Studies on Energy Consumption and Frequency Allocation for Satellite Communication Systems

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Abstract

The present dissertation offers several satellite system solutions that can be affordable in short term to improve the performance of current satellite communication systems. The leading idea is to enrich the already known applications, or to find new applications, in order to allow satellite communication to be involved in future wireless communication systems. The goal is to focus on new satellite applications and to design trendy communication systems. Each proposal seeks to responds current users necessities in terms of bandwidth capacity, energy consumption, mobility and design flexibility.

The dissertation is divided into the introduction chapter, three main technical chapters, and the future overview and discussions chapter. Each technical chapter consists of a deep explanation of one of our proposals. The proposals are: “Adjustable Energy Consumption Access Scheme for Satellite Cluster Networks”, “Delay-Tolerant Satellite Networks employing Off-loading Access Scheme and Adaptive Beam Forming” and “Priority Code Scheme for Flexible Scheduling in High Throughput Satellites”.

The adjustable energy consumption access scheme (AECS) is an access scheme that is focused on satellite cluster network. The purpose is help satellites to be able to decrease energy consumption, along their utility life to extend the satellite cluster longevity. The research illustrates the communication between cluster elements by implementing optical inter satellite links. The adjustable energy consumption access scheme process is explained through two principal scenarios: the scenario when the source and destination nodes belong to the same cluster, and the scenario when the source and destination nodes belong to different clusters.

The Delay-Tolerant Satellite Network is a network that employs a suitable access scheme, called as off-loading communications to wisely use energy resources.

The combination of the off-loading access scheme with the adaptive beam forming technique brings the possibility to increase the signal strength to/from satellites and ground stations, and to save energy resources to extend the longevity of the satellite communication systems. The off-loading access scheme seeks to offer benefits to current DTN services and applications. The proposal is based on employing low orbit satellites (LEOs) to take full advantage of low transmission delay, and large coverage.

Priority code scheme for flexible scheduling in high throughout satellites proposes a suitable scheme, capable to respond users demands, by dynamically scheduling frequency resources into specific satellite coverage areas. The priority code scheme (PCS) is based on increasing capacity in those footprints with high demand of resources, and at the same time decreasing the amount of resources dedicated to low loaded regions. The goal is reduce the under and overloaded resource allocation into specific footprints.

The future overview and discussions chapter, concludes and summarizes each technical topic, with the purpose to define solutions and problems to over come. For future understanding, the achievement and reference chapter is included at the end of this document.

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Chapter 1

Introduction

1.1 General Perspective

Since the creation of the satellite technology, satellites have been used to provide services that are unaffordable by other technologies. One of the main reasons of that is that the orography of the territory causes that other technologies are not able to reach final users. This problem does not exist in satellite communications. Thus, passing over the characteristics of the territory, satellites might be launched to connect faraway networks, or to relay other systems. However, what ever the purpose might be, the truth is that a satellite system represents a unique alternative to fulfill a huge variety of missions, such as communication, interplanetary, monitoring, forecast, and exploration.

Due to the existence of the great advantages offered by the satellite technology, satellite communication systems have spread out very fast all over the world, and nowadays there are several countries, including Russia, the United States, France, Japan, China, India, Israel, Iran, North Korea, among others, that have orbital launch capability. Many other nations are not able to launch satellites by themselves, but they have been involved in the satellite technology by developing new ideas and by doing research. This enthusiasm allows those countries to have their own satellites in space. There are countries with null satellite technology activity, but they are working towards it. This fact, let us understand that the opportunities of developing the satellite technology are still vey large. Refer to fig. 1.1 (1) to see the satellite development activity in the world. The information shown in the figure was updated in February, 2015.

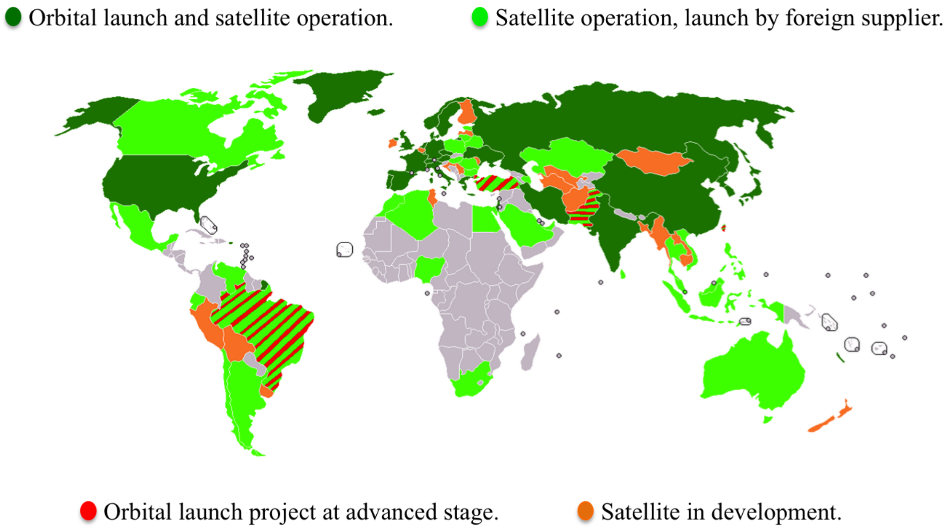


Figure 1.1: Development of the satellite technology in the world.

The investments and technical efforts to develop the satellite technology are admirable. It is a reality that satellites are the terricola giants flying in space. Over time, many other technologies, like unamed vehicular aircraft (UAV) and high altitude platform (HAP), have also emerged trying to replace the satellite technology. However, the experience has shown that the satellite technology is the only one that can simultaneously offer the same service coverage over huge terrestrial zones. Of course, it does not mean that other technologies are unnecessary. Conversely, it means that pre/post-satellite technologies may cooperate each other with the satellite technology to reach a common target.

That is the case of cluster networks and satellite systems, which combine strengths to build satellite cluster networks. Satellite cluster networks have been satisfactorily implemented in a number of new applications, such as positioning and sensor networks, with the purpose of improving communication system capabilities. However, due to the use of clusters requires good management of resources, these trendy applications imply new challenges within communication environments. The importance of improving the data management between cluster elements is also a basic concept into cluster networks, because the larger number of cluster elements are involved in, the more processing tasks exist. In addition, by considering that cluster networks are formed by satellites, the data management between satellites becomes more challenging than the data management between fixed network nodes.

Satellite clusters work in cooperation with others to provide real-time and non-real-time services into different footprint areas over inter/intra-cluster links. If the number of inter/intra-cluster links is very large, the system has higher energy consumption. The starvation of energy resources impacts the network operation by causing black outs or, in the worst cases, by causing the total cut off of the service provided by the network. Then, the energy consumption is a sensitive issue that concerns green network operations, and it is directly related to the cooperation and coordination between network elements. Therefore, the development of new protocols and access schemes, which care of energy resources, are essential to the continuous transformation, and healthy adaptation, of satellite technologies.

As a result of combining wire and wireless communication systems, novel communication systems emerged to overcome unresolved problems, or to fulfil new services. For instance, combining satellite communication systems with other technologies, such as cellular networks, the mobile positioning system becomes truth. Similarly, new environments also emerged to increase the challenge within communication systems. Consequently, the creation of new protocols and access schemes, once again, is very necessary. The networks that currently operate are hybrid networks. For example, every day we - as a final users - can take full advantage of services that are provided by a non-single technology. The new systems are networks that combine different technology layers and have to deal with challenging environments. Thus, the delay-tolerant network technology emerged to satisfy our new communication claims and their challenging communication environments.

A delay-tolerant network (DTN) is defined as a network that faces continuos interruption events along its transmissions, causing blackouts or cutt-off of service. The service drawbacks also have a negative impact on the service delivery timing, but the network can not avoid such long delays due to the inherent characteristics of the network. Conversely, the delay-tolerant network need to learn how to deal with such long delays. Satellite communication systems, that work into challenge environments, are one kind of delay-tolerant networks. In this case, the interruptions are caused by low link availability among satellite network elements.

Generally speaking, energy resources are very important in satellite systems, but they are not the only concern. Radio frequency resources, in combination with their correct allocation, represent another concern to improve. The correct allocation of frequency resources brings to the system the capability to fulfil a variety of tasks, and to perform all functions that are supposed to be made. How to assign the frequency resources sounds to be very easy, however, the more sophisticated system we create, the more complicated decisions have to be made to decide how much resources to give, to whom and for how long. This decisions are studied through the scheduling. Scheduling is the method by which processes or data flows are given access to system resources. The scheduler allows task to process at especific moments. The main goal is to complete the tasks with high quality of service. In satellite communications, like other wireless communications, the scheduler is a medular component to manage system resources. Therefore, many systems combine several schedulers to reach final users expectations about the quality of service.

As far as we have pointed along this section, satellite communications systems still have advantages to offer to the trendy solutions in communication. The new communication systems become more robust as a result of having more requirements. Our work, as a researches, is find out how to overcome the communication problems and think towards the sustainability of coming communication generations.

Finally, to conclude this section, fig. 1.2 illustrates a world cloud that includes satellite communication concepts and the probable concerns that might be come out in the next future. All topics introduced in this chapter, as well as the questions and concerns involved in, are going to be explain in more detail in future chapters.

Figure 1.2: Satellite technology word cloud.

1.2 Motivation

In communications, the access scheme concept is more related to the way by which different terminals access to the frequency channel provided for the communication system. However, the access scheme concept is even wider than that. By definition Access Scheme is the process by which the network elements access to the diverse network resources to be able to perform specific functions and tasks. Regarding satellite systems, those tasks may be establishing a link, regulating temperature, correcting tracking paths, monitoring the coverage area, etc. Of course, the main purpose is to establish communication with other network elements, but it will be impossible to be performed on condition that the system energy resources are insufficient. Thus, the energy consumption access scheme has vital importance because it may help to increase the satellite system lifetime.

The present dissertation seeks to provide different possible solutions to face energy consumption problems with satellite networks that work in very specific environments, such as cluster networks and delay-tolerant networks. In recent years, these kind of networks have become priority to wireless applications because the tendencies towards wireless communication services require to work into challenging environments where an efficient management of energy resources is a claim.

On the other hand, frequency resources have always represented a sensitive concern within satellite technology. However, nowadays this worry is even greater due to the invention of more powerful satellite systems such as high throughput satellites. Thus, this dissertation proposes a dynamic scheduling that might follow and adapt to the dynamic user necessities. I really hope the present dissertation might help to future research towards satellite communications improvements.

1.3 Organization of the Dissertation

The remainder of this dissertation is organized as follows:

In chapter 1, a general point of view of satellite communications is presented. The motivation of the present dissertation and its organization is also part of the introduction chapter.

In chapter 2, the brief history of satellite communications is introduced. In addition, theoretical concepts of satellite networks, cluster network, delay-tolerant network, energy access scheme, and inter-satellite links are reviewed.

In chapter 3, this dissertation introduces an access scheme which intends to decrease the consumption of energy resources within satellite cluster networks. The scheme is called adjustable energy consumption access scheme (AECS). The AECS is one possible solution response to particular necessities of communication and at the same time, a way of wisely using energy resources in space. The scheme is based on two concepts the transmission distance between cluster elements, i.e. satellites, and the type of service to transmit, it means real-time services or non-real-time services.

In chapter 4, this dissertation proposes a novel access scheme which intends to decrease the energy consumption within Delay-Tolerant LEO Satellite Networks. The scheme proposed is called off-loading access scheme. The off-loading access scheme is combined with the adaptive beam forming technique to improve the signal strength to/from satellites and ground stations. Thus, the solution introduced in chapter 4 seeks to overcome problems caused by the lack of energy resources, delay time and low accurate transmissions within Delay-Tolerant Networks (DTN).

In chapter 5, this dissertation introduces a novel scheme called Priority Code Scheme (PCS). The priority code scheme is a suitable scheme, capable to respond users demands, by dynamically scheduling capacity resources into specific satellite footprints. According to the users needs, the goal is using the PCS scheme to increase the efficient utilization of frequency resources, all through the satellite lifetime. The PCS is based on the idea of implementing priority codes at every beam deployed on High Throughput Satellites (HTS). To measure the advantages of using the PCS, it is intended to compare its performance in terms of efficiency and capacity.

In chapter 6, the final conclusions and future work are summarized.

Chapter 2

Satellite Communications Overview

In the present chapter, the history of the satellite technology is briefly introduced, following by the description of some satellite networks, e.g. satellite cluster networks and delay-tolerant satellite networks. The definition of the access scheme concept, as far as basic satellite communication concepts, are also part of this chapter.

2.1 History of Satellite Communications

Basically, talking about the history of satellite communications is talking about the history of the social evolution, because the satellite technology is the result of scientific and social events in which curiosity, science fiction, power, war, peace, business, and communication necessities were the principal factors.

The history of satellite communications started in 1610 when Galileo Galilei (1565 - 1642) saw the moons of Jupiter. Galileo Galilei thought that the stellar objects orbiting around that giant planet behaved like the servants at that time, who were called ”Satelles” (2). Therefore, he called the moons of Jupiter as satelles after the servants, because the moons behaved like they were bound to obey the commands of their master, Jupiter. Later on, the name turn to ”Satellites”, but before satellites were objects orbiting around Earth to obey people commands and requirements, many events took place in history.

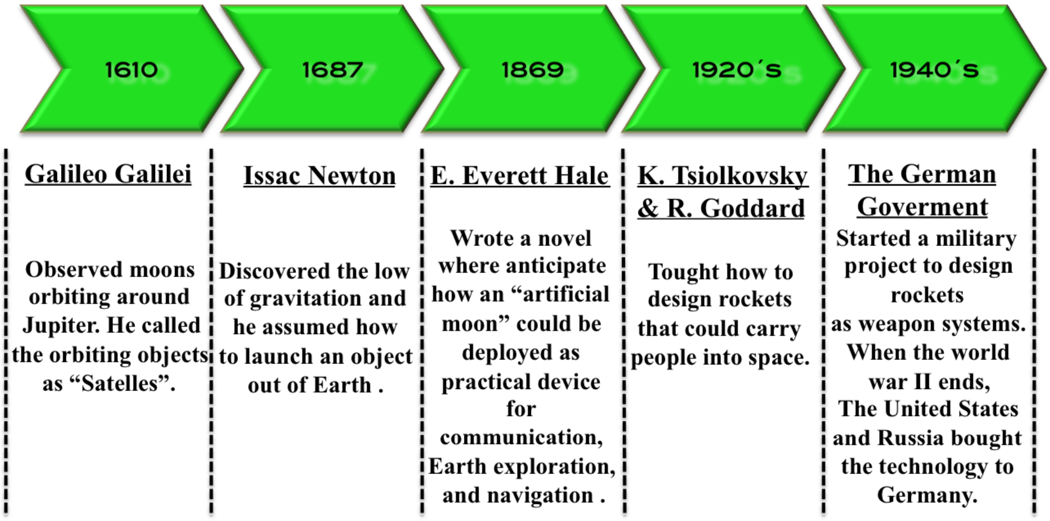
Almost 80 years later than Galileo Galilei, the physicist and mathematician Issac Newton (1643 - 1727) discovered the gravity law in 1687 by observation. This discovery helps to understand the kind of forces that govern the object movements on Earth, but more important was the fact that that assumption could be applied to stellar objects on space. For more than two centuries people thought that the idea of artificial orbiting objects on space was part of science fiction. Even more, the idea that those objects could benefit people on Earth was out of mind of human beings. Perhaphs, there was a man with different thinking. His name was Edward Everett Hale (1822 - 1909).

In his novel called ”The Brick moon”, that was written in 1869, he exposed the idea of how an artificial moon may offer communication from space to people on Earth. The idea was hilarious for most of the people at that time. However, the book inspired others like Konstantin Tsiolkovsky (1857 - 1935) and Robert Goddard (1882 - 1945), a Russian and an American scientists, respectively. K. Tsiolkovsky contributed with the first astronautic mathematical equation called as the Tsiolkovsky's rocket equation after him. Robert Goddard participate in many rockets designs and jointed his team to launch several of the designs.

The satellite technology was unstoppable at this point. Refer to figs. 2.1, 2.2, 2.3, and 2.4 to get a visual understanding about the timeline of the satellite technology and its master minds from XVII to XXI century. The timeline highlights the principal events occurred around the satellite technology, summarizing the investigations done by other researches (2).

The history of satellite communications is not finished yet. After 2000, the satellite technology has been taken different paths. Some developers have been attracted by the idea of using satellites as free global positioning systems. Others prefer to use satellites as a connection point between faraway commercial networks, e.g. cellular networks based on different regions on Earth. The option of minimizing the satellite sized has been also investigated by using nanotechnology.

Lately, other researches have been successful at making satellite communication solutions less expensive than before by deploying high throughput satellites (HTS) instead other satellites. Generally speaking, all those results have allowed the satellite technology to be financially competitive against other wireless technologies. We, as a researches, also hope to be capable to do tiny contributions in the amazing history of satellite communications.



Galileo Galilei

Observed moons orbiting around Jupiter. He called the orbiting objects as “Satelles”.

Issac Newton

Discovered the low of gravitation and he assumed how to launch an object out of Earth .

E. Everett Hale

Wrote a novel where anticipate how an “artificial moon” could be deployed as practical device for communication, Earth exploration, and navigation .

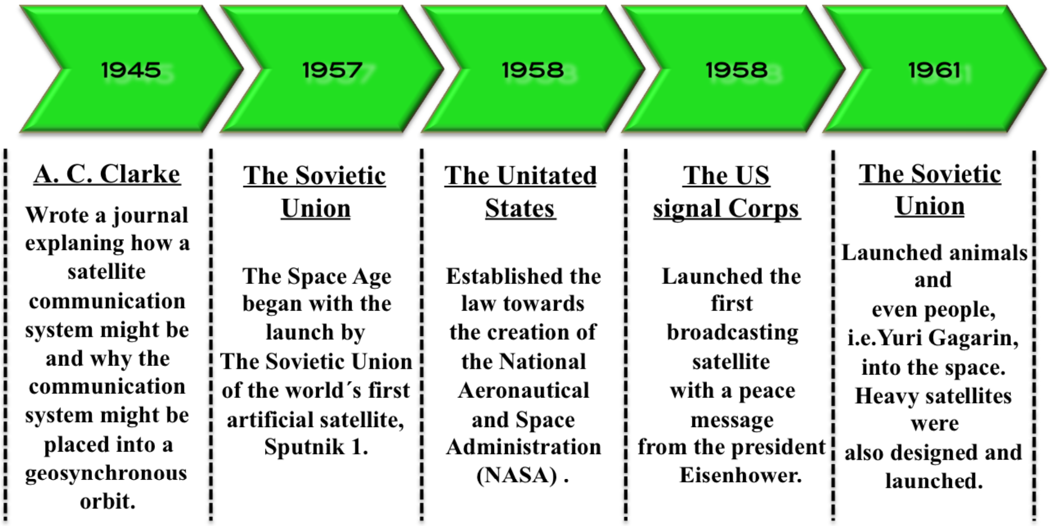
K. Tsiolkovsky & R. Goddard

Tought how to design rockets that could carry people into space.

The German Goverment

Started a military project to design rockets as weapon systems. When the world war II ends, The United States and Russia bought the technology to Germany.

Figure 2.1: First Part: Satellite technology timeline.



A. C. Clarke

Wrote a journal explaning how a satellite communication system might be and why the communication system might be placed into a geosynchronous orbit.

The Sovietic Union

The Space Age began with the launch by The Sovietic Union of the world´s first artificial satellite, Sputnik 1.

The Unitated States

Established the law towards the creation of the National Aeronautical and Space Administration (NASA) .

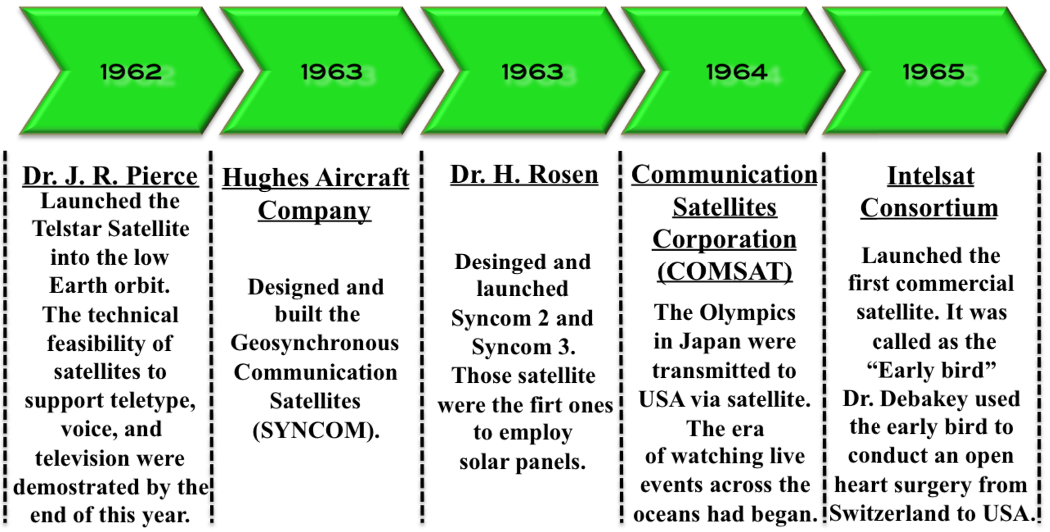
The US signal Corps

Launched the first broadcasting satellite with a peace message from the president Eisenhower.

The Sovietic Union

Launched animals and even people, i.e.Yuri Gagarin, into the space. Heavy satellites were also designed and launched.

Figure 2.2: Second Part: Satellite technology timeline.



Dr. J. R. Pierce
Launched the Telstar Satellite into the low Earth orbit. The technical feasibility of satellites to support teletype, voice, and television were demostrated by the end of this year.

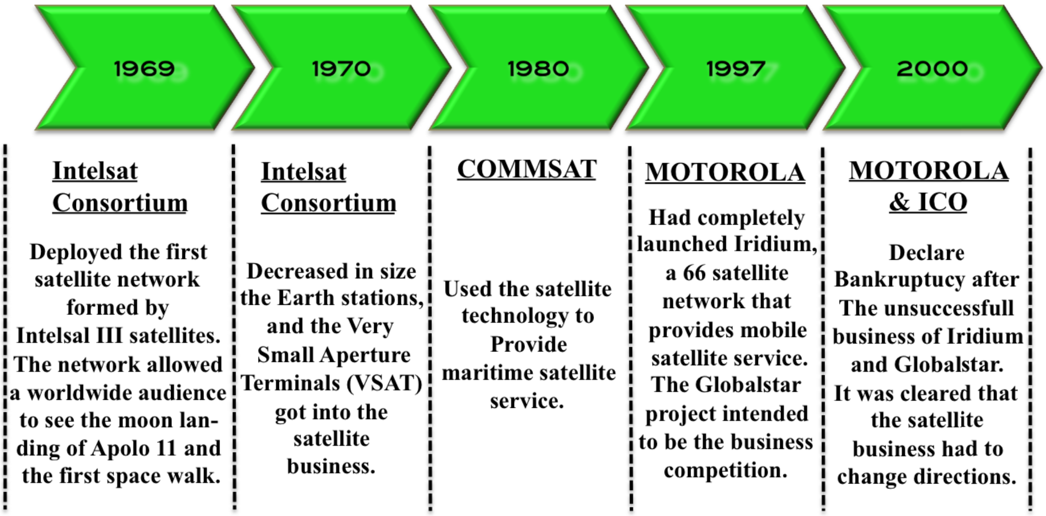
Hughes Aircraft Company
Designed and built the Geosynchronous Communication Satellites (SYNCOM).

Dr. H. Rosen
Desinged and launched Syncom 2 and Syncom 3. Those satellite were the firt ones to employ solar panels.

Communication Satellites Corporation (COMSAT)
The Olympics in Japan were transmitted to USA via satellite. The era of watching live events across the oceans had began.

Intelsat Consortium
Launched the first commercial satellite. It was called as the “Early bird” Dr. Debakey used the early bird to conduct an open heart surgery from Switzerland to USA.

Figure 2.3: Third Part: Satellite technology timeline.



Intelsat Consortium
Deployed the first satellite network formed by Intelsal III satellites. The network allowed a worldwide audience to see the moon landing of Apolo 11 and the first space walk.

Intelsat Consortium
Decreased in size the Earth stations, and the Very Small Aperture Terminals (VSAT) got into the satellite business.

COMMSAT
Used the satellite technology to Provide maritime satellite service.

MOTOROLA
Had completely launched Iridium, a 66 satellite network that provides mobile satellite service. The Globalstar project intended to be the business competition.

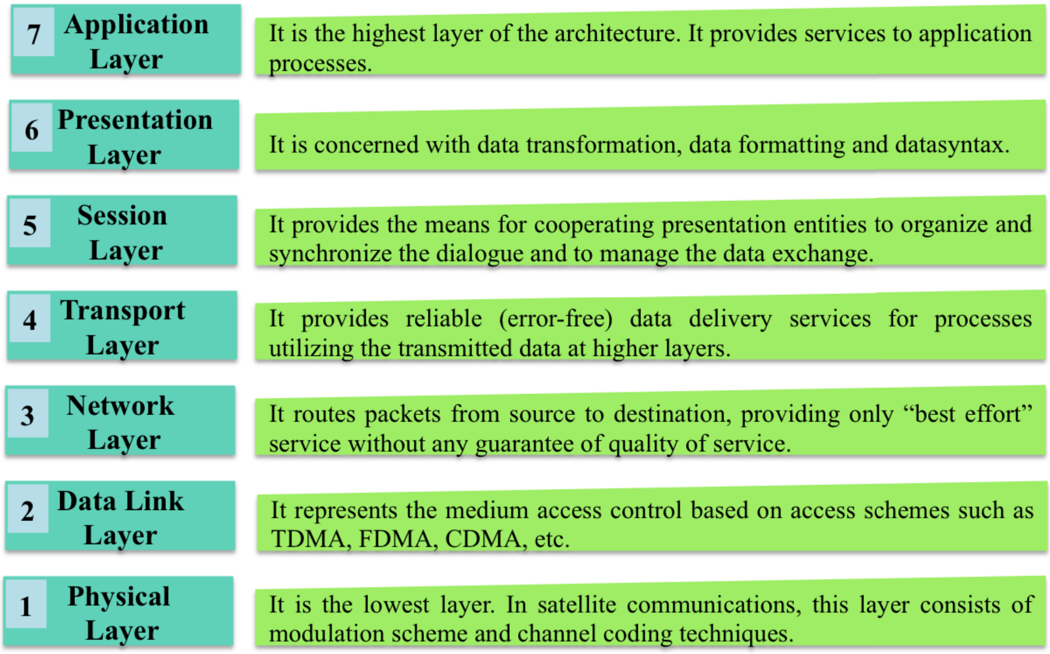
MOTOROLA & ICO
Declare Bankruptcy after The unsuccessfull business of Iridium and Globalstar. It was cleared that the satellite business had to change directions.

Figure 2.4: Fourth Part: Satellite technology timeline.

2.2 Satellite Networks

All satellite networks are designed based on a network layer model. This model follows the principle of identifying and grouping similar functions, which in turn are divided into different layers. This principle is called as layering principle because each group of functions represents a different layer in the network layer model. Every layer has a different protocol that establishes a set of rules in that layer. Network entities are known as the active elements of each layer. The communication between peer elements is fundamental to complete functions and tasks, but peer entities can only communicate each other if they belong to the same layer. The reason of that is that for communication purposes, it is necessary that the peers, which are attempting to communicate, follow the same protocol. In other words, it is necessary that the peers speak the same language, and it is only possible if they belong to the same layer.

In order to complete a particular satellite network task, all layers in the system are involved. Thus, it is also necessary the communication between layers. To do so, a stack layer layout is used. The layers share their information with the adjacent upper and lower layers, and those adjacent layers use that information to start their own processes. A layer reference model can be describe in fig. 2.5 (3) which is no other than the OSI model. When researches design a satellite network, they primarily focus on layers 1, 2, 3 and 4. Layers 5, 6 and 7 are considered application layers and they are more related to the final user side.



7	**Application Layer**	It is the highest layer of the architecture. It provides services to application processes.
6	**Presentation Layer**	It is concerned with data transformation, data formatting and datasyntax.
5	**Session Layer**	It provides the means for cooperating presentation entities to organize and synchronize the dialogue and to manage the data exchange.
4	**Transport Layer**	It provides reliable (error-free) data delivery services for processes utilizing the transmitted data at higher layers.
3	**Network Layer**	It routes packets from source to destination, providing only “best effort” service without any guarantee of quality of service.
2	**Data Link Layer**	It represents the medium access control based on access schemes such as TDMA, FDMA, CDMA, etc.
1	**Physical Layer**	It is the lowest layer. In satellite communications, this layer consists of modulation scheme and channel coding techniques.

Figure 2.5: Seven-layer reference model.

There are several types of satellite networks. In this dissertation, we are going to talk about Cluster Satellite Networks and Delay-Tolerant Satellite Networks because those are the network un which we apply and analyzed the proposal solutions.

2.2.1 Satellite Cluster Network

The cluster concept was firstly applied by computer network manufacters in 1960 (4). The main idea was to connected several computers via local area network to view them as a single system. The general purpose was to build a super computer with the ability to perform intensive scientific calculations, but other benefits, such as load-balancing and high availability of services were discovered. Later on, the cluster concept was also employed to built networks in different computing fields, for instance to build powerful sensor networks. Nowadays a cluster network is very common solution to fulfil wire and wireless services.

Cluster elements, e.g. satellites, joint capabilities and resources to be able to share the cluster network tasks. The tasks are scheduled by using different process that help the cluster head to manage the network resources. The resources are jointed in a single stock which is only accessed by the cluster head. Any cluster element could be the cluster head, but inside a cluster only one cluster element can perform as cluster head. The cluster head selection is done time by time.

Cluster elements might be connected over different network topologies by using wire or wireless connections depending on the nature of the network. It means, if the cluster network is a wire network, cluster elements must be connected over optical fibres or any other wire cores. If the cluster network is a wireless network, the medium of connection is the air by employing radio frequency or optical links.

A satellite cluster network is an application of the cluster concept employing satellites as cluster elements. For this particular case, the cluster elements are connected over inter satellite links with the particularity that cluster elements are mobile elements. This characteristic makes satellite cluster networks more challenging than cluster network with fixed elements. Within a satellite cluster network two types of links may be established: inter cluster links, i.e. links between two cluster elements inside different clusters, and intra cluster links, i.e. links between two cluster elements inside the same cluster.

2.2.2 Delay-Tolerant Networks

Delay-Tolerant Networks (DTN) began as a research project under the United States government that has the necessity of sustaining significant delays and packet corruption of space travel. The solution was networking technologies. Initially, these projects only managed missions to the moon, but the field quickly expanded making possible the technological advance of the Interplanetary Internet. Later on, other technologies were interconnected to provide also services on Earth.

A DTN architecture is deployed in environments with end-to-end interoperability problems of the network elements. The interoperability problems are caused by long delay paths and network partitions. However, these kind of problems are more risky on condition that the network elements have limited power and limited memory resources. The DTN architecture joints different technology networks. It emulates an overlay above the transport layers of the networks it interconnects and provides key services such as data storage, retransmission and forwarding.

Since the protocol in the transport layer, i.e. TCP, needs a reliable end-to-end connection, but because of sender and receiver experience interoperability problems, the DTN delivers the acknowledgement hop-by-hop by following a store and forward method. It means a hop, between the source and destination elements, stores the data and it is responsible to transmit the data once the next hope is available. After the next hop has been linked, it receives the data and becomes the current hop in charge to transmit the data. The previous hop releases its resources from the transmission already done. If an error is detected the previous hop is responsible to retransmit the data onto the current hop.

This method allows data to be retrieved in case there is transmission errors. This type of architecture is useful for satellite networks because the satellites experience long delay paths and link availability problems between satellite nodes. In addition, by combining the satellite technology with other technologies in the same network, the interoperability between nodes is even more risky. Satellites are nodes with limited power because they have to be very careful about their energy consumption.

2.3 Satellite Links

In satellite communications there are three types of links: uplinks, i.e. links from earth stations to the satellites, downlinks, i.e. links from the satellites to earth stations, and inter-satellite links ,i.e. links between satellites. A basic configuration of a satellite link over a radio frequency carrier is described in fig. 2.6 (3). The satellite links might carry out over a radio frequency carrier or over an optical medium. In order to design a reliable satellite link, it is very important to indentify the elements that participate in it. Those elements may be clasify in five groups:

- the antenna parameters, i.e. gain, radiation pattern, angular beam width, and polarization,
- the radiated power,
- the received signal power,
- the noise power spectral, i.e. system noise temperature, noise temperature of an antenna, and noise characterzation,
- the influence of the atmosphere, i.e. rain attenuation, scintillation, multi path contributions, fading, shadowing, and atmospheric gases.

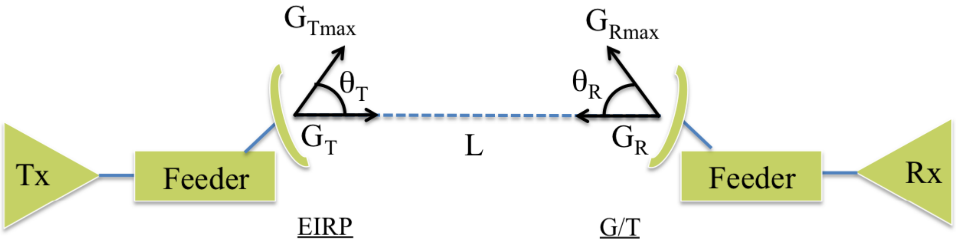


Figure 2.6: Configuration of a satellite link.

2.4 Energy Consumption Access Scheme

Like Earth's living beings, an artificial system also performs different tasks by using the system resources. The artificial system decides how to invest, or how to storage, its resources by following several steps which are indicated by the scheme adopted. Concerning satellite communication systems, there are different types of schemes. All of them are designed by considering specific principles of prioritizing events, cases, or even particular scenarios that might occur inside the satellite communication system. According to that prioritization, each scheme is able to set preferences and make decisions differently to another scheme.

The kind of decisions that the schemes might make are, for example, how to use the system resources, how and when to access to the system resources, and how long to retain the system resources. Satellite communication systems commonly use schemes that have preferences to manage the delay time to reach high delivery rates, regardless the amount of energy used. However, schemes which prefer to manage the energy consumption behavior are vital for any satellite system because those schemes might help to extend, or to reduce, the satellite system lifetime.

It is assumed that every satellite deployed has an expected lifetime, which is about 8 years in normally conditions. However, the satellite lifetime might change depending on the network environment and technical characteristics of the network which the satellite belongs to. These satellite lifetime differences are larger in cases where the satellite is an element of a challenging network which requires a larger number of connections and high retransmission activity.

Commonly, satellite manufactures and designers do not pay attention on the energy consumption schemes when they are designing a satellite. The reason of that is that the main point of a satellite is to offer communications services. Another reason of that is that the satellites, once they are deployed, have their own solar panel systems implemented to charge the battery energy supply. But I insists that there are a lot of opportunities to improve the satellite technology by involving and paying more attention on energy consumption schemes. This might make the satellite technology less expensive. Generally speaking, the energy consumption is a tradeoff between the consumption of other systems resources and it is important to equally focus on all of them.

In literature, most of the information concerning to the scheme concept is related to the modulation schemes and access schemes. I hope the present dissertation make help to develop more interests on energy consumption access schemes.

Chapter 3

Adjustable Energy Consumption Access Scheme for Satellite Cluster Networks

3.1 Introduction

Satellite communication represents a suitable option to support fixed and mobile networks in cases where ground networks are limited. Satellite clusters help to increase network advantages and communication alternatives because clusters provide the ability to modify the formation of the satellites. At the same time, based on their tracking path, satellite clusters are able to fulfill a large variety of missions and purposes. These characteristics mean satellite clusters guarantee a large and adjustable coverage area at low cost, and at the same time, help to form a virtual backbone network in space. In other words, a satellite cluster promotes the spatial reuse of resources, and the creation of smaller and more stable aircraft structures. However, there are some inherent issues to consider. For instance, how to command and control satellite clusters and how to manage the communication between them.

Due to long distances, vibrations, and characteristics of the propagation medium, satellite cluster communications suffer various effects, such as transmission delays, signal dissipation, and link data errors. These effects decrease the reliability of the received data. In order to solve those problems Lee, Luu and Konangi (5) present the development of an effective satellite cluster in terms of reduction of data transmissions. P. Zetocha (6) optimizes the lifetime of the cluster based on the knowledge of position data, sensor states and fuel levels, amongst other parameters. Ganz and Kami (7) analyze the minimal system configuration for a cluster system of two satellites connected by Inter-Satellite Links (ISL). Chen and Gardner (8) study the effects of random pointing and tracking errors to define an optimal transmitter gain for inter-satellite communications between geostationary satellites. Arnon, Rotman and Kopeika (9) design a model to perform the communication between GEO satellites, using discrete elements, optical phase array transmitter and telescope gain. There are also works related to the possible precision pointing and tracking accuracy between satellites (10) and laser communication applications (11).

In this chapter, a relevant scheme is proposed as a solution to decrease the energy consumption of satellite cluster networks. The resource management within cluster networks represents a sensitive point in the system. The reason for that is that by adding element resources, the cluster network must balance the single storage of resources to improve the network performance. There are several types of resources, such as radio frequency and energy resources. Radio frequency resources are responsible for setting the total payload capacity of the system. For example, if there are not enough radio frequency resources, the system is limited in the number of applications and users it can assist at the same time. On the other hand, energy resources are vital because they can extend or limit the satellite′s lifetime.

Considering that it is expensive to implement satellite technology solutions, the satellite lifetime has a direct impact on the cost of satellite services. At the same time, energy resources directly feed every module in the satellite system, providing them with a sufficient power supply to ensure good functionality. For instance, if there are insufficient energy resources, the power supply constrains efficient communication links due to the low power transmission levels. This means that, in the worst cases, the lack of energy resources may cut off the satellite service. Satellites act as cluster elements; therefore, satellite lifetime directly impacts the cluster network longevity and good performance.

It is important to mention that the satellites are provided with solar panels to charge themselves with energy and to be able to perform their functions. However, these kinds of devices have a lifetime to use and it is actually what researches intend to extend. Nowadays, satellites lifetime has been studied in terms of hardware trying to improve the material used on space, however another way to improve the satellite lifetime is by implementing new schemes and software applications.

The goal of the solution described in this chapter is to ensure low energy consumption by limiting long distance transmission links. The proposal of limiting long distance links might considerably extend the lifetime of satellite cluster networks. Of course, the proposal described in this chapter also works to mitigate other issues, which were addressed previously. The scheme proposed in this chapter is called the Adjustable Energy Consumption Access Scheme (AECS). AECS is a novel scheme which allows cluster elements to communicate with each other by only two types of links: intra-cluster and inter-cluster links.

The cluster elements involved are GEO and LEO satellites. GEO to LEO, and LEO to LEO communications are carried out over short or long distances by intra-cluster links. In contrast, GEO to GEO communications are only performed over long distances by inter-cluster links. The system may carry out either of two types of services: real-time services, such as VoIp, and teleconferences; or non-real-time services, such as SMS, email transmission, internet browsing, and software downloading, amongst others.

The AECS scheme decreases the network energy consumption by allowing or refusing transmission links based on the type of service to be run and the transmission link distances. For example, in the case of real-time requirements - due to the relevance of the service - satellite links must be established over both short and long distances. In contrast, for non-real-time services, satellites are only allowed to make the transmissions over short distances. The reason for that is because in order to decrease energy consumption levels, according to AECS, non-real-time services can be transmitted later when the satellites involved are closer to each other. This important characteristic helps satellites to wisely use their energy resources. Since optical link solutions offer improvements in satellite communications, we also study the link availability and link budget in optical free space communications. Finally, it is important to mention that the principal motivation of this chapter is to provide sustainable reasons for satellite technology to continue being involved in communication solutions, and the energy consumption analysis is a good starting point.

The present chapter consists of five content subchapters. Subchapter 3.2. System and Scheme Description, which includes the satellite cluster definition, proposed network structure, formation and the communication between network nodes. Subchapter 3.3. System Analysis, which describes the network transmission costs and provides a link availability analysis. Subchapter 3.4. Performance Evaluation, which shows the proposed system′s performance in terms of the energy consumption, specific link margins, *BER* and main delay. Subchapter 3.5. QoS and Data Storage, which presents the quality of service analysis based on the impact of holding transmissions and storing data. Subchapter 3.6. Conclusions, which presents a summary of results highlighting the strong and weak points of the proposed model.

3.2 System and Scheme Description

The cluster network technique was developed with the purpose of improving the network performance. Cluster formation is based on the idea that adjacent network elements can join the same group and work as a single system. By adding all the resources attached to each node, a single storage of resources is created. Grouping elements is a good way to build powerful communication systems. However, there are issues involved that make cluster formation and its correct management more difficult. If we consider that cluster nodes dynamically change their position, the cluster formation takes place every time cluster nodes move respect to others. Therefore, the cluster network topology changes from time to time. Once all clusters in the network have been created, it is necessary to establish the role of the nodes inside each cluster.

There are two main roles: the cluster head role and the normal role. Only one node per cluster has the cluster head role, whereas the rest of the nodes have the normal role. For simplicity, the node with the cluster head role is known as the cluster head. The nodes with the normal role are referred to as normal nodes. The role decision is based on the position of each node in respect to others, the buffer overflow of each node, and the remaining energy of each node. The simple action of making the cluster head selection implies the use of resources, lengthening the system computing process. Once all roles have been set, the cluster head performs four main tasks. The first task is to coordinate connections between all nodes inside its cluster. The second task is to manage cluster resources. The third task is to create a database that includes basic information of the grouped nodes inside its cluster. And the fourth task is to act as connection point with other clusters. The conventional cluster scheme implies that normal nodes must connect to each other through the cluster head by performing intra-cluster links. The cluster head coordinates the intra-cluster links by intelligently managing the resources. If two normal nodes, inside different clusters, need to link to each other, the connection involves two intra-cluster links and one inter-cluster link between the corresponding cluster heads (5),(6). Basically, the cluster scheme emulates a star logical topology.

3.2.1 Satellite Cluster Formation

The proposed system consists of three clusters ($cluster_1$, $cluster_2$, and $cluster_3$) sharing tasks through intra-cluster and inter-cluster links. All clusters are formed by one GEO satellite and two LEO satellites. Refer to fig. 3.1 for an illustration of the structure of the satellite cluster network. Observing fig 3.1, there are two LEO satellites per cluster. Each GEO satellite is always the cluster head of the cluster that it belongs to. Thus, it is not necessary to perform the cluster head selection process and by default, LEO satellites are always normal nodes. By simplifying the cluster formation and cluster head selection process, the system can skip part of the computer process and save energy at the same time (6). The reason that only GEO satellites are chosen as cluster heads, is the GEO satellite position. Based on the proposed design, due to the GEO position and orbital altitude characteristics, GEO satellites are always visible to each other. Therefore, the communication between clusters can be carried out at any time without interruption. Another assumption is that GEO satellites always belong to the same cluster. Referring to fig.3.1, the previous assumption means that Geo_1 is always the cluster head of $cluster_1$, and it will never be the cluster head of $cluster_2$ or the cluster head of $cluster_3$. Geo_2 and Geo_3 follow the same logic.

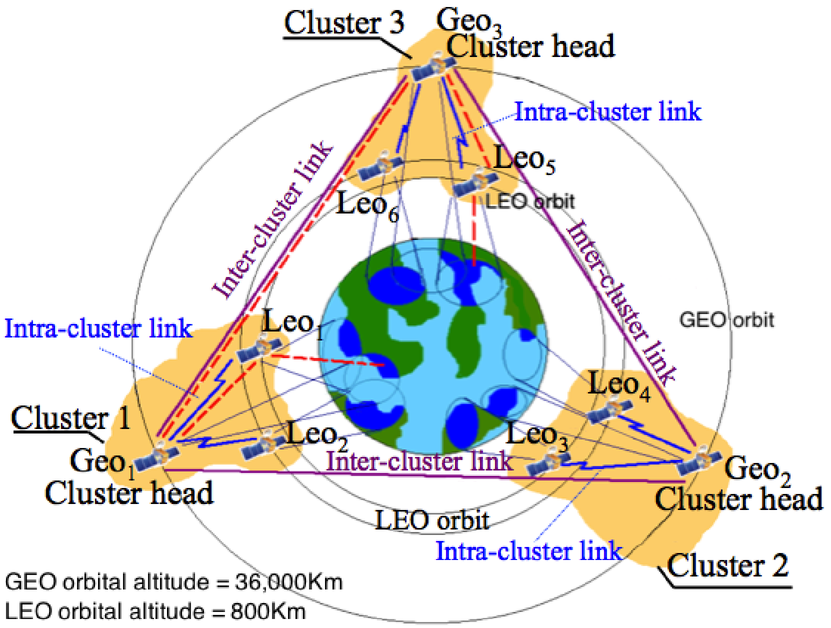


Figure 3.1: Satellite cluster model based on GEO and LEO satellites deployment.

Regarding cluster formation, it is necessary to consider that GEO satellites have a longer orbital period than LEO satellites. The GEO and LEO satellite speed is around 4.64 km/s and 7.8 km/s, respectively, which means LEO satellites change their position faster in comparison with GEO satellites. Observing fig. 3.1, assume that at time t_1, Leo_1 and Leo_2 are inside $cluster_1$ and they are coordinated by Geo_1. However, due to the speed difference between GEO and LEO satellites, at time t_2, LEO satellites their position slightly more, in comparison with Geo_1. This fact implies that Leo_1 and Leo_2 might be inside another cluster at time t_3, t_4, or at any other subsequent moment. Therefore, LEO satellites are dynamically grouped into different clusters based on their position during a specific period of time. Bearing this in mind, if two LEO satellites are coordinated by the same GEO satellite, i.e. the same cluster head, it means those LEO satellites belong to the same cluster. Alternatively, if two LEO satellites are coordinated by two different cluster heads, those LEO satellites belong to two different clusters.

3.2.2 Satellite Cluster Communication

The communication between satellites that are inside the same cluster is called intra-cluster communication. Based on fig 3.1, e.g. inside $cluster_1$, intra-cluster links are established at different distances between Leo_1 and Leo_2 or between one of the LEO satellites and Geo_1, when the transmission involves one normal node and the cluster head. If an attempted intra-cluster link is up to 200 km in length, the intra-cluster link is considered as a short distance link. Short distance intra-cluster links are always established, regardless of whether the transmission is related to a real-time or non-real-time service.

For short distance links, the vibration effects in Optical Inter-Satellite Links (OISL) are considered negligible (12). If the source and destination nodes of an attempting intra-cluster link are farther than 200 km from each other; the intra-cluster link is considered as a long distance link. Long distance intra-cluster links are only established if the links are related to real-time services. Otherwise the links are rejected. The rejection takes place because in order to efficiently use energy resources, AECS considers that long distance intra-cluster links, can be established later at shorter distances, when the source and destination node are closer to each other.

There is a second type of cluster communication, known as an inter-cluster communication. This represents the communication between cluster heads. Observing fig. 3.1, in the system design, inter-cluster links are only performed between Geo_1, Geo_2, and Geo_3; because GEO satellites are the cluster heads. GEO satellites are placed, at the same orbit, with a separation of 120° arc distance between each other. This distance is fixed and cluster heads never will be closer to or farther from each other. As a result, inter-cluster links have the fixed length of 72,000 km. Consequently, it does not matter if inter-cluster links are related to real-time or non-real-time service; inter-cluster links are never rejected because the distance between cluster heads never will be closer. In order to illustrate the application of inter-cluster links, observe fig. 3.1 and consider that $cluster_1$ and $cluster_3$ are involved in a satellite transmission. Leo_1 inside $cluster_1$ wants to transmit data to Leo_5 inside $cluster_3$. This transmission path is represented by the red dotted lines in the figure. For this scenario, firstly an intra-cluster link is established between Leo_1, i.e. the source node, and its cluster head, Geo_1. Secondly, Geo_1 and Geo_3 are linked by an inter-cluster communication. Finally, another intra-cluster link is established between the cluster head of $cluster_3$, Geo_3, and the final receiver, Leo_5. As may be observed, the main aim of inter-cluster links is to ensure contact duration between GEO satellites, which means between cluster heads.

We can conclude that GEO satellites are the connection point between different clusters, and the number of links that go through them is quite high. The traditional cluster scheme suffers overflow issues due to the high number of connections that are made through cluster heads. In order to avoid cluster head buffer overflow, AECS suggests that if two normal nodes, inside the same cluster, want to communicate with each other, they should establish one intra-cluster link to each other without going through the cluster head. For instance in fig. 3.1, if Leo_1 and Loe_2, which are inside $cluster_1$, are involved in an intra-cluster transmission, they must directly link to each other through a single intra-cluster link.

In contrast, the connection between Leo_1 and Leo_5, must be established by two intra-cluster links and one-inter cluster link (because they belong to two different clusters), i.e. the connection must be established by one intra-cluster link between Leo_1 and Geo_1, by one inter-cluster link between cluster heads, Geo_1 and Geo_3 and finally, by a second intra-cluster link between Geo_3 and Leo_5. Only intra-cluster links can be rejected if they are requested at long distances and they are related to a non-real-time service. For that reason, the AECS scheme must figure out the link lengths and the type of service related to the link, before allowing an intra-cluster satellite link.

Finally, there is a third type of communication link. This type is represented by the well-known downlinks and uplinks. Both represent a connection interface between the satellite cluster network itself, and a fixed network on Earth. The ground network is formed by a group of ground stations GS. A GS is the connection point to the final users and its role is to manage the ground network resources and services. A GS might be linked by GEO or LEO satellites of the cluster network. In this way, GEO and LEO satellites can receive uplinks from the GS that are placed inside their corresponding footprints. Downlinks are performed by GEO and LEO satellites in direction of the GS. The GS is responsible for starting or concluding the transmission towards the final users, just as a typical fixed network does. This proposal assumes that intra-cluster links, inter-cluster links, downlinks and uplinks employ optical wireless communication technology.

These three types of communication links are considered for the scheme evaluation; however improvements in the downlink and uplink side are beyond the scope of the proposed scheme. Perhaps this point will be considered in future work.

3.2.3 Adjustable Energy Consumption Access Scheme

To begin the AECS description, it is important to mention that this proposal assumes uplinks and downlinks are performed following the well-known current process. This means that the uplink and downlink follow the same process when real-time or non-real-time service transmissions are attempted. At the same time, uplink and downlink paths are considered to be at a constant distance. Thus, there is no transmission differentiation due to the uplink and downlink length. Every time a final user U_e requests a service, it is served by the GS with a better carrier. The GS links to its most visible satellite by an uplink. The satellite involved might be an LEO or GEO satellite that is member of a cluster inside the cluster network. After the satellite communication takes place by using AECS scheme, the satellite involved performs a downlink to the GS. The GS establishes a final connection to the U_e by the traditional process of ground networks. Downlinks and uplinks are transparent in the AECS scheme process, so they are not mentioned in the following AECS description.

There are two important differences between the conventional cluster scheme and AECS scheme. The first one is related to the network topology. According to the conventional cluster scheme, if two nodes inside the same cluster, e.g. LEO_1 and LEO_2 in fig.3.1, need to establish a connection to each other, these nodes must be linked by their cluster head, i.e. GEO_1. In contrast, for the AECS scheme, if LEO_1 and LEO_2 are close to each other, AECS allows direct connection between LEO_1 and LEO_2 without going through GEO_1. If the two nodes involved belong to two different clusters, e.g. LEO_1 and LEO_3 in fig. 3.1, the conventional cluster scheme and the AECS scheme have similar behavior. For this scenario, LEO_1 must contact its cluster head, i.e. GEO_1. GEO_1 makes connection with the cluster head of LEO_3, i.e. GEO_2. Finally, GEO_3 directly links to LEO_3.

The second difference is related to the idea of allowing, or rejecting, links based on the type of service to be run and the distance between nodes. For example, the AECS scheme refuses long distance links that are related to non-real-time services. The reason is that the AECS scheme assumes that a non-real-time service, such as email, SMS, etc., can be delayed without causing a major impact on the final users due to the type of service itself. Then, the AECS scheme considers that in order to save energy, non-real-time services using long distance links, can be transmitted later when the satellites involved are closer to each other. If the transmission links are related to real-time services - due to the tight delay tolerance of this type of service - satellite links must be carried out over short or long distances. On the other hand, the conventional cluster scheme does not take into account distance length parameters to reject links. In fact, the possibility of rejecting links is not even considered by the conventional cluster scheme. In conclusion, the AECS scheme also follows the star logical topology; however in order to save energy resources, there are additional variations involved in the scheme process.

The AECS process involves two scenarios: $scenario_1$ and $scenario_2$. $Scenario_1$ considers a transmission between two nodes that belong to the same cluster. $Scenario_2$ takes place when two nodes, which are grouped into two different clusters, need to establish a transmission. Refer fig. 3.2 to illustrate $scenario_1$.

The $scenario_1$ process is explained as follows: Step 1. The AECS verifies the type of service related to the link. Step 2.a. If the transmission is related to a real-time service (case a), the intra-cluster link is performed without asking for assistance from the cluster head, regardless of the distance between the source node and the destination node. Step 2.b. If the transmission is related to a non-real-time service, AECS verifies the distance between the source node and the destination node. Step 2.b.1. If the distance between the source and destination nodes is long (case b), the intra-cluster link is rejected until both satellites are closer to each other.

Meanwhile, the source node holds the data transmission. Step 2.b.2. If the distance between the source node and the destination node is short (case c), the intra-cluster link must be directly performed between the nodes, without asking for assistance from the cluster head. Fig. 3.3 illustrates the $scenario_1$ flow chart process.

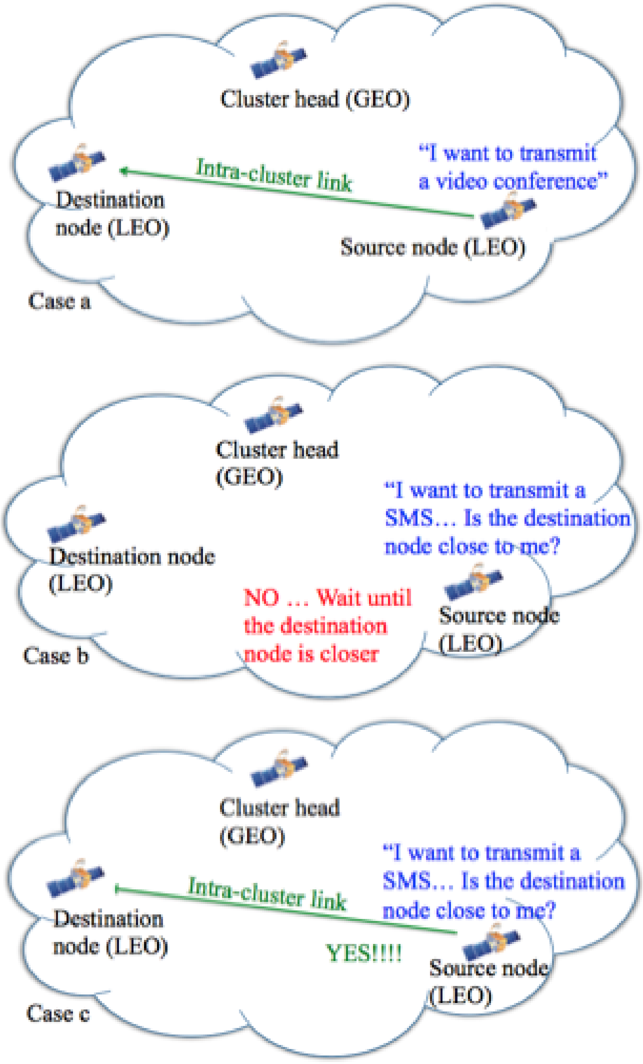


Figure 3.2: AECS performance for scenario 1. Case a: Real-time service. Case b: Non-real-time service over long distance between the source and the destination node. Case c: Non-real-time service over short distance between the source and the destination node.

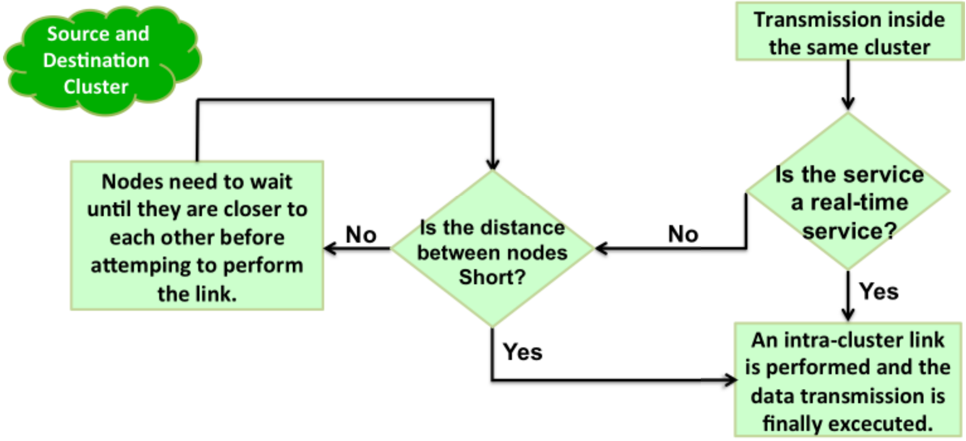


Figure 3.3: AECS inside the same cluster.

$Scenario_2$ performs two intra-cluster links and one inter-cluster link involving two clusters. Fig. 3.4 illustrates $scenario_2$. The process is explained as follows: Step 1. The AECS must verify the type of service related to the link. Step 2.a. If the transmission is related to a real-time service, one intra-cluster link is performed between the source node and $clusterhead_1$, regardless of the distance between the satellites (case a, $cluster_1$). Step 2.b. If the transmission is related to a non-real-time service, the AECS verifies the distance between the source node and $clusterhead_1$. Step 2.b.1. If the distance between nodes is long, the intra-cluster link is rejected until the satellites are closer to each other (case b, $cluster_1$). Step 2.b.2. If the distance between nodes is short, an intra-cluster link is established between the source node and $clusterhead_1$ (case c, $cluster_1$). Step 3. Once the first intra-cluster link is performed, $clusterhead_1$, establishes an inter-cluster link to $clusterhead_2$.

Step 4. After performing the inter-cluster link, the second intra-cluster link has to be established. Then, the AECS verifies again the type of service related to the link. Step 5.a. If the transmission is related to a real-time service, the second intra-cluster link is established between $clusterhead_2$ and the destination node, regardless of the distance between them (case a, $cluster_2$). Step 5.b. If t -real-time service, the AECS verifies the distance between $clusterhead_2$ and the destination node. Step 5.b.1. If the distance between the nodes is long, $clusterhead_2$ refuses to perform the intra-cluster link (case b, $cluster_2$). In this case, $clusterhead_2$ holds the data inside its buffer and waits before attempting another intra-cluster link.

The intra-cluster link is rejected until both satellites - *clusterhead*$_2$ and the destination node - are closer to each other. Step 5.b.2. If the distance between nodes is short, an intra-cluster link is carried out between *clusterhead*$_2$ and the destination node (case c, *cluster*$_2$). Then, the data transmission is finally executed. The flow chart of the *scenario*$_2$ process is illustrated in fig.3.5.

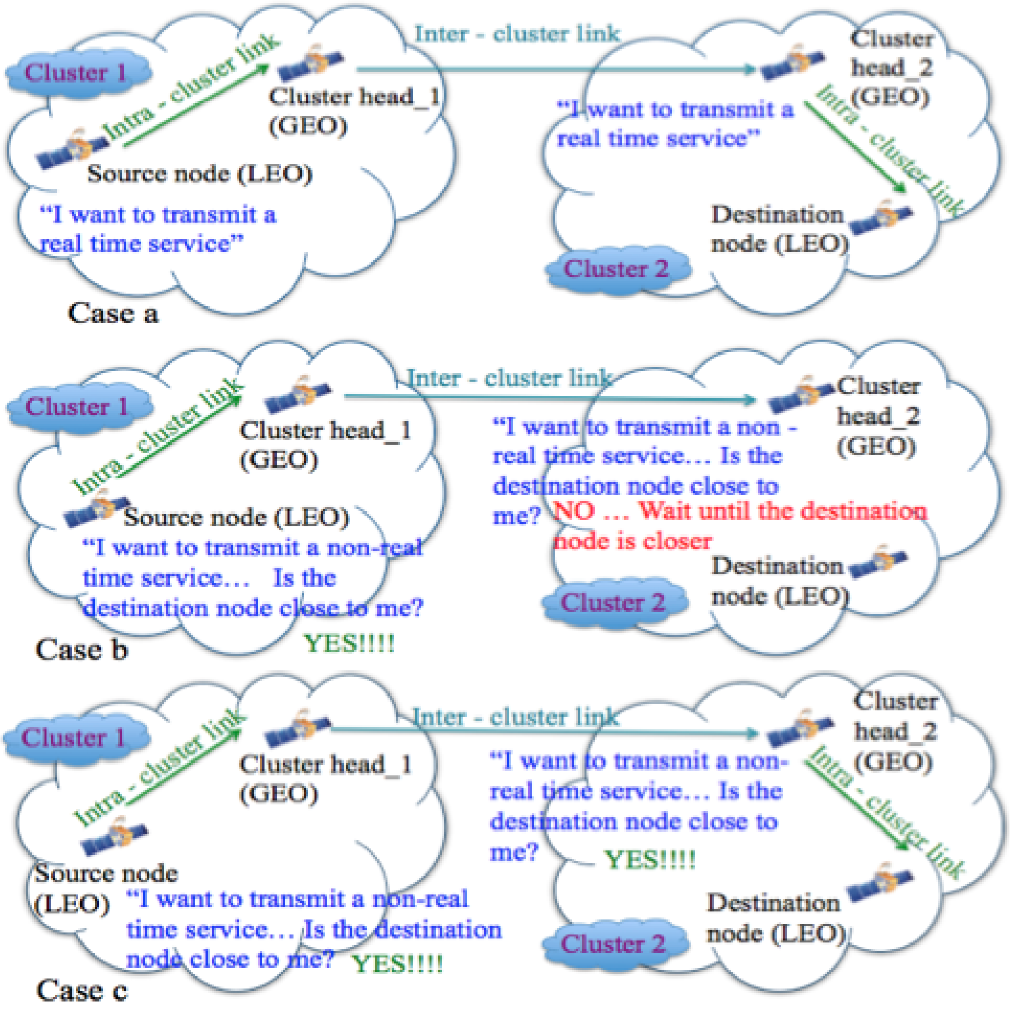


Figure 3.4: AECS performance for scenario 2. Case a: Real-time service. Case b: Non-real-time service over long distance between the source and the destination node. Case c: Non-real-time service over short distance between the source and the destination node.

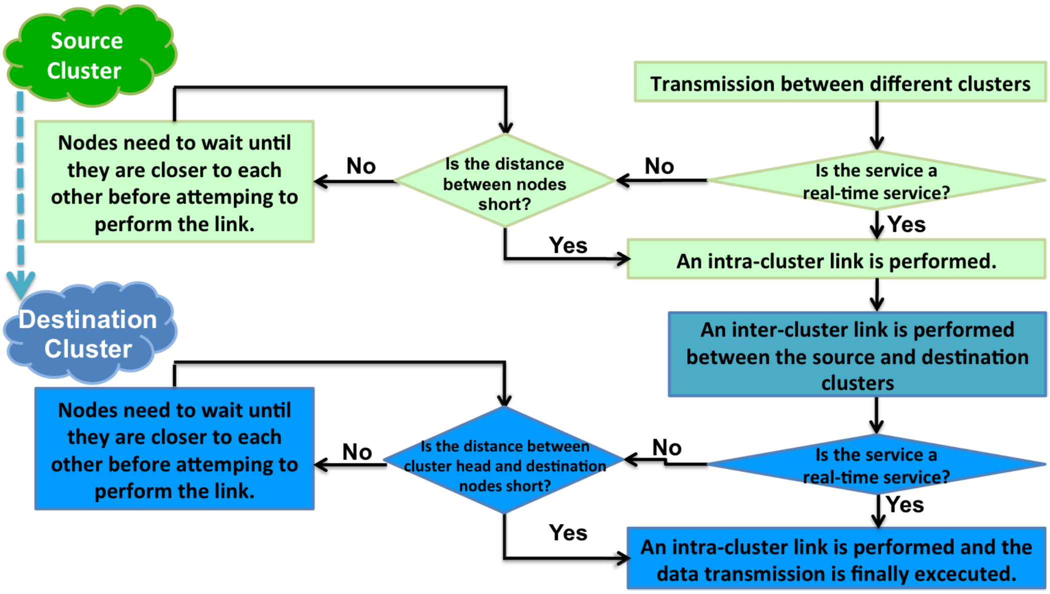


Figure 3.5: AECS between two clusters.

3.3 System Analysis

The transmission power efficiency, and the sensitivity of the receiver, represent the main criteria for choosing an appropriate transmission medium (13). Free space optic (FSO) links successfully cover large distances between mobile nodes. In comparison with space medium, FSO transmissions dissipate less power thanks to the use of narrower beams.

On the other hand, narrow beams face issues such as pointing error angles, and the acquisition of good tracking functions. Another way to decrease *BER* is by increasing the transmission link intensity. This solution demands more energy resources, which is contradictory to the purpose of reducing energy consumption. Since FSO communications help to reduce *BER* and to save energy resources at the same time, in our proposal, satellites link to each other through OISL. Therefore, to analyze the intra-cluster and inter-cluster link availability, it is necessary to consider several medium parameters. For instance, mechanical vibration effects, background noise, pointing error angles, and power dissipation along the link tracking path. If previous parameters have high values, the received power in the system is seriously affected. As a result, *BER* dramatically increases. We divide the system analysis into two sections: a transmission cost section, which refers to energy consumption measurements, and a link availability section, which is an evaluation of the link margin, *BER* and transmission delay.

3.3.1 Transmission cost

In communication systems, transmission cost refers to the amount of energy required to transmit a message between two nodes of the network. It can be expressed by eqs. 5.1 and 5.2 (14).

$$E_{tx} = E_{elec}K + E_{amp}Kd^{\xi} \tag{3.1}$$

$$E_{rx} = E_{elec}K \tag{3.2}$$

In the above, E_{elec} is the dissipated energy by the transceiver t_x and the receiver r_x. E_{amp} is the dissipation energy at the transmission amplifier, K is the length of the messages in bits, d means the distance between t_x and r_x, and ξ is the path loss exponent.

Analyzing previous equations, the transmission cost is directly proportional to the link distance. As a result, the transmission cost for performing intra-cluster links, is always smaller than the energy necessary for transmitting data over inter-cluster links. Following the same analogy, the system requires more energy to transmit large messages than to transmit small ones. The AECS scheme saves energy resources based on the idea of allowing long distance transmissions only when necessary. The AECS scheme allows long distance transmissions if they are related to real-time services; although it refuses long distance transmissions if they involve non-real-time services. The reason is that the AECS scheme assumes non-real-time services must be transmitted when the transceiver and receiver involved are close to each other. Based on this principle, the AECS scheme efficiently manages the system energy.

3.3.2 Link availability

The link availability depends on the power link budget for local conditions. Availability A means the probability that a system has good performance (15). The power link budget should be divided into three segments: transmitter, channel and receiver. The link budget inside the transmitter segment consists of the sum of the laser power, modulation losses, transmitter antenna gain and optical losses. This calculation is made in both a constructive and a destructive way. Inside the channel segment, the link budget includes space loss, absorption, scattering and pointing losses. Finally, the receiver segment involves the receiver antenna gain, optical losses, and receiver sensitivity (16). Eqs. 5.3 and 5.4 describe the relations between Optical Output Power P_{TX}, System Power Factor P_{SYS} and Received Power P_{RX}.

$$P_{SYS} = P_{TX} + G_{TX} + A_{RX} - \Sigma(L_{TX} + L_{RX}) \tag{3.3}$$

$$P_{RX} = P_{SYS} - D_L = P_{SYS} - 20log\frac{2g}{1m} \tag{3.4}$$

$$G_{TX} = 10log\frac{4\pi}{2\pi(1 - cos(0.5\alpha))} \tag{3.5}$$

$$A_{RX} = 20log(RA) \tag{3.6}$$

In the above, G_{TX} is the geometrical transmitted gain at specific full beam divergence angles α, while A_{RX} represents the geometrical received gain at different optic aperture radii RA. L_{TX} means the optic losses in the transmitter, and L_{RX} indicates the respective losses in the receiver. D_L is the decibel value of the geometrical distance g between satellites in meters. Based on previous expressions, we are able to get the specific link margin M_{SPEC} and the power received limit P_{RS} by eqs. 3.7, 3.8 and 3.9 (17).

$$M_{SPEC} = \frac{1000}{g}(P_{RX} - P_{RS}) \tag{3.7}$$

$$P_{RS} = K_B(T_{tx} + T_{rx})B(S/N_o) \tag{3.8}$$

$$\alpha_{scat,spec} = 10log\frac{1/\gamma}{V} \tag{3.9}$$

$$V = \frac{ln(\frac{1}{\gamma})}{\lambda} \tag{3.10}$$

In the above, g is the geometrical distance between satellites, K_B is the Boltzmann constant, T_{tx} and T_{rx} are the equivalent noise temperature in the transmitter and the receiver, B is the bandwidth, and S/N_o is the required signal to noise radio at the output. In eq. 3.9, $\alpha_{scat,spec}$ means the specific scattering attenuation, γ represents the transmission threshold, and V is the atmospheric path distance for a specific transmission threshold. V is mathematically described in eq. 3.10. The link availability is determined by the attenuation $\alpha_{scat,spec}$ for a specific transmission threshold γ. If M_{SPEC} is bigger than $\alpha_{scat,spec}$, the availability is equal to 1. For any other value, there is no link availability at all. Observing previous mathematical relations, the transmission threshold γ is an important parameter for establishing the existence and quality of the link. In our calculations, we set γ at 2%.

Since FSO links are susceptible to transmission conditions, BER is a useful parameter for qualifying the system performance. If too much or not enough optical power is received, BER tends to increase. Therefore, it is necessary to establish a power threshold to ensure good quality transmissions. This power threshold, which is defined by eq. 3.8, is also known as the received power limit P_{RS}. During data transmissions, our proposal requires both satellites to be aligned to each other all the time. However, due to constant movements, and the existence of interstellar objects, there are vibrations that affect the direct visibility between satellites. An approximation of how those effects modify the BER is considered in eq. 3.11. In eq.3.11, θ is considered as the radial pointing angle, and σ_o is the tracking standard deviation signal (9).

$$BER = 1/2 \int_0^{\infty} 1 - erf[Q(\theta)]exp(-\theta^2/2\sigma_o^2)d\theta \tag{3.11}$$

To analyze the system transmission delay, it is necessary to consider several factors, such as packet transmission time, round trip propagation delay R_{TT}, main delay from satellite W, and retransmission delay. We also must differentiate between packets traversing intra-domain or inter-domain environments. Eq. 3.12 describes the delay for intra-domain traffic, whereas eq. 3.13 refers to the delay for inter-domain traffic (7).

$$D_{intracluster} = 1 + R_1 + W_{11}^1 + E_1(1 + A_1 + \frac{1}{2}(K_r - 1)) \tag{3.12}$$

$$\begin{aligned} D_{intercluster} = 3 + R_1 + W_{11}^1 + E_1(1 + A_1 + \frac{1}{2}(K_r - 1)) + \frac{1}{2}R_2 + W_{12}^2 + \\ J + \frac{3}{2}R_3 + W_{12}^3 + W_{22}^3 + 2E_3(1 + A_3 + \frac{1}{2}(K_r - 1)) \end{aligned} \tag{3.13}$$

$$W_{ij}^n = \frac{Q_{ij}^n}{S_{ij}} \tag{3.14}$$

In previous equations, R_1, R_2 and R_3 mean the round trip propagation delay for $satellite_1$, $satellite_2$, and $satellite_3$, respectively. K_r is the retransmission range, J means the inter-satellite propagation delay, A_1 and A_3 are the acknowledgement delays from $satellite_1$ and $satellite_3$, respectively. Finally, E_1 and E_3 represent the main number of retransmissions for $satellite_1$ and $satellite_3$, respectively. W_{ij}^n in eq. 3.14 refers to the main delay from $satellite_n$, with traffic from i source domain to j destination domain.

3.4 Performance Evaluation

The system consists of three clusters forming a satellite cluster network. All clusters have the same number of satellites. The satellites share real-time and non-real-time tasks. The AECS scheme follows different processes to transmit real-time and non-real-time services. Even though real-time and non-real-time requests are treated differently, both services have similar occurrence probability. In our system, there is another occurrence probability to take into account. It is the probability of performing short distance links or long distance links. The occurrence probability means the statistical distribution of different events. Then, combining the distribution of short/long distance links, with the distribution of real/non-real-time requests, our system involves four different events. AECS events follow a binomial distribution.

In statistics, the binomial distribution is a discrete distribution that counts the number of successes in a sequence of n independent trials. The occurrence is a fixed occurrence probability of success across the trials. The occurrence probability between events is independent for each event (18). The reason AECS events follow a binomial distribution is that our proposal events are also independent of each other. To explain this point better, let us assume there is a real-time request in our system. Any real-time request may be established at a short distance or at a long distance because it is not a fact that this request must be transmitted at a specific

Table 3.1: Binomial Distribution for type of services.

Event	Concurrence Probability
Real-time service at short distance	0.025
Real-time service at long distance	0.375
Non-real-time service at short distance	0.0375
Non-real-time service at long distance	0.5625

distance. Thus, a real-time request occurrence is independent of the distance link occurrence. Non-real-time requests follow the same reasoning. Another reason for using binomial distribution is that binomial distribution results are cataloged into just two types of result. As regards AECS events, our system events also have two types of result. If there is a real-time or non-real-time service transmission, there are only two types of link to be performed: short distance links or long distance links. By analyzing a random sequence of events based on binomial distribution equation, the concurrency probability for real-time requests and non-real-time requests is 40% and 60%, respectively, whereas the concurrence probability for short and long distance links is 6.25% and 93.75%, respectively. The final occurrence probability per event is separately calculated and included in Table. 3.1. The evaluation scenario consists of a cluster network with three clusters. Each cluster contains four satellites (one cluster head and three normal nodes). We assume intra-cluster links can be performed at short and long distance between nodes. Based on the AECS scheme, the cluster network refuses to perform long distance intra-cluster links if they are related to non-real-time services. In contrast, inter-cluster links are always performed, although they are related to non-real-time services.

3.4.1 Transmission cost

We calculate the transmission cost for intra-cluster and inter-cluster links by using eqs.5.1 and 5.2. The length of data is set at K=200 bits. The results are depicted in fig. 3.6. From the previous figure, it can be observed that under the same scenario conditions, the AECS scheme uses less energy than the cluster scheme or the free access scheme. The free access scheme is defined as a scheme that is used by a network that does not form clusters at all. Therefore, by using the free access scheme, all nodes in the network freely try to approach any other node, because there is no cluster head selection. The free access scheme follows a mesh logical topology, without paying attention to the type of service or the distance between nodes.

Regarding the cluster scheme, this scheme represents the conventional communication between nodes that form part of a cluster network. The conventional cluster scheme (6), (8) follows a star logical topology by using cluster heads as connection points between nodes and clusters, exactly as the AECS scheme does. However, even though the conventional cluster scheme and the AECS scheme have similarities, they also have several variations in their processes. For instance, the conventional cluster scheme does not reject any transmission. The conventional cluster scheme does not pay attention to the type of service to be run. The conventional cluster scheme does not pay attention to the distance links. Thus, a transmission that uses the conventional cluster scheme goes from the source node and directly passes through the cluster head towards the destination node, without risk of being rejected.

On the other hand, the AECS scheme rejects non-real-time service requests if they are attempted via long distance links. The reason is that non-real-time requests are not urgent and they can be performed at shorter distances later. Therefore, in terms of saving energy, the AECS scheme is more efficient than other schemes because it places restrictions on intra-cluster links attempts at long distance.

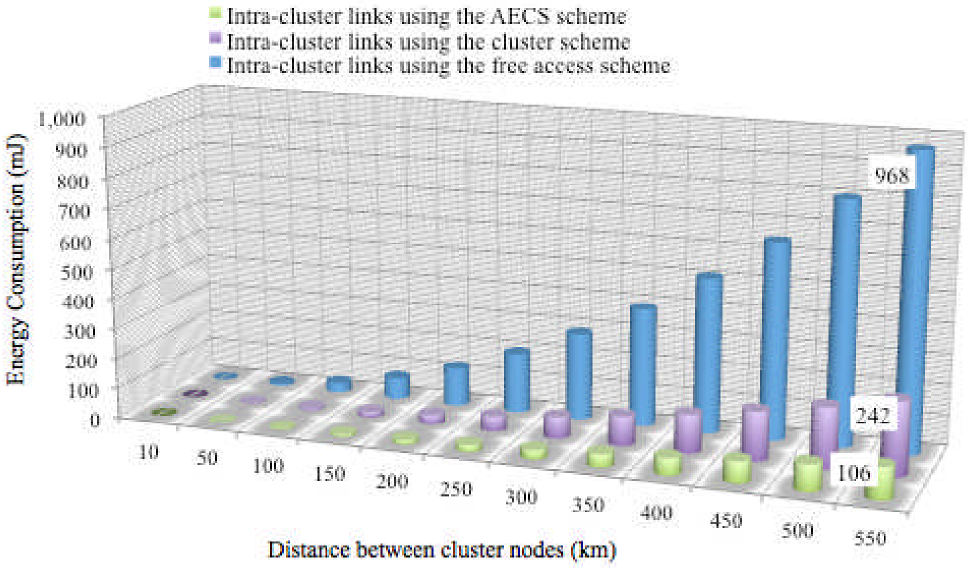


Figure 3.6: Energy consumption using different access schemes.

Observing fig. 3.6, in transmissions where the distance between nodes is around 550 km, the energy consumption of the AECS scheme is 136 mJ smaller than the energy consumption of the conventional cluster scheme, and 862 mJ smaller than the energy consumption of the free access scheme. Thus, the transmission cost of AECS scheme represents 43.8% of the transmission cost of the conventional cluster scheme, and 10.95% of the transmission cost of the free access scheme. Let us assume a GEO satellite is in the scenario described in fig. 3.6. This GEO satellite is one of the cluster heads in the network, and its satellite lifetime is approximately eight years. If the cluster network employs the conventional cluster scheme, the GEO satellite lifetime remains at eight years because this scheme disregards satellite energy consumption. However, if the cluster network uses the AECS scheme, the satellite saves 56.2% of energy in comparison with the conventional cluster scheme. Translating energy savings into satellite lifetime, the GEO satellite that employs the AECS scheme has a satellite lifetime of approximately 12.5 years. The advantages of using the AECS scheme are remarkable.

To estimate the transmission costs of different sized clusters, we change the number of nodes per cluster. For this second evaluation, we only compare the AECS scheme performance with the conventional cluster scheme performance. In figs. 3.7 and 3.8, we reproduce the evaluation with seven and ten nodes per cluster, respectively. In the scenario with seven nodes per cluster (fig. 3.7); the system saves 43.74% of its energy if it uses the AECS scheme instead of using the conventional cluster scheme. As a result the satellite lifetime is increased from eight years to 11.5 years. A similar behavior occurs in clusters with ten nodes (fig. 3.8), where the system saves 45.9% of its energy by using the AECS scheme. In this case, the satellite lifetime is increased from eight years to 11.6 years.

Based on the results depicted in figs. 3.6, 3.7, and 3.8 it can be observed that the energy consumption is directly proportional to the number of nodes per cluster. The cluster network uses more energy if the number of nodes per cluster increases. In this context, there is a remarkable fact to be mentioned. The energy consumption of a cluster with ten nodes using the AECS scheme (fig. 3.8) is still less than the energy consumption of a cluster with seven nodes using the traditional cluster scheme (fig. 3.7) even though the former has more nodes. In other words, by using the AECS scheme, the system might increase the number of nodes per cluster and still use less energy than other scenarios employing other schemes with fewer nodes.

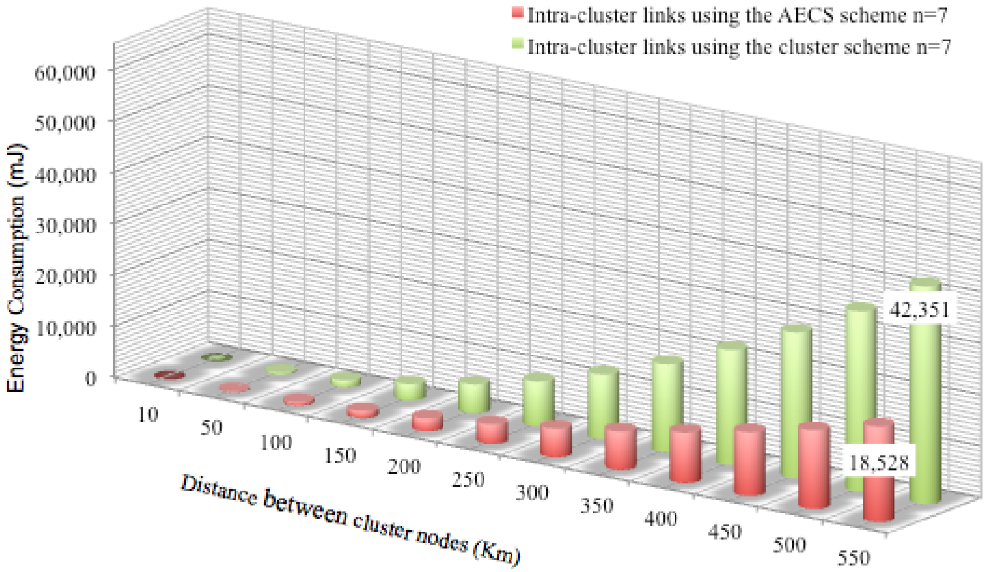


Figure 3.7: Energy consumption of clusters with seven nodes.

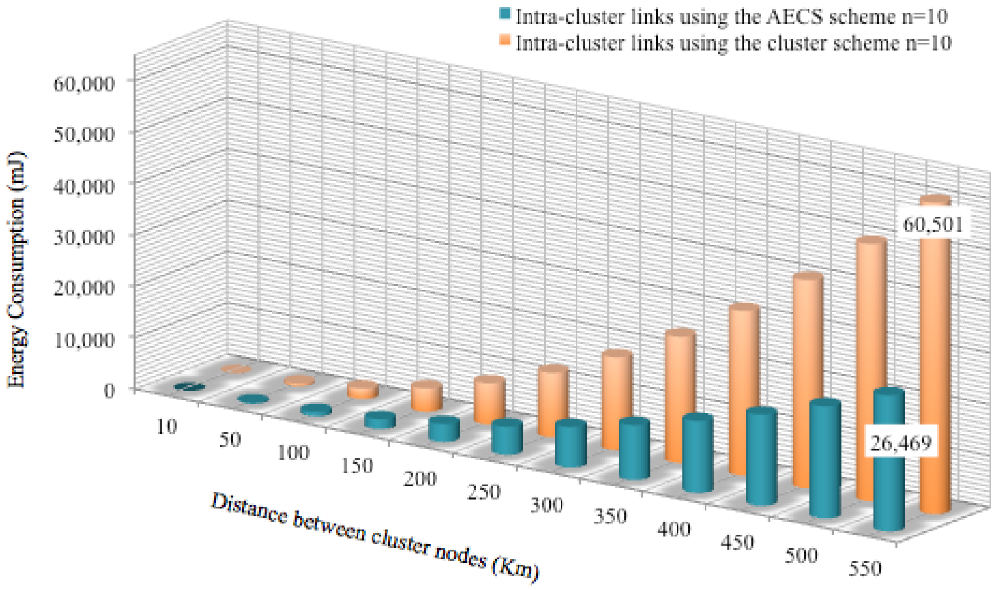


Figure 3.8: Energy consumption of clusters with ten nodes.

3.4.2 Link availability

To proceed with the link margin analysis, it is important to remember that the higher link margin we get, the better quality signal we receive. For long distance links, the beam width increases as a result of increasing the length of the link. As a consequence, the received power level decreases due to diffusion effects. Therefore, for lower received power levels, we get a lower link margin. Using eqs.5.3 and 5.4, we are able to compare the power in the transmitter section with the power in the receiver section for several distances between cluster nodes. By employing eq.3.7, the specific link margin is calculated. The results are depicted in fig. 3.9, where four transmission thresholds are established based on the percentage of availability of the link. For the analytical evaluation, several parameters are involved but only the most representative are shown in Tables. 3.2 and 3.3 (19), (20).

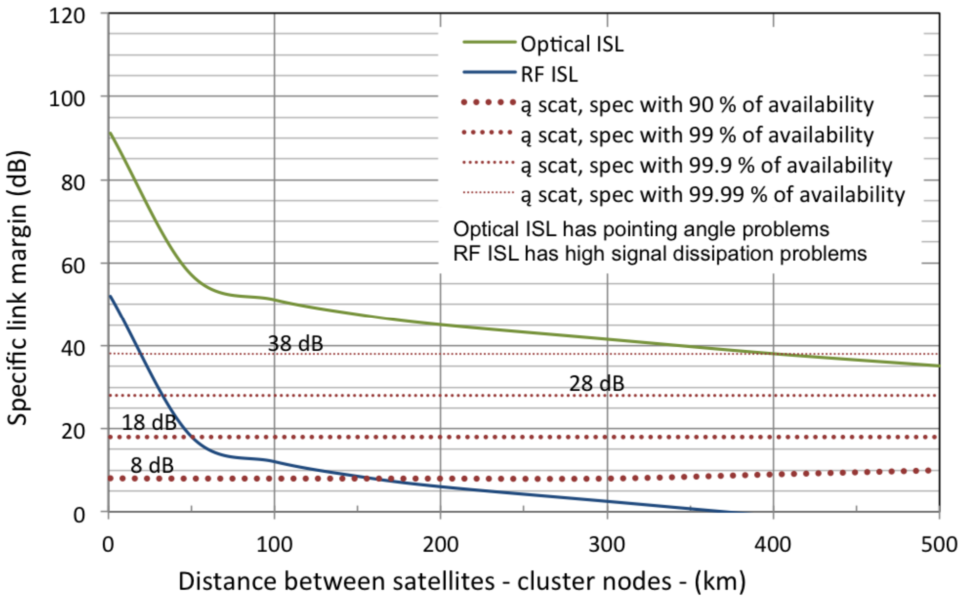


Figure 3.9: Link Margin of Optical and RF inter-satellite links.

Due to the distance, the link margin for intra-cluster links is greater than the link margin for inter-cluster links. On the other hand, at any distance, the link margin for optical links shows better performance than the link margin for RF links. In fact, for distances over 300 km, RF links are no longer 90% available. Therefore, in order to performed intra-cluster and inter-cluster links, there are more advantages to using optical links than using RF links.

Table 3.2: Parameters for Calculating FSO Link Budget.

Parameter	Symbol	Value (units)
Frequency	f	375 (THz)
Positioning Losses	$L_{positioning}$	1 (dB)
Optical losses tx	$L_{opt.tx.}$	6 (dB)
Space Losses	$L_{e.l.}$	208.52 (dB)
Modulation Losses	$L_{mod.}$	3.25 (dB)
Beam waist	W_o	1.5×10^{-6}(m)
Decibel Value of geometrical dist.	D_L	1.53×10^{2}(dBm)
Receiver Antenna Gain	G_{Rx}	115 (dBi)
Optical Losses in rx.	$L_{opt.rx.}$	6 (dB)
Spatial Tracking Losses	$L_{sp.Track.}$	1 (dB)
Noise Temperature Tx	T_{tx}	290 (K)
Noise Temperature Rx	T_{rx}	500 (K)
Antenna Diameter	D	0.2 (m)
Receiver Power Limit OFDM	PRS	100 (dBm)

Table 3.3: Parameters for Calculating RF Link Budget.

Parameter	Symbol	Value (units)
Transmitted Power	P_{TX}	17 (dBW)
Frequency	f	12 (GHz)
Transmitter Antenna Gain	G_{TX}	51 (dBi)
Receiver Antenna Gain	G_{RX}	51 (dBi)
Feeder Loss	L_{feeder}	3 (dB)
Effective Isotropically Radiated Power	$EIRP$	69.1 (dBW)
Pointing Loss	$L_{pointing}$	0.3 (dB)
Path Loss	L_{path}	215 (dB)
Spatial Tracking Losses	$L_{Sp.Track.}$	1 (dB)
System Noise	N_SYST	29.6 (dBK)
Noise Temperature Tx	T_{tx}	290 (K)
Noise Temperature Rx	T_{rx}	500 (K)
Antenna Diameter	D	3 (m)
Receiver Power Limit OFDM	PRS	100 (dBm)

Table 3.4: Parameters for Calculating the BER.

Parameter	Symbol	Value [units]
Modulation index for OFDM	m	0.785
Maximum Antenna Gain	G_{max}	47.724 (dB)
Transmitter Optical Power	P_T	13.010 (dB)
Effective Isotropic Radiated Power	$EIRP$	60.734 (dB)
Free Loss	L	208.529 (dB)
Band Width	B	3.6×10^7(Hz)
Signal to Noise Radio OFDM	S/N_o	4.33 (dB)
Tracking stand. deviation signal OFDM	σ_Θ	1.3×10^{-1}
Transmitter, Receiver Gain	G_T, G_R	3.60 (dB)
Transmitter, Receiver optics efficiency	η_T, η_R	0.8
Optical frequency	υ	3.75×10^{14}
Electronic Band Width	B_e	2×10^{-9}(Hz)
Optical Background Power	P_B	1×10^{-9}(w)

For optical inter-cluster links up to 350 km distance, the link margin is always higher than any of the transmission thresholds, ensuring 99.99% availability. For longer distances, the link availability is 99.9%. For that reason, we assume optical links are always available.

Regarding bit error rate analysis, BER is calculated by eq. 3.11. It is shown as a function of the radial pointing angle between the source and destination satellites. Radial pointing angles might have values from 10 to 90°. Table. 3.4 lists some of the parameters used to get the BER data. For the calculations, different modulation schemes can be used. This proposal employs OFDM just as a suggestion. OFDM is a modulation scheme that uses parallel narrow-band subcarriers instead of a single wide-band carrier to transport information. OFDM offers the advantage of being robust against narrow-band interference. The disadvantages of using OFDM is that it reduces the power efficiency of the RF amplifier at the transmitter. However, since the present proposed system employs optical transmitters, this disadvantage is considered to have a low impact. Fig. 3.10 shows that our proposal promises reliable communication links up to 65°. For pointing angles from 65 to 90°, the BER is greater than 10^{-5} which is not very good because some communication systems require BER is lower than 10^{-5}.

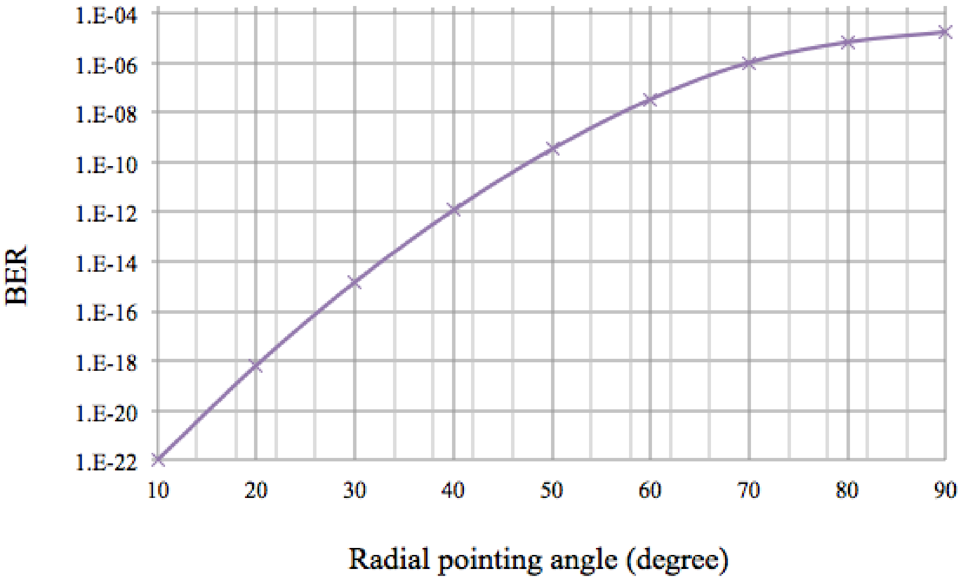


Figure 3.10: BER based on radial pointing angle.

It is well known that the transmission delay is directly proportional to the distance links. Therefore, the greater the distance between the nodes involved in a transmission, the longer the transmission delay. In addition, this proposal considers that main transmission delay is also affected by temporarily rejecting intra-cluster links between satellites. The link rejection is justified because the main objective is to reduce the system energy consumption. However, this fact causes delay effects that must be measured. Therefore, to completely evaluate the AECS scheme effectiveness, we compare the AECS main transmission delay with the main transmission delay related to the cluster scheme. The main delay represents the delay when the traffic originates from one satellite but the destination of this traffic is another satellite. To calculate the main delay from $satellite_n$ (W^n_{ij}) eq.3.14 is employed.

In eqs. 3.12 and 3.13, W^1_{11} refers to the main delay from $satellite_1$, whose traffic originates from and goes to the same cluster, in this case $cluster_1$. W^2_{12} is the main delay from $satellite_2$, whose traffic goes from $cluster_1$ to $cluster_2$. W^3_{12} is the main delay from $satellite_3$, whose traffic goes from $cluster_1$ to $cluster_2$. Finally, W^3_{22} represents the main delay from $satellite_3$, whose traffic originates from and goes to $cluster_2$. The analytical evaluation considers the packet size to 200 bits. The results are inset in figs. 3.11 and 3.12 for $scenario_1$ and $scenario_2$, respectively.

It is assumed that for an intra-cluster domain, the complete path distance may change from 40,000 km to 80,000 km. For an inter-cluster domain, the complete path distance goes from 80,000 km to 160,000 km. Those distances consider the transmission path length to/from ground stations on earth, and the corresponding intra/inter-cluster link distances. In the present evaluation, the uplink and downlink involve one ground station and one satellite placed in LEO orbit. In this system, the LEO orbit altitude is 800 km. For the main delay calculations, an important reference delay is the round trip delay to/from a GEO satellite. This is considered to be 240 ms if the total path distance is 72,000 km.

For *scenario*$_1$ (fig. 3.11) the cluster scheme main delay is 150 ms for the shortest distance, whereas the AECS main delay is 280 ms. Observing the longest distance case, the main delay is 280 ms and 650 ms for the cluster scheme and the AECS scheme, respectively. In conclusion, for intra-cluster domains, the AECS main delay is approximately twice the cluster scheme main delay.

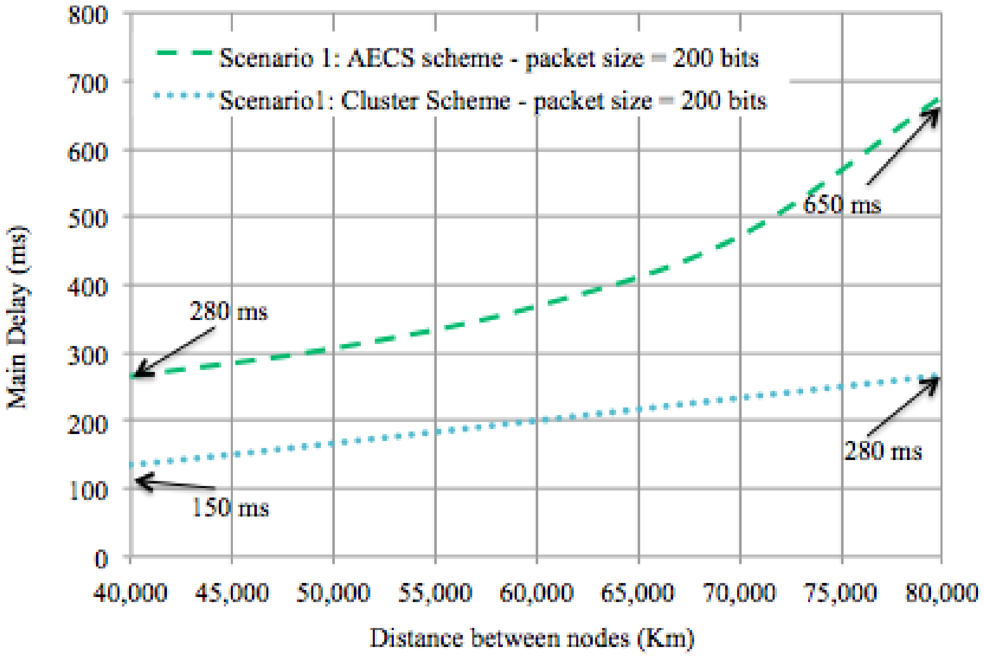


Figure 3.11: Main transmission delay for intra-cluster domain.

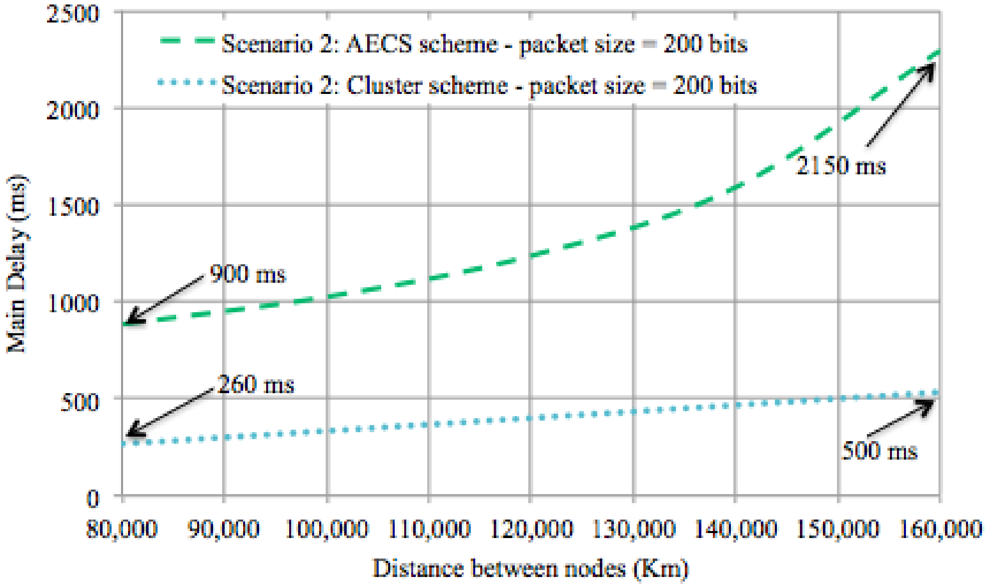


Figure 3.12: Main transmission delay for inter-cluster domain.

For *scenario*$_2$ (fig. 3.12) the difference between the two schemes is even more contrasting. For an 80,000 km distance, the AECS main delay is almost four times longer than the cluster scheme main delay. Considering the longest distance, the AECS main delay is slightly longer than four times the cluster scheme main delay. Even thought in almost all cases the AECS main delay is longer than the reference delay (240 ms), the AECS main delay results are realistic. The reason is that the AECS scheme considers the connection point between several cluster nodes to complete the transmission link. Therefore, the total transmission path length is increased and the transmission delay increases as well. In addition, the AECS delay also involves the holding time that an intra-cluster link must wait before attempting a re-transmission. The results show that the AECS main delay increases faster than the cluster scheme main delay does. Thus, the cluster scheme offers better main delay performance than the AECS scheme. Of course, this fact reduces the AECS scheme′s effectiveness. However, in communication systems, there is no perfect system. Each design establishes its main objectives and faces several tradeoffs. The aim is to reduce as much as possible the inherent effects that impact the system reliability. In this proposal, the system tradeoffs are the main delay and the energy consumption. Using the AECS scheme, the energy consumption compensates the delay increases.

3.5 QoS and Data Storage

Generally speaking, by avoiding unnecessary long distance links, the satellite lifetime increases. However, by rejecting a non-real-time service request at long distance, an inherent consequence appears, namely the reduction of the QoS. Assuming that long distance intra-cluster links will become shorter at a later time, the cluster head may be able to hold the data until it gets closer to the next satellite. How long does the satellite need to wait for a shorter distance between source and destination node? And what happen if there is a buffer overflow inside the holding satellite? Those questions can be solved by analyzing the blocking and holding probability. Fig. 3.13 illustrates the blocking model for the QoS (21). This model operates every time an intra-cluster link rejection is performed. The blocking model shows that for M nodes, there are n intra-cluster link attempts. In the blocking probability model, N is the number of satellite channels with n requests. The link requests can be handled in different ways. If there are no available channels to manage an intra-cluster link request, this request is queued and lined up at the end of Q. Q is the group of queued links waiting for channel resources. If there are no available channel resources, the intra-satellite link can be performed after time t_1, or it can be finally rejected at time t_2. Therefore, eqs. 3.15 and 3.16 are the mathematical expressions for the blocking probability B and holding probability P_h, respectively.

$$B = \frac{\Sigma_{n=N}^{M}(\frac{M}{n})(\frac{\rho_o}{1-\rho_o})^n}{(\frac{1+\rho_o}{1-\rho_o})^M} \tag{3.15}$$

$$P_h = \Sigma_{n=N}^{M-1}(\frac{M-1}{n})\rho_o^n(1-\rho_o)^{M-1-n} \tag{3.16}$$

In previous equations, ρ_o refers to the average source activity, calculated as the product of the average link intended rate and the link duration. M is the number of nodes pretending to establish an intra-cluster link. N is the number of channels available to allocate intra-cluster links. Finally, n refers to the number of attempted intra-cluster links. The blocking and holding probability results for ρ_o set at 0.95 are illustrated in fig. 3.14. This figure shows that the larger the number of nodes inside a cluster, the greater blocking probability the system has. In contrast, the behavior of the holding probability is exactly the opposite. For holding probability cases, the larger the number of nodes, the smaller holding probability the system has.

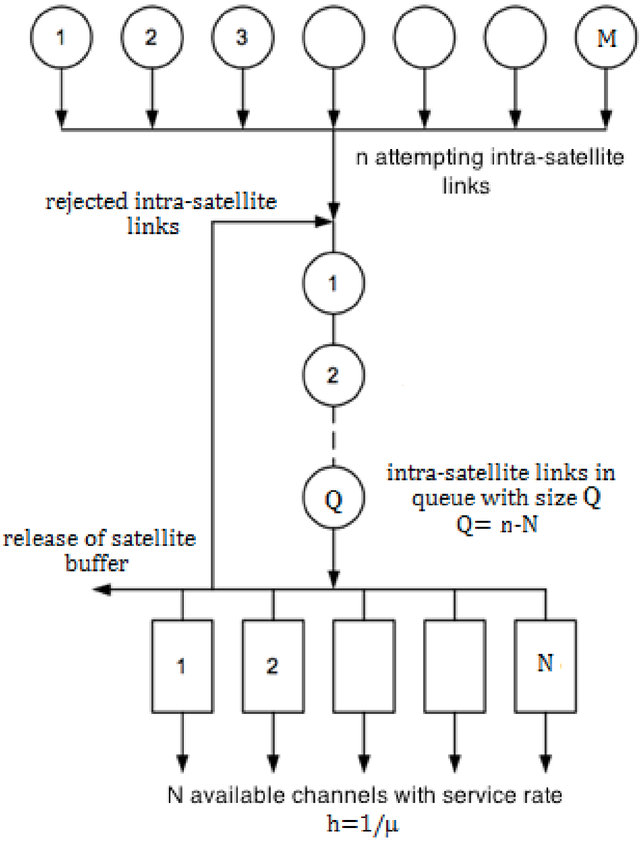


Figure 3.13: Satellite cluster link blocking model.

The last but not the least important observation is that the holding probability declines very fast, whereas, the blocking probability increases a little slower in contrast to the holding probability decrements. However; after increasing the number of nodes up to 16 nodes per cluster, the holding and blocking probabilities tend to have slow decrements and increments, respectively. If the number of nodes per cluster goes from four to 20, the blocking probability is no higher than 16 %, and the holding probability is no smaller than 6 %. The impact of having small holding probability is that links have few chances to be completely performed. This behavior is not very satisfactory because it means intra-cluster links might not never reach their final destination.

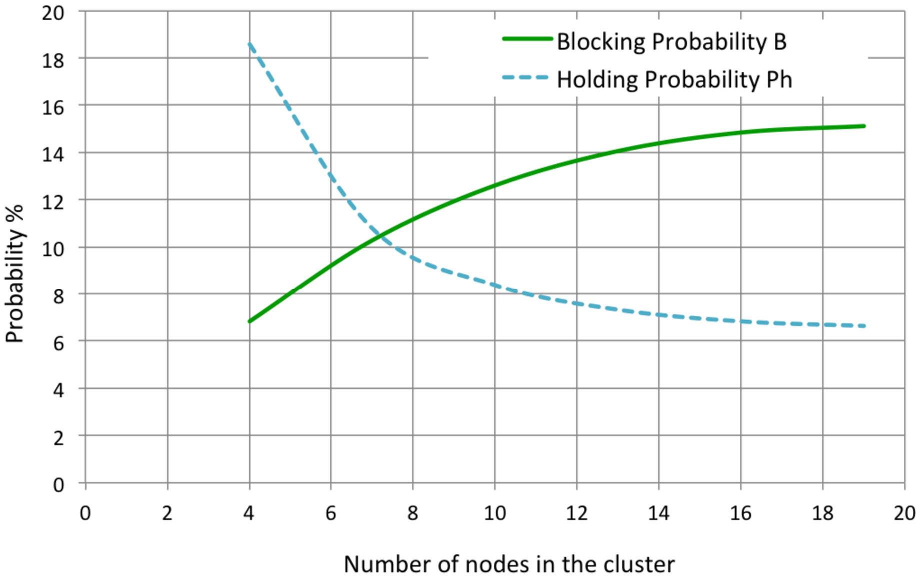


Figure 3.14: Blocking and Holding probability performance.

3.6 Conclusions

Along the present chapter it has been proved that the AECS scheme works efficiently in cluster networks with a variable number of nodes. This conclusion is very important because in real situations, a cluster network with an unfixed number of nodes can easily accomplish dynamic requirements. The AECS scheme has excellent performance in terms of energy consumption. Without doubt, the AECS scheme has better energy consumption than the traditional cluster scheme and the free access scheme. The energy consumption has a direct impact on the satellite lifetime. In this proposal, the satellite lifetime has been increased by at least 4.5 years by using the AECS scheme. The best case is reached when a satellite increases its lifetime by 7.1 years. This means the satellite almost doubles its lifetime. This is another important result because by using AECS, the reduction of energy consumption is also shown to have economic effects. Satellite cluster networks are able to provide services for a longer time, and to reduce operating costs at the same time.

As expected, the transmission delay increases as result of increasing the number of nodes and increasing the distance of intra-cluster links. In the worst case, the AECS main delay is four times longer than the cluster scheme main delay. The main delay performance is considered as the tradeoff to accept for improving the energy consumption.

According to the present network conditions, OISL ensures availability of communication along the links between nodes inside the same or different clusters. However, the link reliability is only guaranteed for radial pointing angles up to 65°. For higher radial pointing angles, the link availability is at risk. Future work can be conducted to improve the reliability of optical links at any radial pointing angle, ensuring better BER values. The blocking and holding probability figures suggest that for clusters with many nodes, both probabilities have few variations. This fact makes the system more reliable for larger cluster sizes. However, the holding probability is still low even for clusters with few nodes. Finally, improvements in the downlink and uplink side by using the AECs scheme should be considered in future work.

Chapter 4

Delay-Tolerant Satellite Networks employing Off-loading Access Scheme and Adaptive Beam Forming

4.1 Introduction

At first, Delay-Tolerant Network (DTN) technology was developed to perform interplanetary missions. Over time it was realized that taking full advantage of this technology, DTN could also offer affordable solutions on Earth. Nowadays, DTN satisfy several applications including deep space explorations, undersea networks, ad-hoc networks, sensor networks, Internet and any other application that involves transmission disruptions. Generally speaking, the DTN is a carry-store-forward technology characterized by getting along with challenged networks. A challenged network is a network whose connections are interrupted along the transmissions due to low, or null, link availability. Thus, the challenged network elements cannot exchange the whole data by a single transmission link, which increase the error rate and the necessary time to complete the network task. Some of the DTN peculiar characteristics are the lack of connectivity and the multiple-copy generation of messages to increase the opportunity of delivering data. The lack of connectivity results in a lack of instantaneous end-to-end paths between network elements causing long deliver timing whereas the multiple-copy generation of messages cause overloading the payload mass which helps to increase the network congestion. Thus a good development of DTN may offer flexible, accurate and feasible solutions for critical infrastructures.

4. DELAY-TOLERANT SATELLITE NETWORKS EMPLOYING OFF-LOADING ACCESS SCHEME AND ADAPTIVE BEAM FORMING

The role of DTN in Low Earth Orbit (LEO) satellite networks might be explained with applicative examples. Considering that the DTN technology works against problems caused by connection-loss events and meanwhile LEO satellite networks might satisfy different missions based on the orbital inclination to reach inaccessible zones, then the Delay-Tolerant LEO satellite network might be a good choice to offer competitive solutions into challenged terrestrial environments to provide, for instance, Internet in urban, sub-urban, rural and remote areas on Earth. This type of Internet might be provided in cooperation with other technologies as well. The remarkable point is that DTN collaborate by managing the challenge of the network environment and LEO satellite networks concur by helping to reach areas with difficult access.

In the literature, several researches have worked towards DTN applications in UMTS (22), HSDPA (23), and LTE (24) providing an insight of the transport and application layers. C. Caini et al. (25) suggest that DTN technology is an alternative solution for future satellite applications, thus the authors analyze how to over come congestion and quality of service constrains. N. Uchida, N. Kalahari, and N. Williams (26) design a disaster information network system based on DTN applications. R.S. Mangrulkar, and M. Atique (27) offer an interesting comparison between different routing protocols based on a DTN insight. C. P. Mayer and O. P. Waldhorst (28) proved the advantages of applying off-loading schemes in DTN inside mobile network environments to mitigate network congestion. Despite the authors did not analyzed energy consumption aspects, they concluded that this analysis represents an interesting point to be investigated in the future.

Regarding beam forming technique aspects, F. Yang, M. Huang, S. Zhang, and W. Zhou (29) study the communication between terrestrial sources and destination terminals via a geosynchronous (GEO) multi-beam satellite in satellite mobile communication (SMC) systems. In their re-laying process, inter-beam interference plays a key role due to frequency re-use between adjacent beams and side-lobe beams. A.I. Zaghloul, Kilic, Ozlem, and E.C. Kohls (30) review early developments of phased arrays for multiple-beam satellite communication applications. They encourage the analysis of the communication link in multi-beam satellite systems, based on three parameters: the intermodulation components that are generated at the non-linear amplifier outputs, the bit error rate (BER) degradation due to the multi-carrier operation, and the co-channel interferences caused by frequency re-use in multiple-beam systems.

The studies and ideas presented above are impressive. However, as it was mentioned before, the energy consumption of delay tolerant networks is not investigated yet. We have analyzed the performance of energy consumption schemes within satellite cluster networks in chapter 3 (31). In contrast, the research presented in this chapter analyzes how to reduce the consumption of energy resources within delay tolerant satellite networks by employing an suitable access scheme. The reason to study energy consumption aspects is because energy resources are vital for the lifetime of all communication systems. For example, considering that it is expensive to implement DTN solutions based on satellite systems, the satellite lifetime is directly related to the cost of the service offered by Delay-Tolerant Satellite Networks. The energy resources are also responsible to provide sufficient power supply to ensure functionality to every module in the system.

The proposal presented in this chapter consists of a novel access scheme for DTN based on Low Earth Orbit Satellites (LEO). The scheme is called off-loading access scheme. The off-loading access scheme is combined with the adaptive beam forming technique with the purpose to improve the signal strength to/from satellites and ground stations. The motivation is to over come problems caused by the lack of energy resources, delay time and low accurate transmissions within Delay-Tolerant LEO Satellite Networks. By implementing the off-loading access scheme, the Delay-Tolerant LEO Satellite Network might reduce the energy consumption to increase the longevity of the system. By implementing the adaptive beam forming technique, the Delay-Tolerant LEO Satellite Network seeks to achieve good accuracy in the transmissions to/from satellites and ground stations.

The off-loading access scheme supports the idea of establishing two types of communication between LEO satellites: the Inter-Satellite Link (ISL) communication and the off-loading communication. The ISL communication is only performed by adjacent satellites, but if the satellites are non-adjacent each other; the off-loading access scheme performs the off-loading communication. The off-loading communication involves the establishment of two links. The first link goes from the source satellite S_s to an specific ground station GS. The second one goes from that specific ground station GS to the destination satellite S_d. As a conclusion, the off-loading access scheme performs the off-loading communication only when the destination satellite is not adjacent to the source satellite. The reason for that is that the distance between two non-adjacent satellites is larger than the distance between two adjacent satellites.

The increments of distance have a negative impact in the delay time, the energy consumption, the visibility between satellites, and the transmission accuracy. Refer fig. 4.1 to illustrate the scenario study. The proposal presented in this chapter employs satellites that are placed on LEO orbits because low altitudes have the inherent advantage of minimizing the main transmission delay (32). In contrast, by employing LEO orbits, the satellite network model must consists of a large number of satellites to ensure wide coverage. The reason for that is that LEO satellites move faster than Earth and they are visible from the same *GS* for short period of time. Since LEO satellites change their position very fast, the proposal introduced in this research does not advice to use optical links due to the radio pointing angle issues involved. Therefore, RF links are used instead.

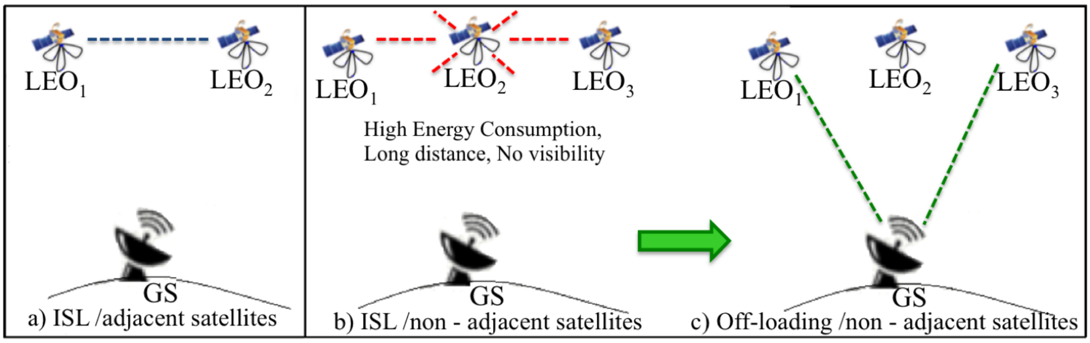


Figure 4.1: Scenario study with the communication problem to over come.

Regarding the adaptive beam forming technique, this technique performs an adaptive spatial signal processing based on the outputs of an antenna array. Therefore, after getting a constructive and a destructive signal, the resulting signal might be intentionally transmitted to a chosen direction to increase the signal strength to/from satellites and ground stations, and to degrade the signal to undesired directions (33). This concept involves practical applications; for instance, to make stronger the signals inside a specific network and at the same time, to reduce interference to other networks. In the present research, the adaptive beam forming technique is applied to fulfill off-loading communication cases. It means fig. 4.1, case c.

The remainder of this chapter is organized in four subchapters. Subchapter 4.2 introduces the proposal system and the scheme description. Subchapter 4.3 refers to the necessary mathematical expressions to evaluate the system performance in terms of energy consumption, delay time, bit error rate, and co-channel interference.

Subchapter 4.4 consists of the analysis and performance evaluation based on hipothetic scenarios. Finally, Subchapter 4.5 concludes the chapter by summarizing the results. Next steps are also included in this subchapter as part of future works.

4.2 Proposal System and Scheme Description

4.2.1 Proposal System

The system proposal consists of a Delay-Tolerant LEO Satellite Network that groups sixteen LEO satellites into two circular orbits - eight satellites each - with an angular distance of 45° to each satellite. $Orbit_1$ and $Orbit_2$ are set at 800 and 750 km altitude, respectively. The intersection between orbits is perpendicular with an orbital inclination of 60°. Fig. 4.2 represents the Delay-Tolerant LEO Satellite Network model. According to the network design presented in this chapter, a hypothetic GS might be inside the footprint of minimum two satellites and maximum three satellites. The satellite visibility window duration is 15 min by considering a minimum elevation angle equal to 10°. The orbital velocity is about 7.45 km/s. Thus, the translation movement takes 100 min approximately.

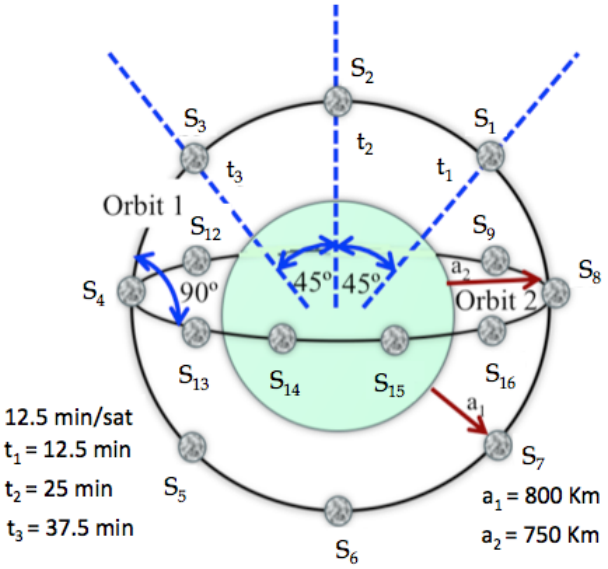


Figure 4.2: Delay-Toleran LEO Satellite Network model.

Observing fig. 4.2, S_1 needs 12.5 min to reach the position of S_2, and 25 min to reach the position of S_3. S_1 needs 50 min to reach the location of S_5 and so on. Satellites S_2, S_3,... , S_{14}, S_{15} and S_{16} follow the same behavior than S_1. The present design is just a reference to describe the satellites' motion inside the Delay-Tolerant LEO Satellite Network. To get the performance evaluation of different system designs, in following sections other settings are considered based on several orbital altitudes and different number of satellites per orbit.

4.2.2 Scheme Description

The off-loading access scheme consists of two types of communication: the Inter-Satellite Link (ISL) communication and the off-loading communication. The decision of performing either of two types of communication is done by the satellite which decides to start a transmission, that is the source satellite, and the decision relies on to accomplish the adjacent condition between satellites. The ISL communication is only performed by adjacent satellites, and consists of a single ISL between the source satellite S_s and the destination satellite S_d. If satellites are not adjacent they perform the off-loading communication instead. The off-loading communication consists of a downlink and an uplink between the source satellite S_s, the destination satellite S_d and the GS. The downlink goes from the source satellite S_s to a specific ground station GS whereas the uplink goes from the ground station GS to the destination satellite S_d.

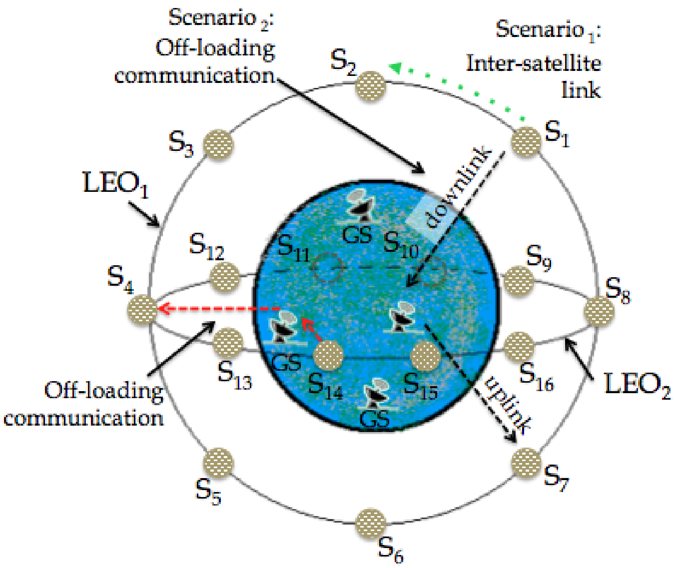
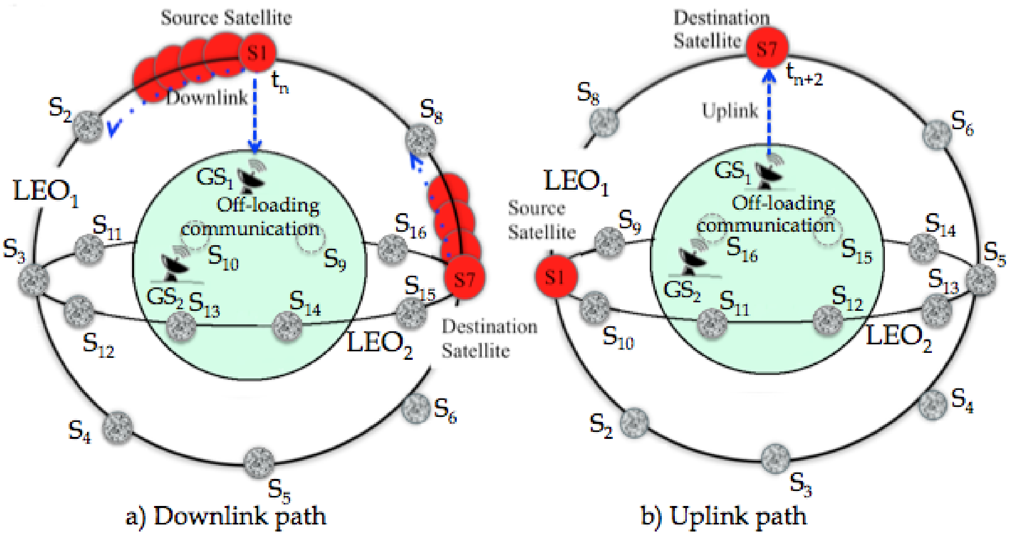


Figure 4.3: Communication scenarios based on the Delay-Tolerant LEO Satellite Network.

Fig. 4.3 illustrates an example of the off-loading access scheme. Based on fig. 4.3 two scenarios are observed: $Scenario_1$, a transmission between two adjacent satellites and $scenario_2$, a transmission between two non-adjacent satellites. $Scenario_1$ refers to a communication established by an inter-satellite link between two adjacent satellites, e.g. S_1 and S_2. Conversely, $scenario_2$ refers to an off-loading communication between non-adjacent satellites, e.g. S_1 and S_7. Those satellites must perform a relaying transmission through a GS. According to $scenario_2$, the whole transmission path is formed by two secondary paths, which are the downlink path from the source satellite, that is S_1, to the GS and an uplink path from the GS to the destination satellite, that is S_7.

It is expected that the off-loading communication helps to reduce the energy consumption because if the distance between satellites is very long, instead of transmitting over a single long distance path, the transmission can be established over two short distance paths. Observing fig. 4.3, if the downlink and uplink distances between S_1 and S_7 are added; and the resulting distance is longer than the direct distance between them, the off-loading access scheme must consider an additional requirement. This requirement implies that the downlink and uplink to/from the GS are only established when the satellites, that is S_1 and S_7, are just above the GS. In this case, the downlink and uplink paths have the shortest possible length. The resulting distance after adding the uplink and downlink path length is twice the orbital altitude.



a) Downlink path b) Uplink path

Figure 4.4: Off-loading communication process.

Fig. 4.4 illustrates $scenario_2$ when a source satellite, e.g. S_1, starts the off-loading communication in direction to a destination satellite, e.g. S_7. The left side of fig. 4.4 (case a) shows that at time t_n, S_1 is just above the GS_1. At this moment the downlink from S_1 to GS_1 takes placed and the GS_1 holds data until S_7 gets closer to him. The right side of fig. 4.4 (case b) illustrates that at t_{n+2}, S_7 is just above GS_1 and the uplink can be established. Thus, t_{n+2} represents the time when the GS_1 transmit the data to the final destination satellite S_7.

By following the off-loading access scheme, the energy consumption is reduced because the transmissions are established over the shortest possible distances. In order to decide when and to where send the data, the satellites that perform the off-loading communication must carefully follow the off-loading access scheme. It is important to mention that all satellites involved in the proposal system follow the same previous behavior and considerations.

To continue with the off-loading access scheme description, it is necessary to introduce an important concept: the holding time. Holding time is the total time that the GS holds a transmission from the source satellite S_s before starting a transmission to the destination satellite S_d. Therefore, the holding time is part of the transmission delay time, and it is an important parameter to evaluate the off-loading access scheme performance. The corresponding holding time expression is introduced in following subchapters. Fig. 4.5 summarizes the off-loading access scheme characteristics.

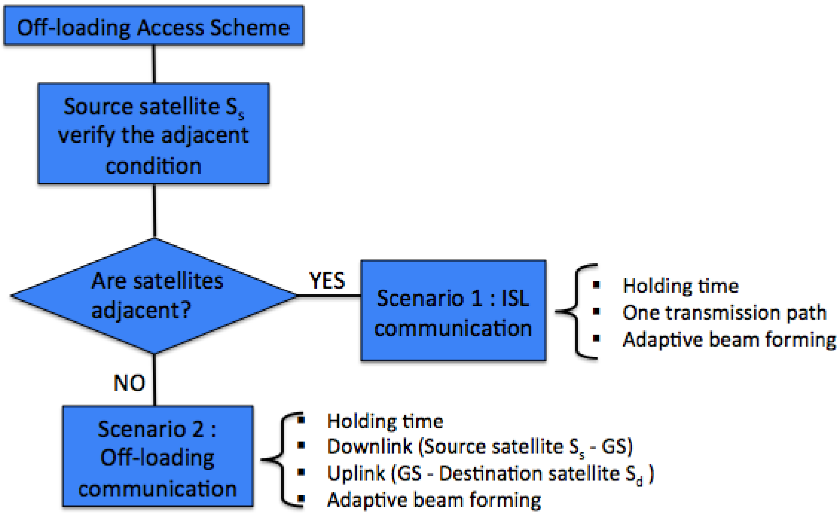


Figure 4.5: Off-loading access scheme diagram summary.

In order to illustrate the off-loading communication by considering two final users on Earth, that are U_1 and U_2, refer to Fig. 4.6. According to our assumptions, U_1 and U_2 are served by satellites placed on different LEO orbits and they need to communicate by performing an off-loading communication. It is important to mention that the reason to use satellites placed on different LEO orbits is because in such cases, satellites placed on LEO_1 may serve a particular region, whereas satellites launched on LEO_2 provide a different coverage footprint on Earth.

As we can see Fig. 4.6 a) shows the $connection_1$ and the $connection_2$. $Connection_1$ is terrestrial transmission between the U_1 (original transmitter) and the Ground Station GS_1 as a first receiver. $Connection_2$ is the uplink between the relaying node GS_1 as the second transmitter, and the satellite S_7 as the second receiver. Fig. 4.6 b) represents the $connection_3$ and the $connection_4$. $Connection_3$ is the downlink between S_7 and GS_2 , whereas $connection_4$ is the uplink between GS_2 and S_{11}. Fig. 4.6 c) illustrates the $connection_5$ and the $connection_6$. $Connections_5$ is the downlink between S_{11} and GS_3 and the $connection_6$ is the terrestrial transmission between GS_3 and the final user U_2. Then, Figs. 4.6 a), b) and c) represent the off-loading communication that is needed to perform between satellites that are not adjacent to each other, but at the same time they need to share transmissions to fulfil a common task between two faraway users on Earth, that are U_1 and U_2.

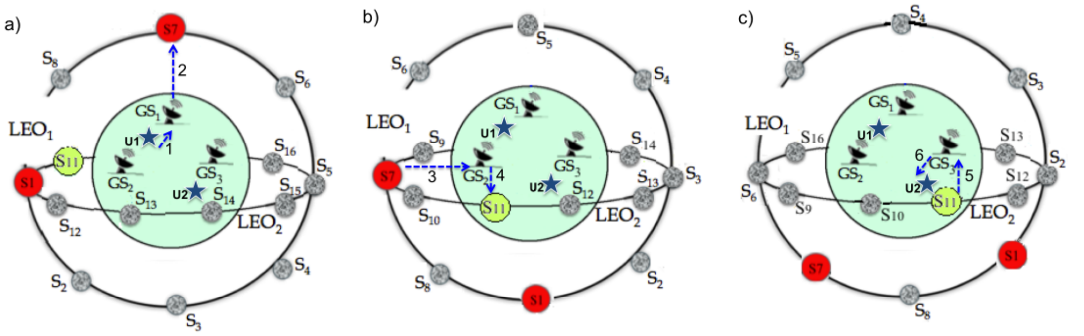


Figure 4.6: Final users on Earth performing the off-loading communication.

To introduce the concept of the adaptive beam forming technique, some of its characteristics are summarized to support its implementation in the present proposal.

- The beam forming technique is based on overlapping waves. Therefore, it is possible to create higher or lower amplitude waves to increment the desired signals and to decrement the interferences.

- The adaptive beam forming technique continually applies beam forming to a moving receiver. Then, this technique is capable to dynamically adapt itself to maximize or minimize a desired parameter(33).
- The adaptive beam forming technique allows to achieve high data rates and to perform illumination over specific areas. Thus, it is possible to improve the transmission towards targeted final users.
- The adaptive beam forming technique is particularly important for the time division duplex mode, which is used by different technologies, such as LTE (34).

Observing fig. 4.4, let us assume satellites S_1 and S_7 establish a transmission by performing an off-loading communication. In order to increase the opportunity to perform a successful downlink from S_1 to GS, our design considers that every satellite has an antenna array formed by four antennas. Those t_x antennas are equally responsible to spread out exactly the same information. Then, there are four primary beams with S_1 as a source. Assuming that there are one primary lobe and several side lobes per each antenna, if the number of antennas in the array increments, the number of primary and side lobes also increases. Therefore, the larger number of antennas in the array, the higher interference in the transmissions due to primary and side lobes. Perhaps, employing the adaptive beam forming technique, the interference might be reduced in decided directions. Therefore, the implementation proposed might offer a good accuracy in the downlink transmissions.

Regarding the uplink side, the GS has the same antenna array configuration. Thus, the GS has also four t_x antennas to transmit the same information to the final destination satellite, that is S_7. To complete the design, the destination satellite S_7 must also have an antenna array formed by four r_x antennas to received the signal from the GS. The antenna array described is equally used by the ISL communication scenario and the off-loading communication scenario.

The beam forming technique has two primary technical requirements. The first one consists of the distance between antennas, which is referred as d_a, must not be too large. The reason for that is that the distance d_a is directly related to the size of the side lobes. Thus, the larger distance d_a, the larger side lobe size. Consequently, the higher interference exists between primary and side lobe beams. The design presented in this chapter assumes that the distance d_a is set at 0.5 m with λ equals 4 cm. The second requirement is that the beam forming technique needs to use correlated channels. Therefore, elements with the same polarization must be used (34). In the present research the suggestion is to use the following polarization between elements: 45°, -45°, 135°, and -135°. Fig. 4.7 illustrates the adaptive beam forming design. It follows an antenna array formed by four antennas.

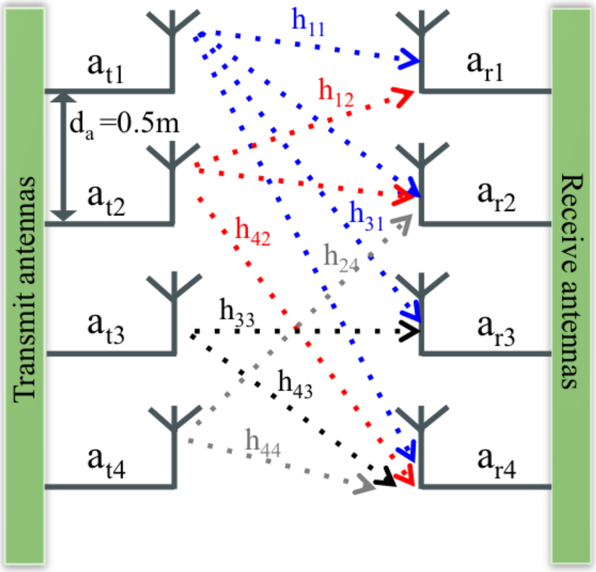


Figure 4.7: Configuration of the adaptive beam forming antenna array with four elements.

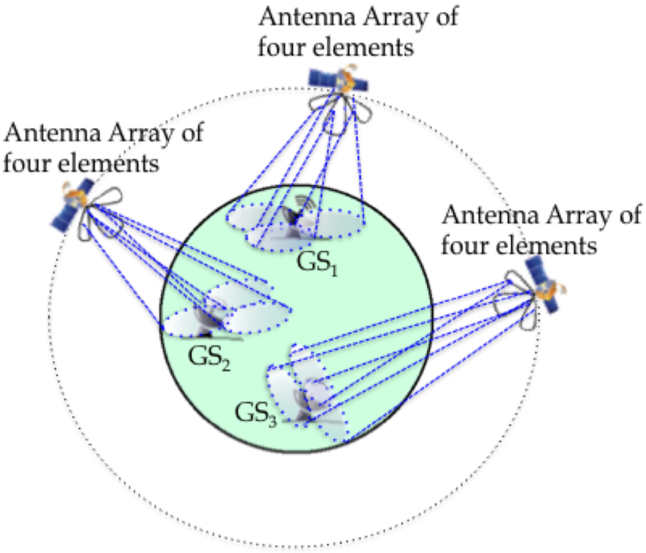


Figure 4.8: Interference scenario within the Delay-Tolerant LEO Satellite Network.

The interference scenario is shown in fig. 4.8. To conclude this subchapter, it is important to emphasize that the proposal presented in this solution considers radio frequency as the transmission interface. The reason for that is that the surrounding speed of LEO satellites is very fast, and the directivity between transmitter and receiver is narrow (32). If optical ISL are implemented, the system needs to deal with pointing angle accuracy issues.

4.3 Scheme Analysis

To evaluate the off-loading access scheme proposed in this research, it is necessary to measure its performance based on four parameters: the energy consumption, the delay time, the bit error rate and the co-channel interference.

4.3.1 Energy Consumption

The energy consumption is defined as the amount of energy necessary to transmit a message between two network elements. It can be expressed by eqs. 4.1 and 4.2 (35), where E_{elec} is the energy dissipated by the transmitter t_x and the receiver r_x, E_{amp} is the dissipation energy at the transmission amplifier, K_{length} is the length of the message in bits, d means the distance between t_x and r_x, and ξ is the path loss exponent.

$$E_{tx} = E_{elec}K_{length} + E_{amp}K_{length}d^{\xi} \tag{4.1}$$

$$E_{rx} = E_{elec}K_{length} \tag{4.2}$$

To calculate the energy consumption, just as a suggestion, K_{length} might equal to LTE and LTE-Advanced packet sizes. The analysis is separately done to the uplink and downlink segments.

4.3.2 Delay Time

Generally speaking, the delay time represents the total time that a system employs to transmit a signal from the source to the destination. The off-loading access scheme described in this research considers that the delay time involves an additional transmission time. It is called as the holding time. The holding time is the time while which the source node holds the data before attempting to transmit the data to the destination node. Regarding the holding time calculation, it involves the Earth rotation velocity, the satellite velocity and the satellite motion respect to the Earth. Thus, the orbital inclination has a relevant impact because it is directly related to the period of the satellite and, as a consequence, on the satellite motion respect to the Earth. In real conditions, those velocities change time to time; however, in the present analysis it is considered that the Earth and the satellite angular velocities are constant because it has been proved that the velocity deviations are very small (36). As a result, the variations of velocity are considered negligible for simplicity. In future sections this parameter is reviewed and included in the corresponding performance analysis. Eqs. 4.3 and 4.4 (21, 37) describe the delay time related to the inter-satellite link communication and the off-loading communication, respectively.

$$D_{ISL} = (h-n)T_{pi} + \Sigma_{i=1}^{n}(T_{px} - n) + (h-1)(T_q + T_r + T_s) + T_h \tag{4.3}$$

$$D_{offload} = T_h + T_{pu} + T_{pd} + 2(T_q + T_r + T_s) + \frac{2r}{V_S \sin^{-1}(\frac{d}{2r})} \tag{4.4}$$

Where h is the total number of inter-satellite links, n is the total number of inter-orbit satellite links, T_{pi} is the inter-satellite link propagation delay over a single intra-orbit, T_{px} is the propagation delay on the n^{th} inter-orbit satellite link, T_q is the delay due to queuing, T_r is the routing delay, T_s the switching delay, T_h is the holding time, T_{pu} is the propagation delay in the uplink, T_{pd} is the propagation delay in the downlink, r is the satellite altitude, V_S is the satellite velocity, and d is the geometrical distance between the source satellite S_s and the destination satellite S_d.

4.3.3 Bit Error Rate

To analyze the bit error rate (BER) figure, by employing the adaptive beam forming design described above in this chapter, it is necessary to consider the Rayleigh multi-path channel distribution in the calculations. The Rayleigh distribution is suitable for environments where there are large number of receivers. Thus, the analysis consists of involving the received power signal from a single path, and the total received power signal in the Rayleigh multi-path distribution. The total received power signal in the Rayleigh fading channel can be expressed by eqs. 4.5 and 4.6 (38, 39). Where Ω_N and V_N are the total power of specular components and the power superposition of specular components, respectively, N represents the number of specular components, a_i is the power amplitude at an specific component i, and Φ is the power phase of the specular component from 0 to 2π rad.

$$\Omega_N = \Sigma_{i=1}^{N}(a_i^2) \tag{4.5}$$

$$V_N = \Sigma_{i=1}^{N}(a_i e^{i\Phi}) \tag{4.6}$$

Therefore, the BER considering a radio frequency interface can be expressed by eq. 4.7 (39) and eq. 4.8 (40, 41). Eq. 4.8 represents the signal to noise radio per bit. It is expressed in terms of the energy per bit E_b, the noise spectral density N_o, the transmitter power P, the line loss L_l, the transmitter antenna gain G_t, the space loss L_s, the transmission path loss L_a, the receiver gain G_r, the Boltzmann constant k, the system noise temperature T_s, and the data rate R. To simplify the mathematical expressions, the parameter δ_b is introduced to represent the signal to noise radio in the equations.

$$BER = \Omega_N\left(\frac{1}{2(\delta_b\Omega_0 + 1)}exp\left(\frac{-\delta_b V_N}{\delta_b\Omega_0 + 1}\right)\right) \tag{4.7}$$

$$\delta_b = \frac{E_b}{N_o} = \frac{PL_lG_tL_sL_aG_r}{kT_SR} \tag{4.8}$$

4.3.4 Co-Channel Interference

To study the Co-channel interference, the analysis is divided in two sections: the downlink and uplink sections. In the downlink section, the transmission goes from the source satellite S_s to the ground station GS. In the uplink section, the transmission goes from the ground station GS to the destination satellite S_d. The signal-to-interference and noise radio ($SINR$) in the downlink $\gamma_{S_s,GS}$ and the uplink γ_{GS,S_d} are represented by eqs. 4.9 and 4.10 (42), respectively.

$$\gamma_{S_s,GS} = \frac{P_{B_{S_s}} L_{S_s,B_{S_s}} \mid h_{S_s,GS} \mid^2}{N_{S_s} + \Sigma_{j=1}^{N} P_{B_j} L_{S_s,B_j} \mid h_{S_s,GS} \mid^2} \tag{4.9}$$

$$\gamma_{GS,S_d} = \frac{P_{S_d} L_{S_{d},B_{S_d}} \mid h_{S_d,GS} \mid^2}{N_{S_d} + \Sigma_{i=1}^{M} P_{T_i} L_{T_i,B_{S_d}} \mid h_{T_i,GS} \mid^2} \tag{4.10}$$

Considering that two satellites, that is the source satellite S_s and the destination satellite S_d, are going to establish a transmission through the GS by using the off-loading communication. B_s and B_d are the main serving beams for the satellites S_s and S_d, respectively. In the scenario involved, there are M satellites in the network, i.e. S_1, S_2, ..., S_M, using the same channel that the satellite S_x uses. There are also N Beams, i.e. B_1 ,B_2 , . . . ,B_N, sharing the same band with the beam B_{S_x}. The satellite S_x might represent the source satellite S_s, or the destination S_d, depending on the section path.

P_{S_d} stands for the transmitted signal strength in the satellite S_d for the uplink. $P_{B_{S_s}}$ stands for the transmitted signal strength in the beam B_{S_s} for the downlink. The path loss between the satellite S_x and the beam B_{S_x} is denoted by $L_{S_x,B_{S_x}}$. The fading coefficient of the channel $S_x - GS$ is represented by $h_{S_x,GS}$. N_{S_x} stands for the noise power in the satellite S_x. T_i represents the co-channel interferences with i={ $1, 2, \ldots, M$ }. The interference that flows from the side lobe beams, and reaches S_s and S_d, is represented by B_j with j={ $1, 2, \ldots, N$}. In the system design proposed in this research, M might have values from 1 to 3. The reason for that is that there are maximum three visible satellites at the same time from the GS.

The first footprint belongs to the satellite that is mainly communicating with the GS. The second and third footprints belong to the two other visible satellites from the GS. The fact that a single GS might be served by maximum three visible satellites was mentioned in previous sections. Based on the design presented in this research, which stands that every satellite has an antenna array of four elements, the parameter N might have values from 1 to 12. Finally, the parameter γ stands for the $SINR$, and it is denoted by eq.4.11 (42).

$$\gamma = min(\gamma_{S_s,GS}, \gamma_{GS,S_d}) \tag{4.11}$$

The free-space path loss $L_{S_x,B_{S_x}}$ is expressed by eq.4.12 (30). Where G_{GS} and G_{S_x} stand for the transmitter and receiver antenna gain, respectively; λ is the carrier wave length, and d(GS,S_x) is the distance between the GS and the satellite S_x.

$$L_{S_x,B_{S_x}} = G_{GS} G_{S_x} \left(\frac{\lambda}{4\pi d(GS, S_x)} \right)^2 \tag{4.12}$$

The co-channel interference is finally defined by eq.4.13 (43) in the downlink section, and by eq.4.17 (43) in the uplink section. The demonstration of previous equations is outside the scope of the research presented in this chapter, but both are demonstrated in the reference (30).

$$\begin{aligned} & F_{\gamma_{S_s,GS}} \gamma_{th} = \\ & \qquad \left\{ \gamma_{th} < \frac{a}{b} : 1 - Q_1 \left(\sqrt{2k_2}, \sqrt{\frac{2(1+k_2)\gamma_{th}}{a - b_{\gamma_{th}}}} \right) \right\} \\ & \qquad \left\{ \gamma_{th} \geq \frac{a}{b} : 1 \right\} \end{aligned} \tag{4.13}$$

$$k_2 = k_{GS,N_{S_s}} \tag{4.14}$$

$$a = \frac{P_{B_{S_d}} L_{S_s,B_{S_d}}}{N_{S_s}} \tag{4.15}$$

$$b = \frac{\Sigma_{j=1}^{N} P_{B_j} L_{S_s,B_j}}{N_{S_s}} \tag{4.16}$$

$$\begin{aligned} & F_{\gamma_{GS,S_d}}(\gamma_{th}) \approx \\ & \qquad 1 - \left(\frac{\exp(-k_1 - (1+k_1)\gamma_{S_d,th})}{\Gamma(\frac{\ell}{\xi})(2\alpha_\xi)^{\frac{\ell_\xi}{2}}} \right) \\ & \qquad \sum_{m=0}^{\propto} \sum_{n=0}^{\propto} \left(\frac{k_1^{m+n} [(1+k_1)\gamma_{S_d,th}]^n}{n!(m+n)!} \right) \\ & \qquad \sum_{p=0}^{n} \binom{n}{p} \Gamma(p + \frac{\ell_\xi}{2}) \\ & \qquad [(2\alpha_\xi)^{-1} + (1+k_1)\gamma_{S_d,th}]^{-(p+\frac{\ell_\xi}{2})} \end{aligned} \tag{4.17}$$

4.4 Performance Evaluation

To have a better understanding about the characteristics of the Delay-Tolerant LEO Satellite Network introduced in this research, table 4.1 describes the most representative parameters and their suggested values.

4.4.1 Energy Consumption

To evaluate the off-loading access scheme performance, in terms of the energy consumption, two theoretic scenarios are analyzed: $Scenario_A$ and $Scenario_B$. $Scenario_A$ consists of a transmission established by two non-adjacent satellites that do not employ the off-loading access scheme, e.g. fig. 4.1 (case b). In $scenario_A$ satellites establish an ISL regardless the distance between them is long. $Scenario_B$ consists of a transmission established by two non-adjacent satellites which employ the off-loading access scheme, e.g. fig. 4.1 (case c). In $scenario_B$ satellites employs the off-loading communication. That means that if satellites are not adjacent, they communicate by off-loading communication because the distance between them is long and they try to avoid energy consumption due to long path transmissions.

In order to compare the off-loading access scheme based on different Delay-Tolerant LEO Satellite Network configurations, the evaluation section considers several settings for the number of satellites per orbit and different orbital altitudes. To figure out the individual impact of changing the number of satellites per orbit, the analysis related to fig. 4.9 considers that the orbits have eight or 16 satellites and the orbital altitude is fixed at 800 km. Conversely, the analysis related to fig. 4.10 seeks to illustrate the individual impact of changing the orbital altitude. Thus, the number of satellites per orbit is fixed at eight satellites but the orbital altitude might have values from 200 to 1,400 km. These values correspond to the orbital altitude of LEO satellites. Since the first Van Allen belt starts around 1,500 km, the present research considers orbital altitudes up to 1,400 km to avoid extra considerations and to simplify the analysis. Eqs. 4.1 and 4.2 (35) involve the orbital altitude into the transmission distance d. The packet size is represented by K_{length}, which is set at 5,15kbit for the uplink, and at 10, 20kbit for the downlink.

Observing fig. 4.9, it can be seen that the energy consumption performance is related to the transmitted packet size and to the number of satellites per orbit. Based on the results, satellites that do not use the off-loading access scheme consume more energy resources than satellites

Table 4.1: Parameter symbols and values.

Parameter	Symbol	Value [units]
Propagation delay in uplink	T_{pu}	2.6 [μs]
Propagation delay in downlink	T_{pd}	2.6 [μs]
Queuing delay	T_q	0.6 [μs]
Routing delay	T_R	0.2 [μs]
Switching delay	T_s	0.2 [μs]
Satellite velocity	V_s	7.8 [km/s]
Satellite altitude	r	200 - 800 [km]
Geometrical distance	d	200 - 40,000 [km]
Data Rate	R	500 [$Mbps$]
Syst. Noise Temperature	T_s, N_{S_s}, N_{S_d}	500 [$K°$]
Free Space Loss	L_s	208.5296 [dB]
Trans. Path Loss	L_a	10 [dB]
Line Loss	L_l	238 [dB]
Trans. Power	P	13 [dB]
Tx Antenna Gain	G_t	16.9 [dB]
Rx Antenna Gain	G_r	16.9 [dB]
Frequency uplink	f_{up}	1.995 [GHz]
Frequency downlink	f_{down}	2.185 [GHz]
Rice Factor	k_1, k_2, k_{T_i}	4.8794 [1]
Boltzmann Constant	K_B	1.38 x 10^{-23} [$J/K°$]
Transmit Signal Strength	P_{S_s}, P_{S_d}	26 [dBm]
Power Signal Strength at beam	B_s, a_i	30 [dBm]
Bandwidth	BW	300 [MHz]
Single Bandwidth	BW_{single}	180 [kHz]
Footprint	B_{radio}	200 [km]
Beam Antenna Gain	G	54.4 [dBi]

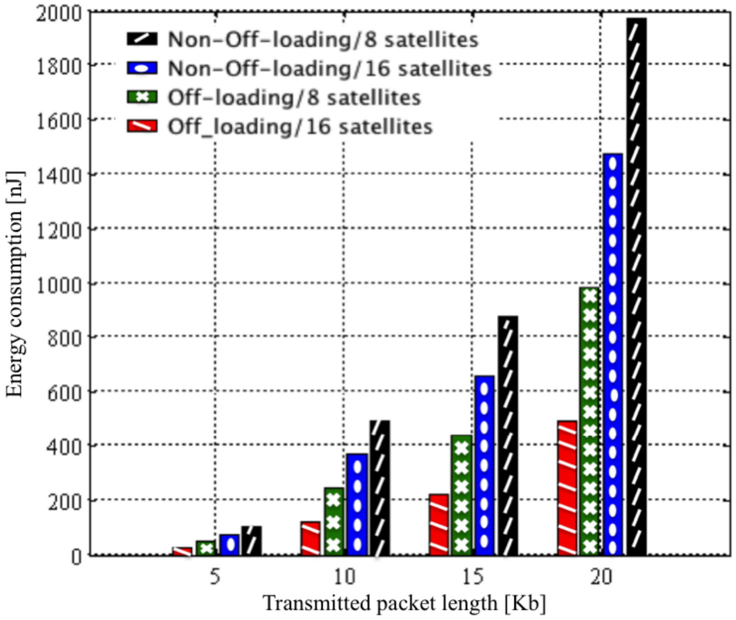


Figure 4.9: Energy consumption for diff. number of satellites per orbit at 800 Km altitude.

that use the off-loading access scheme. This fact ensures that by employing the off-loading access scheme, the Delay-Tolerant LEO Satellite Network is able to wisely use the energy resources.

The term of ”non-off-loading” into the reference label of figs. 4.9 and 4.10 simply refers to the performance of non-adjacent satellites on $Scenario_A$. In contrast, the term of ”off-loading” refers to the performance of non-adjacent satellites on $Scenario_B$.

Regarding the transmitted packet size, in fig. 4.9 it can be observed that the energy consumption is directly proportional to the packet size. This behavior is expected because larger packets need more energy resources to be transmitted. Regarding the number of satellites per orbit, the results in fig 4.9 show that the energy consumption is lower in configurations with sixteen satellites than in configurations with eight satellites. The reason for that is that by employing more satellites per orbit, the arc distance between satellites is reduced. If the arc distance between satellites is reduced, the energy necessary to establish a transmission between satellites is also reduced. Therefore, fig. 4.9 shows that the energy consumption is inversely proportional to the number of satellites per orbit, but directly proportional to the distance between satellites.

In order to analyze how the off-loading access scheme bears on the lifetime of the Delay-Tolerant LEO Satellite Network, it is necessary to compare the ”off-loading/16 satellites” case with the ”non-off-loading/16 satellites” case, for a 20kbit transmission. The ”off-loading/16 satellites” case uses 500nJ. In contrast, the ”non-off-loading/16 satellites” case uses 2000nJ. Thus, the ”non-off-loading/16 satellites” case uses four times the energy needed by the ”off-loading access scheme” case. Assuming that the energy resources are directly related to the satellite lifetime, the previous comparison means that by employing the off-loading access scheme, the Delay-Tolerant LEO Satellite Network might extend four times its lifetime. This result is very promising because it means that if the system is able to extend its lifetime, it is also able to decrease its service costs. Based on the previous results, it might be said that the off-loading access scheme offers advantages in terms of the energy consumption.

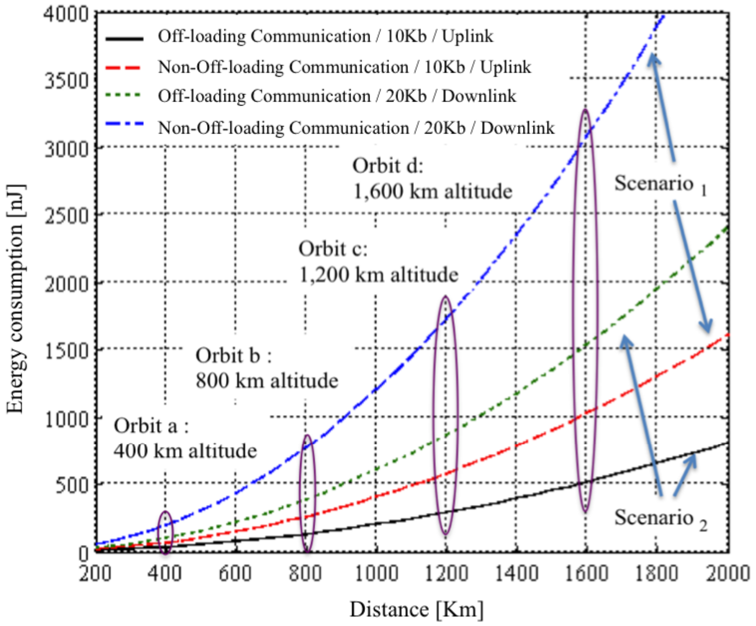


Figure 4.10: Energy consumption for diff. orbital altitudes with 8 satellites per orbit.

Fig. 4.10 represents a closer insight of the off-loading access scheme. Once again, the analysis considers two hypothetic scenarios: $Scenario_A$ and $Scenario_B$. $Scenario_A$ represents a transmission established by two non-adjacent satellites which do not use the off-loading access scheme, e.g. fig. 4.1 (case b). $Scenario_B$ represents a transmission established by two non-adjacent satellites that use the off-loading access scheme, e.g. fig. 4.1 (case c).

Observing fig. 4.10, the energy consumption is directly proportional to the orbital altitude and to the transmission packet size. Despite $Scenario_A$ and $Scenario_B$ share same radio frequency condition; $Scenario_B$ has better energy consumption performance than $Scenario_A$. The reason for that is that $Scenario_B$ considers the off-loading access scheme to save energy on long transmissions paths. $Scenario_A$ is careless about the distance between satellites employing much more energy in the transmissions. Both scenarios show that the energy consumption performance has slightly increments up to 800 km orbital altitude, regardless the transmission packet size. However, for higher altitudes, the energy consumption dramatically rises. Therefore, it is better to deploy satellites up to 800 km orbital altitude. More remarkable is the fact that a downlink transmission based on $Scenario_B$ with 1,200 km path length requires less energy than a downlink transmission based on $Scenario_A$ with 1,000 km path length. It means that satellites that use the off-loading access scheme might be placed at higher altitudes than satellites which do not use the off-loading access scheme and still require less energy resources than them. Based on the previous results, by employing the off-loading access scheme, Delay-Tolerant LEO satellite networks take full advantage of deploying its satellites at different orbital altitudes, and at the same time, to do better management of its energy resources.

4.4.2 Delay Time

To evaluate the off-loading access scheme performance in terms of the delay time the analysis equally involves eqs. 4.3 and 4.4 (21, 37). Eq. 4.4, which is related to the off-loading communication, considers that the parameters T_{pu} and T_{pd} have the same value. This occurs because according to the off-loading access scheme, the off-loading communication is only established to/from satellites and ground stations when the source satellite S_s and the destination satellite S_d are located above a specific ground station GS. Consequently, the uplink and downlink paths have the same length. If the uplink and downlink have the same distance, then the uplink propagation delay T_{pu}, and the downlink propagation delay T_{pd} have the same value. In the delay time analysis, in order to compare the advantages of using or not using the off-loading access scheme, two theoretic scenarios are studied: $Scenario_A$ and $Scenario_B$.

In $Scenario_A$ the off-loading access scheme is not used in the transmission process. Thus, the complete transmission path from the source satellite S_s to the destination satellite S_d consists of a single long path between S_s and S_d. In $Scenario_B$ the off-loading access scheme is used in the transmission process. Therefore, the complete transmission path from the source satellite S_s to the destination satellite S_d consists of a downlink path between the S_s and the GS, and an uplink path between the GS and the S_d. In $scenario_B$ the complete transmission length between S_s and S_d is always twice the orbital altitude.

To analyze different configurations between $Scenario_A$ and $Scenario_B$, the present analysis considers that the orbital altitude must have different values. Due to the satellites are placed on LEO orbits, the orbital altitude might change from 200 to 1,400 km. Involving more considerations, the number of satellites per orbit may also change from eight to 16 satellites per orbit. The reason for that is that the number of satellites is related to distance between satellites, in turn it is related to the transmission delay. The delay time performance by employing the off-loading access scheme, that is $Scenario_B$, and by not employing the off-loading access scheme, that is $Scenario_A$, is illustrated in figs 4.11 and 4.12. Fig. 4.11 shows the delay time as a function of the orbital altitudes. The number of satellites is fixed at eight or 16 satellites. Fig. 4.12 refers to the delay time based on changing the number of satellites per orbit. Thus, the orbital altitudes are set at 800 or 1,200 km.

Observing the plot in fig. 4.11, it might be noticed that the delay time is directly proportional to the orbital altitude. Since, the transmission time is longer for longer distances, the current behavior is expected. However, by comparing the delay time that corresponds to $Orbit_b$ and $Orbit_c$ it might be observed that the delay time has slightly variations by changing the orbital altitude. Conversely, by comparing the delay time based on different number of satellites, that is eight or 16 satellites per orbit, it might be noticed that the delay time has big changes. Consequently, it is a fact that the delay time rises more by increasing the number of satellites than by increasing the orbital altitude. The reason for that is that the transmission path distance changes more by changing the number of satellites, in the order of thousand kilometers, than by changing the orbital altitudes, in the order of hundred kilometers.

Observing the plot in fig. 4.12, it might be noticed that the delay time is inversely proportional to the number of satellites per orbit. This occurs because the larger number of satellites, the shorter distance between satellites and the shorter delay time. In fig. 4.12 it might be also observed that the delay time increments more by changing the number of satellites per orbit than by changing the orbital altitude. Comparing the performance of both scenarios in figs. 4.11 and 4.12, it might be concluded that the delay time in $Scenario_A$ is higher than the one in $Scenario_B$. The reason for that is that the satellites in $Scenario_A$ do not used the off-loading

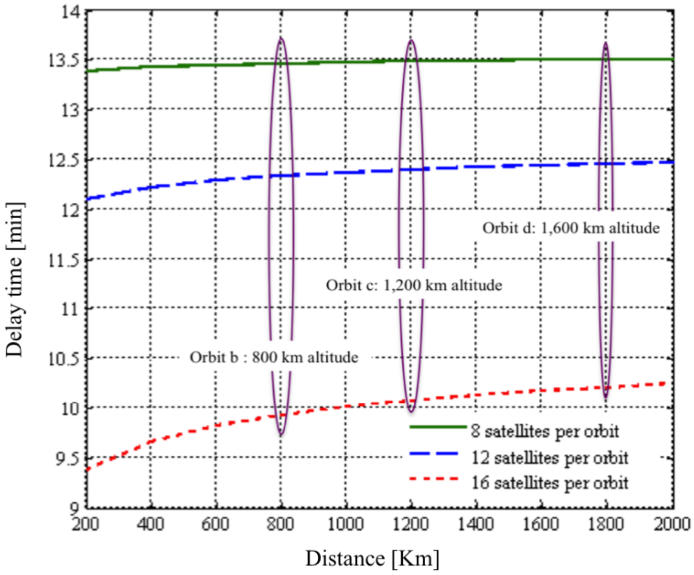


Figure 4.11: Delay time based on different orbital altitudes.

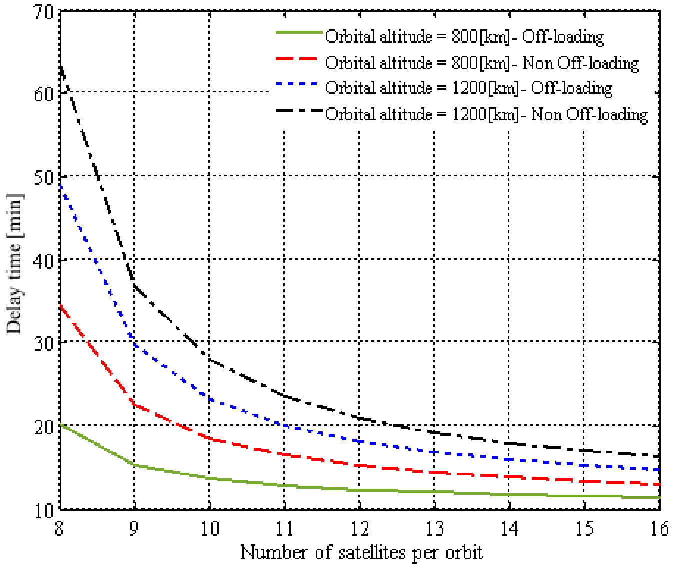


Figure 4.12: Delay time based on number of satellites per orbit.

access scheme, despite being non-adjacent satellites. By using the off-loading access scheme, Delay-Tolerant LEO Satellite Network may be applied to satisfy services that require low arrival timing saving energy resources. Therefore, the advantages of using the off-loading access scheme are proved.

4.4.3 Bit Error Rate

To continue with the evaluation of the Delay-Tolerant LEO Satellite Network proposed in this research, the BER analysis employs eqs. 4.7 and 4.8 (39, 40, 41) for the calculations. The system proposed in this research takes full advantage of the adaptive beam forming technique characteristics by using an antenna array of four elements. However, for illustrative purposes, three hypothetical antenna array configurations are considered: the antenna array configuration with two antennas, the antenna array configuration with four antennas, and the antenna array configuration with six antennas. Finally, an additional hypothetic configuration is used. It is the hypothetic configuration that does not consider the adaptive beam forming deployment at all. The results are inset in fig. 4.13. It may be observed that fig. 4.13 consists of the distribution of four lines. The solid line represents the hypothetic configuration without adaptive beam forming considerations. The other three pointed lines represent the three hypothetic antenna array configurations mentioned above.

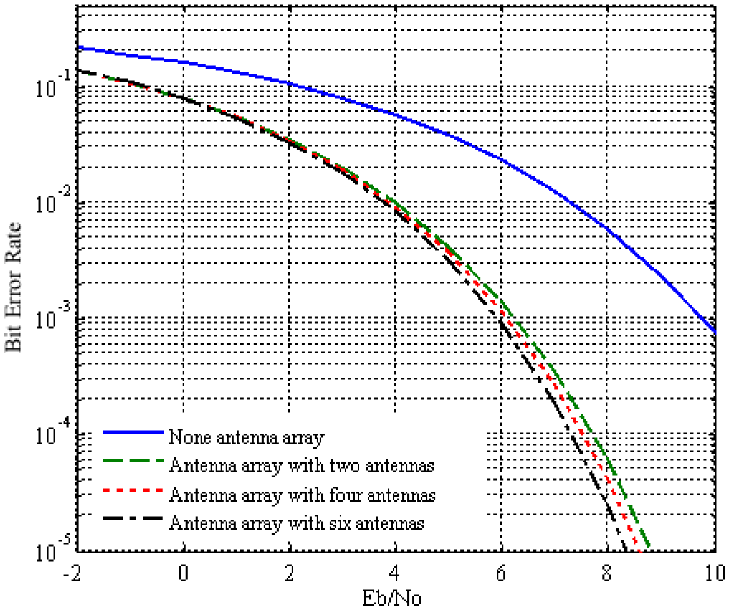


Figure 4.13: BER considering Rayleigh multi-path channels employing adaptive beam forming.

Based on the results, it might be observed that the configurations that employ the adaptive beam forming technique have BER values from 10^{-1} to 10^{-5}. Either of those configurations shows good enough BER values to successfully perform accurate transmissions. It is a fact that the configurations that use the adaptive beam forming technique, offer lower BER values than the configuration that does not consider the adaptive beam forming technique. It is important to say that the larger E_b/N_o, the larger BER difference between the configuration without adaptive beam forming and the configuration with adaptive beam forming. For instance, for E_b/N_o equals to 2, the BER difference between configurations with and without adaptive beam forming is 0.07 at least. On the other hand, the BER difference among the three hypothetic adaptive beam forming configurations is very narrow. However, the larger the number of antennas in the array, the better BER performance.

4.4.4 Co-Channel Interference

To evaluate the co-channel interference, authors use eqs. 4.13 and 4.17 (43). For the downlink and uplink sections, P_{T_i} with [i=1, 2, ... , M] and P_{B_j} with [j=1, 2, ... , N] are all set at 26 and 30 dBm, respectevily (30). The rest of the parameters are described in table 4.1. To have a better understanding about the system proposed; the analysis uses different re-use frequency factors (*ReF*). *ReF* factor is defined as 1 divided by the number of different frequencies available to re-use. Thus, *ReF* equals to 1, 1/2, and 1/3. That is one, two, and three different frequencies to re-use. Fig. 4.14 represents the co-channel interference as a function of the number of antennas in the antenna array.

Despite the system proposed in previous sections uses an antenna array with four antennas, the analysis considers different configurations. Once again, three hypothetic antenna array configurations are examined: the antenna array configuration with two antennas, the antenna array configuration with four antennas, and the antenna array configuration with six antennas.

Based on the results depicted in fig. 4.14, it might be observed that systems that use *ReF* = 1/3 show better performance than systems that use other *ReF* values, regardless the number of antennas in the configuration. The reason of that is that by using three different frequencies, the systems experience lower interference from the main adjacent beams. Therefore, the co-channel interference is minimal. In the current simulation considering *ReF* = 1/3, the co-channel interference is around 0, 0.25, and 1 dBm by using an antenna array with two, four, and six antennas, respectively. In contrast, if *ReF* = 1/2, the co-channel interference shows a completely different behavior. Observing the dashed line of the plot, it may be distinguished that the co-channel interference remains low if the number of antennas in the antenna array is up to 2, i.e. 2.5 dBm. The co-channel interference increases three times, if the number

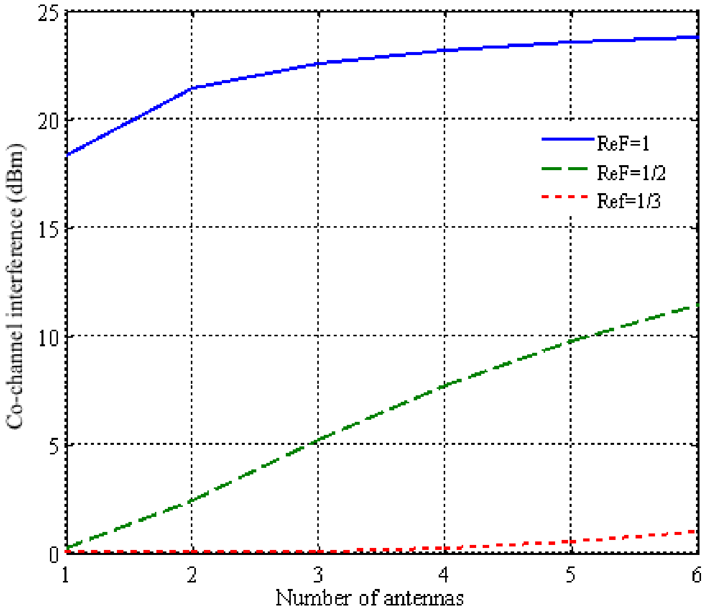


Figure 4.14: Co-channel interference employing adaptive beam forming.

of antennas in the antenna array increases up to four antennas and the co-channel interference increases almost five times, if the antenna array consists of six antennas. This behavior suggests that if the *ReF* value is more restrictive, the number of antennas in the array plays an important role in the co-channel interference performance.

Finally, the co-channel interference performance for $ReF = 1$ shows that if there is not frequency re-use at all the co-channel interference dramatically increments. The co-channel interference is directly proportional to the number of antennas in the antenna array. Thus, the co-channel interference reaches its highest value at 23.5 dBm by using an antenna array with six antennas. It is important to stand out that if the number of antennas in the antenna array changes from two to six antennas, the co-channel interference shows slightly increments. In other words, if $ReF = 1$, the co-channel interference performance is very stable despite the high co-channel interference values.

4.5 Conclusions

According to the simulation results, it has been proved that the off-loading access scheme is a reliable scheme to be used by Delay-Tolerant LEO Satellite Networks. By using the off-loading access scheme, satellites might use less energy resources in their transmissions despite transmitting larger packets than satellites that do not use the off-loading access scheme. This fact allows that the satellites in the system may be placed, if it is needed, at higher altitudes and still have a competitive energy consumption performance.

In contrast to scenarios that do not use the off-loading communication scheme, the scenarios that employ the off-loading communication scheme show better delay time performance, regardless the system configuration.

The main delay time related to the off-loading access scheme is about 13.5 min in the worst case. This delay time is still satisfactory for DTN system environments, where the delay time may be around several minutes, hours, and days in some cases. In addition, the advantage of using the adaptive beam forming technique is remarkable in terms of BER and co-channel interference. The BER analysis shows that the adaptive beam forming technique ensures reliable and accurate transmissions.

The off-loading access scheme proposed in the present research, in combination with the adaptive beam forming technique, has undoubted advantages for Delay-Tolerant LEO Satellite Networks. The proposal itself allows employing different configurations to satisfy several systems according to their particular goals and requirements. This fact offers the possibility to fulfill a huge number of applications into DTN environments. Finally, it is concluded that the off-loading access scheme, in combination with the system proposed, might reduce the energy consumption and mitigate problems caused by longer delay times and transmission errors. The future work is towards considering high throughput satellite (HTS) (44) as part of the Delay-Tolerant LEO Satellite Network. HTS satellites can be also deployed at LEO orbits. HTS consider larger number of antennas in their configuration as well. Therefore, there are several similarities between the HTS and the current system design to take full advantage of.

Chapter 5

Priority Code Scheme for Flexible Scheduling in High Throughput Satellites

5.1 Introduction

In real satellite communication systems, the bandwidth demand of each beam changes from time to time due to the fickle user needs served by those beams. Therefore, one of the main tasks of any mobile communication system face to is how to perform a suitable allocation of frequency resources. Currently, the bandwidth allocation tends to be arbitrary. One possible reason for unfair bandwidth allocations is that the schedulers employed assign frequency resources once at the beginning of the algorithm, but they do not adjust the resource assignation later when the user demands have changed. It means that the current schemes assign fixed bandwidth allocations to each beam in the system, assuming that the users have constant needs. Nevertheless, real users, in accordance with the incoming necessities, adopt different behaviors from time to time requiring a peculiar amount of frequency resources at a particular moment and requiring another quantity of resources few seconds, or minutes, later.

As a result of considering that users have static behaviors, current schemes succeed in employing a practical method that is easy to handling. Conversely, current schemes fail by performing frequency resource allocations that tend to be unsatisfactory and arbitrary among the massive number of final users. This evidence causes either of two undesirable scenarios: 1) the waste of allocated frequency resources due to the lack of service requests, defined as the overload bandwidth scenario and 2) the rejection of service requests due to the lack of frequency resources, defined as the underload bandwidth scenario. An inadequate frequency resource allocation causes various effects in the satellite systems. For instance, low throughput, the abortion of current tasks, and the rejection of incoming requirements. Therefore, to have an efficient management of frequency resources, it is indispensable to reduce deficient bandwidth allocations. In order to improve the bandwidth allocation process, the creation of new schemes is necessary.

The analysis presented in this chapter involves a scheduling process for high throughput satellites (HTS) (45, 46) and their operation environments. HTS represent an affordable solution that provides high data rates to a huge number of users. This aid is one of the principal advantages offered by HTS. In addition, HTS offer compatibility with ground networks improving throughput rates, efficiency, coverage, and network architecture. In terms of cost/benefit contributions, increasing the satellite's throughput makes the satellite technology relevant for future communication systems.

To support previous network requirements, several works recently proved (45, 49) that increasing the transmission power level enriches the system's bandwidth. However, the benefits are not enough to support services that have high throughput demands. Therefore, it is necessary to improve the bandwidth management by taking full advantage of other techniques. In this context, the multi-beam technique (50) successfully reaches instantaneous data rates up to 100 Gbps. On the other hand, the beam hopping technique (51), in comparison to the non-beam-hopped system, adds flexibility and satisfies changing user demands. Another interesting analysis (52) presents the combination of switching and beam hopping techniques to reach the targeted capacity in a geostationary (GEO) satellite network.

To perform a frequency resource allocation in Spatial Division Multiple Access (SDMA) satellite systems, the beam moving technique (53) involves continuous adjustment of satellite beams and offers the advantage of dealing with non-linear changes of interference. On the other hand, the frequency resource allocation, that is based on finding the Maximum Weight Independent Set (MWIS) (54) in a weighted interference graph of each single channel, shows a promising allocation technique. However, the inter-beam interference represents a critical factor to attend to.

In order to improve the bandwidth allocation process of systems with multi-beam environments, this chapter proposes a novel scheme known as the priority code scheme (PCS) (55). The PCS basic principle is to execute a dynamic bandwidth allocation in accordance with several factors. These factors are the user's frequency demands, the unallocated frequency resources, the efficiency ratio and the efficiency threshold associated to each beam. The efficiency threshold identifies the undesirable scenarios: 1) the overload bandwidth scenario and 2) the underload bandwidth scenario. Therefore, the PCS is a useful alternative to perform bandwidth allocations in realistic environments, where the users' needs constantly change.

Hence, the scheme description explains the importance of the PCS. Due to the PCS cyclically repeats its algorithm, the evaluation of the concurrency time and the algorithm tardiness are crucial confirmations. Therefore, the analysis of both parameters takes part of the present chapter. To enhance the use of frequency resources, the frequency-reuse process is included in the scheme analysis as well. Furthermore, the frequency-reuse process might increase the inter/intra-beam group interference among the multi-beams in the system. Consequently, a deeper analysis of the PCS is conceived considering the additional alternatives and their risks involved. To evaluate the PCS performance, the analysis implies the study of the bandwidth utilization, the interference among beams, the concurrency time, and the algorithm tardiness. The evaluation employs the Shannon's channel coding theorem (56).

Fig. 5.1 illustrates the PCS system model, whereas fig. 5.2 represents an image of the PCS frequency-reuse pattern of 70 beams in the HTS in GEO orbit. The Priority Code Scheme (PCS) system model is formed by the monitoring module and the operative module. The monitoring module reviews the efficiency ratio, the efficiency threshold, and the efficiency indicator parameters. This action helps the PCS to estimate the underload and the overload bandwidth capacities in order to establish the concurrence time, the monitoring time, and the priority codes of the beams. In turn, the operative module assigns the new bandwith allocation and the priority codes based on the monitoring module outputs. It is assumed that the PCS takes part of the TTC&M (Telemetry, Tracking, Command and Monitoring) satellite subsystem. The PCS system model perfectly summarizes the PCS operation and represents a useful tool to understand the process of its algorithm.

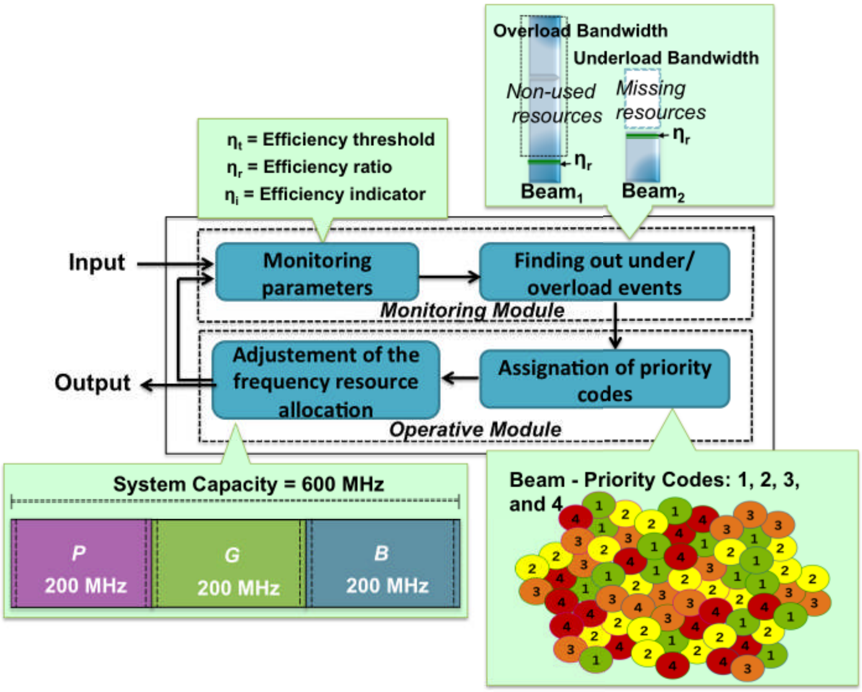


Figure 5.1: PCS system model.

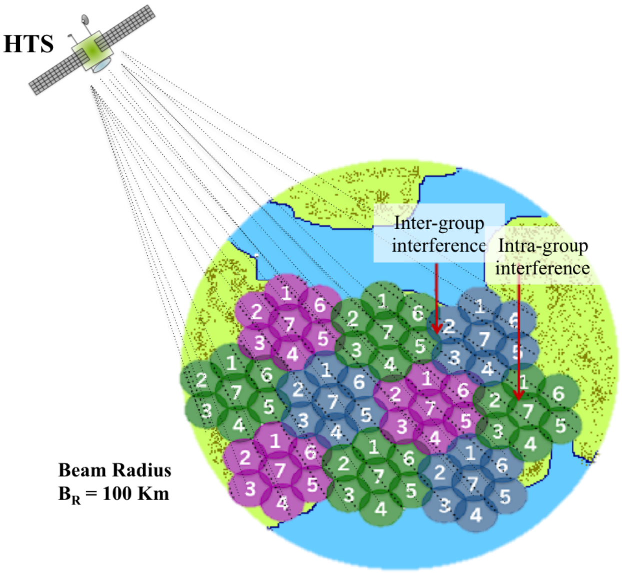


Figure 5.2: PCS frequency-reuse pattern.

The present chapter is organized in four sections. Section 2 briefly describes the principle of the PCS. Section 3 introduces the PCS's additional challenges and describes the problems involved. Section 4 presents the evaluation of the PCS in terms of the inter/intra-beam interference, the concurrence time, and the frequency-reuse effectiveness. Finally, section 5 concludes the paper, highlighting the merits of the PCS's new design and future works.

5.2 Principles of the Priority Code Scheme

The PCS seeks to increase the bandwidth capacity of beams that shadow specific footprints with a high bandwidth demand. In addition, the PCS intends to minimize the amount of resources allocated to beams with low bandwidth demand. Based on the PCS algorithm (55), the PCS dynamically increases or reduces the frequency resource allocation by identifying three possible scenarios: the accurate bandwidth allocation, the underload bandwidth allocation and the overload bandwidth allocation. The underload and the overload bandwidth allocations are undesirable occurrences.

To identify undesirable allocation occurrences, the PCS algorithm use three parameters: the efficiency ratio η_r, the efficiency indicator η_i, and the efficiency threshold η_t. The efficiency ratio η_r represents the ratio of bandwidth utilization and bandwidth capacity at a particular moment. The efficiency ratio η_r changes time by time in accordance to the bandwidth utilization variations. The efficiency indicator η_i is the efficiency ratio value that indicates when the PCS executes an accurate bandwidth allocation. The efficiency indicator η_i is a constant variable defined in the PCS initial premises. Therefore, it is fundamental to set it up at the beginning of the PCS algorithm.

The efficiency threshold η_t represents a range of efficiency ratio values that tend to be equal to the efficiency indicator value. The efficiency threshold η_t is the result of adding an approximation parameter to the efficiency indicator η_i and contributes to identifying the under load and overload bandwidth allocations. For instance, if the efficiency ratio η_r is inside the range of values of the efficiency threshold η_t, the bandwidth allocation is correct. Otherwise, the bandwidth allocation is underloaded or overloaded. For an under load bandwidth allocation, the efficiency ratio η_r is bigger than the values within the efficiency threshold η_t. To solve an underload bandwidth allocation, the beam needs to receive additional bandwidth and its priority code must increase. In contrast, an overload bandwidth allocation occurs when the efficiency ratio η_r is smaller than the values within the efficiency threshold η_t. The overload bandwidth allocation takes place every time the beam receives more capacity than it needs. Therefore, to reverse the overload bandwidth allocation, the beam must release part of its bandwidth until this bandwidth satisfies the current demands of the beam without implicating unused frequency resources.

The priority code in this scenario decreases in order to match the new bandwidth allocation among the beams. Fig. 5.3 illustrates the bandwidth allocation scenarios (55) where the efficiency indicator η_i is equal to 0.8 and the approximation parameter is equal to 0.05. Observing fig. 5.3, B_{w3} depicts the situation in which the PCS executes an accurate bandwidth allocation. For such scenarios, the PCS does not need to execute a bandwidth adjustment and the priority code remains unchanged. The reason for B_{w3} shows an accurate allocation scenario is that B_{w3} has an efficiency indicator η_i equal to 0.8 and this value is inside the efficiency threshold η_t defined, that is equal to 0.8 ± 0.05. In turn, the underload bandwidth allocation is the scenario in which the efficiency ratio η_r approximates to 1 and $\eta_r > 0.85$, for instance the one performed in B_{w2}. In contrast, the overload bandwidth allocation occurs when the efficiency ratio η_r approximates to 0 and $\eta_r < 0.85$, for example the one executed in B_{w1}. Regarding the priority codes of B_{w1} and B_{w2}, the PCS matches their bandwidth utilization with new priority codes in order to determine which beams require major attention. The bandwidth allocation adjustment is faster in high-demand beams than in low-demand beams.

Refer to fig. 5.4 to understand the adequacy offered by an efficiency indicator η_i is equal to 0.8. The most convenient efficiency indicator η_i is the one adjacent to the maximum bandwidth utilization, because this ensures high bandwidth utilization percentage. Furthermore, the efficiency indicator η_i should be sufficiently distant to the maximum bandwidth utilization.

The reason for that is that the PCS algorithm requires sufficient time to identify unsuitable bandwidth allocations and to execute the appropriated bandwidth adjustments. In addition, the PCS algorithm demands to adjust the bandwidth allocation before the beam reaches its maximum bandwidth capacity to avoid the underload bandwidth allocation or before the beam decrease its bandwidth utilization to avoid the overload bandwidth allocation. In conclusion, fig. 5.5 illustrates the PCS algorithm that consists of seven steps.

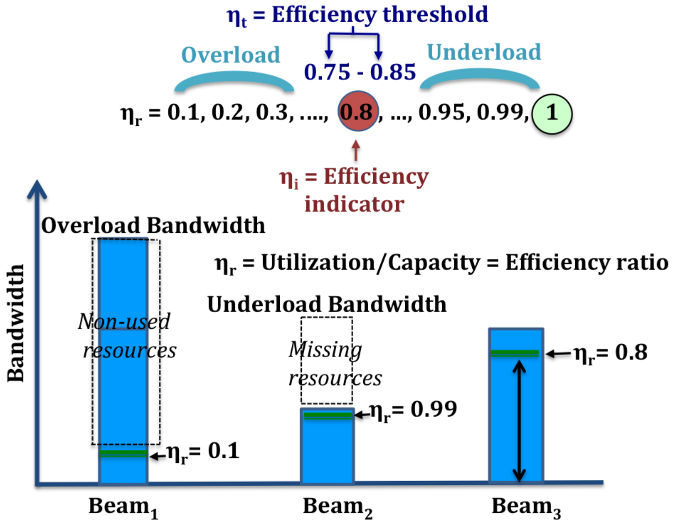


Figure 5.3: Allocation scenarios of the PCS.

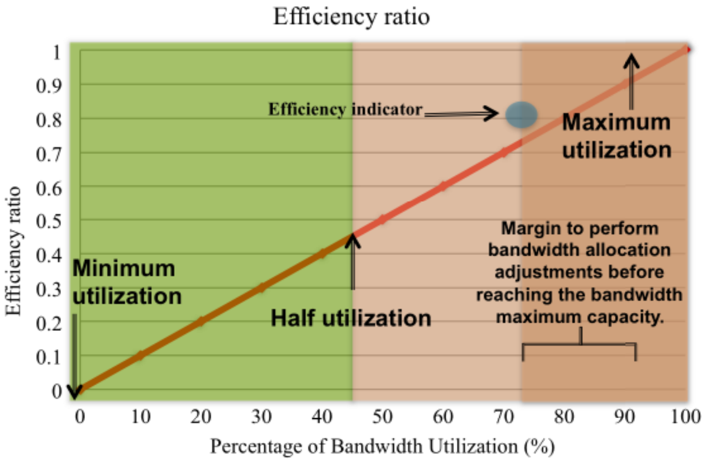


Figure 5.4: Performance of the PCS efficiency ratio.

The PCS algorithm initiates assuming all beams receive the same capacity, that is, all beams have a correlative amount of bandwidth. All beams receive an identical priority code as well. That is because, at the beginning of the PCS algorithm, there is no capacity utilization information, nor are there beam efficiency records. The initial priority code corresponds to the given initial bandwidth requirements. Therefore, once the PCS sets the initial bandwidth capacity and the priority code of each beam, the monitoring process starts to operate to obtain the current parameter information related to the bandwidth requirements of each beam in the system.

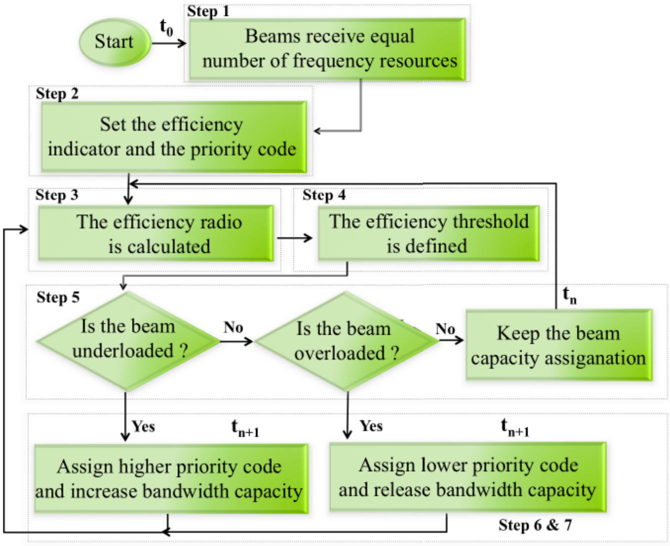


Figure 5.5: Scheduling algorithm of the PCS.

The information obtained helps to categorize the allocation events under the accurate bandwidth allocation, the underload bandwidth allocation, and the overload bandwidth allocation. The PCS algorithm performs as follows:

- Step 1: The PCS starts. All beams receive the same amount of frequency resources.
- Step 2: The PCS sets an efficiency indicator and a priority code for each beam.
- Step 3: The PCS calculates the efficiency ratio of each beam, dividing the bandwidth utilization by the bandwidth capacity per beam. The PCS learns the bandwidth requirements of the beams by monitoring the efficiency ratio that corresponds to a particular footprint.
- Step 4: The efficiency threshold of each beam is defined based on the efficiency indicator.
- Step 5: The PCS employs the efficiency indicator, the efficiency threshold, and the efficiency ratio to judge which beams have an underload or an overload bandwidth allocation.
- Step 6: The PCS provides a new priority code to each beam that corresponds with the current bandwidth needs by considering the efficiency ratio.

- Step 7: The PCS adjusts the amount of frequency resources assigned to each beam, increasing or decreasing the amount of resources it. Finally, the PCS algorithm cyclically repeats from Step 3 to measure the efficiency ratio of each beam again.

5.3 Priority Code Scheme Analysis

The PCS intents to offer advantages in terms of capacity allocation by dynamically allocating bandwidth resources based on user demands in situations in which fixed bandwidth allocations are unsuitable. This goal is remarkable because in ongoing situations, due to the dynamic behavior of user demands, the network requierements follow an unstable patterns. To reach this goal, the PCS must face several challenges, such as how to execute the bandwidth allocation. In this context, eqs. 5.1 and 5.2 (56) define the maximum bandwidth capacity of the beams where BW represents the bandwidth, $S/(N+I)$ is the signal-to-noise ratio plus interference, P_{TWTA} is the payload on the spacecraft, G_{TX} and G_{RX} are the antenna gain at the transmitter and receiver, respectively, d represents the distance between the transmitter and receiver, λ stands for the wavelength, K_B is the Boltzmann's constant, T_{SYST} is the system noise temperature, and I stands for the interference.

$$C = BW\, log_2 \left(1 + \frac{S}{N+I}\right) \tag{5.1}$$

$$\frac{S}{N+I} = \frac{P_{TWTA}\, G_{TX}\, G_{RX}}{(\frac{4\pi d}{\lambda})^2 K_B\, T_{SYST}\, BW\, I} \tag{5.2}$$

In addition, other challenges are how to deal with the concurrence time and the tardiness of the algorithm, how to perform the frequency management based on the increments and decrements of the bandwidth assigned, and how to mitigate the interference between adjacent beams.

5.3.1 Concurrence Time and Algorithm Tardiness

The concurrence time defines how regularly the PCS runs its algorithm with the purpose of monitoring the efficiency ratio of all beams in the system. Hence, it is relevant to point out that the concurrence time benefits from being part of a priority algorithm (57) to manage the existence of conflicts between diverse tasks in progress. When the monitoring process of a *beam*$_X$ with *priority code X* is still in progress and the monitoring process related to a *beam*$_Y$ with *priority code Y* is scheduled, the task with the higher priority keeps going and the task with the lower priority is set to a waiting mode until the PCS algorithm becomes available to assist it. Therefore, this type of decision-making process involves a conflict management analysis. The investigation presented in this research includes these kinds of complexities; however, the progress towards the conflict management process is beyond the scope of this manuscript.

Equation 5.3 (58) represents the expression of the concurrence time where I_j is the number of incoming beams to be scheduled, R_j is the number of remaining beams to be scheduled, D_j is the number of beams already scheduled, and n stands for the total number of beams.

$$CT(t) = \Sigma_{j=1}^{n}\left(\frac{D_j}{n}\right)\left(\frac{R_j + I_j}{R_j}\right) \tag{5.3}$$

Algorithm tardiness is defined as the speed with which the PCS algorithm monitors the efficiency ratio of all beams and adjusts the bandwidth allocation of the total number of beams that demand the adjustment. In other words, the algorithm tardiness is an indication of how quickly the PCS runs its algorithm, and it is measured in beams per second (beam/s). As soon as the scheduler accomplishes the total number of tasks, the algorithm starts again. The PCS algorithm is a short-term scheduling algorithm. Therefore the algorithm tardiness must be quite fast in order to facilitate the tasks in short waiting times. In order to deduce the algorithm tardiness, it is essential to analyze the PCS similarly to a concurrence real-time system (57).

As a real-time system, the PCS needs to respond to precise external conditions within a specific finite time in which the processes are treated as tasks. As a concurrence system, the PCS repeatedly runs several tasks. Therefore, PCS effectiveness depends on the correctness of the results and the time within which the PCS executes them. The algorithm tardiness classifies this scheme similarly to an algorithm of the constructive type. A constructive type is suitable for algorithms that start without a schedule and gradually build one by adding a task at a time.

In this context, the PCS dispatches bandwidth allocation to beams one by one, and once the PCS concludes the allocations, the remaining beams with the highest priority are processed. Equation (5.4) (58) defines the algorithm tardiness.

$$T(t) = \left(\frac{R_j + I_j}{R_j}\right) exp\left(\frac{-max\,(D_j - R_j)t}{K_1}\right) exp\left(\frac{S_j}{K_2}\right) \tag{5.4}$$

Where I_j represents the number of incoming beams to be scheduled, R_j is the number of remaining beams to be scheduled, and D_j is the number of beams already scheduled. The S_j is the average of the setup times of the beams remaining to be scheduled, K_1 is the due related scaling parameter, K_2 represents the setup-time-related scaling parameter, and t is the time in seconds. K_1 and K_2 are dimensionless quantities and are defined as follows:

$$C_{max} = (\,\Sigma_{j=1}^{n} R_j\,) + n\,S_j \tag{5.5}$$

$$\Gamma = \frac{D_{max} - D_{min}}{C_{max}} \tag{5.6}$$

$$\tau = 1 - \left(\Sigma_{j=1}^{n}\frac{D_j}{n\,C_{max}}\right) \tag{5.7}$$

$$\begin{aligned} K_1 = &\{\Gamma < 0.5 : 4.5 + \Gamma\} \\ &\{\Gamma \geq 0.5 : 6 - 2\Gamma\} \end{aligned} \tag{5.8}$$

$$K_2 = \frac{\tau}{2\sqrt{\delta}} \tag{5.9}$$

$$\delta = \frac{S_j}{R_j} \tag{5.10}$$

Where C_{max} represents the maximum due beams to be scheduled, Γ is the due beam range factor, D_{max} stands for the maximum number of the beams already scheduled, D_{min} is the minimum number of the beams already scheduled, τ represents the due date tightness factor, δ stands for the effectiveness factor of the remaining beams to be scheduled, and n is the total number of beams.

5.3.2 PCS Frequency-Reuse Process

Frequency-reuse refers to the repeated use of the same set of frequencies among several beams. It involves a basic principle that establishes that adjacent beams cannot share the same set of frequencies. The frequency-reuse factor is the rate at which the beams use the same set of frequencies, and it is defined as $R{=}1/M$, where M stands for the number of sets of frequencies or the number of beams that cannot share the same set of frequencies. Consequently, the frequency-reuse pattern is related to the configuration of beams that follow the frequency-reuse factor. The PCS frequency-reuse build follows the subsequent statements:

- There are 70 multi-beams deployed in the HTS.
- The beams are grouped into collections of seven beams each to shape 10 beam groups.
- The beam groups use labels, namely, G, B, and P, to distinguish them from others. Besides, adjacent beam groups cannot share the same label.
- Beam groups with different labels do not share the same set of frequencies and beam groups with same label share the same set of frequencies. Therefore, considering the frequency-reuse pattern, the inter-group frequency reuse factor is R_{inter} = 1/3.
- In turn, the beams inside the same group are numbered from 1 to 7, and none of them share a subset of frequencies. Thus, the intra-group frequency-reuse factor is R_{intra} = 1/7.

Bearing the previous frequency-reuse descriptions in mind, fig. 5.6 illustrates the PCS frequency-reuse plan. The PCS uses Ka-band frequencies of the range of 19.6 - 22.2 GHz. Accordingly, the total available bandwidth is 600 MHz, and it is divided to create three sets of frequencies. The PCS frequency-reuse replicates each set every three beam groups. In turn, each set of frequencies is organized into seven subsets of frequencies.

Therefore, there is one subset of frequencies for each beam of the group. At the beginning of the algorithm, each set and subset of frequencies is correlatively sized so that each beam group receives a maximum of 200 MHz and each beam receives maximum of 28 MHz, respectively. A remaining bandwidth of 5 MHz is used to form the guard bands of the inter/intra beam groups.

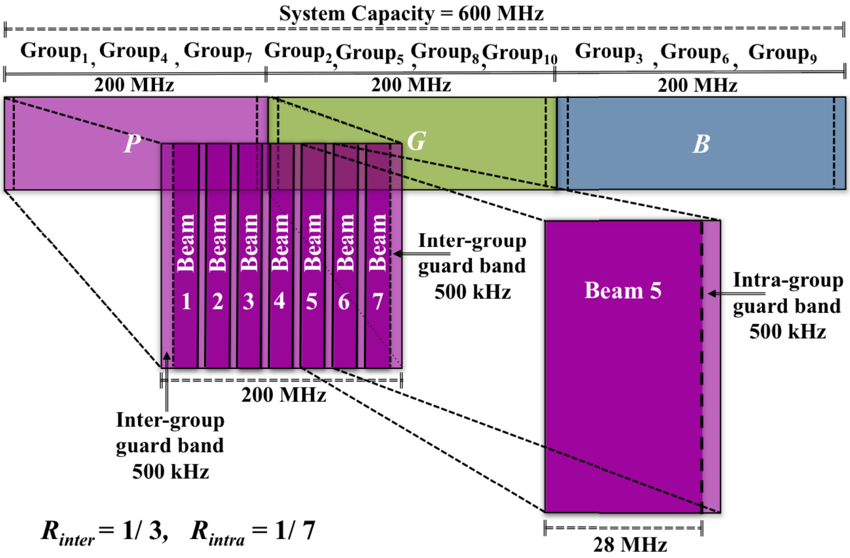


Figure 5.6: PCS Frequency-Reuse Plan.

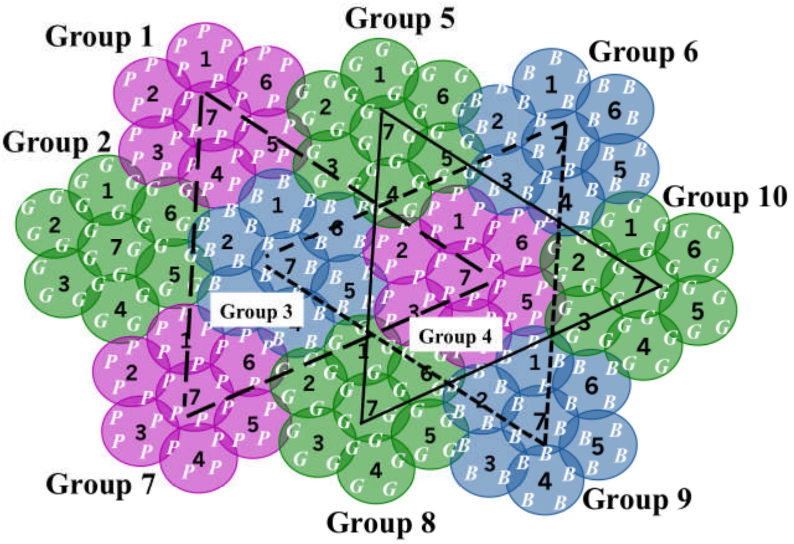


Figure 5.7: HTS Scenario using the PCS Frequency-Reuse Plan.

The PCS uses this bandwidth distribution only at the beginning of the algorithm because, after the PCS initialization, the sets of frequencies might be not correlatively sized. After the initialization of the algorithm, the subsets of frequencies might be not correlative either. However, the number of sets and subsets of frequencies and the amount of bandwidth used as guard bands remain without variations to decrease interference among beams.

In conclusion, fig. 5.7 depicts the scenario of the PCS frequency-reuse plan. Observing fig. 5.7, the beams numbered similarly and belonging to beam groups with the same label might have the same subset of frequencies. Following the rules of the frequency-reuse plan, all beams might increase their bandwidth capacity by three times. This evidence is more productive when a PCS beam experiences an underload bandwidth scenario because that scenario is one in which the PCS beam requires extra bandwidth.

5.3.3 PCS Interference

Interference conditions are significant parameters in the quality of service (QoS) of satellite communication systems. The interference conditions might be overwhelmed by: 1) the existence of beams in the same frequency band with overlapping footprints, that is, intra-band interference, and 2) the existence of beams in adjacent frequency bands with overlapping footprints, that is, inter-band interference. The PCS interference model considers 70 multi-beams in an HTS in the GEO orbit. The beam radius B_R is equivalent in all beams, and it is equal to 100 Km. This research involves two types of interference in the PCS. They are intra-group interference and inter-group interference. In turn, both types of interference include intra-band and inter-band interference. By definition, intra-group interference is interference that affects beams inside the same group. According to the PCS frequency-reuse plan, beams inside the same group use different subsets of frequencies. Therefore, intra-band interference is negligible, resulting in the PCS intra-group interference that only involves the inter-band interference. The PCS interference pattern is based on the presumption that are intra-group guard bands of 500 kHz between beam groups. Fig. 5.8 represents the PCS intra-group interference model of $Group1$.

In fig. 5.8 the arrows illustrate the direction of the inter-band interference between adjacent beams belonging to the same group. For instance, $Beam_1$ interferes with $Beam_2$, $Beam_6$, and $Beam_7$. In turn, $Beam_2$ interferes with $Beam_1$, $Beam_3$, and $Beam_7$. $Beam_3$, $Beam_4$, $Beam_5$, and $Beam_6$ follow the same interference behavior. As $Beam_7$ is the only beam that interferes with all beams in the group, it is a unique beam. All beam groups have the same PCS intra-group interference model.

The inter-group interference affects beams belonging to different groups. Fig. 5.9 represents the PCS inter-group interference model in which only four groups, 28 beams, are illustrated. The inter-group interference involves intra-band and inter-band interference as well.

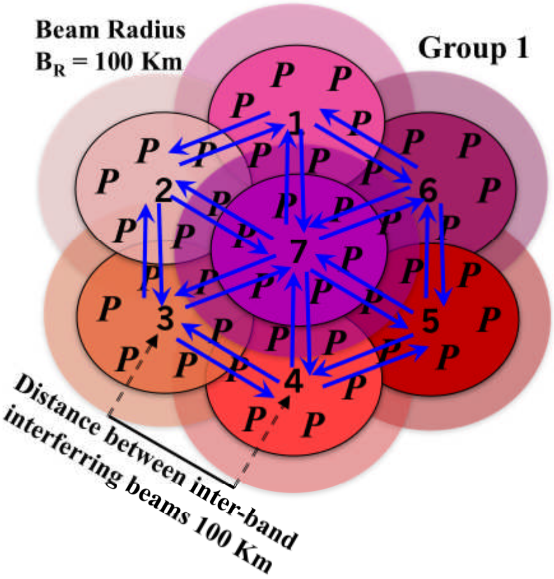


Figure 5.8: PCS intra-group interference model.

Where intra-band interference is concerned, as the interfering beams must share the same subset of frequencies, they must accomplish three conditions: be numbered similarly, belong to different groups, and share the same label (G, B, P). This is because beams in different groups with the same label have the same subset of frequencies and beams in different groups with different labels do not have the same subset of frequencies. For example, observing the dashed arrows in Fig. 5.9, $Beam_7$ in $Group_1$ only causes intra-band interference with $Beam_7$ in $Group_4$. In turn, $Beam_7$ in $Group_4$ only causes intra-band interference with $Beam_7$ in $Group_1$. $Beam_1$, $Beam_2$, $Beam_3$, $Beam_4$, $Beam_5$, and $Beam_6$ follow the same intra-band interference performance from $Group_1$ to $Group_{10}$.

Regarding the inter-band interference involved in inter-group interference, the authors observed that the interfering beams must: be numbered similarly, belong to different groups, and have different labels (G, B, P). This is because, based on the PCS frequency-reuse pattern, beams in different groups with different labels have adjacent subsets of frequencies. Accordingly, in fig. 5.9, the bold arrows represent inter-band interference. Observing fig. 5.9, $Beam_7$ in $Group_1$, $Beam_7$ in $Group_3$, and $Beam_7$ in $Group_5$ cause inter-band interferences among each other. $Beam_1$, $Beam_2$, $Beam_3$, $Beam_4$, $Beam_5$, and $Beam_6$ in $Group_1$ to $Group_{10}$ follow the same inter-band interference performance.

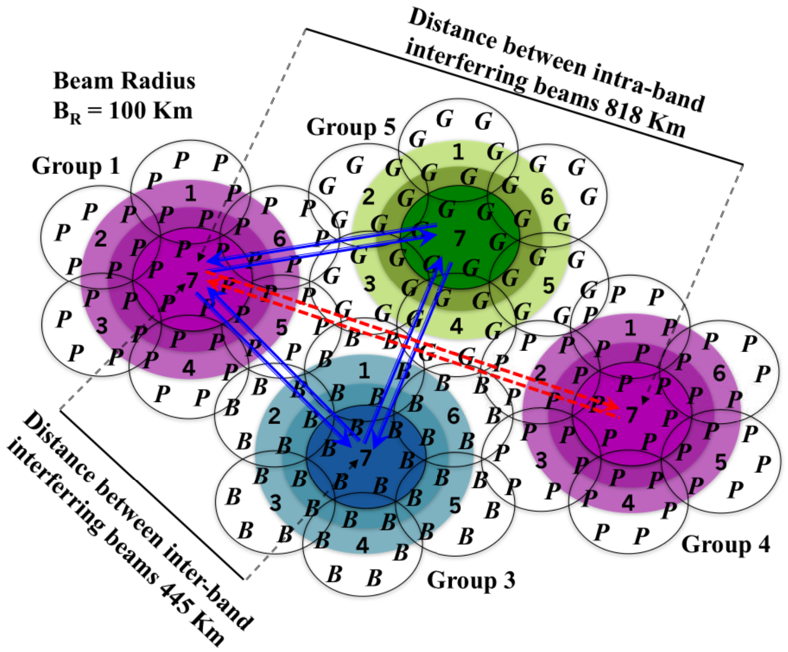


Figure 5.9: PCS inter-group interference model.

The intra-group interference and inter-group interference are respectively defined in (5.11) and (5.12) (59) where Ψ is the inter-band interference that occurs in each group, Υ represents the intra-band interference that occurs between different groups, and Ω is for the inter-band interference that occurs between different groups. In addition, $EIRP$ is the equivalent isotropically related power, G_r represents the antenna gain of the satellite, L is the free space loss, G_{sh} stands for the shadowing components of the satellite link, BG is the number of beam groups, k is the number of beams in each group, m is the number of beam groups using adjacent subsets of frequencies, and q stands for the number of beam groups using the same subset of frequencies.

$$I_{intra-group} = \Sigma_{BG=1}^{10}\ \Psi_{BG} \tag{5.11}$$

$$I_{inter-group} = \Sigma_{BG=1}^{10}\left(\Upsilon_{BG}\ +\ \Omega_{BG}\right) \tag{5.12}$$

$$\Psi = \Sigma_{k=1}^{7}\ EIRP_k\ G_{r\ k}\ L_k\ G_{sh\ k} \tag{5.13}$$

$$\Upsilon = \Sigma_{k=1}^{7} \Sigma_{q=1}^{2} EIRP_{(k,\, q)}\, G_{r\ (k,\, q)}\, L_{(k,\, q)}\, G_{sh\ (k,\, q)} \tag{5.14}$$

$$\Omega = \Sigma_{k=1}^{7} \Sigma_{m=1}^{4} EIRP_{(k,\, m)}\, G_{r\ (k,\, m)}\, L_{(k,\, m)}\, G_{sh\ (k,\, m)} \tag{5.15}$$

5.4 Evaluation and Results

Regarding the bandwidth allocation process, Shannon's channel coding theorem (56) is applied to calculate the maximum bandwidth capacity of each beam. The evaluation only involves the forward link and uses Ka-band frequencies of the range of 19.6-22.2 GHz. The theoretical scenario refer to 70 beams ($B_{w1}, B_{w2}, \ldots, B_{wn}$) sharing the total bandwidth of 600 MHz that is divided into blocks of 100 kHz. Thus, the total number of available bandwidth blocks is 6000. For the present evaluation, we set $PTWTA$ and I = 30 dB, G_{TX} and G_{RX} = 19 dB, d = 800 km, T_{SYST} = 500 K°, and the efficiency threshold η_t = 0.8.

Based on the priority codes shown in Table 5.1, the PCS determines the codes that the beams may adopt based on their efficiency ratio values. In this context, Table 5.1 includes four codes in which the beam with priority code 4 has the highest importance and the beam with priority code 1 has the lowest importance. Figs. 5.10 and 5.11 depict the PCS initial evaluation results (55). These results represent an average of the tracking performance of the PCS algorithm against the temporal change of the traffic demand based on multiple cases of traffic demand.

Observing fig. 5.10, it considers two types of bandwidth distribution: the fixed bandwidth allocation in which every beam receives a correlative bandwidth capacity and the PCS bandwidth allocation in which the beams receive dynamic bandwidth allocations. The fixed bandwidth allocation does not take care of ongoing user requirements. Consequently, the existence of under load and overload bandwidth allocations, without the opportunity to reverse their effects, is inevitable. Conversely, the PCS bandwidth allocation fairly shares the bandwidth among beams according to the prevailing user needs.

Table 5.1: Priority codes based on efficiency ratio.

Demand	Priority Code	Efficiency (%)
High	4	60
Medium	3	25
Low	2	10
Little	1	5

In addition, applying the PCS a beam with $\eta_r > \eta_t$ receives extra bandwidth in comparison with other beams. Beams with $\eta_r < \eta_t$ release bandwidth. At the same time, beams with higher priority codes receive faster assistance from the PCS algorithm than beams with lower priority codes. Fig. 5.10 shows the scenarios with 70 beams deployed. The dotted line represents the fixed bandwidth allocation case with 8.5 MHz per beam. The bars in gray represent the PCS bandwidth allocation and the bars in black represent the available capacity. Each bar in fig. 5.10 corresponds to a particular beam in the system configuration. At first sight, we observed that, regardless the number of beams, PCS avoids the under load and overload scenarios, offering a good performance among all beams in the HTS. The PCS proves that it is able to adjust the bandwidth allocation as a function of the number of beams and the fickle bandwidth requirements.

Fig. 5.11 shows the behavior of the bandwidth utilization against the available bandwidth as a function of the number of beams deployed in the HTS. The corresponding calculations employ different efficiency threshold values ($\eta_t = 0.8, 0.9$) and consider the average of the user's traffic demands by running several iterations. Fig. 5.11 suggests that the optimal performance is at 12 beams with contrasted variations from one up to 60 beams.

In terms of PCS concurrence time, the analysis employs 70 multi-beams with fickle bandwidth requirements. Table 5.1 describes the priority codes used. The prediction of the concurrence time involves 3600 iterations with duration of one second. Observing fig. 5.12, we determined that the concurrence time might fall into two types of values, that is short and long values. We assumed that the concurrence time is short, if the concurrence time falls into the range of 0 to 0.05 s. In contrast, the concurrence time is long, if the concurrence time is up to 0.18 s. Furthermore, most long values approach to 0.08 s, whereas most short values approximate to 0.01 s.

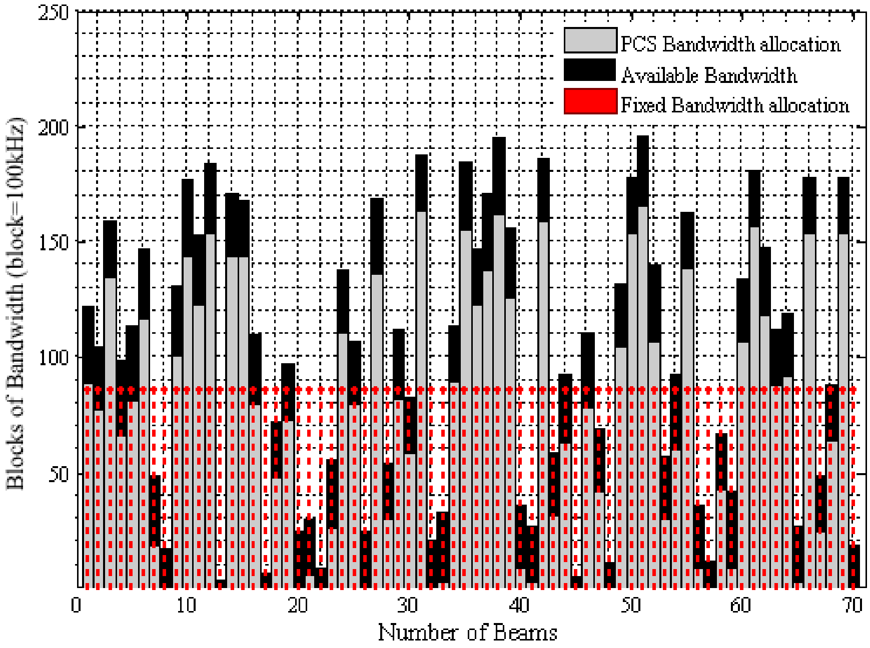


Figure 5.10: PCS scenario employing 70 Beams.

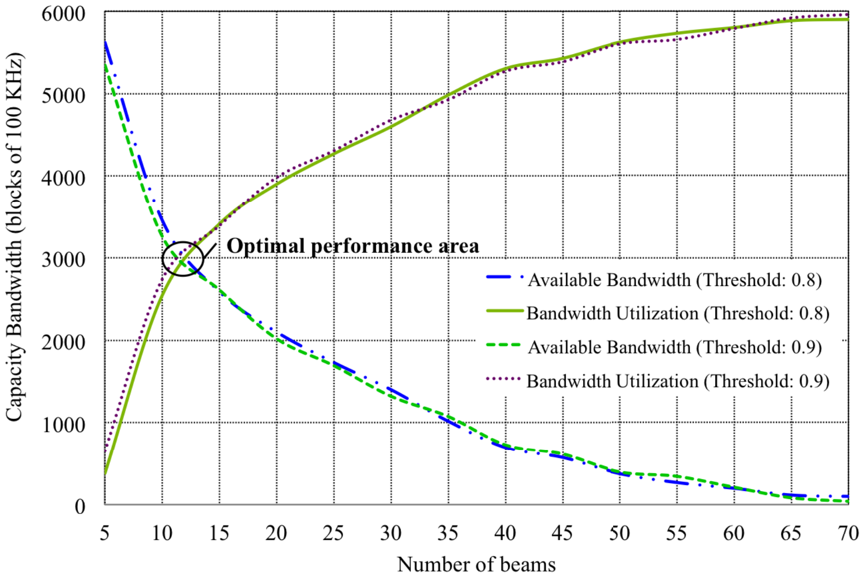


Figure 5.11: PCS capacity for different efficiency thresholds.

Based on fig. 5.12, the authors concluded that the concurrence time might adopt different behaviors. For instance, if there are many bandwidth adjustments, the concurrence time is short and the PCS algorithm rapidly runs. Conversely, if there are few bandwidth adjustments, the concurrence time is long and the PCS algorithm slowly runs.

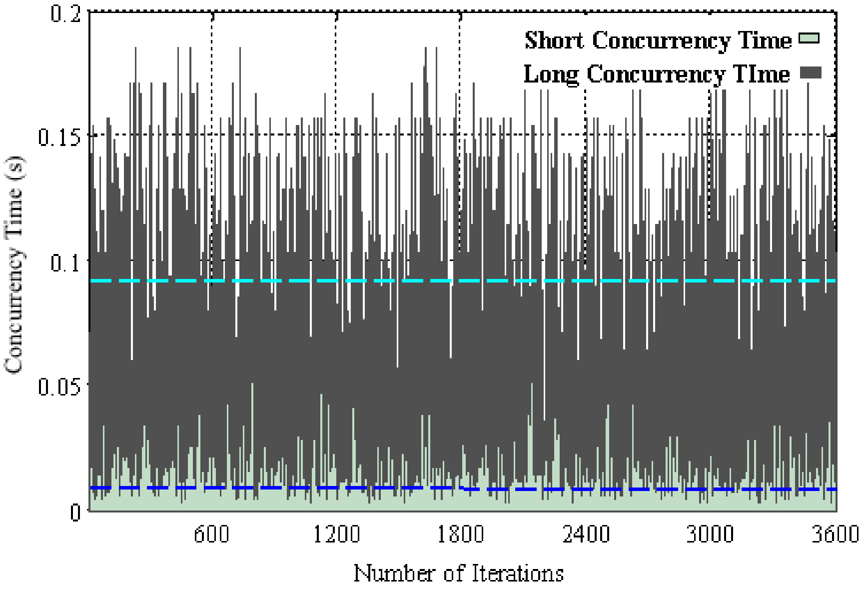


Figure 5.12: Performance of the PCS concurrency time.

In conclusion, the docility of the concurrence time proves that the PCS algorithm is flexible and, in consequence, the PCS responds to dynamic bandwidth demands. In terms of algorithm tardiness, the present analysis attempts three consecutive events. Thus, fig. 5.13 depicts these events as follows: fig. 5.13.a represents $Event_1$ from 0 to 60 s, fig. 5.13.b shows $Event_2$ from 60 to 120 s, and fig. 5.13.c illustrates $Event_3$ from 120 to 180 s.

Each event reflects the average behavior of 70 beams with dynamic bandwidth requirements. Figure 5.13 shows that the algorithm tardiness follows unstable patterns among events. We expected this result because the hypothetical scenario considers that all beams have different bandwidth requirements time by time resulting in modifications of the algorithm tardiness. Observing fig. 5.13, the longest algorithm tardiness falls in the range of 0 to 30 s, that is $Event_1$. The reason for that is that before the algorithm initialization occurs, all beams receive correlative bandwidth.

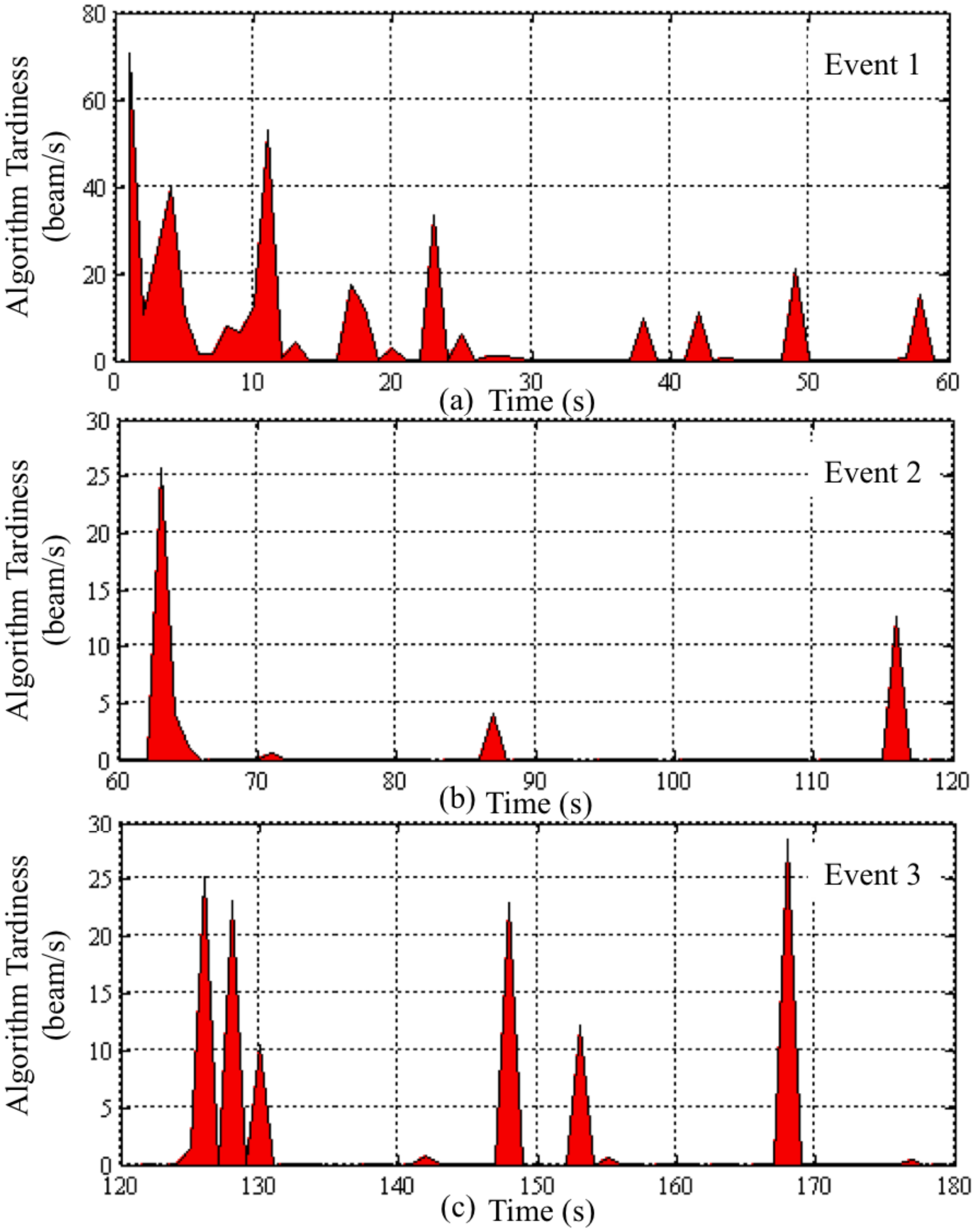


Figure 5.13: Performance of the PCS algorithm Tardiness. Fig. 13.a illustrates the performance of the algorithm tardiness tested from 0 to 60 s, that is Event 1. Fig. 13.b shows the performance of t . fig. 13.c represents the performance of the algorithm tardiness tested from 120 to 180 s, that is Event 3.

Therefore, once the PCS algorithm begins, all beams suffer a vast number of bandwidth adjustments to match the bandwidth capacity with the current bandwidth requirements. In consequence, the algorithm tardiness is long at the beginning of the algorithm.

The algorithm tardiness is short if the beams experience few bandwidth modifications. For example, the algorithm tardiness of $Event_2$ from 90 to 120 s. Observing figs. 5.13.b and 5.13.c, those frames suggest that after the PCS algorithm initializes, the PCS becomes passive and the algorithm tardiness is short. Comparing $Event_1$, $Event_2$, and $Event_3$, the longest algorithm tardiness is equal to 70 beam/s. This evidence means that the monitoring course and the bandwidth adjustment process of each beam need to be performed within 0.014 s. Therefore, the PCS requires a fast algorithm. The shortest algorithm tardiness is approximately 1 beam/s. This conclusion means that the monitoring course and the bandwidth adjustment process should be performed in 1 s. Therefore, the PCS needs a slow algorithm. The difference between those two values of the algorithm tardiness shows that the PCS algorithm has very contrasting behaviors.

To complete the PCS evaluation, we also analyzed the PCS considering that this scheme uses the frequency-reuse pattern previously described. The analysis involves 70 multi-beams deployed on a HTS with frequency-reuse factors $R_{inter} = 1/3$ and $R_{intra} = 1/7$. Fig. 5.14.a illustrates the PCS performance at $t_1 = 60$ s, whereas fig. 5.14.b shows the PCS performance at $t_2 = 180$ s. Observing fig. 5.14, the performance of the PCS bandwidth allocation applying the frequency-reuse process is more promising than the performance of the Fixed Bandwidth allocation applying Frequency-reuse process. The fixed bandwidth allocation represented by the dotted lines, suggests that disregarding the time and the bandwidth demands, the bandwidth allocation of all beams is correlative. In contrast, the PCS assigns a particular capacity of each beam and this bandwidth allocation might change time by time in accordance with the user's bandwidth requirements. The PCS bandwidth allocation performance without reusing frequency resources, that is shown in fig. 5.10, in comparison with the PCS bandwidth allocation with frequency-reuse, that is shown in fig. 5.14, differs because in the first scenario the total available bandwidth is shared among the total number of beams in the system. Instead, in the second scenario, the HTS extends the availability of frequency resources because the total bandwidth is divided by a smaller bunch of beams and this pattern is repeated several times to cover the total number of beams in the system.

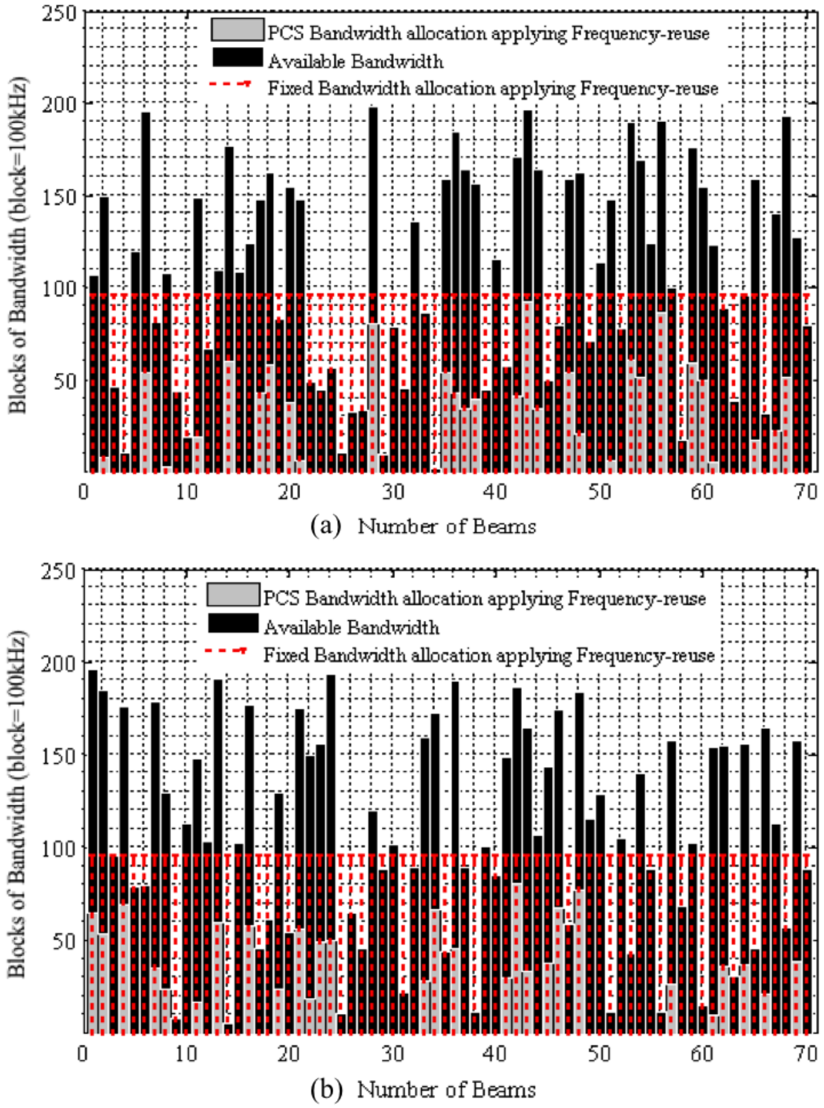


Figure 5.14: Performance of the PCS Employing Frequency-Reuse.

Generally speaking, the beams that are scheduled by the PCS frequency-reuse extend their bandwidth capacity. Based on the Frequency-reuse pattern previously described, the evaluation results suggest that the bandwidth capacity is extended by tree times.

Regarding the PCS interference, we assume that the satellite deploys horn antennas with high directivity (20 dB) to increase the directivity of multi-beams. Table 5.2 recaps some parameters to calculate the intra-band and inter-band interferences. Fig. 5.15 depicts the results of the PCS interference evaluation.

Table 5.2: PCS Interference Parameters.

Parameter	Symbol	Value (units)
Effective Isotropically Radiated Power	$EIRP$	60.734 (dB)
Free Space Loss	L	208.52 (dB)
Antenna Gain	G_r	119.5 (dBm)
Shadowing Components	G_{sh}	110 - 140 (dBm)

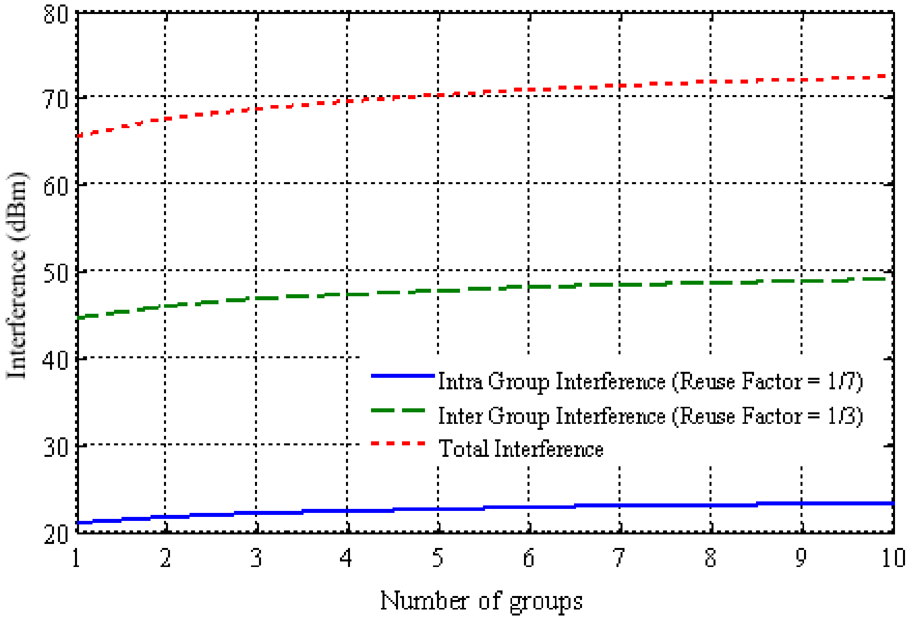


Figure 5.15: PCS Interference Evaluation.

Based on the results provided, the existence of high interference levels in environments that involves the PCS frequency-resource pattern is inevitable. Due to large number of adjacent beams within HTS systems, the authors expected these results. In conclusion, the interference performance compromises the PCS effectiveness.

In order to qualify the PCS effectiveness in terms of throughput, the PCS throughput is calculated as the ratio between the PCS bandwidth utilization and the round trip time (RTT) as function of number of beams deployed on a HTS. The bandwidth utilization employs the frequency-reuse process and the HTS is assumed to be placed on GEO orbit. The throughput performance of three different threshold's values is show in fig. 5.16. Observing fig. 5.16, it might be seen that the larger number of beams deployed, the greater the PCS throughput. The PCS throughput has values from 100 to 900 Mbps, from five to 100 beams, respectively. This fact accomplishes the goal of HTS because the PCS throughput assures a throughput of hundreds of Mbps. The PCS throughput presents contrasting variations from five to 35 beams deployed. Considering different efficiency threshold's values, in order to have a higher throughput, it is recommendable that the PCS uses an efficiency threshold equals 0.7 up to 20 beams. The reason for this is that based on the PCS throughput tendency, it is better that the PCS uses a low-restrictive algorithm from five to 20 beams. However, from 65 to 100 beams deployed, the PCS throughput has similar tendencies regardless different efficiency threshold values.

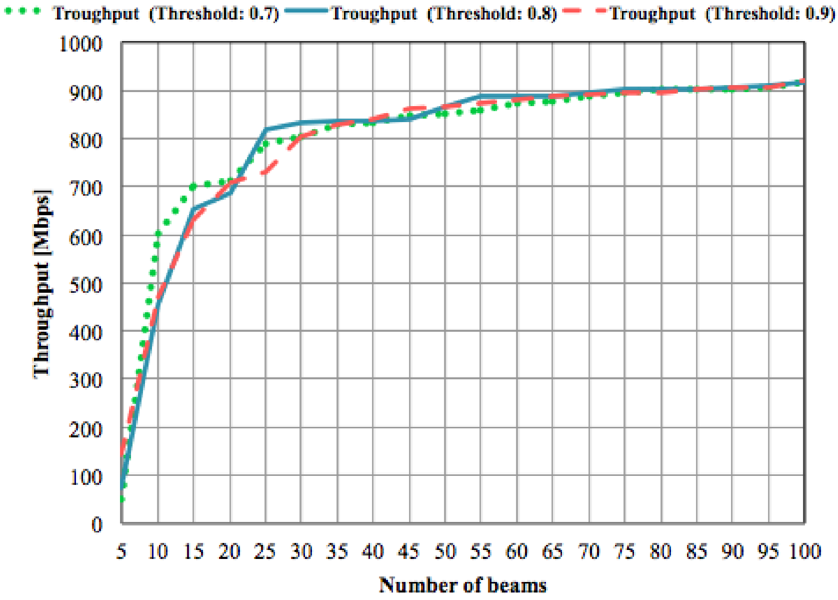


Figure 5.16: Throughput performance by using the PCS.

To exemplify the effectiveness of the PCS collaborating with other technologies under real conditions and throughput requirements, consider the following scenario involving a LTE network assisted by a HTS which uses the PCS. In LTE, the basic average throughput of 20 UE with 20 MHz bandwidth is about 3.49 Mbps. Therefore, if the HTS offer at least 100 Mbps, the HTS might be capable to respond 34 times the LTE users' demand. If the HTS offer at most 900 Mbps, the HTS may be capable to assist 257 times the LTE users' demand. These results suggest that the PCS is a suitable solution within cooperative scenarios.

5.5 Conclusions

The present chapter proved that the PCS offers advantages in terms of capacity allocation. The PCS algorithm succeeded in dynamically allocating bandwidth resources, based on user demands. This merit is remarkable because in ongoing situations, due to the dynamic behavior of user demands, the capacity needs of the network follow an unstable pattern. Thus, it is not convenient to set a fixed permanent bandwidth allocation for the beams. The results confirmed that applying the frequency-reuse process, the PCS also successfully deals with the scheme purpose. Furthermore, the PCS frequency-reuse pattern helps to increase the dynamism and the efficiency of the bandwidth utilization. On the other hand, the frequency-reuse process compromises the interference performance within the HTS. Therefore, the frequency-reuse process compensates the interference with increments in the utilization of frequency resources.

Regarding the efficiency threshold values, the results showed that this parameter is more a determinant for configurations with fewer beams than for configurations with a larger number of beams. Considering the concurrency time and the algorithm tardiness, the results proved that the PCS succeeded in reflecting, in time and manner, the user habits by increasing or decreasing the bandwidths previously assigned. The concurrency time and the algorithm tardiness are related to each other. The concurrency time tends to two types of values that are suitable in case to have a few or a large number of bandwidth adjustments. The algorithm tardiness also poses two sort of values. In order to qualify the PCS in terms of throughput, future works are conducted to compare the PCS with other techniques, such as beam hopping. Finally, regarding the PCS throughput analysis, it might be said that the PCS assures to reach a throughput of hundreds of Mbps. Additionally, the PCS throughput results suggest that the PCS is a suitable solution to satisfy the throughput requirements of other technologies, such as LTE.

Chapter 6

Conclusions and Future Work

General speaking, energy and frequency resources are the main affairs in current satellite systems. Along the present dissertation, the energy consumption and the frequency resources management were analyzed.

Respecting the energy resources, the principal concern is that energy consumption is directly related to the longevity of satellites systems. Therefore, the cost of satellite services and the general satellite system functionality are also involved. As a result, an efficient energy consumption access scheme is necessary in current satellite systems. In order to have a wisely use of the energy resources, in chapter 3 and 4 two different access schemes were proposed. Those solutions are called as ”Adjustable Energy Consumption Access Scheme” and ”Off-loading Access Scheme”.

Chapter 3 described the Adjustable Energy Consumption Access Scheme (AECS) into a Satellite Cluster Network environment. Four scenarios were analyzed, i.e. transmitting real/non-real time services over short/long distance links, employing several cluster network configurations by changing the number of nodes per cluster. The idea of changing the length of the links was also studied. The results proved that the AECS efficiently works in cluster networks with variable number of nodes. This conclusion is very significant because in real situations is almost impossible to have a cluster network without dynamic formation capability. In terms of energy consumption, the AECS scheme showed excellent performance in contrast to the other two schemes analyzed.

Due to the energy consumption has a direct impact on the satellite lifetime, the proposal of using AECS makes available to increase the satellite lifetime by at least 4.5 years. The increments of satellite lifetime have positive effects on the cost of satellite services. The reason of that is that satellite cluster networks which are able to provide services for longer time, may reduce their operating expenses. As it is expected, the transmission delay increases as result of increasing the number of nodes, increasing the distance path of intra-cluster links, and increasing the holding time duration. The AECS main delay is four times longer than the main delay related to the other two cluster schemes. Thus, within satellite cluster networks there is a tradeoff between the main delay and the energy consumption.

On the other hand, the off-loading access scheme was studied in chapter 4. It was proved that the off-loading access scheme is a reliable scheme within Delay-Tolerant LEO Satellite Networks. By using the off-loading access scheme, satellites might use less energy resources despite transmitting larger packets than satellites which do not use the off-loading access scheme. The main delay time related to the off-loading access scheme is about 13.5 min in the worst cases. This time is still satisfactory for Delay-Tolerant Network (DTN) system environments, where the delay time might be around several minutes, hours, or even some days. In addition, the advantage of using the adaptive beam forming technique is remarkable in terms of BER and co-channel interference. By using off-loading access scheme, Delay-Tolerant LEO Satellite Networks may fulfill a huge number of applications into DTN environments. For instance, Delay-Tolerant LEO Satellite Networks may be used to locate people during natural disasters, or to monitor climatic changes.

Concerning frequency resources, the scheduling process is very important to accomplish system tasks. In chapter 6 it was proved that even though the Priority Code Scheme (PCS) is very simple, it might offer advantages in terms of dynamic allocation of frequency resources. This point is quite determining in real situations. For example, if user demands follow a dynamic behavior, then, the network capacity allocation needs to follow a non-stable pattern as well. The PCS algorithm shows favourable results with different number of beams in the configuration. At the same time, variations of the efficiency threshold values are also possible. Basically, the results help to predict huge possible scheduling responses based on different configurations. However, in all cases, good performances are gotten.

Future works seek to improve the reliability of optical inter/intra satellite links at any radial pointing angle, ensuring good *BER* values. The improvements in the down/uplink sides, by using the AECs scheme, should be also included. Talking about the off-loading access scheme, future analysis may involve high throughput satellites (HTS) as network elements of the Delay-Tolerant Network. We think there are several similarities between off-loading access scheme, employing adaptive beam forming, and HTS. The combination proposal may have a beneficial impact on the performance of future HTS satellite systems. Regarding the PCS scheme, future works are going to compare the PCS scheme to other techniques. This analysis will fully complete the PCS scheme because it will help to measure the PCS scheme effectiveness.

The proposals introduced in the present dissertation might be considered as possible solutions of the resource management problems. However, they do not represent the magic formula. Once more, it is right to say that perfection does not exist within communication systems. New schemes, process, etc., maybe overcome some problems, but there are always tradeoffs to face. The good thing is that as soon as the environment characteristics and requirements change, there is always a solution to suggest.

Finally, to conclude the dissertation, it is essential to mention that, in my persona opinion, the satellite technology still has a lot to offer for the present and future communication generations.

Chapter 7

Achievements

Articles in refereed Journals:

- Lilian del Consuelo Hernandez Ruiz Gaytan, Akira Numakami, Jiang Liu, and Shigeru Shimamoto, ”Delay-Tolerant LEO Satellite Network: Off-loading Access Scheme employing Adaptive Beam Forming”, GITS/GITI Research Bulletin, Vol.XX, No.XX, pp.-, Augst. 2015. In Progress.

- Lilian del Consuelo Hernandez Ruiz Gaytan, Jiang Liu, and Shigeru Shimamoto, ”Dynamic Scheduling for High Throughput Satellites employing Priority Code Scheme”, Journal of IEEE Access in Communications (IEEE), Vol.3, pp. 2044-2054, Oct. 2015. Published.

- Lilian del Consuelo Hernandez Ruiz Gaytan, Zhenni Pan, Jiang Liu, and Shigeru Shimamoto, ”Adjustable Energy Consumption Access Scheme for Satellite Cluster Networks”, IEICE Transactions on Communications, Vol.E98-B, No.05, pp. 949-961, May. 2015. Published.

Presentations at International Conferences:

- Lilian del Consuelo Hernandez Ruiz Gaytan, Jiang Liu, and Shigeru Shimamoto, ”Priority Code Scheme for Flexible Scheduling on HTS”, in Proc. IEIE - IEEE Internal Conference on Electronics Information and Communication (ICEIC), Singapore, Jan. 2015.

Presentation at Domestic Conferences:

- Akira Numakami, Lilian del Consuelo Hernandez Ruiz Gaytan, Noun Chandarong, Jiang Liu, and Shigeru Shimamoto, ”Off-loading based Global LEO Satellite Network employing Adaptive Beam Forming”, IEICE General Conference, Kyoto, Japan, March. 2015.
- Noun Chandarong, Lilian del Consuelo Hernandez Ruiz Gaytan, and Shigeru Shimamoto, ”Energy Efficient Off-loading Scheme for LEO Satellite System”, IEICE Society Conference, Tokushima, Japan, Sept. 2014.
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- Lilian del Consuelo Hernandez Ruiz Gaytan and Shigeru Shimamoto, ”International Workshop at College of Electrical Engineering and Computer Science of National Taiwan University”, NTU, Taipei, Taiwan, Nov. 2012.

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List of academic achievements

Category	
Articles in refereed Journals	○ Lilian del Consuelo Hernandez Ruiz Gaytan, Akira Numakami, Jiang Liu, and Shigeru Shimamoto, "Delay-Tolerant LEO Satellite Network: Off-loading Access Scheme employing Adaptive Beam Forming", GITS/GITI Research Bulletin. Under Reviewing process. ○ Lilian del Consuelo Hernandez Ruiz Gaytan, Jiang Liu, and Shigeru Shimamoto, "Dynamic Scheduling for High Throughput Satellites employing Priority Code Scheme", The Journal of IEEE Access (IEEE), Vol.3, pp. 2044-2054, October, 2015. Published. ○ Lilian del Consuelo Hernandez Ruiz Gaytan, Zhenni Pan, Jiang Liu, and Shigeru Shimamoto, "Adjustable Energy Consumption Access Scheme for Satellite Cluster Networks", IEICE Transactions on Communications, Vol.E98-B, No.05, pp. 949-961, May, 2015. Published.
Presentations at International Conferences	○ Lilian del Consuelo Hernandez Ruiz Gaytan, Jiang Liu, and Shigeru Shimamoto, "Priority Code Scheme for Flexible Scheduling on HTS", in Proc. IEIE - IEEE Internal Conference on Electronics Information and Communication (ICEIC), Singapore, January, 2015.

Presentation at Domestic Conferences	Akira Numakami, Lilian del Consuelo Hernandez Ruiz Gaytan, Nuon Chandarong, Jiang Liu, and Shigeru Shimamoto, "Off-loading based Global LEO Satellite Network employing Adaptive Beam Forming", IEICE General Conference, Kyoto, Japan, March, 2015. Noun Chandarong, Lilian del Consuelo Hernandez Ruiz Gaytan, and Shigeru Shimamoto, "Energy Efficient Off-loading Scheme for LEO Satellite System", IEICE Society Conference, Tokushima, Japan, September, 2014. Lilian del Consuelo Hernandez Ruiz Gaytan, Wang Niandong, and Shigeru Shimamoto, "Elevation Angle Diversity for Quasi Zenith Satellite Communication", in Proc. IEICE Technical Committee Advanced Program on Space Aeronautical and Navigation Electronics / Satellite Communication (SANE/SAT), Technical Report - Special Session, Vol. 110, No. 426, Kobe, Japan, February, 2011. Published.
International Workshops	Lilian del Consuelo Hernandez Ruiz Gaytan and Shigeru Shimamoto, "International Workshop at College of Electrical Engineering and Computer Science of National Taiwan University", NTU, Taipei, Taiwan, November, 2012.