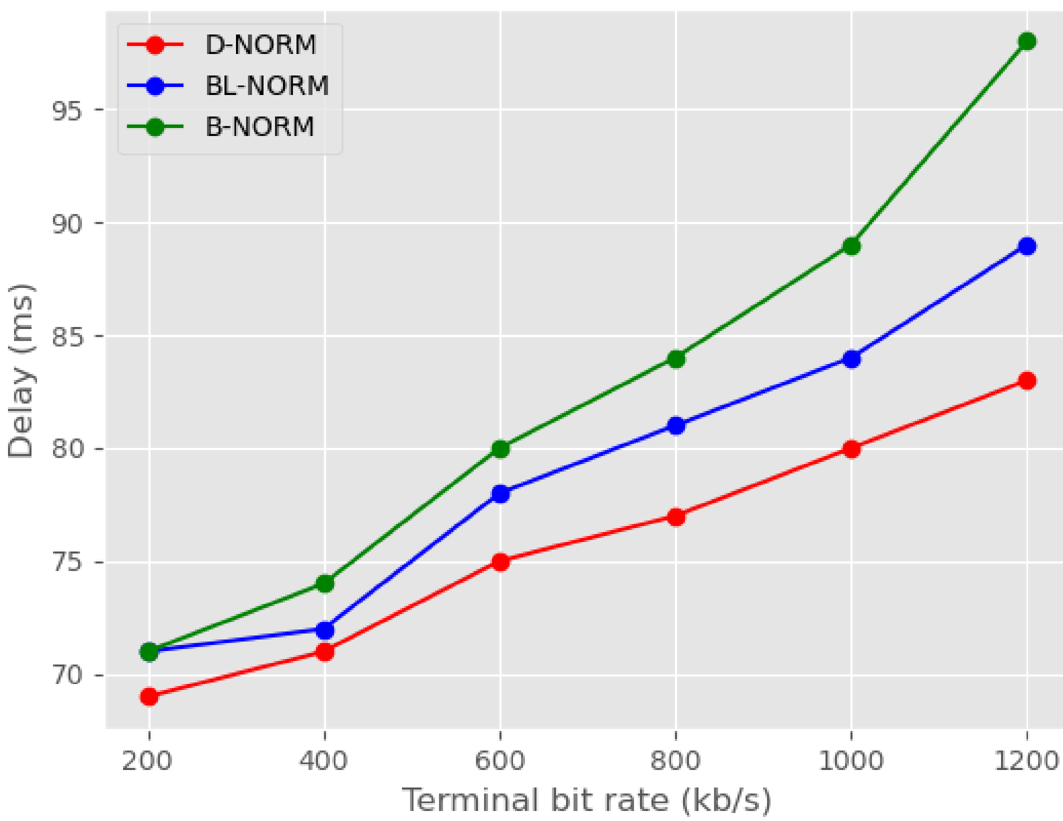


Figure 5.1: Experiment results show the terminal bit rate versus delay with different $\omega_1$, $\omega_2$ weight factors

On the other hand, for the B-NROM, we achieved the best results for battery performance at the expense of the performance of the data routing; the BL-NROM is balanced results between the two metrics, which is satisfactorily fair. In this simulation, the results we obtained show a clear superiority of the D-NROM scale on the other two metrics results, and for one important reason since it is the equivalent scale of the DSP metric which is directly concerned with the speed of data delivery regardless of the levels of battery charge in the satellite.

### 5.2.3 Experiment 2: Battery Depth of Discharge

Depth of discharge (DoD) refers to the percentage of the rated capacity taken from the battery. The discharge depth of shallow cycle batteries should not exceed 25%, and deep cycle batteries can release 80% of the electricity. Because the battery life is affected by the average state of charge of the battery, we must coordinate the relationship between the battery's cycle depth and capacity when designing a system.

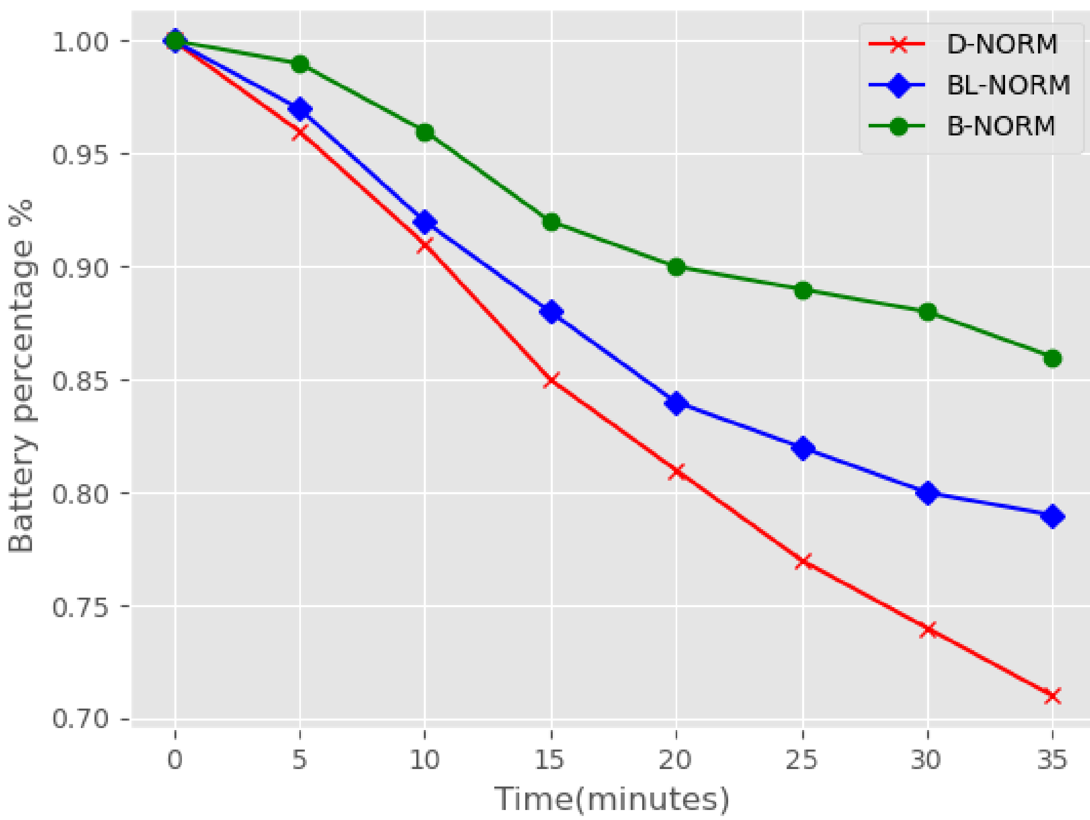


Figure 5.2: B-NROM and BL-NROM reduce the depth of discharge (DoD) by as much as 10% and 15%, respectively, over a D-NROM metric that does not take battery discharge into account.

| **Time (m)** | **D-NROM** | **BL-NROM** | **B-NROM** |
|---|---|---|---|
| 0 | 1 | 1 | 1 |
| 5 | 0.96 | 0.97 | 0.99 |
| 10 | 0.91 | 0.92 | 0.96 |
| 15 | 0.85 | 0.89 | 0.92 |
| 20 | 0.81 | 0.87 | 0.90 |
| 25 | 0.77 | 0.85 | 0.89 |
| 30 | 0.74 | 0.83 | 0.88 |
| 35 | 0.71 | 0.81 | 0.86 |

Table 5.4: Results for Battery Depth of Discharge (DoD)

The experiment was started for evaluating B-NROM in terms of battery DoD. For this, 100 terminals are distributed over six continents according to the distribution used in table 5.1 and traffic generator parameters as shown in table 5.2 at 15 Mbps is attached to each one of them. The average packet size is set to 1000 Bytes. The results show a similar attitude for the three metrics but it clearly show that B-NROM has the best result, that this is the best metric to maintain the battery charge level, from zero to 35 minutes, which is the time the satellite stays in the shadow area, so that its operation depends on the use of batteries. Figure 5.2 shows the simulation results and Table 5.4 shows the battery percentage level for all three metric simulation experiment. The results clearly show 15 % difference between B-NROM and D-NROM which means doubling the service life time of the battery and therefor doubling the service life time for satellite as well , on the other hand there is nearly 10% difference between BL-NROM and D-NROM which also significantly affect the service lifetime of the satellite constellation as well.

### 5.2.4 Experiment 3: Packet Delivery Ratio

To investigate the abilities of the B-NROM and BL-NROM in supporting QoS, we evaluate its performance in terms of the achieved packet delivery ratios. Figure 5.3 shows that using BL-NROM leads to a much better packet delivery ratios over the LEO constellation when compared to D-NROM and B-NROM. This is to be expected since BL-NROM adapts to the position and battery level of the satellites. In other words, BL-NROM has multi-path to select data route, while D-NROM always uses the shortest path to the destination. This performance is attributable to the fact that the D-NROM algorithm bases its routing strategy on only finding paths with the shortest delay. The packet delivery ratio is the ratio of packets successfully received to the total sent. Throughput is the rate at which information is sent through the network. If a network becomes congested and there is good discipline, packets may queue up at the source and never enter the network.

Table 5.5: Results Packet Delivery Ratio for different terminal bitrates

| Terminal bit rate (kb/s) | D-NROM | BL-NROM | B-NROM |
|---|---|---|---|
| 200 | 1 | 1 | 1 |
| 400 | 1 | 1 | 1 |
| 600 | 1 | 1 | 1 |
| 800 | 0.99 | 1 | 0.99 |
| 1000 | 0.97 | 0.99 | 0.97 |
| 1200 | 0.94 | 0.98 | 0.94 |

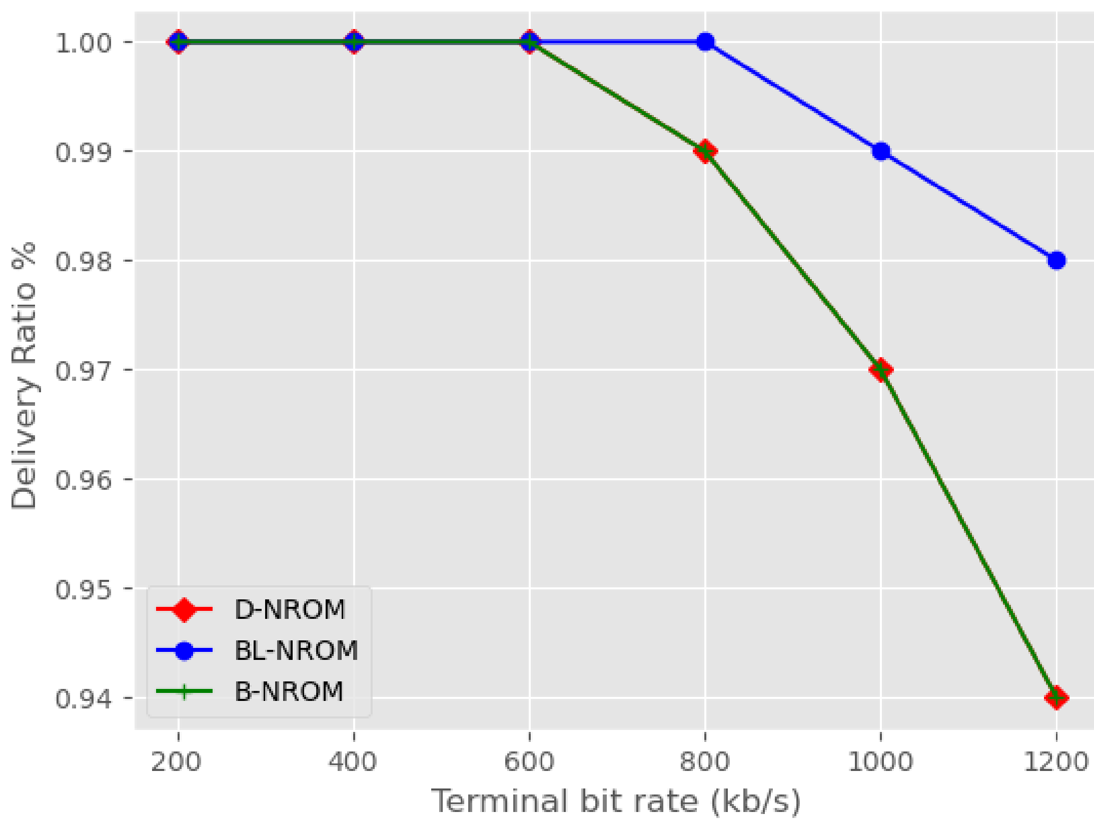


Figure 5.3: Experiment results for Packet Delivery Ratio for different terminal bit-rates

### 5.2.5 Experiment 4: Load Distribution Index

Load Distribution Index refers to network resources, such as how busy the router is. The load can be calculated in many ways, including CPU usage and the number of packets processed per second. Continuous monitoring of these parameters is itself very resource intensive. The load distribution index was tested based on the results we obtained from previous tests, and therefore showed similar behaviour between metrics D-NROM and B-NROM. But the third metric BL-NROM shows a clear superiority on them as shown as in the figure 5.4 and table 5.6 below, and these results are very logical because this metric has more than one option and there is more than one way to distribute the path of data.

Table 5.6: Results for Load Distribution Index for different terminal bitrates

| **Terminal bit rate (kb/s)** | **D-NROM** | **BL-NROM** | **B-NROM** |
|---|---|---|---|
| 200 | 0.25 | 0.45 | 0.27 |
| 400 | 0.27 | 0.48 | 0.28 |
| 600 | 0.29 | 0.52 | 0.29 |
| 800 | 0.31 | 0.57 | 0.32 |
| 1000 | 0.35 | 0.66 | 0.36 |
| 1200 | 0.39 | 0.7 | 0.4 |

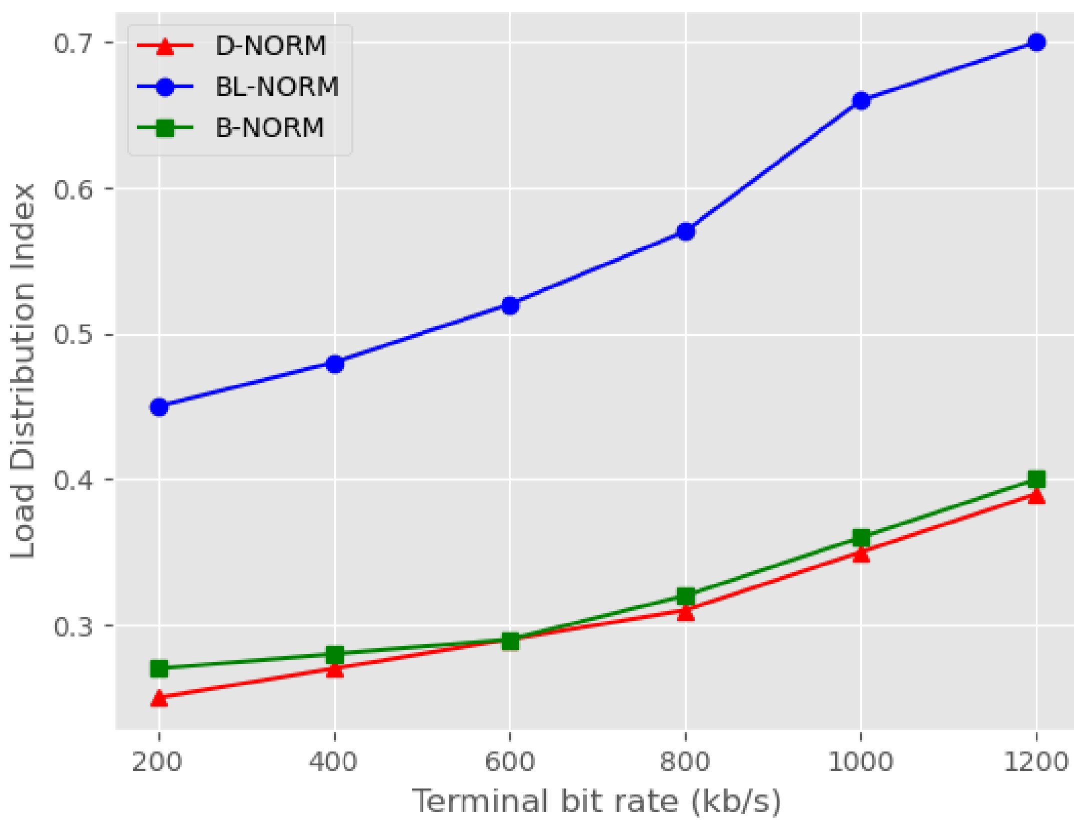


Figure 5.4: Experiment results for Load Distribution Index for different terminal bitrates

## 5.3 Conclusion And Future Work

Satellite communication has been paid more and more attention in the process of communication development because of its large coverage area and not restricted by geographical conditions. The urgent demand for broadband mobile multimedia communication services and the improvement of satellite equipment manufacturing technology have made satellite communications move from a single-satellite, pure forwarding mode of work to a multi-satellite network mode with on-board processing capabilities. Compared with Geostationary Earth Orbit (GEO) satellites, non-geosynchronous orbit satellites such as Low Earth Orbit (LEO) satellites have smaller propagation, time delay and low user terminal Effective radiated power requirements, so including multiple non-synchronous orbit satellites, on-board processing capabilities and inter-satellite links (Inter Satellite Link) have become common features of the current satellite mobile communication network structure. Satellite communication in the 21st century is climbing to a new level. Broadband, digital, IP, penalization, service integration and low cost are the ideal goals that satellite communication needs to achieve. New goals bring new topics, which are worthy of attention and research.

This thesis focuses on the research of satellite mobile communication network structure and routing technology, introduces new concepts in the structure design process of satellite mobile communication network from the perspective of meeting demand, deeply digs into the essential difference between satellite communication network and terrestrial communication network, and proposes new routing optimized metric. In this work, we proposed two routing metrics, B-NROM and BL-NROM that try to strike a balance between extending the LEO satellites service life and performance. The key intuition underlying B-NROM and BL-NROM is that eclipsed satellites – powered by batteries – should be less favoured for routing data traffic when compared to satellites exposed to the sun. Our simulation analysis showed that B-NROM and BL-NROM could lead to significant improvement in the battery depth of discharge and by extension to increased satellite service life. This was accomplished by trading off very little in terms of end-to-end delay. As future work, we intend to extend B-NROM and BL-NROM to take into account the link error rate and evaluate their performance across a richer set of parameters and on a more realistic setting.

==============================================

# Bibliography

[1] S. RM, "Computation of eclipse time for low-earth orbiting small satellites," *International Journal of Aviation, Aeronautics, and Aerospace*, vol. 6, no. 5, p. 15, 2019.

[2] L. Cheng, J. Zhang, and K. Liu, "Core-based shared tree multicast routing algorithms for leo satellite ip networks," *Chinese Journal of Aeronautics*, vol. 20, no. 4, pp. 353–361, 2007.

[3] N. Encyclopedia, "Quality of service (qos)," *https://networkencyclopedia.com/quality-of-service-qos/*, vol. 28, no. 2, pp. 1–8, 2020.

[4] T. Shtark and P. Gurfil, "Regional positioning using a low earth orbit satellite constellation," *Celestial Mechanics and Dynamical Astronomy*, vol. 130, no. 2, p. 14, 2018.

[5] Y. Yang, M. Xu, D. Wang, and Y. Wang, "Towards energy-efficient routing in satellite networks," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 12, pp. 3869–3886, 2016.

[6] S. Li and F. Tang, "Load-balanced cooperative transmission in meo-leo satellite network," in *2018 IEEE 32nd International Conference on Advanced Information Networking and Applications (AINA)*, pp. 564–571, IEEE, 2018.

[7] R. M. Gagliardi, *Satellite communications.* Springer Science & Business Media, 2012.

[8] W. W. Wu, E. F. Miller, W. L. Pritchard, and R. L. Pickholtz, "Mobile satellite communications," *Proceedings of the IEEE*, vol. 82, no. 9, pp. 1431–1448, 1994.

[9] D. E. Sterling and J. E. Hatlelid, "The iridium system-a revolutionary satellite communications system developed with innovative applications of technology," in *MILCOM 91-Conference record*, pp. 436–440, IEEE, 1991.

[10] S. D. Ilčev, *Global Mobile Satellite Communications Theory.* Springer, 2016.

[11] R. A. Wiedeman and A. J. Viterbi, "The globalstar mobile satellite system for worldwide personal communications," 1993.

[12] S. Cornara, T. Beech, M. Belló-Mora, and A. Martinez de Aragon, "Satellite constellation launch, deployment, replacement and end-of-life strategies," 1999.

[13] M. Mohorcic, M. Werner, A. Svigelj, and G. Kandus, "Adaptive routing for packet-oriented intersatellite link networks: performance in various traffic scenarios," *IEEE Transactions on Wireless Communications*, vol. 1, no. 4, pp. 808–818, 2002.

[14] C. E. Davis, "Solar energy system with relay satellite," Dec. 15 1981. US Patent 4,305,555.

[15] K. Weinersmith and Z. Weinersmith, *Soonish: Ten Emerging Technologies That'll Improve And/or Ruin Everything*. Penguin, 2017.

[16] P. J. Callen and P. R. Pierce, "Satellite dual bus power system," Jan. 15 1985. US Patent 4,494,063.

[17] S. Q. Kidder and T. V. Haar, "A satellite constellation to observe the spectral radiance shell of earth," in *Proceedings of 13th conference on satellite meteorology and oceanography, Norfolk, Virginia, USA*, 2004.

[18] V. K. Srivastava, M. Pitchaimani, B. Chandrasekhar, *et al.*, "Eclipse prediction methods for leo satellites with cylindrical and cone geometries: a comparative study of ecsm and escm to irs satellites," *Astronomy and Computing*, vol. 2, pp. 11–17, 2013.

[19] L. H. Thaller and T. P. Barrera, "Modeling performance degradation in nickel hydrogen cells," tech. rep., AEROSPACE CORP EL SEGUNDO CA ELECTRONICS TECHNOLOGY CENTER, 1991.

[20] A. Dutta and Y. Yemini, "Power management of leos under bursty broadband traffic," in *17th AIAA international communications satellite systems conference and exhibit*, p. 1317, 1998.

[21] G. Ning and B. N. Popov, "Cycle life modeling of lithium-ion batteries," *Journal of The Electrochemical Society*, vol. 151, no. 10, pp. A1584–A1591, 2004.

[22] J.-W. Lee, Y. K. Anguchamy, and B. N. Popov, "Simulation of charge–discharge cycling of lithium-ion batteries under low-earth-orbit conditions," *Journal of Power Sources*, vol. 162, no. 2, pp. 1395–1400, 2006.

[23] E. Del Re, "A coordinated european effort for the definition of a satellite integrated environment for future mobile communications," *IEEE Communications Magazine*, vol. 34, no. 2, pp. 98–104, 1996.

[24] X. Fang, S. Misra, G. Xue, and D. Yang, "Smart grid—the new and improved power grid: A survey," *IEEE communications surveys & tutorials*, vol. 14, no. 4, pp. 944–980, 2011.

[25] A. Zimmerman, "Life modeling for nickel hydrogen batteries in geosynchronous satellite operation," in *3rd International Energy Conversion Engineering Conference*, p. 5623, 2005.

[26] A. P. Trishchenko and L. Garand, "Spatial and temporal sampling of polar regions from two-satellite system on molniya orbit," *Journal of Atmospheric and Oceanic Technology*, vol. 28, no. 8, pp. 977–992, 2011.

[27] L. J. Ippolito, *Satellite communications systems engineering.* Wiley Online Library, 2017.

[28] T. Ball and V. Risser, "Stand-alone terrestrial photovoltaic power systems," in *Proceedings of the 20th IEEE Photovoltaic Specialists Conference*, 1988.

[29] J. Wang, L. Li, and M. Zhou, "Topological dynamics characterization for leo satellite networks," *Computer Networks*, vol. 51, no. 1, pp. 43–53, 2007.

[30] E. Ekici, I. F. Akyildiz, and M. D. Bender, "A distributed routing algorithm for datagram traffic in leo satellite networks," *IEEE/ACM Transactions on networking*, vol. 9, no. 2, pp. 137–147, 2001.

[31] J. R. Wertz, "Mission geometry: orbit and constellation design and management: spacecraft orbit and attitude systems," *Mission geometry: orbit and constellation design and management: spacecraft orbit and attitude systems/James R. Wertz. El Segundo, CA; Boston: Microcosm: Kluwer Academic Publishers, 2001. Space technology library; 13*, 2001.

[32] V. K. Srivastava, M. Pitchaimani, B. Chandrasekhar, *et al.*, "Eclipse prediction methods for leo satellites with cylindrical and cone geometries: a comparative study of ecsm and escm to irs satellites," *Astronomy and Computing*, vol. 2, pp. 11–17, 2013.

[33] C. R. O. Longo and S. L. Rickman, *Method for the calculation of spacecraft umbra and penumbra shadow terminator points.* National Aeronautics and Space Administration, 1995.

[34] O. Montenbruck and E. Gill, *Satellite orbits: models, methods and applications.* Springer Science & Business Media, 2012.

[35] J. L. Russell, "Kepler's laws of planetary motion: 1609–1666," *The British journal for the history of science*, vol. 2, no. 1, pp. 1–24, 1964.

[36] J. B. Schodorf, "Land-mobile satellite communications," *Wiley Encyclopedia of Telecommunications*, 2003.

[37] E. Lutz, M. Werner, and A. Jahn, *Satellite systems for personal and broadband communications.* Springer Science & Business Media, 2012.

[38] R. J. Cameron, C. M. Kudsia, and R. Mansour, *Microwave filters for communication systems.* John Wiley & Sons, 2015.

[39] M. D. Yacoub, *Foundations of mobile radio engineering.* Routledge, 2019.

[40] M. Richharia, *Satellite communication systems: design principles.* Macmillan International Higher Education, 2017.

[41] C. Ravishankar, J. Corrigan, R. Gopal, Y. Vasavada, J. J. JONG, N. BENAMMAR, G. Zakaria, A. Noerpel, H. Ramchandran, X. Huang, *et al.*, "Approaches for high speed global packet data services for leo/meo satellite systems," Jan. 8 2019. US Patent App. 10/177,837.

[42] A. Meloni and L. Atzori, "The role of satellite communications in the smart grid," *IEEE Wireless Communications*, vol. 24, no. 2, pp. 50–56, 2017.

[43] Q. Yang, D. I. Laurenson, and J. A. Barria, "On the use of leo satellite constellation for active network management in power distribution networks," *IEEE Transactions on Smart Grid*, vol. 3, no. 3, pp. 1371–1381, 2012.

[44] G. Maral and M. Bousquet, *Satellite communications systems: systems, techniques and technology.* John Wiley & Sons, 2011.

[45] P. Muri, J. McNair, J. Antoon, A. Gordon-Ross, K. Cason, and N. Fitz-Coy, "User datagram and bundle protocol for distributed small satellite topologies," *J. Wireless Netw. Commun.*, vol. 3, no. 3, pp. 19–28, 2013.

[46] M. P. Helme and T. L. Magnanti, "Designing satellite communication networks by zero—one quadratic programming," *Networks*, vol. 19, no. 4, pp. 427–450, 1989.

[47] Y. Zhang, *Internetworking and computing over satellite networks.* Springer Science & Business Media, 2012.

[48] L. Wood, A. Clerget, I. Andrikopoulos, G. Pavlou, and W. Dabbous, "Ip routing issues in satellite constellation networks," *International Journal of Satellite Communications*, vol. 19, no. 1, pp. 69–92, 2001.

[49] M. R. Bhalla and A. V. Bhalla, "Generations of mobile wireless technology: A survey," *International Journal of Computer Applications*, vol. 5, no. 4, pp. 26–32, 2010.

[50] S. M. Mutula, "The cellular phone economy in the sadc region: Implications for libraries," *Online Information Review*, vol. 26, no. 2, pp. 79–92, 2002.

[51] G. L. Stüber and G. L. Stèuber, *Principles of mobile communication*, vol. 2. Springer, 1996.

[52] M. Jiang, Y. Liu, W. Xu, F. Tang, Y. Yang, and L. Kuang, "An optimized layered routing algorithm for geo/leo hybrid satellite networks," in *2016 IEEE Trustcom/BigDataSE/ISPA*, pp. 1153–1158, IEEE, 2016.

[53] W. Xu, M. Jiang, F. Tang, and Y. Yang, "Network coding-based multi-path routing algorithm in two-layered satellite networks," *IET Communications*, vol. 12, no. 1, pp. 2–8, 2017.

[54] P. Narvaez, A. Clerget, W. Dabbous, *et al.*, "Internet routing over leo satellite constellations," in *Third ACM/IEEE International Workshop on Satellite-Based Information Services (WOSBIS'98)*, Citeseer, 1998.

[55] L. Wood, "Satellite constellation networks," in *Internetworking and Computing over Satellite Networks*, pp. 13–34, Springer, 2003.

[56] D. Day, *Eye in the sky: the story of the CORONA spy satellites.* Smithsonian Institution, 2015.

[57] S. Murthy and J. J. Garcia-Luna-Aceves, "An efficient routing protocol for wireless networks," *Mobile Networks and applications*, vol. 1, no. 2, pp. 183–197, 1996.

[58] L. Franck and G. Maral, "Routing in networks of intersatellite links," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 38, no. 3, pp. 902–917, 2002.

[59] Z. Wu, G. Hu, F. Jin, Y. Song, Y. Fu, and G. Ni, "A novel routing design in the ip-based geo/leo hybrid satellite networks," *International Journal of Satellite Communications and Networking*, vol. 35, no. 3, pp. 179–199, 2017.

[60] S. Wei, H. Cheng, M. Liu, and M. Ren, "Optimal strategy routing in leo satellite network based on cooperative game theory," in *International Conference on Space Information Network*, pp. 159–172, Springer, 2017.

[61] T. R. Henderson and R. H. Katz, "Transport protocols for internet-compatible satellite networks," *IEEE journal on selected areas in communications*, vol. 17, no. 2, pp. 326–344, 1999.

[62] M. Atiquzzaman, S. Fu, and W. Ivancic, "Trash-sn: A transport layer seamless handoff scheme for space networks," in *NASA Earth Science Technology Conference (ESTC)*, 2004.

[63] A. Houyou, R. Holzer, H. Meer, and M. Heindl, "Performance of transport layer protocols in leo pico-satellite constellations," *University of Passau, Passau, Germany, MIP-0502*, 2005.

[64] A. Hauschild and O. Montenbruck, "Real-time clock estimation for precise orbit determination of leo-satellites," in *Proceedings of the ION GNSS meeting*, pp. 16–19, 2008.

[65] J. B. Schodorf, "Land-mobile satellite communications," *Wiley Encyclopedia of Telecommunications*, 2003.

[66] A. E. Braun, "Intelligent transportation systems: mirage or reality?," *Microwave Journal*, vol. 40, no. 8, pp. 22–31, 1997.

[67] P. Du, S. Nazari, J. Mena, R. Fan, M. Gerla, and R. Gupta, "Multipath tcp in sdn-enabled leo satellite networks," in *MILCOM 2016-2016 IEEE Military Communications Conference*, pp. 354–359, IEEE, 2016.

[68] H. Schulzrinne, S. Casner, R. Frederick, and V. Jacobson, "Rtp: A transport protocol for real-time applications," tech. rep., 2003.

[69] C.-X. Liu, Y. Liu, Z.-J. Zhang, and Z.-Y. Cheng, "High energy-efficient and privacy-preserving secure data aggregation for wireless sensor networks," *International Journal of Communication Systems*, vol. 26, no. 3, pp. 380–394, 2013.

[70] M. van Der Schaar *et al.*, "Cross-layer wireless multimedia transmission: challenges, principles, and new paradigms," *IEEE wireless Communications*, vol. 12, no. 4, pp. 50–58, 2005.

[71] H. Huang, G. Hu, and F. Yu, "Energy-aware geographic routing in wireless sensor networks with anchor nodes," *International Journal of Communication Systems*, vol. 26, no. 1, pp. 100–113, 2013.

[72] X. Mao, X.-Y. Li, W.-Z. Song, P. Xu, and K. Moaveni-Nejad, "Energy efficient opportunistic routing in wireless networks," in *Proceedings of the 12th ACM international conference on Modeling, analysis and simulation of wireless and mobile systems*, pp. 253–260, ACM, 2009.

[73] W.-W. Huang, M. Yu, L.-Q. Xiong, and J. Wen, "Energy-efficient hierarchical routing protocol for wireless sensor networks," in *2008 IEEE Pacific-Asia Workshop on Computational Intelligence and Industrial Application*, vol. 1, pp. 640–644, IEEE, 2008.

[74] S. O. Dulman, J. Wu, and P. J. M. Havinga, *An energy efficient multipath routing algorithm for wireless sensor networks.* Centre for Telematics and Information Technology, University of Twente, 2003.

[75] F. Zabin, S. Misra, I. Woungang, H. F. Rashvand, N.-W. Ma, and M. A. Ali, "Reep: data-centric, energy-efficient and reliable routing protocol for wireless sensor networks," *IET communications*, vol. 2, no. 8, pp. 995–1008, 2008.

[76] S. Meguerdichian and M. Potkonjak, "Low power 0/1 coverage and scheduling techniques in sensor networks," tech. rep., UCLA Technical Reports 030001, 2003.

[77] S. J. Marinkovic, E. M. Popovici, C. Spagnol, S. Faul, and W. P. Marnane, "Energy-efficient low duty cycle mac protocol for wireless body area networks," *IEEE Transactions on Information Technology in Biomedicine*, vol. 13, no. 6, pp. 915–925, 2009.

[78] F. Ingelrest, D. Simplot-Ryl, and I. Stojmenovic, "Optimal transmission radius for energy efficient broadcasting protocols in ad hoc and sensor networks," *IEEE Transactions on parallel and distributed systems*, vol. 17, no. 6, pp. 536–547, 2006.

[79] H. Hassanein and J. Luo, "Reliable energy aware routing in wireless sensor networks," in *Second IEEE Workshop on Dependability and Security in Sensor Networks and Systems*, pp. 54–64, IEEE, 2006.

[80] K. Akkaya and M. Younis, "Energy and qos aware routing in wireless sensor networks," *Cluster computing*, vol. 8, no. 2-3, pp. 179–188, 2005.

[81] R. Asorey-Cacheda, A. García-Sánchez, F. García-Sánchez, J. García-Haro, and F. González-Castano, "On maximizing the lifetime of wireless sensor networks by optimally assigning energy supplies," *Sensors*, vol. 13, no. 8, pp. 10219–10244, 2013.

[82] A. Misra and S. Banerjee, "Mrpc: Maximizing network lifetime for reliable routing in wireless environments," in *2002 IEEE Wireless Communications and Networking Conference Record. WCNC 2002 (Cat. No. 02TH8609)*, vol. 2, pp. 800–806, IEEE, 2002.

[83] Z. A. Eu, H.-P. Tan, and W. K. Seah, "Routing and relay node placement in wireless sensor networks powered by ambient energy harvesting," in *2009 IEEE wireless communications and networking conference*, pp. 1–6, IEEE, 2009.

[84] J.-H. Chang and L. Tassiulas, "Energy conserving routing in wireless ad-hoc networks," in *Proceedings IEEE INFOCOM 2000. Conference on Computer Communications. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies (Cat. No. 00CH37064)*, vol. 1, pp. 22–31, IEEE, 2000.

[85] K. Akkaya and M. Younis, "A survey on routing protocols for wireless sensor networks," *Ad hoc networks*, vol. 3, no. 3, pp. 325–349, 2005.

[86] Y. Xue, Y. Li, J. Guang, X. Zhang, and J. Guo, "Small satellite remote sensing and applications–history, current and future," *International Journal of Remote Sensing*, vol. 29, no. 15, pp. 4339–4372, 2008.

[87] J.-W. Lee, J.-W. Lee, T.-W. Kim, and D.-U. Kim, "Satellite over satellite (sos) network: a novel concept of hierarchical architecture and routing in satellite network," in *Proceedings 25th Annual IEEE Conference on Local Computer Networks. LCN 2000*, pp. 392–399, IEEE, 2000.

[88] P. Chini, G. Giambene, and S. Kota, "A survey on mobile satellite systems," *International Journal of Satellite Communications and Networking*, vol. 28, no. 1, pp. 29–57, 2010.

[89] A. Aragon-Zavala, J. L. Cuevas-Ruíz, and J. A. Delgado-Penín, *High-altitude platforms for wireless communications*. John Wiley & Sons, 2008.

[90] F. Alagoz, O. Korcak, and A. Jamalipour, "Exploring the routing strategies in next-generation satellite networks," *IEEE Wireless Communications*, vol. 14, no. 3, pp. 79–88, 2007.

[91] J. A. R. de Azúa, A. Calveras, and A. Camps, "Internet of satellites (iosat): Analysis of network models and routing protocol requirements," *IEEE access*, vol. 6, pp. 20390–20411, 2018.

[92] X. Pan, Y. Zhan, P. Wan, and J. Lu, "Review of channel models for deep space communications," *Science China Information Sciences*, vol. 61, no. 4, p. 040304, 2018.

[93] Q. Chen, R. Xie, F. R. Yu, J. Liu, T. Huang, and Y. Liu, "Transport control strategies in named data networking: A survey," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 3, pp. 2052–2083, 2016.

[94] E. Crawley, R. Nair, B. Rajagopalan, and H. Sandick, "Rfc2386: A framework for qos-based routing in the internet," 1998.

[95] S. Olariu and P. Todorova, "Qos on leo satellites," *IEEE Potentials*, vol. 23, no. 3, pp. 11–17, 2004.

[96] E. Papapetrou and F.-N. Pavlidou, "Qos handover management in leo/meo satellite systems," *Wireless Personal Communications*, vol. 24, no. 2, pp. 189–204, 2003.

[97] N. Christin and J. Liebeherr, "A qos architecture for quantitative service differentiation," *IEEE Communications Magazine*, vol. 41, no. 6, pp. 38–45, 2003.

[98] S. Malomsoky, D. Orincsay, and G. Szabo, "Technique for classifying network traffic and for validating a mechanism for classifying network traffic," Jan. 27 2011. US Patent App. 12/922,019.

[99] T. Szigeti, C. Hattingh, R. Barton, and K. Briley Jr, *End-to-End QoS Network Design: Quality of Service for Rich-Media & Cloud Networks.* Cisco Press, 2013.

[100] M. Hussein, G. Jakllari, and B. Paillassa, "On routing for extending satellite service life in leo satellite networks," in *2014 IEEE Global Communications Conference*, pp. 2832–2837, IEEE, 2014.

[101] O. Grodzevich and O. Romanko, "Normalization and other topics in multi-objective optimization," 2006.