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Satellite communication optimization using multi-layer constellation algorithm

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Dedication

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To my professors and mentors, your guidance and wisdom have shaped the foundation of this achievement.
And to my friends, thank you for standing by me through every challenge and triumph.
This accomplishment is not mine alone—it belongs to all of you.

Abstract:

This thesis presents a comprehensive study on optimizing satellite communications using multi-layer satellite constellations. It investigates orbital dynamics, coverage geometry, and routing challenges in modern satellite networks, particularly in Low Earth Orbit (LEO). Special attention is given to inter-satellite links (ISLs), Free Space Optics (FSO), and laser-based communication systems. The thesis also explores handover strategies, constellation architectures like Walker and SoC models, and mitigation techniques for orbital collision risks.

The work proposes a novel 3D routing algorithm that selects communication paths based on signal-to-noise ratio (SNR), link congestion, and geometric positioning to enhance data transmission reliability and energy efficiency. Through simulation and analytical modelling, the study evaluates the system's performance and its ability to maintain communication under failure or high-traffic conditions.

Keywords: Satellite communication, Laser link, Signal-to-noise ratio, LEO constellation, Routing algorithm.

الملخص:

تعرض هذه الأطروحة دراسة شاملة لتحسين الاتصالات عبر الأقمار الصناعية باستخدام كوكبات متعددة الطبقات. يتم فيها تحليل الديناميكيات المدارية، وهندسة التغطية، وتحديات التوجيه في شبكات الأقمار الصناعية الحديثة، وخاصة في المدار الأرضي المنخفض .(LEO) يتم التركيز على الروابط بين الأقمار الصناعية(ISL) ، وتكنولوجيا البصريات في الفضاء الحر(FSO) ، وأنظمة الاتصالات الليزرية. وتشمل الأطروحة أيضاً استراتيجيات التمرير بين الأقمار، وتصميمات الكوكبات مثل نماذج Walker وSoC، وأساليب تقليل مخاطر الاصطدام المداري .تقترح هذه الأطروحة خوارزمية توجيه جديدة ثلاثية الأبعاد، تعتمد على نسبة الإشارة إلى الضجيج (SNR)، والازدحام في الروابط، والموقع الهندسي لتحسين موثوقية الاتصال وكفاءة الطاقة. كما تقيّم الدراسة أداء النظام من خلال النمذجة التحليلية والمحاكاة، ومدى قدرته على الحفاظ على الاتصال في حالات الفشل أو الازدحام.

الكلمات المفتاحية: الاتصالات الساتلية، الوصلات الليزرية، نسبة الإشارة إلى الضجيج، كوكبةLEO ، خوارزمية التوجيه.

Résume :

Ce mémoire présente une étude approfondie sur l'optimisation des communications par satellite à l'aide de constellations multi-couches. Il analyse la dynamique orbitale, la géométrie de couverture et les défis de routage dans les réseaux de satellites modernes, notamment en orbite terrestre basse (LEO). Une attention particulière est accordée aux liaisons inter-satellites (ISL), aux technologies optiques en espace libre (FSO) et aux communications par laser. Le mémoire explore aussi les stratégies de handover, les modèles de constellations comme Walker et SoC, et les mesures d'atténuation des collisions en orbite.

Le travail propose un algorithme de routage 3D innovant qui sélectionne les chemins de communication en fonction du rapport signal/bruit (SNR), de la congestion des liaisons et de la position géométrique, afin d'améliorer la fiabilité et l'efficacité énergétique de la transmission. À travers des simulations et des modèles analytiques, la performance du système est évaluée, notamment sa capacité à maintenir la communication en cas de surcharge ou de panne.

Mot clé: Communication satellitaire, Lien laser, Rapport signal/bruit, Constellation LEO, Algorithme de routage.

Table of Contents:

Chapter I: Introduction to satellite communication

Chapter II: Satellite Constellation and Handover

Chapter III: Satellite Communication Optimisation

List of figures:

Chapter I: Introduction to satellite communication

Chapter II: Satellite Constellation and Handover

Chapter III: Satellite Communication Optimisation

List of tables:

Chapter I: Introduction to satellite communication

Chapter II: Satellite Constellation and Handover

Chapter III: Satellite Communication Optimisation

List of Notations:

General Introduction

- LEO: Low Earth Orbit
- MEO: Medium Earth Orbit
- GEO: Geostationary Earth Orbit
- ISL: Inter-Satellite Link
- FSO: Free Space Optics

Chapter I

- LOS: Line of Sight
- TT&C: Tracking, Telemetry, and Command
- TTC&M: Tracking, Telemetry, Command, and Monitoring
- VSAT: Very Small Aperture Terminal
- SNG: Satellite News Gathering
- NIR: Near-Infrared
- BOL: Beginning of Life
- EOL: End of Life
- RF: Radio Frequency
- THz: Terahertz
- *n*: Mean motion
- *t*: Observation date
- *p*: Time of passage at perigee
- *ra*: Apogee distance from Earth’s center
- *rp*: Perigee distance from Earth’s center

Chapter II

- SoC: Street-of-Coverage
- Δv: Delta-V (Change in velocity)
- SSA: Space Situational Awareness
- CDM: Conjunction Data Message
- GNSS: Global Navigation Satellite System

- T: Total satellites
- P: Total orbital planes
- F: Phasing parameter
- $\Delta\lambda$: Angular spacing between satellites
- N: Number of orbital planes
- S: Satellites per plane
- *i*: Inclination angle
- *h*: Orbital altitude
- θ: Half-angle of coverage cone
- $\Delta\Omega$: Spacing between orbital planes
- Δv: Spacing between satellites within a plane
- Rf: Ground footprint radius
- Re: Earth’s radius

Chapter III

- MLSN: Multi-Layer Satellite Networks
- AI: Artificial Intelligence
- ML: Machine Learning
- HRL: Hierarchical Reinforcement Learning
- RNN: Recurrent Neural Network
- IOL: Inter-Orbit Link
- GA: Genetic Algorithm
- MAE: Mean Absolute Error
- TDMA: Time Division Multiple Access
- DQN: Deep Q-Network
- PPO: Proximal Policy Optimization
- SNR: Signal-to-Noise Ratio
- NTN: Non-Terrestrial Networks
- QoS: Quality of Service
- Ei: Energy level of node *i*

- *Emax*: Max energy capacity

α: Energy penalty weight

General Introduction

General Introduction:

The use of satellites in communications systems is very much a fact of everyday life, as is evidenced by the many homes equipped with antennas, or “dishes,” used for reception of satellite television. What may not be so well known is that satellites form an essential part of telecommunications systems worldwide, carrying large amounts of data and telephone traffic in addition to television signals.[1]

Satellites offer a number of features not readily available with other means of communications. Because very large areas of the earth are visible from a satellite, the satellite can form the star point of a communications net, simultaneously linking many users who may be widely separated geographically. The same feature enables satellites to provide communications links to remote communities in sparsely populated areas that are difficult to access by other means. Of course, satellite signals ignore political boundaries as well as geographic ones, which may or may not be a desirable feature.[1]

Laser satellites offer several advantages over standard satellites, making them highly important in the field of communication. They have made communication between different regions of the world faster and more efficient. The main complexity of an optical transmission system using laser satellites lies in the pointing system. Laser beams can sometimes partially or completely miss the receiving satellite due to continuous vibrations in the pointing system, caused by internal and external surrounding sources. Various methods can be used to overcome these disturbances and, consequently, improve communication quality. [2,3,4]

The calculation of the link budget is a crucial step in satellite data transmission to ensure the availability and quality of the connection.

A Low Earth Orbit (LEO) network is composed of dozens to hundreds of satellites that circle the Earth at relatively low altitudes and high velocities. These systems operate independently of terrestrial geography, which enables rapid restoration in case of natural disasters such as earthquakes. Moreover, they provide significant benefits in delivering seamless global mobile communication coverage. [5,6]

Satellites operate in three main orbits: LEO (160 km to 2,000 km) for low-latency, Highspeed tasks like Earth observation and (STARLINK) systems. MEO (2,000 km to 35,786 km) supports navigation systems like GPS. GEO (35,786 km) offers wide coverage for broadcasting and communication but with higher latency. Each orbit type serves specific needs based on coverage, Latency, and cost.

Until the last decade, one satellite was enough to carry out most space missions. Over the past decade, it has become clear that for some applications, a single spacecraft cannot achieve mission objectives. One way to achieve mission objectives is to use a satellite array in different orbits in orbital terminology a "satellite constellation”

A satellite constellation refers to a coordinated network of artificial satellites that operate collectively as an integrated system. In contrast to individual satellites, constellations are capable of ensuring continuous global or near-global coverage, guaranteeing that at any given moment and location on Earth, at least one satellite remains within view. These satellites are commonly deployed in multiple complementary orbital planes and maintain communication links with ground stations distributed worldwide. Additionally, inter-satellite communication may be employed to enhance connectivity and network efficiency. [7]

For most constellations, ground coverage is the main reason for using multiple satellites. A constellation can provide more frequent observations and communications than a single satellite. Given this objective, the normal trade of constellation design is coverage as a measure of performance versus number of satellites as a measure of cost. [8]

In a constellation of satellites, we use inter-satellite links (ISL) electrical or optical radio links are used to provide a connection between satellites without the need for intermediate ground stations. The ISL Radio have the advantage of having a mature technique, so that the risk of failure is minimized. However, bandwidth limits the transmission speed and the optical systems, with their much higher frequencies have a much larger bandwidth. [1]

RF-FSO communication uses a combination of RF and FSO links to transmit data. The RF link provides a reliable and continuous communication channel that can transmit data through obstacles and adverse weather conditions. On the other hand, the FSO link provides a high-speed and secure communication channel that is immune to interference from other RF sources. The combination of these two links provides a robust and reliable communication system that can operate in diverse environments. RF-FSO communication has several advantages over traditional RF or FSO communication. First, it provides high-speed communication with data rates up to several Gbps, which is much higher than traditional RF communication. Second, it is immune to interference from other RF sources, making it suitable for use in crowded RF environments. Third, it provides a secure communication channel because the FSO link cannot be intercepted without physical access to the transmitter and receiver, and it can be mitigated against environmental factors such as atmospheric turbulence.[9]

In general, existing routing strategies in LEO satellite constellations can be classified into centralized and distributed ones. Centralized strategies typically leverage virtual topology or virtual node approaches to transform the satellite topology into a static one, and Dijkstra Shortest Path (DSP) algorithm can be executed on the static topology to obtain a routing path with minimum propagation delay. Furthermore, as the traffic within constellation increases, routing strategy design should jointly considers propagation delay and queuing delay[10]. this aspect, The chapter also identifies critical challenges, including link congestion, energy constraints, and real-time adaptability, and proposes a novel 3D laser-based, signal-aware routing algorithm that selects communication paths based on signal quality, delay, and fallback options to ensure reliable and optimized satellite connectivity.

This manuscript is divided into three chapters:

Chapter One introduces the foundations of satellite communication, including orbital mechanics, satellite components, RF and FSO technologies, and network structure.

Chapter Two focuses on satellite constellations and handover strategies. It explains constellation design methods like Walker Delta and Streets of Coverage, their parameters, and their role in global coverage. It also details various handover types (spotbeam, satellite, ISL, network layer) and introduces collision avoidance and hybrid constellation architectures.

Chapter Three explores optimization techniques for satellite communication, focusing on routing, resource efficiency, and system performance. proposes a novel algorithm for routing in satellite networks using 3D laser link simulation and real-world scenarios and simulations validate the method's performance in delay, reliability, and SNR.

Finally, the thesis concludes with a general summary.

CHAPTER I:

Introduction to satellite communication

I. Introduction

Satellites are devices placed in outer space for telecommunications purposes. A satellite is a man-made object launched into orbit around a celestial body, particularly the Earth, by a rocket or a space transport system. Originally developed for political reasons, artificial satellites have become essential tools for science, defense, telecommunications, and for a wide range of applications such as weather forecasting, pollution control, and the rescue of sailors in distress. [11]

This chapter is a general introduction to satellite telecommunications systems. The objective is to define and present the main essential characteristics of these systems.

I.1 History of Communication Satellites

The concept of geostationary communication satellites was initially proposed by Arthur C. Clarke in 1945. The launch of Sputnik 1 by the Soviet Union in 1957 marked the beginning of the Space Age. Early satellites functioned as either passive devices that merely reflected signals or active ones capable of amplifying and retransmitting them. Over time, satellite communications have progressed from theoretical concepts to a vital element of the modern global infrastructure, influencing a wide range of applications from worldwide navigation systems to everyday internet connectivity.

Satellite communications have revolutionized global connectivity, enabling everything from television broadcasting to internet services and military applications. Below is a timeline of key developments in satellite communications history.[12]

a. Early Concepts & Theoretical Foundations (Pre-20th Century – 1950s)

- ✓ 1865: Jules Verne, in his novel From the Earth to the Moon, imagined an artificial satellite.
- ✓ 1903: Konstantin Tsiolkovsky, a Russian scientist, laid the groundwork for space exploration in The Exploration of Cosmic Space by Means of Reaction Devices.
- ✓ 1945: British scientist Arthur C. Clarke proposed the idea of geostationary communication satellites in his paper Extra-Terrestrial Relays. This concept later became the basis for modern satellite communications.

b. Early Satellites & First Communications (1950s – 1960s)

- ✓ **1957:** The Soviet Union launched *Sputnik 1*, the first artificial satellite. It transmitted simple radio pulses back to Earth.

- ✓ **1958:** The United States launched *Explorer 1*, detecting the Van Allen radiation belts.
- ✓ **1960:** NASA launched *Echo 1*, a passive communications satellite that reflected radio signals.
- ✓ **1962:** *Telstar 1* became the first active communications satellite, successfully transmitting the first live television signal across the Atlantic.
- ✓ 1963: Syncom 2, the first geosynchronous satellite, was launched by NASA, proving that satellites could provide continuous global communications.

c. Expansion of Satellite Communications (1970s – 1980s)

- ✓ **1972:** The launch of *Anik A1* made Canada the first country with a domestic communications satellite.
- ✓ **1976:** The *Marisat* satellites beganproviding satellite communications for maritime applications.
- ✓ **1983:** The first GPS satellite was launched as part of the U.S. Department of Defense's NAVSTAR GPS program.
- ✓ **1988:** The *Iridium* project was proposed, aiming to provide global satellite phone coverage.

d. Digital Revolution & Global Connectivity (1990s – 2000s)

- ✓ **1993:** The Global Positioning System (GPS) became fully operational, revolutionizing navigation.
- ✓ **1997:** The launch of *Iridium* satellites began, offering worldwide satellite phone coverage.
- ✓ **2000s:** High-throughput satellites (HTS) such as *ViaSat-1* and *KA-SAT* improved broadband internet via satellite.

e. Modern Satellite Communications (2010s – Present)

- ✓ **2010s:** Private companies like SpaceX, OneWeb, and Amazon entered the satellite market with plans for low-Earth orbit (LEO) broadband constellations.
- ✓ **2015:** SpaceX launched the first test satellites for *Starlink*, a project aimed at providing global internet coverage.
- ✓ 2020s: The rapid expansion of satellite constellations, including Starlink, OneWeb, and Project Kuiper, is transforming global broadband access.

I.2 Definition of a Telecommunications Satellite

A communications satellite is a microwave repeater station that permits two or more users with appropriate earth stations to deliver or exchange information in various forms. As discussed later in this chapter, a satellite in a geostationary Earth orbit (GEO) revolves around the Earth in the plane of the equator once in 24 hours, maintaining precise synchronization with the Earth's rotation. There are two other classes of 24-hour orbits: the geosynchronous orbit and the highly elliptical synchronous orbit. Both involve satellites that appear tomove relative to a fixed point on the Earth. [13]

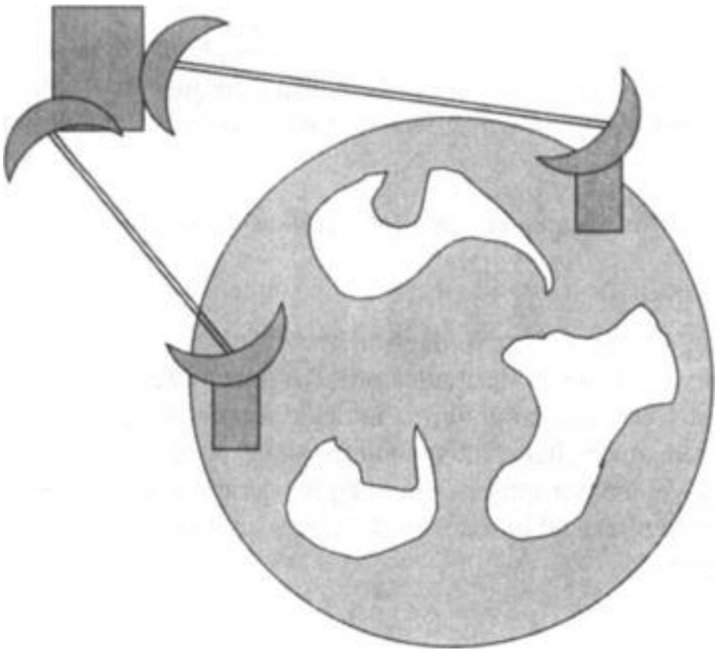

Figure I.1: Satellite Telecommunications

Satellites serve as fundamental components of the global communication network, enabling a wide range of services including television broadcasting, internet access, telephony, and military communications. Their performance and functionality vary according to their orbital classification—geostationary (GEO), medium Earth orbit (MEO), or low Earth orbit (LEO)—each offering distinct advantages in terms of coverage, latency, and data transmission capacity. Generally, satellites are divided into two main types: passive satellites, which reflect signals, and active satellites, which amplify and retransmit them.

a.Passive satellites: As the name suggests, a passive satellite is one that acts passively in relaying the signal it receives; that is, it simply reflects the incident signal.

b.Active satellites: An active satellite, on the other hand, receives the signal, processes it to some extent, then amplifies and relays it.. [14]

I.3 Definitions of Satellite Communication Systems

Satellite communication, in telecommunications, the use of artificial satellites to provide communication links between various points on Earth. Satellite communications play a vital role in the global telecommunications system. Approximately 2,000 artificial satellites orbiting Earth relay analog and digital signals carrying voice, video, and data to and from one or many locations worldwide. [15]

I.3.1 Segments of Satellite Communications

In some cases, the requirements may be so extensive that a dedicated satellite or constellation is justified. The purpose of this book is to define and describe all the parts of such a system because an understanding of satellite communication requires the development of a feel for the breadth of the technology. This section describes the system in terms of two major parts, the space segment and the ground segment [13]

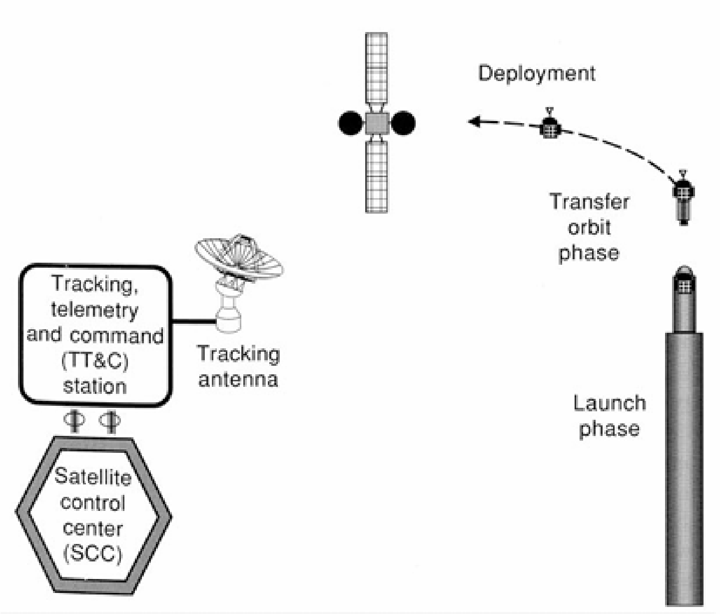

Figure I.2: The space segment of a satellite telecommunications network.

I.3.1.1 The Space Segment

Figure I.2 is an overview of the main elements of the space segment. As can be seen from the figure, placing a satellite into orbit and operating it for 12 or more years involves a great deal. Placement in orbit is accomplished by contracting with a spacecraft manufacturer and a launch agency and allowing them about three years to design, construct, and launch the satellite,After the spacecraft is placed in the proper orbit, it becomes the responsibility of a satellite operator to control the satellite for the duration of its mission (its lifetime in orbit).[13]

I.3.1.2 The Ground Segment

The ground segment provides access to the satellite repeater from Earth stations to meet communications needs of users (television viewers, information network providers, enterprises, disaster workers, and Websurfers).a single satellite is shown to indicate that the links are established through its repeater rather than directly from Earth station to Earth station. Incidentally, Earth station is an internationally accepted term that includes satellite communication stations located on the ground, in the air (on airplanes), or on the sea (on ships). Many commercial applications are through Earth stations at fixed locations on the ground; thus, the international designation for such an arrangement is fixed satellite service (FSS). Related to FSS is broadcasting satellite service (BSS), targeted to individual home reception of a variety of broadcast information (e.g., TV, radio, and data). Mobile satellite service (MSS) has been in operation for some time, offering interactive voice and data services for ships, aircraft, and individuals. Fixed Earth stations have experienced atremendous reduction in size at the same time that satellites have grown in size and power capability. Earth stations have evolved from the first international FSS behemoths with 30m antennas to the inexpensive BSS systems, with their half-meter fixed dishes. For the new generation of MSS Earth stations, the requirements are being met with handheld devices about the size of a PDA. [13]

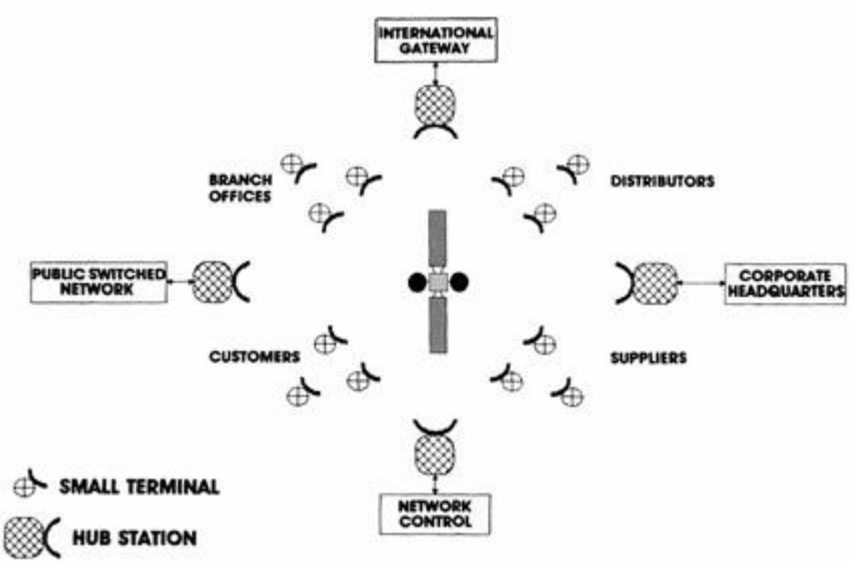

Figure I.3: The ground segment of a satellite network providing two-way interactive services to a variety of locations [13]

Figure I.4: An example of a small customer-premise VSAT used in two-way data communications [13]

I.3.2 Advantages of Satellite

Satellites are widely utilized across numerous communication applications due to several well-established advantages. These benefits stem primarily from the fundamental physics underlying satellite systems—most notably, their ability to cover vast geographic areas simultaneously. In addition, satellites operate using microwave radio frequencies, granting them the flexibility and mobility inherent to wireless communication technologies. Many of these advantages are interconnected, and their relative importance continues to evolve alongside advancements in technology and emerging applications. When effectively leveraged, satellite communication can serve as a highly efficient and versatile medium. For example, direct-to-home television networks rely on satellites to deliver content directly to users, national retail chains employ VSAT networks to bypass inadequate or fragmented terrestrial infrastructures, and maritime operators depend on satellite links for reliable ship-to-shore communication. Establishing such connections through satellite technology provides a robust foundation for expanding both business operations and strategic initiatives. [13]

I.3.3 Different Categories of Satellites

There are five types of satellites:

- ✓ **Astronomical Satellites**: Positioned above the atmosphere, they provide better views of stars and black holes since they are not hindered by air layers and pollution.
- ✓ **Navigation Satellites**: Used to locate the position of ships and ocean currents.

- ✓ Weather Satellites: Used to take pictures of Earth, which help in weather forecasting. They can either be geostationary or constantly orbiting the Earth.
- ✓ **Telecommunication Satellites**: Used for telephone communications, television broadcasting, and radio.
- ✓ **MilitarySatellites**:Used for telecommunications and surveillance (land and maritime reconnaissance).

Once a satellite has completed its mission, it is disposed of in the following ways:

- ✓ It is allowed to fall back to Earth: Scientists calculate its reentry to ensure it lands in an uninhabited area (often in the middle of the ocean). If it is small, it disintegrates in the atmosphere due to friction.
- ✓ It is moved to a higher orbit around Earth. [3,16]

I.4 Satellite Orbits

I.4.1 Definition of Orbit:

Almost all satellites, whether used for observation or telecommunications, have orbits, meaning specific trajectories for a body with periodic motion, tailored to their purpose. Three types of orbits can be distinguished: geostationary orbit, medium-altitude orbits, and low-altitude orbits, each having different characteristics. Orbits can also be classified based on their shapes, where two types are identified: circular orbits and elliptical orbits. [17,18]

I.4.2 Orbital Mechanics of Satellites

This section describes the **mechanics of satellite orbits** and their significance concerning **communication satellites**, along with the fundamental **laws governing satellite orbits** and the key **parameters** that define the motion of **artificial Earth satellites**.

The problem of determining a satellite's position and trajectory in space over time has been a subject of interest for scientists and philosophers for thousands of years. It was ultimately Johannes Kepler in the 17th century who discovered the properties of planetary motion based on observations of the Sun and its planets. [13,19]

I.4.3 Satellite in Keplerian Orbit

I.4.3.1 Three Laws of Kepler

The three laws of Kepler concerning planetary motion are:

A. Law of Ellipses: In 1609, Kepler established that the orbit of each planet is an ellipse with the Sun at one of its foci. The following figure outlines this law of ellipses.

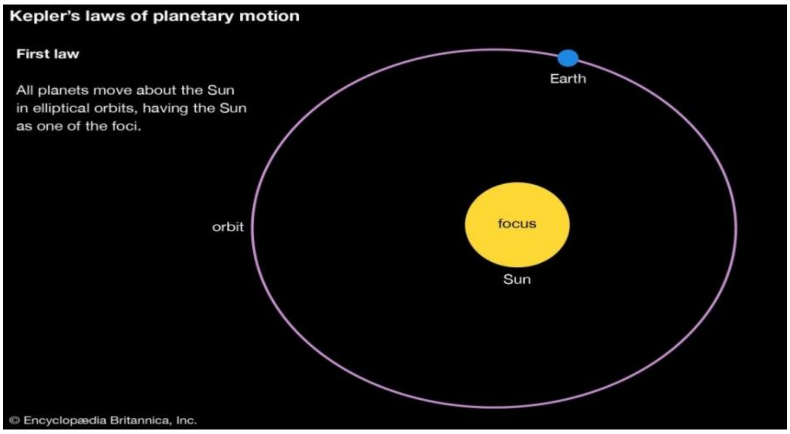

Figure I.5: First law of Kepler

B. Law of Areas: The law of areas states that the area swept by the satellite is proportional to the time, meaning that in equal intervals of time, equal areas are swept [20]. The following figure illustrates this law of areas. [17]

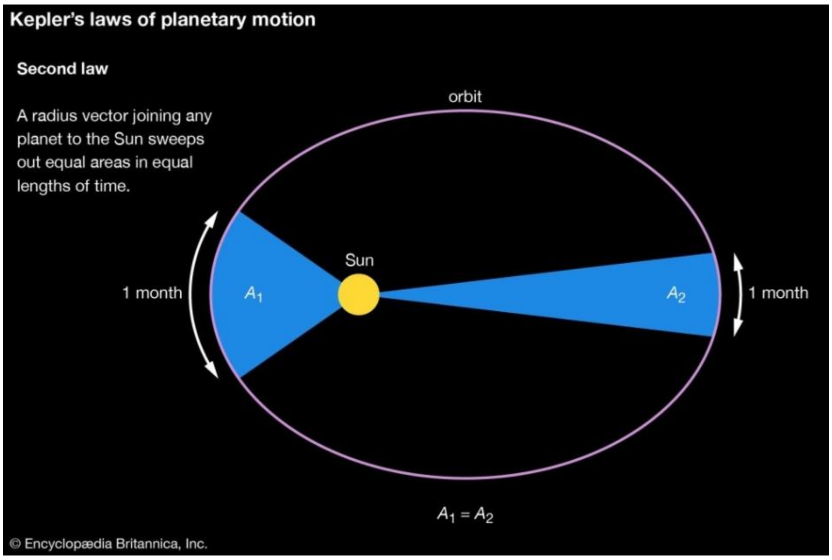

Figure I.6: Second law of Kepler

C. Law of Periods: This law explains that the squares of the revolution periods are proportional to the cubes of the lengths of the major axes. [18,20]

Newton’s discovery of the universal law of gravitation allowed scientists to identify the forces underlying Kepler's laws. Specifically, each mass (M_1) attracts another mass (M_2) with a force (F) directed along the line connecting the two masses, given by the equation:

$$F = G.(M1.M2)/r2 \qquad (I.1)$$

Where **G** is the **universal gravitational constant**. [1,8,21,22]

I.4.4 Satellite Position on the Orbit

If the orbit is defined, it is necessary to specify where the satellite is located on it. For this, the position of the satellite is determined by:

A. Mean Anomaly (M):

This is the angle the satellite makes with the perigee, coinciding with the true anomaly of a satellite in a circular orbit with the same period t. It is defined as:

$$M = n(t - tp)M \ = \ n(t - t_p)M = n(t - tp) \qquad \text{(I.2)}$$

Where:

- n is the mean motion, defined as:
  $$M = n(t - tp) \qquad \text{(I.3)}$$
- $t$is the observation date.
- $tp$is the time of passage at the perigee.

B. True Anomaly (v):

This is the angle v, known as the true anomaly. The satellite's position is determined by this angle, measured in the direction of the satellite's motion from 0° to 360°, between the direction of the perigee and the direction of the satellite.

C. Orbital Eccentricity (e) and Semi-Major Axis (a):

These parameters characterize the shape of the orbit. The eccentricity is defined as:

$$e = \frac{(ra - rp)}{(ra + rp)} \qquad \text{(I.4)}$$

Where:

- ra is the distance between the Earth's center and the apogee.
- rp is the distance between the Earth's center and the perigee.

D. Argument of Perigee (ω):

This represents the orientation of the orbit in its plane. It is the angle between the ascending node's direction and the perigee's direction. [17]

I.4.5 Types of Trajectories: [23,24]

a. Elliptical Orbit:

Satellites in elliptical orbits have a highly variable speed depending on their position along the ellipse. As a result, they do not maintain a fixed position relative to the Earth, requiring the use of mobile ground antennas to track these satellites, unlike geostationary satellites. However, they have the advantage of more easily serving regions far from the equator at a relatively high angle, which means that transmitted signals pass through a thinner atmospheric layer. This type of orbit is illustrated by the following figure.

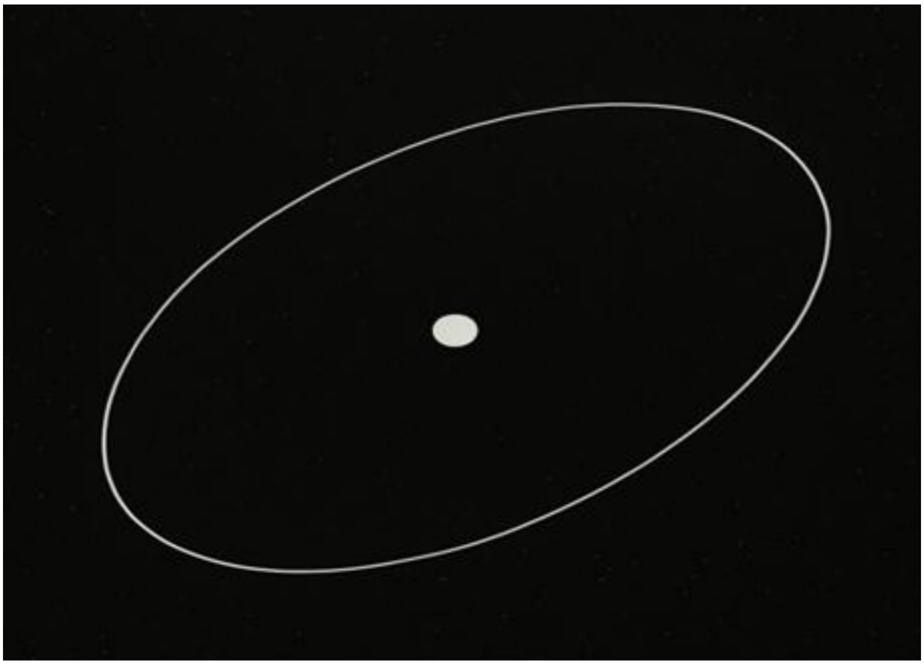

Figure I.7: The elliptical orbit

b. Circular Orbits:

The center of the trajectory coincides with the center of the Earth. A satellite in a circular orbit maintains a constant speed and a fixed distance relative to the Earth. In this case, three types are distinguished:

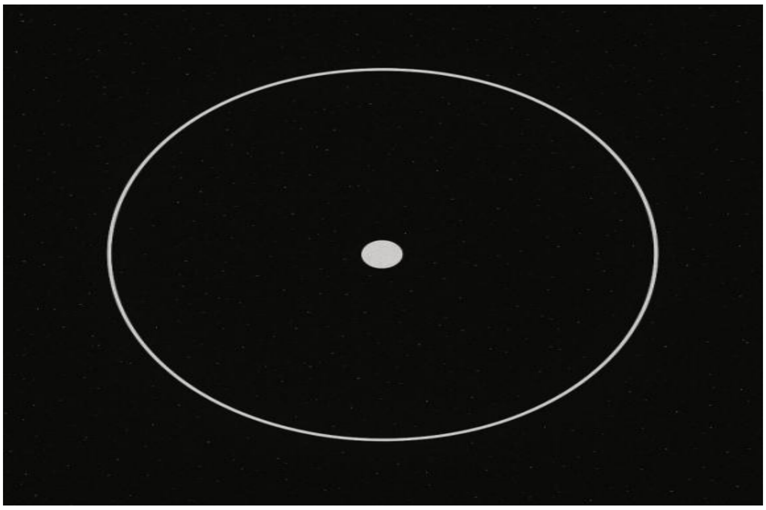

Figure I.8: Circular Orbit

b.1. Polar Circular Orbit:

A polar orbit is a circular path that allows a satellite to pass over both the North and South Poles of the Earth. The primary limitation of this orbital configuration lies in the relatively slow rate of coverage achieved by the satellites. Nonetheless, this slower progression enables the satellite to observe and cover a substantial portion of the Earth's surface—and potentially the entire globe—due to the planet's rotation on its axis.

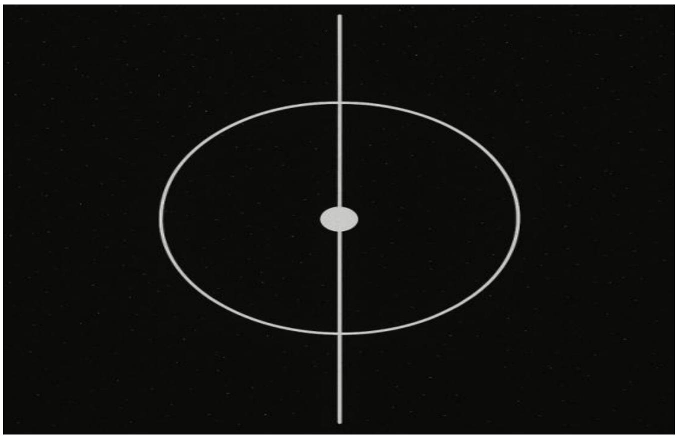

Figure I.9: Polar Circular Orbit

b.2 Inclined Circular Orbit:

Inclined circular orbits are characterized by satellite trajectories that form circular paths around the Earth, each tilted at a defined angle relative to the equatorial plane. The principal limitation of this orbital type is that such satellites are unable to provide complete global coverage, as the maximum latitude they can reach is determined by the degree of orbital inclination. Nevertheless, this configuration offers a key advantage: by adjusting the satellite's altitude, it becomes possible to focus coverage on specific regions of interest, thereby enabling targeted communication or observation of areas that hold economic, military, or strategic significance

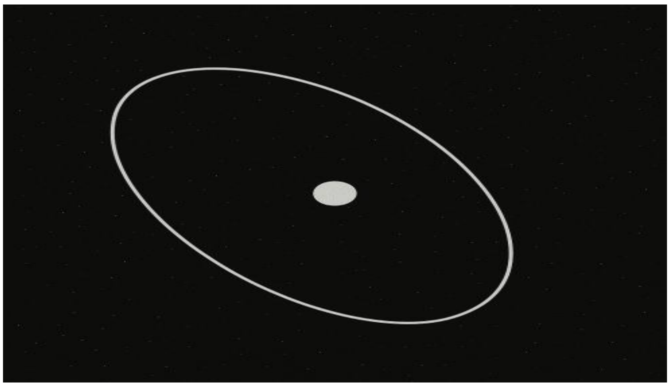

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Figure I.10: Inclined Circular Orbit

b.3 Geostationary Orbit (GEO):

At an altitude of 35,786km above the Equator, the angular velocity of a satellite in thisorbit matches the angular rate of rotation of the Earth's surface. This makes thesatellite appear stationary to an observer on the Earth. This useful feature has resultedin the orbit becoming extremely popular, and satellite spacing in the orbit is at thelimits of terrestrial antenna discrimination (the angle between orbital slots has graduallynarrowed from 3° to 2° and occasionally 1.5°).Coverage of high latitudes is impossible above 81° latitude and rarely possible above75°, so full Earth coverage cannot be achieved by using any purely geostationaryconstellation. However, much of the Earth can be covered with a minimum of threegeostationary satellites.Propagation delay between an earth station and a geostationary satellite varies with thedifference in position in longitude and terminal latitude, but is around 125ms(milliseconds), or around 250ms between ground stations. This leads to the widelyquoted half-second round-trip latency for communications via geostationary satellite.[47]

The most advantageous orbits for various applications are as follows :

I.4.6 Low Earth Circular Orbits (LEO)

At altitudes of typically between 500 and 2000km, lying beyond the upper atmospherebut below the peaks of the inner Van Allen radiation belt, a large number of satellites isrequired to provide simultaneous global coverage in low earth orbit. The actualnumber of satellites used depends upon the coverage required and upon the minimumelevation angle desired for communication. These determine the degree of atmosphereinduced slant loss permitted, and dimension the resulting link budget.With a large number of satellites and their resulting small footprint areas (shown forthe Boeing Teledesic design in figure 1.4) and small spotbeamcoverage areas, largeamounts of frequency reuse become possible across the Earth, providing large systemcapacity. [47]

I.4.7 Medium Earth Circular Orbits (MEO)

At altitudes of between 9,000 and 11,000km, between the inner and outer Van Allenbelts, these orbits can permit full Earth coverage with fewer, larger satellites. Thesatellites have larger coverage footprints from the increased altitude, but also increasedresulting delay. Movement is slower, with visibility times of tens of minutes beforehandover must take place. Propagation delay for the uplink or downlink between earthstation and satellite is typically under 40ms.[47]

I.4.8 Circular Orbits with Zero Inclination (Equatorial Orbits)

The most popular is the geostationary satellite orbit; the satellite orbits the Earth in the equatorial plane according to the Earth's rotation at an altitude of 35,786 km. The period is equal to that of the Earth's rotation. The satellite thus appears as a fixed point in the sky and provides continuous operation as a real-time radio relay for the satellite's visibility area (43% of the Earth's surface).

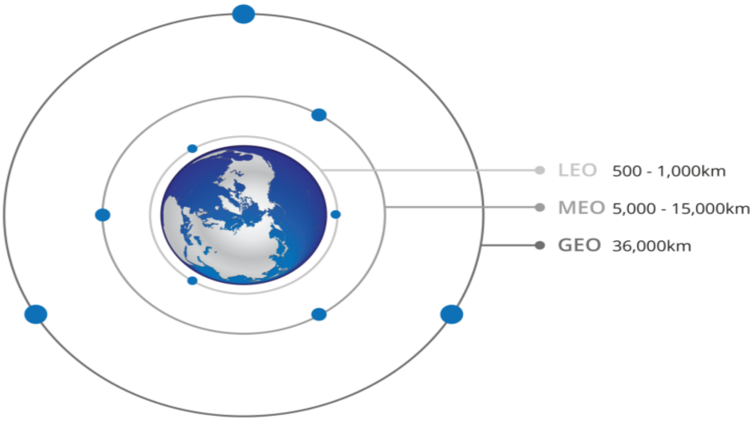


Figure I.11: Satellite Orbits

I.5 Components of a Satellite Telecommunication System

FigureI.8 clearly illustrates the various components of a satellite telecommunication system. These components include: [13,25]

The uplink ground station

Uplink (transmission link)

The space station (satellite)

Downlink (reception link)

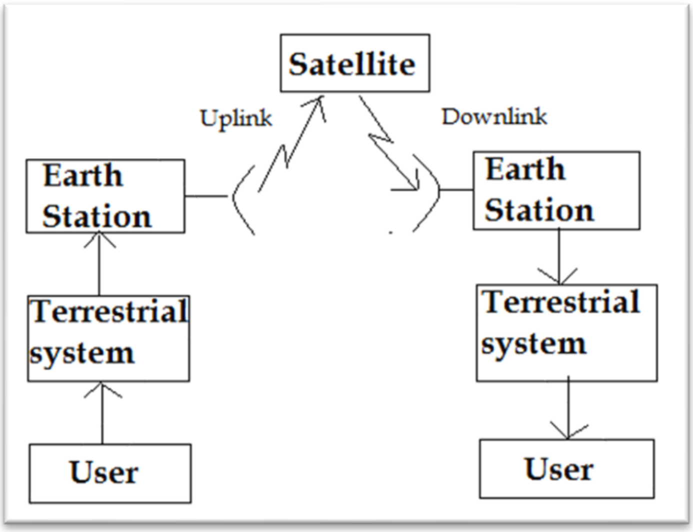


Figure I.12: Components of a Satellite Telecommunications System

a. Uplink Ground Station

This process involves a central facility where the information signals intended for transmission are generated and processed. These may include video and audio signals for television broadcasting, as well as telephone or data signals used in professional communication systems. The prepared signals are then transmitted to the primary uplink station—typically via cable, optical fiber, or microwave links—where the transmission equipment and main transmitter are located.

b. Uplink

The main element within the uplink section of a satellite system is the transmitter of the ground station.

c. Space Station

This includes the satellite and all control systems located on the ground, such as tracking, telemetry, and command (TT&C) stations, as well as the satellite control center. These facilities handle all operations related to maintaining the satellite in position and monitoring its vital functions.

d. Downlink

The main element within the downlink section of a satellite system is the transmitter onboard the satellite. The satellite transmitter consists of the final stages, which are traditionally responsible for amplifying the low-level RF (radio frequency) signal and transmitting it.

I.6 Structure of the Satellite

The satellite consists of a payload and a platform. The payload of a communication satellite includes the reception and transmission antennas and all the electrical equipment ensuring the transmission of signals. The platform contains all the subsystems that allow the payload to function. It includes:

The structure.

The power supply.

Thermal control.

Attitude and orbit control.

Propulsion equipment.

Tracking, telemetry, and command (TT&C) equipment.

The payload of a communication satellite comprises a set of channels (transponders), each channel being equipped with a transmission amplifier operating in a specific sub-band of the frequency band allocated to the satellite. This channel arrangement allows each channel to provide power aligned with the current technological capabilities of the onboard microwave amplifiers, whereas using a single amplifier for the entire band would result in power dispersion from the amplifier. Table is a simple chart listing these systems, their purposes and the principal parameters that characterize them quantitatively. [25]

Table I.1: Structure of the Satellite

System	**Function**	**Principal Quantitative Characteristics**
Communication Transponders Antennas	Receive, amplify, process and retransmit signals; capture and radiate signals	Transmitter power, bandwidth, G/T, beamwidth, orientation, gain, signal-carrier saturated Flux density.
Structure	Support space craft under launch and orbital environment	Resonant frequencies, structural strengths

Primary power	Supply electrical power to spacecraft	Beginning of life (BOL) power, end of life (EOL) power; solstice and equinox powers, eclipse operation
Thermal control	Maintain suitable temperature ranges for all subsystems during life, operating and non-operating, in and out of eclipse	Spacecraft mean temperature range and temperature ranges for all critical components
Telemetry, tracking, and command (TT&C)	Monitor spacecraft status, orbital parameters, and control spacecraft operation	Position and velocity measuring accuracy, number of telemetered points, number of commands
Attitude control	Keeps antennas pointedat correct earth locations and solar cells pointe datthesun	Role, pitch, and yaw tolerances.
Propulsion	Maintain orbital position, major attitude control corrections, orbital changes, andinitialorbit deployment	Specific impulse, thrust, propellant mass
Complete spacecraft	Provide satisfactory communications operations in desired orbit	Mass, primary power, design lifetime, reliability, communications performance; number of channels and types Of signals

I.7 Orbital Perturbations: [26, 27]

A number of physical contributions influence the trajectory of a body in Earth's orbit. These must be considered, for example, to carry out periodic trajectory corrections. Among these perturbations, we can mention:

I.7.1 Third-Body Perturbation

The presence of the sun and the moon causes variations in all orbital elements. For satellites with relatively circular orbits and altitudes higher than geostationary ones, this perturbation predominates.

I.7.2 Perturbation Due to Earth's Non-Sphericity

For satellites whose orbit altitude is equal to or lower than that of geostationary satellites, the flattening of the Earth at the poles dominates, causing variations in the right ascension and the argument of perigee.

I.7.3 Perturbations Due to Atmospheric Drag

This is the primary non-gravitational force affecting low Earth orbit (LEO) satellites. Atmospheric drag causes them to lose kinetic energy, and consequently, altitude. As a result, they may eventually re-enter the atmosphere if the trajectory is not corrected.

I.7.4 Perturbations Due to Solar Radiation

At altitudes above 800 km, another perturbation surpasses atmospheric drag: the pressure from solar radiation, which causes an acceleration in the direction of the sun.

I.7.5 Intrinsic Perturbations:

There are various perturbations directly dependent on the satellite's construction. These include:

Uncertainties in the center of gravity,

Uncertainties in propulsion,

Vibrational modes of the structure.

These intrinsic perturbations mainly affect the attitude (the angular position of the satellite and its variation over time) of the satellite but can also indirectly influence the orbital trajectory. [19]

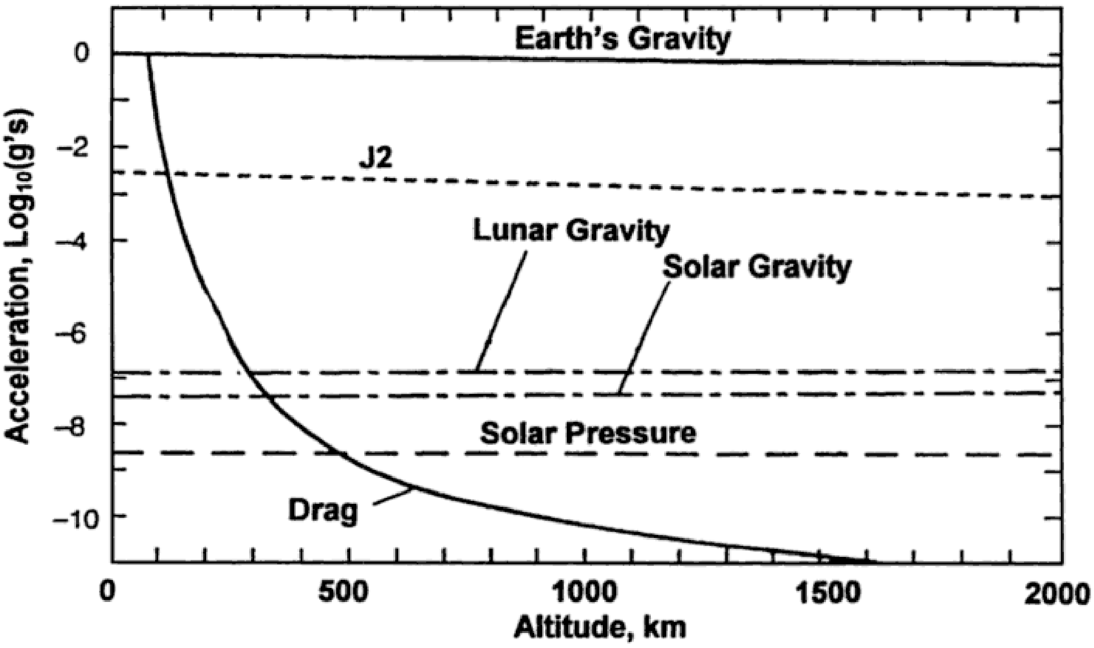


Figure I.13: Orbital Perturbations

I.8 Satellite Constellations :

For most satellite constellations, achieving comprehensive Earth coverage is the primary motivation for deploying multiple satellites. Compared to a single satellite, a constellation enables more frequent communication opportunities and observational access. In designing such systems, engineers often face a trade-off between maximizing coverage performance and minimizing the number of satellites, which directly impacts overall cost. While it is generally assumed that a five-satellite constellation would be less costly than one comprising six satellites, this is not always the case. A larger constellation might operate at a lower altitude or orbital inclination, potentially reducing launch expenses or mitigating exposure to harsh radiation environments. Conversely, a smaller constellation employing elliptical orbits could achieve similar coverage, though the added spacecraft complexity might offset savings gained from deploying fewer satellites. [1,8,21]

I.9 Inter-Satellite Links (ISL):

The inter satellite link is a direct connection between two satellites in space. The main purpose of using ISLs in a satellite communication system is to achieve more flexible connectivity [28], it is used to provide the link between ground stations in the coverage area of one satellite and those in the coverage area of another satellite, when neither satellite succeeds in covering the entire area [29]. The first inter satellite link was established in January 1975 between the two satellites Oscar 6 and Oscar 7[30]. There are usually two types of inter satellite link: the intra plane and the inter plane. The first is used to connect two satellites in the same orbit. The second is used to connect satellites on adjacent orbits.[28]

The advantage of the optical link is that it includes a wide bandwidth, requires low power, and ensures excellent immunity to interference. However, due to the small beam divergence radius, spatial tracking and remote control require greater precision compared to the traditional microwave link. The optical link operating at a wavelength of 850 nm and using a 10 cm diameter transmitting telescope will have a 10 µradian angular effect on the aperture of the transmitting telescope, compared to the microwave link, which has an effect of several milliradians. When operating with such a narrow beam, a significant pointing error can substantially reduce a large portion of the signal power at the receiver, resulting in a high probability of error. [31]

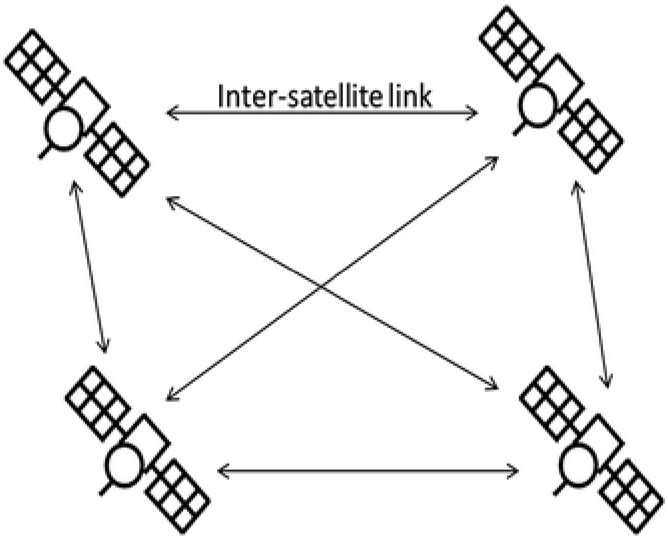


Figure I.14: Inter-Satellite Links (ISL) [10]

I.10 FSO (Free Space Optics) Technology:

In recent years, wireless optical networks using FSO technology have emerged significantly. In contrast, this FSO technology addresses the needs of telecommunications operators. Free Space Optical Links (FSOLs) constitute an optical communication technology that relies on the propagation of light in free space, enabling the transmission of data between two distant points (see Figure I.15). Moreover, it is particularly useful when a physical connection via cable or optical fiber is unsuitable, especially for cost-related reasons. [32,33]

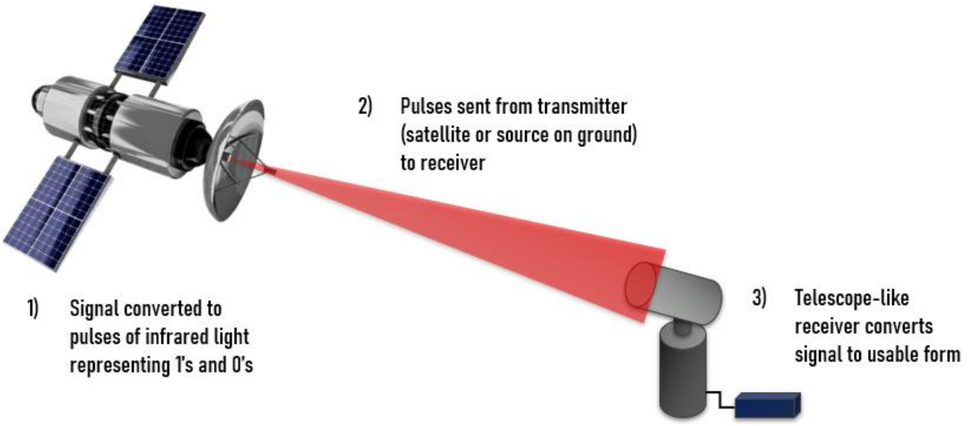


Figure I.15: Free Space Optics Technology

I.10.1 Operating Principle of FSO Technology

The basic principle of FSO (Free Space Optics) technology consists of laser transmission in free space within a part of the visible or infrared light spectrum. FSO systems are designed to establish a connection between two areas or different zones in direct Line-Of-Sight (LOS) at very high data rates. FSO enables the transmission of any type of data at a speed equal to that of optical fiber while providing the flexibility and advantages of a wireless radio network, an FSO link requires a transmitter, a propagation channel, and a receiver. [34,35]

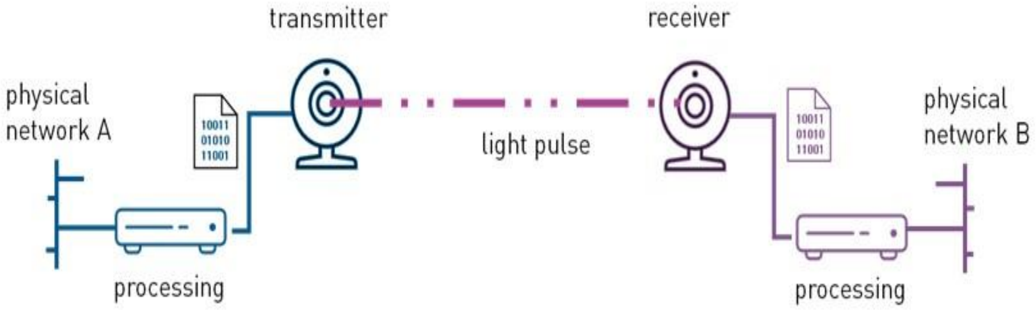


Figure I.16: FSO Technology Principle

I.10.2 Advantages of FSO Communication over RF Communication

The FSO communication system offers several advantages over the RF system.The main difference between FSO and RF communication stems from the large difference in wavelength. For the FSO system, in clear weather conditions (visibility > 10 miles), the atmospheric transmission window is in the near-infrared wavelength range between 700 nm and 1600 nm. The transmission window for the RF system is between 30 mm and 3 m. Therefore, the RF wavelength is thousands of times longer than the optical wavelength. This high wavelength ratio leads to some interesting differences between the two systems, as shown below [36].

I.10.2.1 High bandwidth

It is widely recognized that an increase in carrier frequency enhances the information transmission capacity of a communication system. In radio frequency (RF) and microwave systems, the available bandwidth can reach up to approximately 20% of the carrier frequency. In contrast, optical communication systems operate at much higher frequencies—on the order of 10^{16} Hz—where even a bandwidth equivalent to only 1% of the carrier frequency corresponds to nearly 100 terahertz (THz). Consequently, the usable bandwidth in optical systems lies within the THz range, representing an increase of nearly 10^5 times compared to that of conventional RF communication media.

I.10.2.2 Less power and mass required

Beam divergence is proportional to λ/DR, where λ is the carrier wave length and DR is the aperture diameter. Thus, the beam spread provided by the optical carrier is narrower than that of the RF carrier. This leads to an increase in signal strength at the receiver for a given transmitted power. Figure I.7 shows the comparison of beam divergence for optical and RF signals when returned from Mars to Earth. Thus, a shorter optical carrier wavelength allows the FSO designer to propose a system with a smaller antenna than the RF system to achieve the same gain(because antenna gain scales inversely with the square of the operating wavelength). The typical size of the optical system is 0.3 m compared to 1.5 m fora spacecraft RF antenna.

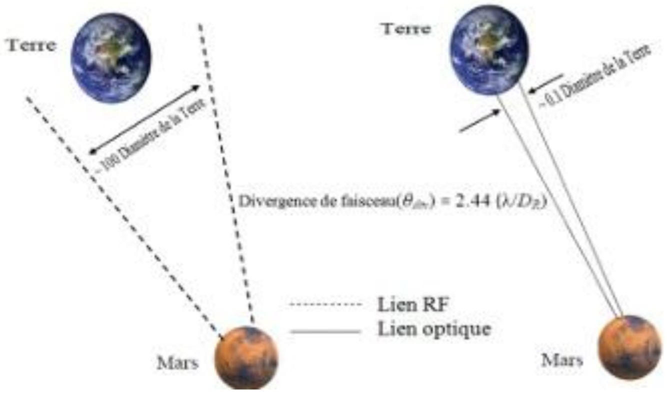


Figure I.17: Comparaison de la divergence des faisceaux optiques et RF de mars vers la terre [36]

The directivity of the antenna is closely related to its gain. The advantage of the optical carrier over the RF carrier [36], Also in RF systems, adjacent channel interference is a major issue due to spectrum congestion. This requires regulatory spectrum licensing, increasing cost and deployment time. Optical systems, however, are license-free, reducing initial cost and development time, FSO communication is highly secure due to its narrow, directional laser beam, making it undetectable by spectrum analysers or RF receivers. Interception is extremely difficult. Unlike RF signals, FSO signals cannot penetrate walls, which helps prevent eavesdropping.

I.11 Some Typical Satellite Routing Algorithms

I.11.1 Dijkstra's Algorithm (Shortest Path)

Dijkstra's algorithm maintains a set of nodes whose shortest distance from the source is already known and a set of nodes whose shortest distance is not yet determined. Initially, the distance to the source is zero and infinity for all other nodes. The algorithm repeatedly selects the node with the smallest known distance from the source, updates the distances to its neighbors, and repeats the process until all nodes have been processed. [58]

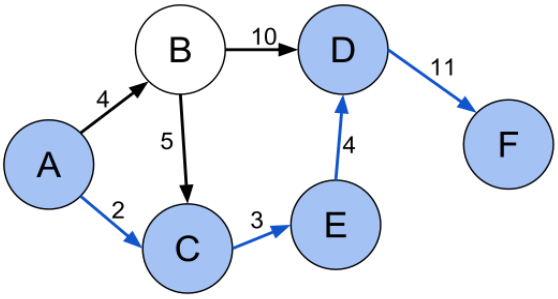


Figure I. 18: Dijkstra's Algorithm

Pros :

- **It guarantees to find the shortest path in graphs with nonnegative edge weights.**
- **It is relatively straightforward to implement.**

Cons:

- **It cannot handle graphs with negative edge weights.**
- **Its computational complexity can be high for dense graphs without optimizations like priority queues.**

I.11.2 Distance Vector Routing

Distance Vector Routing is a traditional routing algorithm employed in packet-switched networks, where each router selects the optimal path to a destination based on the calculated distance to that destination. The term "distance" is most commonly quantified in hop counts, though it may also incorporate additional parameters such as latency, bandwidth, or transmission cost. This algorithm operates on the principles of dynamic programming and is widely recognized for its simplicity, adaptability, and ease of implementation..[58]

How Distance Vector Routing Works:

a. Distance Vectors: Each router maintains a table (distance vector) that contains the best-known distance to every destination in the network and the next hop router on the best path to that destination.

b. Periodic Updates: Routers periodically exchange their distance vectors with their immediate neighbors. Each router updates its own distance vector based on the information received, calculating potential new paths that might be better than the current ones. The update is based on the Bellman-Ford algorithm, which helps in finding the shortest path.

c. Metric Calculation: The cost to reach a destination is calculated using the metric of distance. When a router receives a distance vector from a neighbor, it adds the cost to reach that neighbor to the costs in the distance vector. If this sum for a destination is lower than the known cost, the router updates its distance vector with this new lower cost and the corresponding next hop. [58]

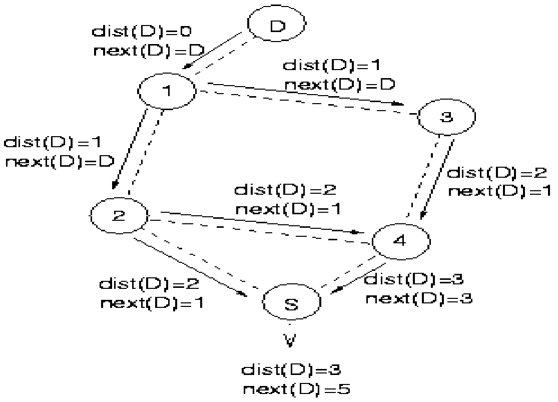


Figure I.19: Distance Vector Routing Algorithm

I.11.3 Multipath Routing

Multipath Routing is a network routing technique that finds multiple feasible paths between a source and a destination in a network. Unlike traditional routing methods that use a single best path for packet delivery, multipath routing leverages the redundancy of network paths to improve reliability, bandwidth, and load balancing. This approach can significantly enhance the overall performance and fault tolerance of network communications. [58]

How Multipath Routing Works:

a. Path Discovery: Multipath routing protocols begin by discovering multiple paths between the source and destination. This can be achieved through various mechanisms, including extending traditional routing protocols or using specialized multipath discovery processes.

b. Path Selection: Among the discovered paths, the protocol selects a subset for use in routing. Selection criteria may include path length, bandwidth, latency, or other quality-of-service (QoS) metrics. The objective is to optimize the network's performance while avoiding congestion and ensuring reliability.

c. Traffic Distribution: Traffic is distributed across the selected paths based on predefined rules or dynamically in response to network conditions. Distribution strategies can range from simple round-robin to more complex algorithms that consider path characteristics and network load.

d. Path Maintenance: Multipath routing protocols monitor the status of active paths and can dynamically adjust the set of paths in use. If a path becomes unavailable or suboptimal due to network changes, the protocol can reroute traffic to maintain performance and reliability.

I.12 Some Modern Routing Algorithms

I.12.1 AEESRA

an energy-efficient clustering and hierarchical routing algorithm named EESRA, aimed at extending the lifespan of wireless sensor networks (WSNs) with increasing network size. This algorithm is an enhancement over the" low-energy adaptive clustering hierarchy" (LEACH) protocol, addressing its scalability issues by adopting a three-layer hierarchy to minimize cluster heads' load and randomize their selection. Moreover, EESRA employs multi-hop transmissions for intra-cluster communications to implement a hybrid WSN MAC protocol. The simulation results demonstrate that EESRA outperforms other WSN routing protocols in terms of load balancing and energy efficiency on large-scale WSNs.[58]

- ✓ An innovative energy-efficient clustering and hierarchical routing algorithm that outperforms existing WSN routing protocols in terms of scalability and energy efficiency.
- ✓ The introduction of a hybrid WSN MAC protocol that incorporates both sleep and collision avoidance mechanisms alongside TDMA slots for efficient data forwarding.
- ✓ A comprehensive simulation analysis demonstrating the algorithm's effectiveness in extending the network lifespan and achieving better load balancing across large-scale WSNs.

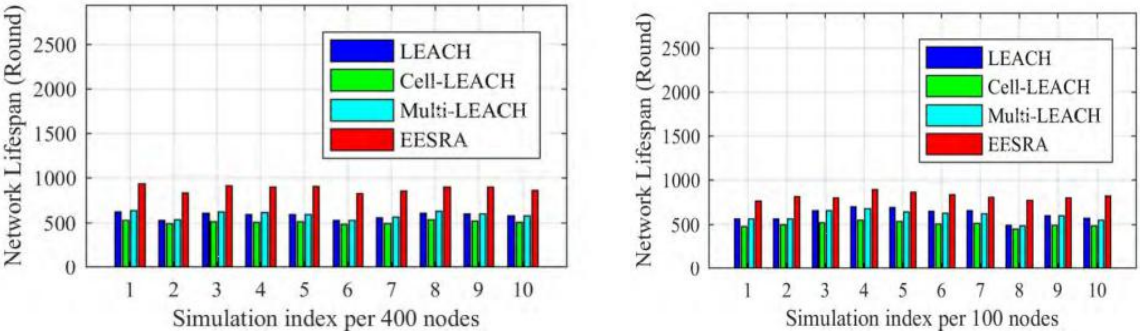


Figure I.20: AEESRA Simulation Result

I.12.1.1 Optimization

The EESRA (Energy Efficient Scalable Routing Algorithm) optimizes traditional energy-efficient routing in several key ways, focusing on addressing the scalability and energy consumption issues inherent in the LEACH protocol and other WSN (Wireless Sensor Network) routing protocols:

a. Three-layer Hierarchy: EESRA introduces a three-layer hierarchical structure to reduce the load on cluster heads (CHs) by incorporating an additional layer of cluster congregations (CGs) between the CHs and the cluster members (CMs). This structure helps in distributing the energy consumption more evenly across the network, thus optimizing energy usage and extending the network lifespan.

b. Hybrid MAC Protocol: The algorithm employs a hybrid Medium Access Control (MAC) protocol that combines sleep and collision avoidance mechanisms for efficient data sensing and transmission. This approach allows for more efficient use of energy, as nodes can enter a low-power state when not actively transmitting data.

c. Multi-hop Intra-cluster Communication: Unlike traditional protocols that may rely solely on single-hop communication, EESRA uses multi-hop transmissions within clusters. This method reduces the energy consumed in data transmission by minimizing the distance over which individual transmissions need to occur.

d. Randomized Cluster Head Selection: To further balance the energy consumption across the network, EESRA implements a randomized selection of cluster heads. This ensures that no single set of nodes bears the brunt of the energy consumption, leading to a more uniform depletion of resources across the network.

e. Load Balancing: By adopting a three-layer hierarchy and utilizing multi-hop communication, EESRA effectively balances the load among nodes. This prevents certain nodes from depleting their energy resources too quickly, thereby optimizing the overall energy usage within the network.

I.12.1.2 Performance Evaluation

The simulation results Fig.3 EESRA outperforms traditional LEACH and its variants in terms of energy efficiency, load balancing, and scalability, especially in large-scale WSNs. By addressing the critical challenges of energy consumption and network scalability, EESRA optimizes traditional energy-efficient routing protocols, offering a significant improvement in extending the network lifespan while maintaining high network performance.

I.12.2 GAPSO-SVM

GAPSO-SVM is proposed as an innovative clustering routing protocol, specifically designed for the IoT perception layer, with an emphasis on energy-aware localization and routing. It integrates a Support Vector Machine (SVM) for precise location estimation and a Genetic Algorithm-Particle Swarm Optimization (GAPSO) for efficient clustering. The primary contributions of this approach include:

a. A hybrid IDSS-based clustering routing protocol that significantly enhances energy efficiency and network longevity over previous methodologies.

b. An SVM-based localization algorithm that enables accurate location estimation without the need for GPS, addressing a common limitation in geographic protocols.

c. A hybrid GAPSO algorithm that optimizes clustering with superior convergence rate and efficiency compared to similar endeavors.

The GAPSO-SVM algorithm’s framework involves specifying sensor nodes and beacons, alongside calculating the energy required for transmitting and receiving data, optimizing the network’s energy consumption for effective data communication from cluster heads (CHs) to the sink.

Through simulation, GAPSO-SVM demonstrated substantial improvements in network lifetime and energy efficiency, utilizing SVM for precise localization without GPS and leveraging GAPSO for efficient clustering. The results indicated marked advancements in convergence rates, network longevity, and energy savings, significantly outperforming the metrics of the existing EEWC algorithm.[58]

I.12.2.1 Optimization Process

The GAPSO-SVM algorithm employs a hybrid optimization strategy that combines the strengths of Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) to enhance the clustering and routing processes in IoT networks. The optimization process is detailed as follows:

a. Initialization: The set of sensor nodes within the network is defined, alongside the specification of beacon and non-beacon nodes. This step forms the basis for the clustering and routing mechanism.

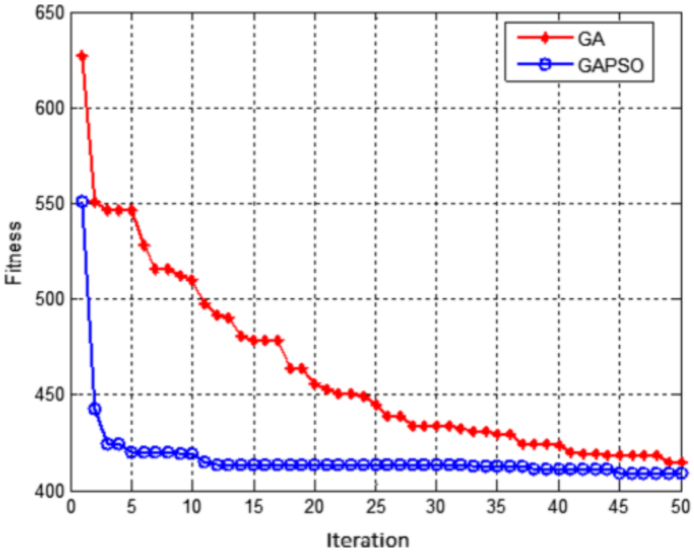
b. Energy Calculation: For each node, the energy required to transmit (ET) and receive (ER) an L-bit message over a distance d is calculated.

c. Hybrid GAPSO Mechanism: The optimization leverages the fast convergence rate of PSO and the robust search capabilities of GA. The population of solutions (sensor nodes' clustering configurations) is evolved using both GA and PSO principles:

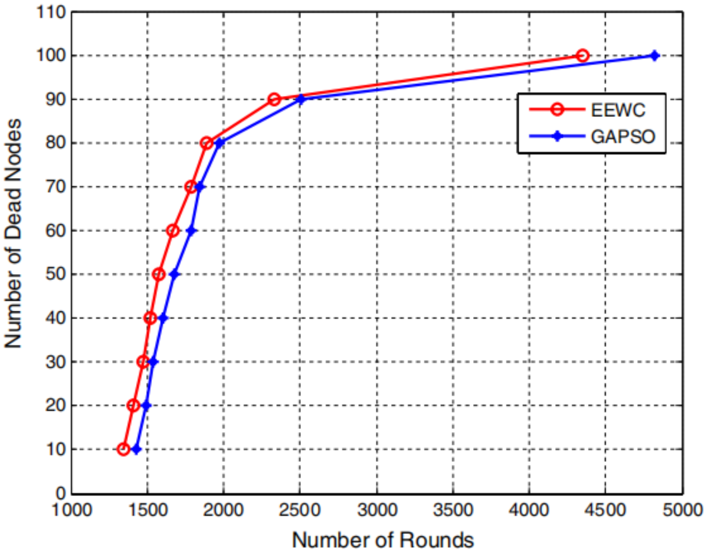
- ✓ Part of the population is processed using GA operations (selection, crossover, and mutation) to explore the search space.
- ✓ The remaining part is updated using PSO rules, guiding the particles (solutions) toward the best-found positions.

d. Hybridization Coefficient (HC): A key parameter in GAPSO, HC determines the proportion of the population to be processed by GA in each iteration. An optimal HC value ensures a balanced exploration and exploitation, enhancing the algorithm's efficiency and convergence

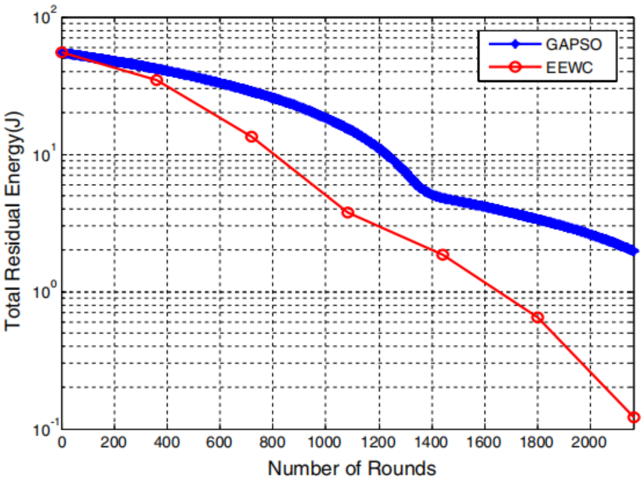
e. Evaluation and Iteration: The fitness of each solution is evaluated based on criteria such as energy efficiency, network lifetime, and connectivity. The population is then updated iteratively, combining GA and PSO updates to find an optimal clustering configuration.



(a)Comparison of GA and GAPSO cost function for each iteration



(b) Network lifetime for 10% beacon nodes



(c)Comparison of residual energy in GAPSO and EEWC algorithms for 10% beacon node

Figure I. 21: Various performance evaluation. (a) Cost function convergence, (b) Network lifetime, and (c) Residual energy comparison

I.12.2.2 Performance Evaluation

The performance of GAPSO-SVM was rigorously tested against the EEWC algorithm, showcasing significant improvements in network lifetime and energy efficiency. Key findings include:

a. Improved Convergence Rate: GAPSO-SVM demonstrated an 80% improvement in convergence rate over EEWC(Fig.4a), leading to faster optimization of CHs.

b. Extended Network Lifetime: The network lifetime under GAPSO-SVM extended by 11% (Fig.4b), attributed to optimized clustering and routing strategies.

c. Energy Efficiency: GAPSO-SVM reduced the energy consumption significantly(Fig.4c), ensuring a sustainable IoT network operation.

The simulation results indicate that GAPSO-SVM outperforms the existing EEWC algorithm in terms of convergence rate, network longevity, and energy efficiency, making it a promising solution for energy-aware localization and routing in IoT networks. [58]

I.13 Conclusion

The use of satellites has brought a revolution in the field of wireless communications, driven by the numerous advantages of using space for communication.

In this chapter, we examined the various components of both the space and terrestrial sectors, as well as the devices that make up a satellite, and the different types of orbits, along with orbital perturbations, we also explored inter-satellite links, both radio frequency and optical, along with FSO Technology and their advantages and characteristics. The goal here was to surround the reader with the principles of space satellite communication, setting the stage for a deeper exploration in the second and third chapters.

CHAPTER II:

Satellite Constellation and Handover

II.1 Introduction to Satellite Constellations

In its classical sense, *coverage* refers to the area on the Earth's surface that lies within the direct line of sight of a satellite. The spatial configuration formed by the overlapping footprints of satellite coverage defines what is known as *coverage geometry*. Most traditional design methodologies concentrate on coverage geometries that assume nadir-pointing sensors capable of instantaneously observing their designated surface areas. This assumption—valid in the context of electromagnetic sensing and imaging—enables the use of the standard coverage geometry illustrated in Figure II.1.

All parameters describing this type of geometry can be derived analytically using fundamental principles of planar and spherical geometry. The core analytical relationship governing this configuration is expressed in Equation (II.1), which is obtained directly from the geometry shown in Figure II.1 through the application of the Law of Sines. In this expression, c denotes the elevation angle, r_e represents the Earth's radius, h corresponds to the orbital altitude, and θ indicates the Earth's central angle of the coverage footprint.

This analytical formulation makes it possible to determine coverage solely based on satellite arrangement. When multiple satellites simultaneously provide visibility to the same surface point, *multi-fold coverage* occurs [37]. Maintaining optimal coverage geometry over time for specific target regions defines the *coverage specification* of a constellation. Classical constellation designs typically adhere to one of three coverage definitions: global (whole-Earth) coverage, latitude-bounded coverage, or localized area-specific coverage.

Coverage performance can also be estimated numerically by evaluating a network of grid points distributed across the Earth's surface. This numerical approach is often used as an alternative to purely analytical methods. In such cases, both the spatial resolution of the grid and the temporal step used in the analysis must be carefully defined. Nevertheless, the determination of coverage at any individual point generally relies on the geometric relationship illustrated in the figure.

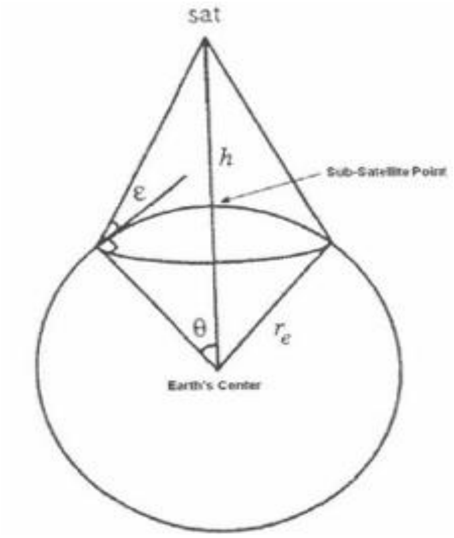


Figure II.1: Earth Central Angle Coverage Geometry

$$\mathrm{Cos}(\theta + \varepsilon) = \left(\frac{\mathrm{Cos}(\varepsilon)}{1 + h/r}\right) \qquad \text{II.1}$$

This section describes the constellations, by successively dealing with their architectures, the general characteristics of the satellites that make up the constellations, and their various functions. It is concluded with some general orders of magnitude [38] Factors to be defined during constellation design are: primary design factors and secondary factors:

II.1.1 Primary Design Factors

- ✓ Number of satellites (Minimize the number consistent with other criteria)
- ✓ Constellation model (Select the best coverage)
- ✓ Minimum elevation angle (Minimum value consistent with the constellation model)
- ✓ Altitude (System-level cost and performance trade-off)
- ✓ Number of orbital planes (Minimize according to coverage requirements)
- ✓ Collision avoidance parameters (Maximize inter-satellite distances at orbital crossings)

II.1.2 Secondary Design Factors

- ✓ Inclination (Compare latitude coverage and launch costs)
- ✓ Interplane Phasing (Select the best coverage from discrete phasing options)
- ✓ Eccentricity (Can reduce the number of satellites required)
- ✓ Station keeping Box Size (Minimize costs based on a low-cost maintenance approach)
- ✓ End-of-Life Strategy (Any mechanism that allows you to clean up after yourself) [8,39].

II.2 Earth Coverage with Circular Orbit Constellations (Star and Delta Patterns)

Whole-Earth coverage is the first coverage definition that was explored for constellation design. The first constellation design methods of Vargo, Liders, Gobetz, Walker, Beste, Ballard, and others, focused on using common inclination and altitude circular orbits about a spherical Earth to achieve coverage [37], these methods are distinguished by the great deal of symmetry in the placement of satellites within the constellation. Symmetrical patterns of satellites are easier to work with because they limit the number of unknown parameters in a design to a handful of common parameters. J2 perturbation effects on the orbital cohesion of symmetric constellations can be ignored by assuming the whole pattern will drift in unison. Also, analysis of the coverage over time becomes an easier problem as well. All satellites follow the same pattern and thus only a short time span of an orbit needs to be analysed to ensure that coverage is maintained indefinitely. This time span is an important 56 simulation parameter and will be explored per constellation type. Once complete coverage is established according to some definition.

In common altitude and inclination circular orbits, little more than a good understanding of spherical geometry is needed to develop a working constellation. Polygon enclosure, sub-satellite separation distance, streets of coverage, and Earth central angle formulations were the first approaches to constellation design based on symmetrical patterns of satellites. While each formulation is slightly different, they all focus on establishing Earth coverage using only commonly inclined circular orbits without regard for relative motion of the Earth underneath. Satellites are placed symmetrically in such a way that coverage will always be maintained. While these assumptions and simplifications restrict the design space, the coverage of the resulting constellations can be quite good. Each of these design approaches will be discussed in further detail below with respect to the whole-Earth definition of coverage. In whole Earth coverage all points on the surface of the Earth must have direct satellite coverage based on the coverage geometry illustrated in Figure II.1.

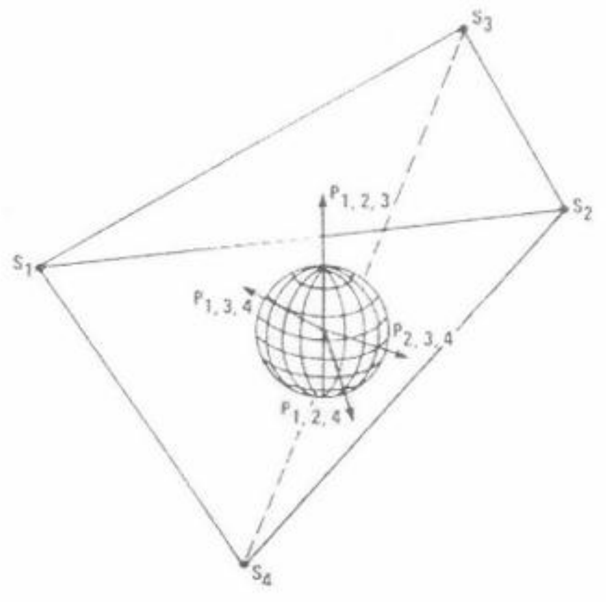


Figure II.2: Polyhedral Enclosure Constellation with Eccentric Orbits

II.2.1.1 The Walker's Method

While extensively studying regular circular orbit models, Walker [1984] developed a notation for labeling orbits that is commonly used in the orbit design community and frequently used as a starting point for constellation design. Specifically, the Walker delta model contains a total of t satellites, with s satellites uniformly distributed in each of the orbit planes p. All orbital planes are assumed to have the same inclination, i, relative to a reference plane, usually the Earth's equator. (For the purposes of constellation design, this is not necessarily the case, but orbit perturbations depend on the inclination relative to the equator, and therefore the equator is the most convenient standard reference plane.) Unlike the coverage streets, the ascending nodes of the p orbital planes in a Walker model are uniformly distributed around the equator at intervals of 360 degrees/p.

In each orbital plane, the satellites are uniformly distributed at intervals of 360 degrees/s. The only remaining problem is to specify the relative phase between satellites in adjacent orbital planes. To do this, we define the phase difference, $\Delta\phi$, in a constellation as the angle in the direction of motion from the ascending node to the nearest satellite at a time when a satellite in the next westernmost plane is at its node.

ascending. For all orbital planes to have the same relationship to each other, $\Delta\phi$ must be an integer multiple, f, of 360°, where f can be any integer from 0 to P-1. As long as this condition holds, each orbit will have the same relationship to the next orbit in the model. The model is fully specified by giving the inclination and the three parameters, t, p, and f. Usually, such a constellation will be written in the shorthand notation of i: t/p/f. [8, 40,41] Although Walker constellations are important for constellation design, they are not the only appropriate options and do not necessarily provide the best characteristics for a given mission. Walker intended to provide continuous, multiple-satellite coverage of the Earth's entire surface with the fewest number of satellites. This plan may or may not achieve all the objectives of a particular program.

For example, coverage evenly distributed across the Earth's surface may not be the most advantageous. We may want to provide global coverage with the best coverage at the poles, mid-latitude regions, or the equator. In these cases, we may want constellation types other than Walker orbits.

couverture aux pôles, aux régions de latitude moyenne ou à l'équateur. Dans ces cas, nous pouvons vouloir des types de constellation autres que les orbites de Walker.

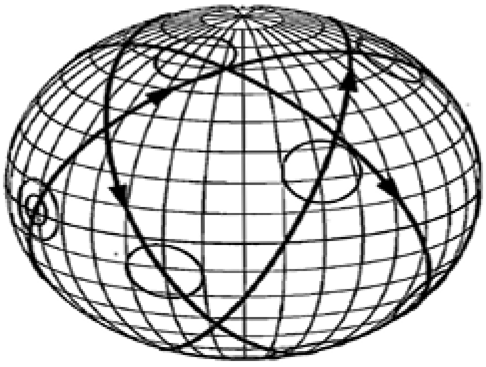


Figure II.3: A 15/5/1 Walker constellation at 65° inclination. The circles are centered on each of the 15 satellites. The double circle is on a satellite at its ascending node [8]

II.2.1.2 Network Saturation:

Smaller networks (with fewer satellites) can handle a higher volume of messages before reaching saturation compared to larger networks

II.2.1.3 Adaptive Routing Algorithm:

An adaptive routing algorithm was proposed, which directs messages through one of several available minimal paths between source and destination, enhancing network efficiency.

The Walker Delta constellation is a practical solution for global satellite networks, particularly when orbital planes and satellites per plane are balanced. Smaller networks are better suited for high-traffic scenarios prior to saturation, while the adaptive routing algorithm further optimizes performance.

Two frequently used satellite constellation classes, LEO or MEO, are the Walker delta and Walker star configurations. These two constellation classes are shown in Figure 1. In a Walker delta constellation, all the orbital planes have the same inclination, the ascending points of these orbits are distributed periodically over the 360 degrees of the equator, the orbital altitudes are all the same, and the satellites on a given orbit are periodically distributed on this orbit. A Walker delta constellation is characterized by a quadruplet noted i : N/M/T, with i the inclination of the orbital planes, N is the total number of satellites, M the total number of orbital planes and T the total number of satellites. The inclination parameter is used to only cover regions located at latitudes that do not exceed a certain threshold. So, for example, the Galileo navigation system is a Walker 56°: 24/3/1 constellation. This means that there are 24 satellites in 3 planes inclined at 56 degrees, distributed periodically over the 360 degrees of the equator. Note that in delta-type constellations, a given observation point may see both south-north and north-south oriented satellites pass at close range; in this case, the distance between two close satellites but with different orientations varies greatly. Walker star constellations use orbits with inclinations close to 90 degrees (i.e. quasi polar). The orbital planes are organized periodically on the equator, but on 180 degrees only, so that on the equator, the satellites are all ascending on the interval 0, 180 degrees and all descending on the complement. The Iridium constellation is a Walker star 86.4° : 66/6/2. Many variants of these basic constellations are used, such as multi-altitude combi nations, or star-delta, or LEO-MEO-GEO [40]

Walker Delta Pattern Parameters (T, P, & F) With either the star or delta pattern, once coverage has been calculated, the coverage must be maintained throughout pattern changes due to satellite motion. To ensure that the delta pattern coverage would repeat itself, Walker imposed a set of basic rules for the design of a delta pattern constellation. These rules specify that the constellation be composed of some number of planes (P) separated equally about the Earth's equator. A common number of satellites must be equally spaced within each orbital plane. The total number of satellites is designated by (T) and must be divisible by P. All satellites are in commonly inclined circular orbits at the same altitude. The satellites from one plane to the next plane are relatively phased from one another by an angle multiplication factor (F), where F takes an integer value from one to P-1. F is a multiplication factor for the pattern unit angle given by PU=360/T degrees. If a satellite is at its ascending note, the next most easterly satellite will be F*PU degrees in its orbit past its own ascending node. With these rules and a given inclination and orbital altitude, a constellation of this fashion can be completely created from only three parameters: T, P, and FI 5 21,'573. With this method the number of variables needed to completely define a constellation is five. To define the location of every satellite in a random constellation configuration would require 6*T variables, as stated earlier. While this method introduces a lot of symmetry to a constellation while removing some design freedom, it does so at a significant drop in the variability of the design space. This makes delta patterns very attractive from a coverage analysis standpoint. The symmetric nature means that delta patterns are repetitive on a definable time scale [40]

II.2.2.1 "Streets of Coverage" Formulation

When satellites operate in low-altitude orbits, the geometric complexity of the polygons required to achieve full Earth coverage increases significantly. To address this challenge, an alternative approach for determining coverage using a sequence of satellites within a single orbital plane was developed. As indicated by Equation (II.1), satellite coverage is strongly influenced by orbital altitude. This insight led to the development of the Streets of Coverage (SOC) method [44].

The SOC approach employs the same cone–sphere analogy as in classical coverage analysis, where the satellite's coverage footprint corresponds to a circular area projected onto the Earth's surface. When multiple satellites are positioned sequentially within the same orbital plane, their overlapping circular footprints form a dense, continuous pattern of coverage zones, as illustrated in Figure II.4 [42]. The resulting street of coverage—representing uninterrupted coverage along the orbit's ground track—has a width denoted as 2C. This width equals twice the distance from the orbital plane trace to the point of minimum overlap between adjacent footprints, as depicted in Figure II.6.

The parameter C is directly related to both the coverage footprint radius (θ) and the number of satellites (S) within the orbital plane, a relationship illustrated in the figure. A single street of coverage ensures continuous visibility along the orbit path but remains insufficient to achieve complete global coverage. However, by deploying multiple orbital planes—each generating its own street of coverage—continuous, whole-Earth coverage can be realized.

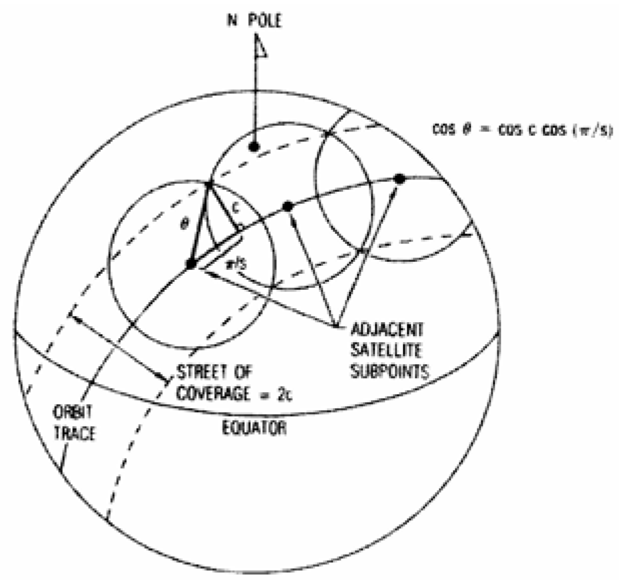


Figure II. 4: Street of Coverage for One Orbital Plane [42]

II.2.2.2 SoC configuration

SoC constellations are defined by the following parameters:

- $\boldsymbol{N}$**:** Number of orbital planes
- $\boldsymbol{S}$**:** Satellites per plane
- $\boldsymbol{i}$**:** Inclination angle
- $\boldsymbol{h}$**:** Orbital altitude
- $\boldsymbol{\theta}$**:** Half-angle of the satellite coverage cone (or elevation angle)
- $\boldsymbol{\Delta\Omega}$**:** Spacing between orbital planes

$\boldsymbol{\Delta\nu}$**:** Spacing between satellites within a plane

This leads to a polar constellation often referred to as “Streets of Coverage,” illustrated in Figure II.5,

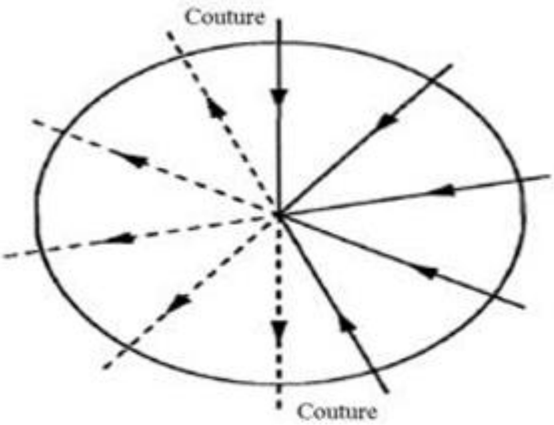


Figure II. 5: Modèle de constellation "Streets of Coverage". Vue du pôle nord [8]

Les parties vers le nord de chaque orbite sont dessinées en traits pleins et les parties vers le sud en pointillés. Pour assurer une couverture complète, plans orbitaux de chaque côté de la couture doivent être plus proches que les autres [8, 38, 43,29].

Table II.1: WALER and SoC Comparison

Feature	Walker Constellation	Street-of-Coverage Constellation
Structure	**Symmetrical, circular**	**Coverage-focused, geometric**
Optimization Goal	**Uniform global distribution**	**Guaranteed regional/global coverage**
Typical Use Case	**GNSS, broadband**	**Earth observation, telephony**

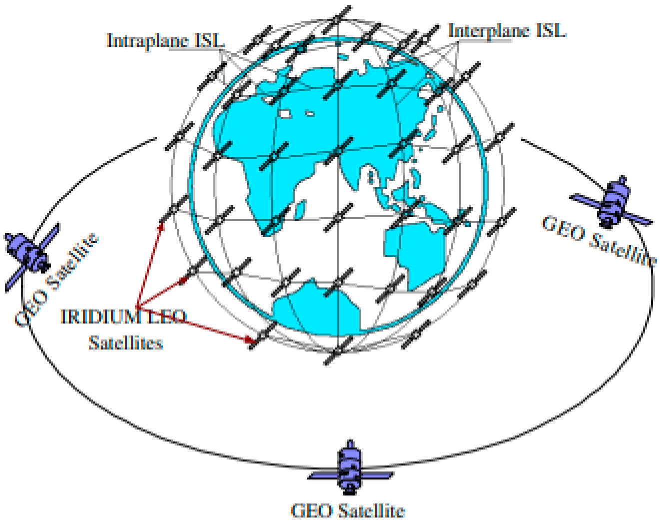


Figure II. 6: Mixed constellation of Iridium and GEO

II.3 Collision and Debris Risk Assessment and Mitigation

One of the most important features of any constellation is collision avoidance. The reason isn't just the loss of colliding satellites, because we expect to lose satellites for many reasons in any large constellation. The fundamental problem is the debris cloud that results from any satellite collision. The velocity imparted to the particles resulting from the collision is small compared to the orbital velocity. Therefore, the net effect of a collision is to take two trackable, possibly controllable satellites and transform them into thousands of untraceable particles that spread over time into the same orbits as the original satellites. Since energy is proportional to mv2, even a small part of a satellite carries a huge amount of kinetic energy at orbital speeds. Since the debris cloud remains in the constellation's orbit, it significantly increases the risk of secondary collisions, which, in turn, continue to increase the amount of debris and the possibility of rendering the orbit "uninhabitable." The implication for constellation design is that we must make great efforts to design both the constellation and the spacecraft to avoid collisions, explosions, or the generation of external debris [8,43].

II.4 Methods Used to Avoid Satellite Collisions

The methods used are summarized as follows:

- ✓ Maximize the spacing between satellites as they cross other orbital planes. (This can impact the phasing between planes and, therefore, coverage.)
- ✓ Retire satellites at the end of their life (Either deorbit them or elevate them above the constellation.)
- ✓ Determine the movement through the constellation of a satellite that "dies in place"(Low-altitude constellations have an advantage).
- ✓ Remove upper stages from the orbital ring or leave them attached to the satellite (Do not leave uncontrolled objects in the constellation model).
- ✓ Design the approach to rephasing or replacing satellites to avoid collisions (All inter-satellite movements should assess the potential for collisions).
- ✓ Capture all ejected components (look for explosive bolts, lens caps, salmon clips, and similar discards).
- ✓ Avoid the potential for self-generated explosions (purge propellant tanks for spent spacecraft) [8,43].

II.5 HANDOVER

Handovers in satellite networks can be broadly classified as:

II.5.1 HANDOVER IN LEO SATELLITE SYSTEMS LEO satellites

Low Earth Orbit (LEO) satellite systems are expected to serve as a central component of next-generation data communication infrastructures due to several advantageous characteristics, including reduced propagation delay, lower power consumption on both the satellite and user sides, and more efficient spectrum utilization enabled by frequency reuse across satellite spot beams [45]. However, unlike geostationary satellites, LEO satellites are not stationary relative to fixed users on the Earth's surface. The ground track velocity (Vtrk) of a LEO satellite far exceeds both the rotational velocity of the Earth and the speed of terrestrial users [46].

Because of the continuous orbital motion of LEO satellites, their visibility period within a given cell is relatively short. Consequently, a user terminal may need to communicate through multiple spot beams and satellites during a single session. Maintaining seamless communication in a LEO-based system often necessitates the dynamic reassignment of communication links and, in some cases, changes in the IP addresses of endpoints. This process requires both link-layer and higher-layer handovers, making mobility management in LEO satellite networks considerably more complex than in GEO or MEO systems.

The mobility behavior of LEO satellite systems bears resemblance to that of terrestrial cellular radio networks, with some notable distinctions. In both systems, the relative position between communication cells and mobile nodes changes continuously, thereby necessitating frequent handovers between adjacent cells [47]. The key difference lies in the nature of movement: in cellular systems, mobile users move across stationary cells, whereas in LEO systems, the satellites—and thus the cells—move across stationary users [47].

Additionally, the cell size in LEO systems is significantly larger than that in terrestrial cellular networks, and the motion of ground users can generally be neglected given its insignificance compared to the high orbital velocity of LEO satellites [47]. When designing mobility management schemes for LEO systems, bandwidth and power constraints must also be taken into consideration. Nonetheless, a major advantage of LEO satellite networks is the predictable nature of satellite movement, which simplifies the process of selecting the next servicing satellite. At any given moment, the precise configuration of the satellite constellation can be determined, allowing for optimal path selection between communication endpoints and minimizing unnecessary handovers.

II.5.2 Spot Beam Handover

The service area or footprint of a satellite is a circular area on the Earth's surface. To allow frequency reuse, the footprint of an individual satellite is divided into smaller cells or spotbeams. This results in better frequency utilization through the use of identical frequencies in non-adjacent spotbeams which are geographically separated to limit interference [48]. To ensure uninterrupted ongoing communications, a current communication link should be handed off to the next spotbeam if needed. A spotbeam handover involves the release of the communication link between the user and the current spotbeam and acquiring a new link from the next spotbeam to continue the call (Figure II.8). Since both spotbeams are served by the same satellite, no other satellite is involved in the handover process. Due to the small area covered by spotbeams and high satellite speed

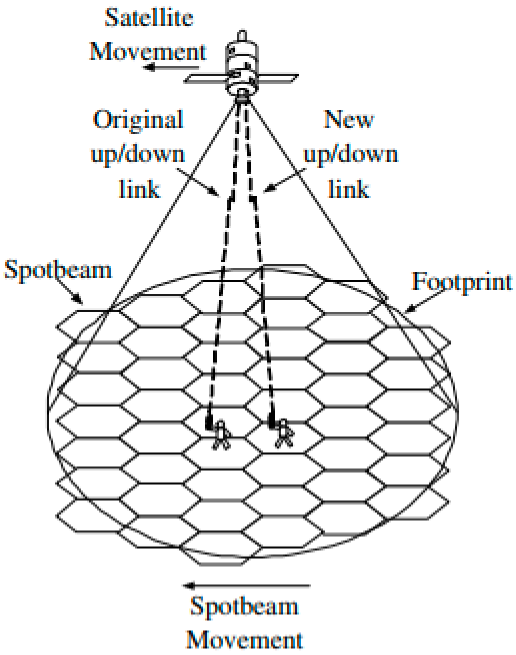


Figure II. 7: Spotbeam handover scenario

spotbeam handovers are the most common type of handovers experienced in LEO satellite systems [49]. We can consider the user mobility negligible compared to high satellite speed. As a result, the deterministic and constant movement of the satellites makes the solving of the spotbeam handover problems easier. During the handover process, if a new link or channel cannot be found in the next spotbeam, the ongoing call should be dropped or blocked. From the user viewpoint, the interruption of a call is less desirable than the blocking of a newly arrived call [49]. It will be the best for a user if handovers can be guaranteed, ensuring smooth ongoing calls. Again, the selection of a suitable policy in resource management (channel allocation) can ensure new channel availability during handover. Thus, the channel allocation strategies and the handover guarantee are the prime issues in managing handover requests.

II.5.3 SATELLITE HANDOVER

Satellite handover occurs when a satellite involved in the connection between two users cannot provide service to a user (one reason may be going out of sight from the user). In that case, the connection has to be transferred to a new satellite. Let us consider the scenario in (FigureII.9(a)). User 1 is in communication with user 2 using satellites A and B. Since the satellites are moving left, user 2 will soon come under the footprint of satellite C. Thus, satellite C should be involved in the connection from user 1 to user 2 to keep the connection alive. The connection of user 2 to satellite B should be handed off to satellite C, and the new communication path from user 1 to user 2 will be through satellites A, B and C (Figure II.9 (b)). Satellite handover is very important in LEO satellite-based diversity systems. In a spotbeam handover, a user is constrained to choosing only one possible next cell. In contrast, for satellite handover, the user can select among different satellites. Moreover, the user has to first select the servicing satellite, and then will be served by the cell covering the user. Satellite handover schemes should aim to select the most suitable satellite depending on Pb, Pf and the quality of communication from the satellite. Consequently, a well investigated satellite handover scheme can reduce bandwidth wastage and also fulfil the QoS requirements of Pb and Pf [50].

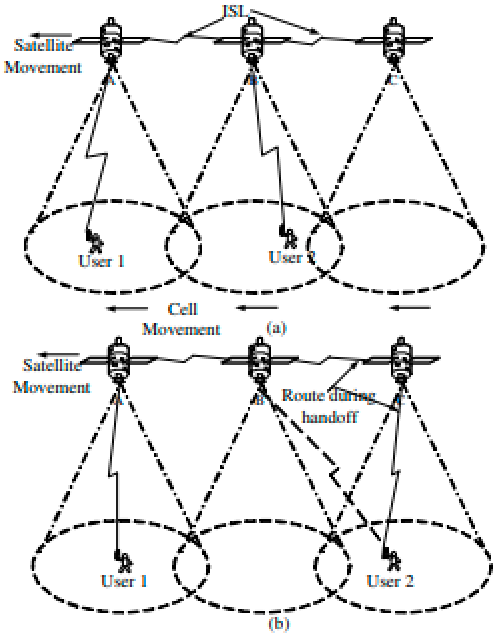


Figure II. 8: Satellite handover: (a) Initially, user 1 and user 2 communicate through satellite A and B. (b) After user 2 hands off to satellite C, the communication is through satellites A, B and C

II.5.4 ISL HANDOVER

Due to the change of the connectivity patterns among the satellites, satellites have to temporarily shut down their ISLs [51]. As a result, ongoing communications using those ISLs have to be rerouted. This handover, referred to as ISL handover, may create a large number of rerouting attempts and call blocking [51] due to resource scarcity in the new satellite. This type of handover is specific to satellite constellations which use ISLs among neighboring satellites for communication. It is important to note that many LEO constellation concepts (like SkyBridge) do not use ISLs [52], and thus do not require ISL handover. In satellite constellations (like Iridium) which use polar orbits, when satellites go into the polar area, the connectivity pattern of the satellite's changes [53]. As seen in Figure II.10, the ISLs between satellite A and its neighboring satellites B & C have to be turned off for a certain time as B and C change their positions relative to A. Other LEO concepts (like Globalstar, Odyssey, ICO) which do not use polar orbits have different ISL handover issues, and ISL handovers occur at different locations in the orbit. The basic question still remains the same, i.e., determining where the ISLs have to be switched off between neighboring satellites and ongoing connections handed over to different satellites. Here, we focus on ISL handovers in polar orbiting satellite constellations. Werner et al. [53] investigate this rerouting problem during ISL handover. They optimized their algorithm to find a unique route with minimum ISL handovers between satellite pairs.

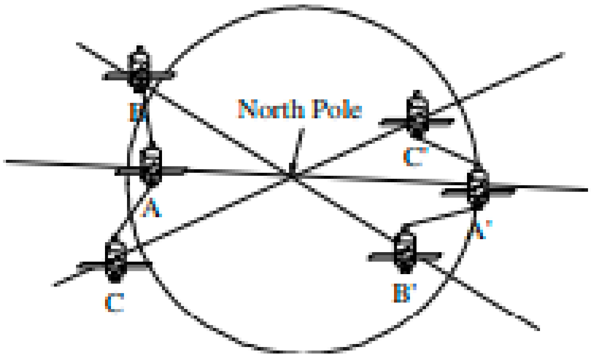


Figure II.9: ISL handover between the satellites in the north polar area

II.5.5 NETWORK LAYER HANDOVER

due to the movement of the satellites and the mobile users, the communication endpoints (user or satellites) may have to change their IP address, requiring a network layer handover. Fu et al. [54] identify two scenarios requiring network layer handover as follows:

- Satellite as a Router: As satellites move, communicating fixed/mobile hosts come under new satellite footprints or spotbeams. Different satellites or even different spot beam scan be assigned with different IP network addresses. This requires a network layer handover during the change of communication links from one satellite or spotbeam to another.

- Satellite as a Mobile Host: When a satellite works as an end point of a communication by generating and receiving data, it can be regarded as a mobile host. Thus, like a mobile host it always changes its communication attachment point requiring a network layer handover.

II.5.6 Satellite Routing

Satellite communication networks possess a distinct advantage over terrestrial networks, as they offer global coverage and reliable communication services that are not restricted by terrestrial geography or infrastructure limitations. However, these benefits come with substantial technical challenges. The topology of satellite networks is inherently dynamic and time-varying, as satellites are in continuous motion relative to the Earth and to one another. Moreover, the limited onboard computational capacity and storage resources—a result of strict constraints on satellite size, weight, and power consumption—further complicate the design of efficient routing mechanisms.

Unlike terrestrial networks, where the nodes are largely stationary and link characteristics remain relatively stable, satellite networks must account for long inter-satellite distances and significant transmission delays. These factors critically influence routing efficiency and overall network performance. Consequently, traditional terrestrial routing algorithms such as OSPF or BGP cannot be directly applied in satellite contexts because of their high computational complexity and inability to adapt quickly to topological dynamics.

To address these issues, researchers and engineers from both academia and industry have sought to develop novel routing algorithms tailored specifically to satellite environments. These algorithms must be adaptive, capable of detecting and responding to rapid changes in network topology, traffic load, and link congestion. In this context, the literature emphasizes the design of routing strategies that can dynamically adjust to variations in satellite connectivity and ensure consistent quality of service (QoS).

While early research primarily focused on single-layer satellite networks, recent developments highlight the superior performance of multi-layer satellite constellations, integrating Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO) satellites.

Such multi-layer architectures enhance network resilience, reduce latency, and provide better load balancing by leveraging the unique advantages of each orbital layer.

In light of these advancements, modern dynamic routing algorithms for multi-layer satellite networks have been designed to optimize communication performance by alleviating link congestion, balancing traffic loads, and adapting QoS parameters in real time according to network conditions. These intelligent routing strategies contribute to achieving higher throughput, maintaining reasonable end-to-end delays, and ensuring robust connectivity across heterogeneous satellite layers. [57]

II.6 Variations and Hybrids

The Hybrid satellite constellation can be configured by several types of combinations between existing orbital solutions today, such as an integration of GEO (Geostationary Earth Orbit) with HEO (Highly Elliptical Orbit), PEO (Polar Earth Orbit) or LEO (Low Earth Orbit) constellations, and integration of MEO (Medium earth Orbit) with HEO or LEO. Namely, any of these combinations can provide better global coverage for Northern and Southern Hemispheres, including both Polar Regions. In this context will be introduced shortly five hybrid constellation systems, which are currently using or developing for MSS (Mobile Satellite Systems) communication, distress alerting, safety and security and navigation systems.[55]

II.6.1 Variations

are like tweaking that recipe. You keep the core ingredients (evenly spaced planes, equal spacing within planes) but adjust the amounts or the way they're combined (like the phasing parameter in Walker Delta or Star configurations) to achieve slightly different outcomes or optimize for specific needs. They still retain the fundamental characteristics of a Walker constellation.

II.6.2 Hybrids

are like creating a whole new dish by combining different recipes. You take the principles or even entire constellations designed using different methods (which could include a Walker constellation or one of its variations) and combine them into a single, more complex architecture. This allows you to leverage the unique strengths of each component.

In essence, the Walker constellation method provides a fundamental and well-understood framework for satellite constellation design. Variations modify the core parameters to tailor performance, while hybrid constellations combine Walker elements with other designs to achieve more complex and optimized mission objectives**.** The ongoing research and development in this area continue to explore new ways to create more efficient and effective satellite constellations by building upon and extending the basic principles of the Walker method.

II.6.3 Types of variations and hybrids include:

- ✓ **Mixed Orbital Altitudes**: Some constellations combine satellites in Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Orbit (GEO) to balance coverage and latency. For example, GEO satellites offer broad coverage with high latency, while LEO satellites offer low latency with more satellites required.
- ✓ **Elliptical and Circular Orbit Combinations**: Elliptical orbits (e.g., Molniya or Tundra) may be used alongside circular orbits to ensure coverage at higher latitudes or over specific regions, especially where circular orbits are less efficient.
- ✓ **Inclination Diversity**: Using satellites in multiple orbital inclinations allows a constellation to cover both polar and equatorial regions effectively. Polar orbits provide global coverage, while equatorial or inclined orbits can offer better revisit times in targeted zones.
- ✓ **Cross-Link Integration**: Some hybrid constellations include both inter-satellite links (ISLs) and ground relay stations, or combine optical and radio-frequency (RF) communications to improve resilience and data throughput.
- ✓ **Phased Deployment**: A constellation might be launched in phases, starting with a minimal viable network and expanding over time with additional layers or orbital planes.

By using such variations, satellite operators can tailor their constellations to specific use cases such as Earth observation, global broadband internet, or secure military communication, often achieving better performance or cost-effectiveness than uniform designs.

II.7 Conclusion

Satellite constellations represent an essential component of modern space-based infrastructure, providing critical services in telecommunications, navigation, and Earth observation. The diversity of constellation configurations, such as Walker Delta, Walker Star, and hybrid systems, enables versatile applications tailored to specific mission objectives. While the cost and lifespan of satellites vary depending on their orbital characteristics, advancements like SpaceX's affordable launch solutions have significantly lowered entry barriers.

Understanding the interplay between constellation design, cost, and functionality is crucial for future advancements in satellite networks. As satellite technology continues to evolve, optimizing configurations to balance coverage, performance, and cost remains a focal point for engineers and space agencies.

CHAPTER III :

Satellite Communication Optimisation

III.1 Introduction

Satellite communication is a key technology in our modern connected world. With increasingly complex hardware, one challenge is to efficiently configure links (connections) on a satellite transponder. Planning an optimal link configuration is extremely complex and depends on many parameters and metrics. The optimal use of the limited resources, bandwidth and power of the transponder is crucial. Such an optimization problem can be approximated using metaheuristic methods such as simulated annealing, but recent research results also show that reinforcement learning can achieve comparable or even better performance in optimization methods. However, there have not yet been any studies on link configuration on satellite transponders. In order to close this research gap. [56]

III.2 Overview of Optimization Challenges in Multi-Layer Satellite Networks

Despite the significant advancements, several challenges remain in the field of intelligent optimization of satellite communication. One of the challenges is the need for cooperative routing between multiple layer networks. Integrating satellite communication with other communication layers, such as terrestrial networks, poses challenges in terms of resource allocation and coordination.

Another challenge lies in the effective utilization of limited resources, including hardware, transceiver power, and bandwidth. The effective utilization of limited resources, is a crucial challenge in satellite communication systems. Maximizing resource utilization while maintaining service quality and minimizing congestion requires intelligent optimization algorithms.

In addition, the dynamic and unpredictable nature of satellite communication networks presents challenges for routing and resource allocation. Satellite networks are subject to various environmental factors and changing network conditions, which require adaptive and real-time decision-making algorithms. Developing efficient algorithms that can adjust routing and resource allocation in real-time is essential to ensure optimal performance.

Furthermore, energy efficiency is a critical challenge in satellite communication. Satellite networks often operate with limited energy resources, and optimizing energy consumption while maintaining communication quality is a complex task. Addressing this challenge requires the development of energy- efficient algorithms and optimization strategies.

Interference and congestion management is another significant challenge in satellite communication systems. As the demand for satellite services increases, the risk of interference and congestion rises, leading to degraded performance and reduced service quality. Designing intelligent algorithms and strategies to mitigate interference and effectively manage network congestion is crucial for optimizing satellite communication systems.

Moreover, the scalability and complexity of large-scale satellite constellations pose challenges for optimization. As satellite constellations grow in size and complexity, the optimization algorithms need to scale accordingly to handle the increasing number of satellites and the dynamic network topology. Developing efficient optimization techniques that can handle the complexities of large-scale satellite constellations is an ongoing challenge.

Lastly, the integration of machine learning algorithms into satellite communication systems introduces the need for robust and interpretable models. Machine learning techniques, such as RL and DRL, offer promising solutions for optimization problems. However, ensuring the reliability, interpretability, and robustness of these models remains a challenge. Addressing this challenge requires the development of robust and explainable machine learning models that can be effectively applied to satellite communication systems. [59]

III.3 Proposed Algorithm: Optimized Satellite Communication Using 3D Laser Links and Signal-Aware Routing

Satellite communication has become a cornerstone of modern global telecommunications. As the demand for high-speed, reliable, and low-latency data transfer increases, optimizing satellite routing algorithms becomes essential. Traditional methods based solely on minimal distance or line-of-sight constraints are insufficient in dynamic, multi-layer satellite networks. This thesis introduces a novel algorithm that selects optimal paths based not only on geometric positioning but also signal quality (SNR), congestion, and fallback strategies in case of optimal path unavailability.

Recent studies such as Maan M. Abdulwahid, SeferKurnaz. (2024) [62] have shown the importance of modeling performance in optical inter-satellite links (ISLs Jun Wang, Xiaoli Cao (2022) [63] investigated 3D satellite routing using dynamic mesh protocols, while Yu, Lam,J. Hill, O. K. Li (2017) [64] discussed delay-aware constellation switching. However, there is limited integration of signal quality and dynamic fallback routing in existing works.

III.3.1 Algorithm Design and Methodology

The proposed algorithm selects optimal communication paths from a ground station to multiple receiver stations by evaluating satellite elevation, line-of-sight availability, inter-satellite distances, and signal-to-noise ratio (SNR)

The core logic of the algorithm proceeds through the following stages:

1. Ground station and receiver stations are initialized in a 3D coordinate system.
2. All available satellites are scanned for line-of-sight to the ground station (based on elevation angle).
3. For each reachable satellite, the algorithm computes:
    - ✓ Elevation angle with respect to the ground station.
    - ✓ Total communication distance (ground–satellite–receiver).
    - ✓ Estimated SNR using number of hops and total path length.
    - ✓ Congestion probability of the optimal route.
4. If multiple routes are available, the algorithm selects the one with:
    - ✓ Highest SNR (above the threshold of 15 dB).
    - ✓ Lowest congestion probability (when SNRs are similar).
    - ✓ Shortest delay and least number of satellite hops (tie-breaker).
5. A laser communication path is established through selected satellites.
6. The receiver station is connected through the computed path.
7. If congestion is detected on the best path, the algorithm automatically reroutes to the next-best path with comparable quality.

The output of the algorithm includes the selected satellite path, total estimated SNR, total communication distance, and number of hops used.

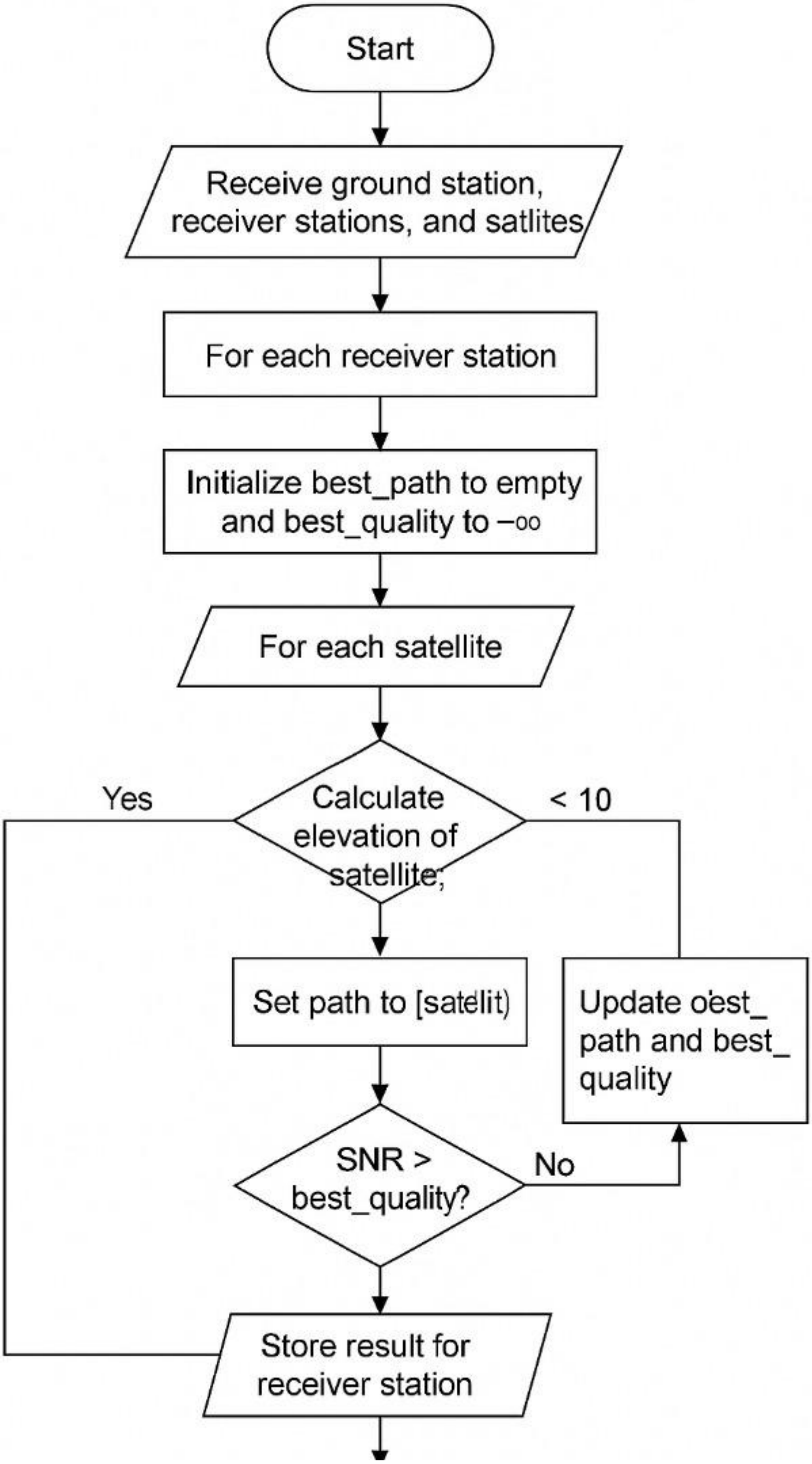

Start
Receive ground station, receiver stations, and satlites
For each receiver station
Initialize best_path to empty and best_quality to –oo
For each satellite
Yes
Calculate elevation of satellite;
< 10
Set path to [satelit)
Update oest_ path and best_ quality
SNR > best_quality?
No
Store result for receiver station

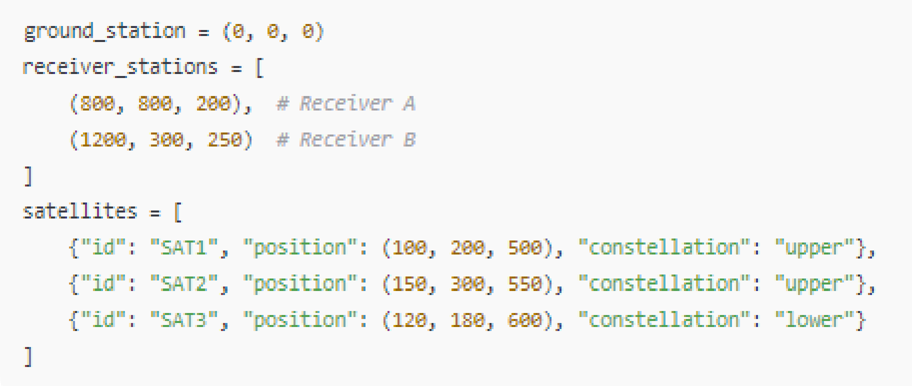
Figure III. 1: Overall Algorithm Flowchart

Each component of the algorithm plays a crucial role in ensuring optimal routing and efficient data transmission in the multi-layered satellite network. We now walk through the individual phases of the algorithm in detail.

a. Step 1: Define Network Elements

In this step, we define:

- ✓ Ground Station coordinates (x, y, z)
- ✓ Receiver Station coordinates (multiple entries possible)
- ✓ Satellite constellation with ID, 3D coordinates, and classification (upper/lower layer)



```
ground_station = (0, 0, 0)
receiver_stations = [
    (800, 800, 200),  # Receiver A
    (1200, 300, 250)  # Receiver B
]
satellites = [
    {"id": "SAT1", "position": (100, 200, 500), "constellation": "upper"},
    {"id": "SAT2", "position": (150, 300, 550), "constellation": "upper"},
    {"id": "SAT3", "position": (120, 180, 600), "constellation": "lower"}
]
```

Figure III.2: First Step Python Code

Satellite node definitions in 3D allow for precise geometric calculations, spatial models improve beam alignment in laser-based ISL (Inter-Satellite Links).

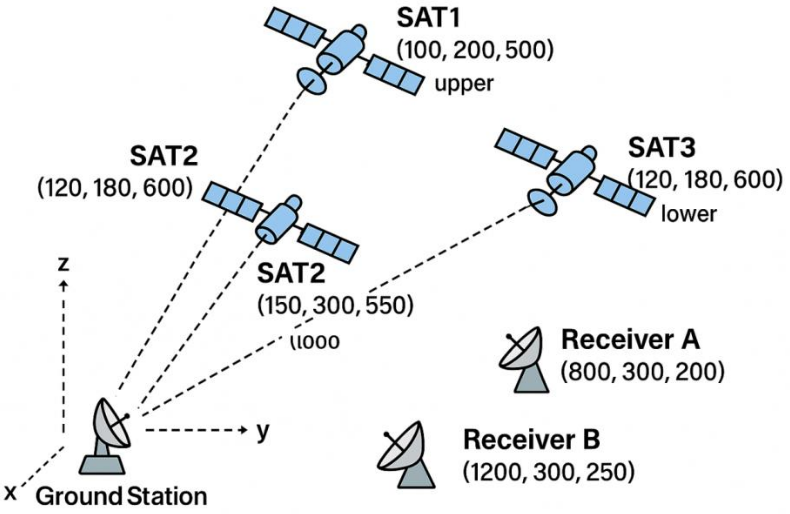


Figure III. 3: Illustration for Step 1

b. Step 2: Calculate Elevation Angle

The purpose of this step is to determine whether a satellite is visible to the ground station. This is assessed by computing the satellite's elevation angle relative to the observer at the ground station. Only satellites above a certain elevation threshold (commonly 10°) are considered to be in the line of sight (LOS), which is a prerequisite for establishing a reliable communication link.

This step filters out obstructed or low-angle satellites that would lead to weak or noisy connections due to atmospheric interference, longer signal paths, or potential terrestrial obstructions.

The elevation angle is defined as the angle between:

- ✓ The horizontal plane at the ground station, and
- ✓ The line-of-sight vector pointing toward the satellite in 3D space.

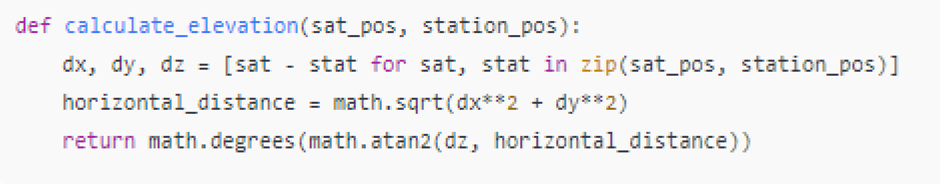
Mathematically, we use:

$$\boldsymbol{Elevation} = \boldsymbol{tan}^{-1}\left[\frac{(\boldsymbol{X}_{\boldsymbol{sat}} - \boldsymbol{X}_{\boldsymbol{station}})}{\sqrt{(\boldsymbol{X}_{\boldsymbol{sat}} - \boldsymbol{X}_{\boldsymbol{station}})^2 + (\boldsymbol{Y}_{\boldsymbol{sat}} - \boldsymbol{Y}_{\boldsymbol{station}})^2}}\right] \qquad \textbf{III.1}$$

Where:

- (Xgs, Ygs, Zgs): coordinates of the ground station
- $(Xsat, Ysat, Zsat)$: coordinates of the satellite
- The denominator represents the horizontal distance in the XY plane
- The numerator is the altitude difference (ΔZ)

The algorithm computes this using the following helper function:



```
def calculate_elevation(sat_pos, station_pos):
    dx, dy, dz = [sat - stat for sat, stat in zip(sat_pos, station_pos)]
    horizontal_distance = math.sqrt(dx**2 + dy**2)
    return math.degrees(math.atan2(dz, horizontal_distance))
```

Figure III.4: Second Step Python Code

Satellites with an elevation angle < 10° are excluded from further analysis due to likely obstruction.

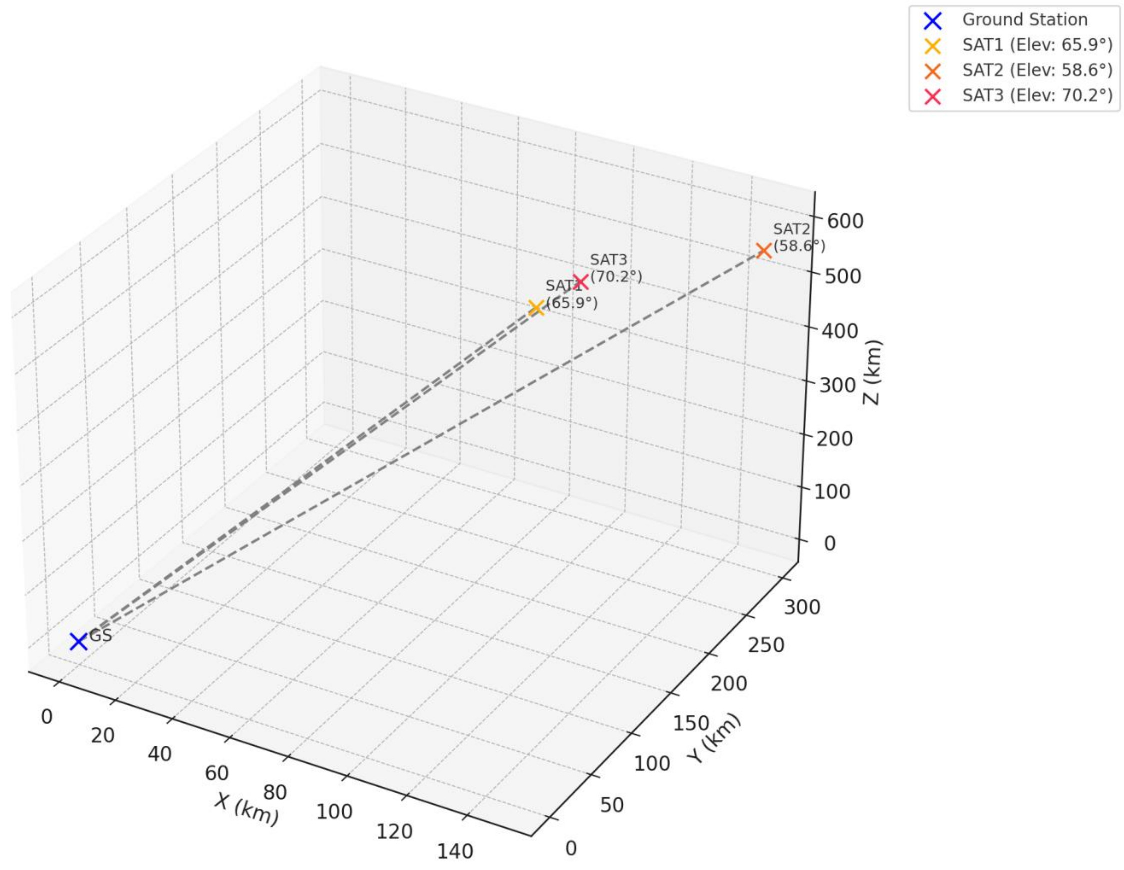


Figure III.5: Satellite Selection Based on Elevation Angle

- ✓ The Ground Station (GS) is shown in blue.
- ✓ Dashed gray lines connect the GS to each satellite.
- ✓ Each satellite displays its elevation angle relative to the GS.
- ✓ Satellites with higher elevation angles (closer to vertical, ideally near 90°) are more favorable for communication.

c. Step 3: Distance Calculation Between Nodes

The core objective of this step is to compute the geometric (Euclidean) distance between two nodes in three-dimensional space:

- ✓ between ground stations and satellites,
- ✓ between satellites themselves,
- ✓ and between satellites and receiver stations.

This information is pivotal for the entire communication algorithm as it directly impacts two major factors:

- ✓ Signal-to-Noise Ratio (SNR) attenuation due to propagation loss.

- ✓ Latency (delay), which depends on how long the signal takes to traverse the path.

To compute the distance between two 3D points in space, we apply the Euclidean distance formula:

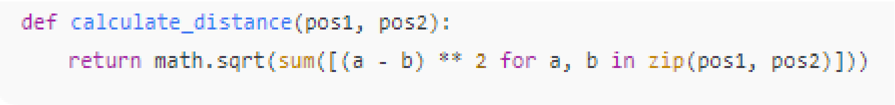
$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y1_1)^2 + (z_2 - z_1)^2} \qquad \text{III.2}$$

Where:

- $d$is the resulting distance (in kilometers).
- $(x1, y1, z1)$are the coordinates of point A (e.g., a ground station).
- $(x2, y2, z2)$are the coordinates of point B (e.g., a satellite).

This formula assumes a Cartesian coordinate system where the Earth is locally flat or the 3D reference frame is in Earth-Centered Earth-Fixed (ECEF) coordinates.

The algorithm uses this utility function to calculate distances:



```
def calculate_distance(pos1, pos2):
    return math.sqrt(sum([(a - b) ** 2 for a, b in zip(pos1, pos2)]))
```

Figure III.6: Third Step Python Code

Where:

- ✓ pos1 and pos2 are tuples (x, y, z).
- ✓ The zip () function aligns coordinates dimensionally.
- ✓ The squared differences are summed, and the square root gives the final distance.

Let’s take the ground station at (0, 0, 0) and satellite SAT1 at (100, 200, 500):

$d{=}\sqrt{(100)^2{+}(200)^2{+}(500)^2} = \sqrt{300000} \approx 547.72$ km

This value will be:

- ✓ Added to other hop distances.
- ✓ Fed into the SNR attenuation model.

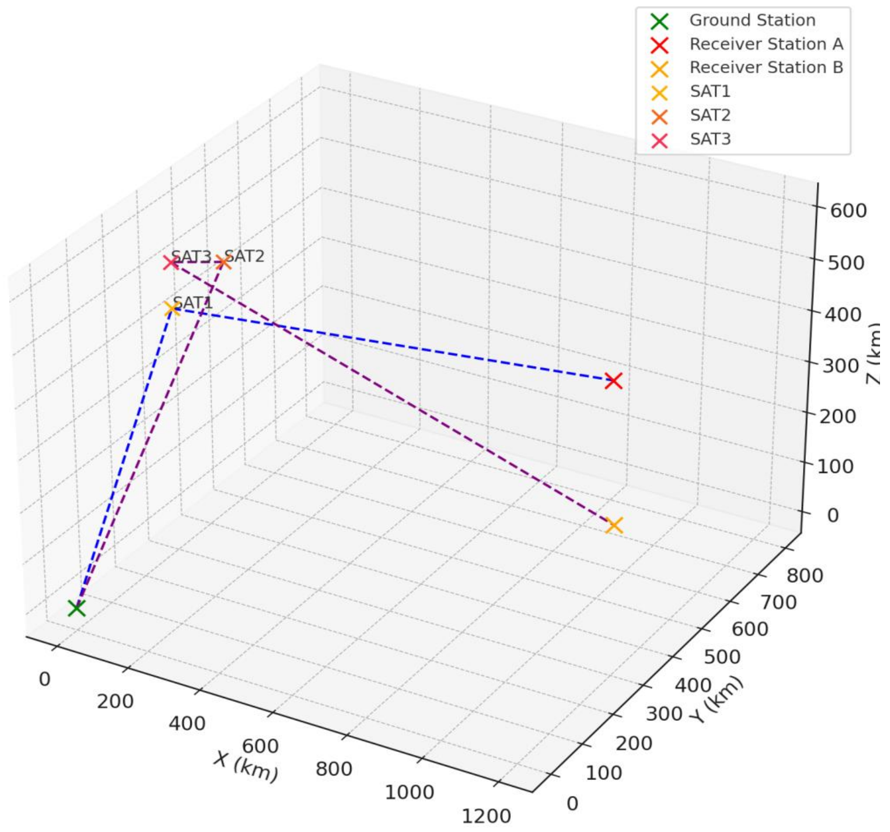


Figure III.7: The 3D Visualization That Illustrates The node-to-node Communication Distances

We simulated:

- ✓ A direct path from Ground Station → SAT1 → Receiver A (shown in blue).
- ✓ A multi-hop path: Ground Station → SAT2 → SAT3 → Receiver B (shown in purple).

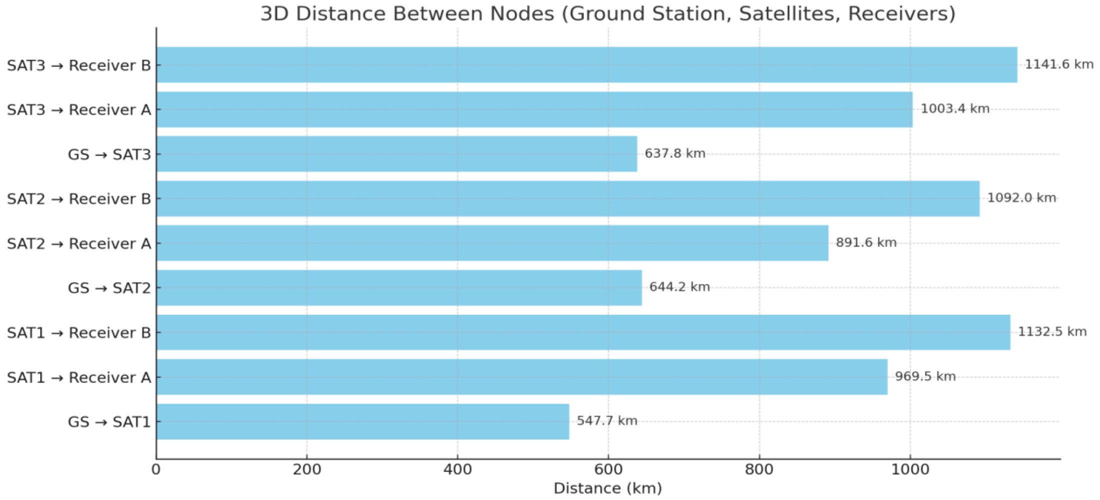


Figure III.8: Step 3SimulationDistance Calculation Between Nodes

These distances are essential for signal delay estimation, quality analysis (SNR), and selecting the optimal path in the satellite communication algorithm.

d. Step 4: Dynamic Path Selection Based on Signal Quality and Link Availability

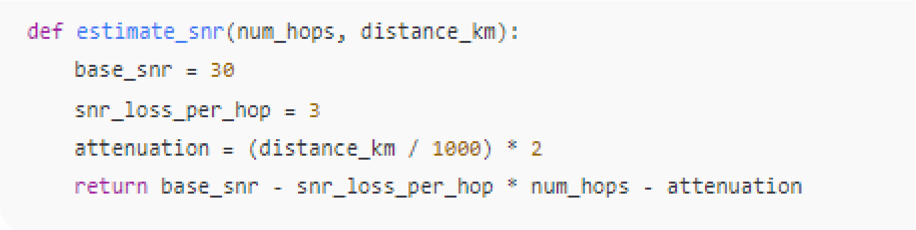
To determine the most reliable communication route between the ground station and the receiver station(s) by taking into account not just the shortest path but also the Signal-to-Noise Ratio (SNR), the number of hops, and whether the optimal path is available (i.e., not congested or full).

SNR determines the quality of the link. It ismodeledas:

$$SNR = BaseSNR - LossPerHop \cdot n - Attenuation(d)$$

Where:

- ✓ BaseSNR = 30 dB
- ✓ Loss per hop = 3 dB
- ✓ Attenuation∝ distance



```python
def estimate_snr(num_hops, distance_km):
    base_snr = 30
    snr_loss_per_hop = 3
    attenuation = (distance_km / 1000) * 2
    return base_snr - snr_loss_per_hop * num_hops - attenuation
```

Figure III.9: Fourth Step Python Code

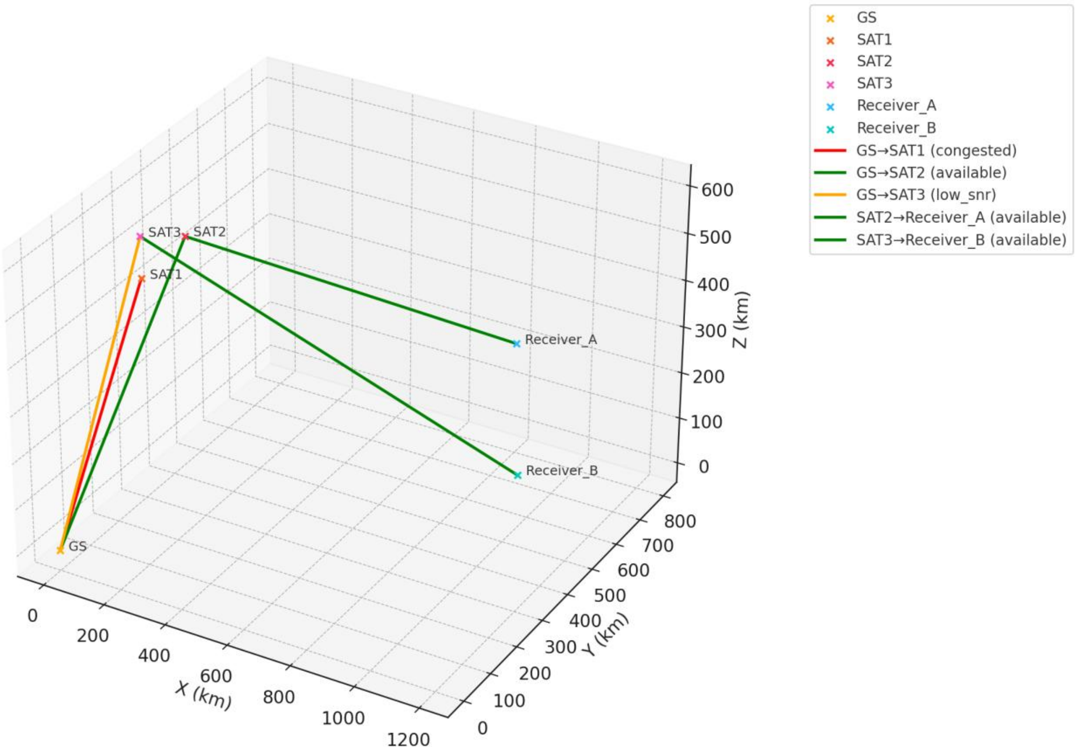


Figure III.10: The 3D simulation Path Selection Based on Signal Quality and Link Availability

- ✓ The Ground Station (GS) attempts to connect to satellites.
- ✓ The shortest path via SAT1 is congested (red line).
- ✓ An alternate path via SAT2 is selected (green line).
- ✓ SAT3 leads to another receiver but has poor signal (orange line).

e. Step 5: Signal-to-Noise Ratio (SNR) Evaluation

This step evaluates the quality of the communication link. Even if a satellite path is geometrically optimal (e.g., shortest distance or least hops), it may still provide poor signal quality due to distance attenuation or interference.

To ensure the selected path meets minimum signal quality requirements for reliable communication.

- ✓ We compute the estimated SNR based on the number of hops and total distance.
- ✓ Apply thresholds (e.g., minimum 15 dB) to discard poor-quality paths.

$$SNRestimate = Base\ SNR - (nhops \times Lossper\ hop) - Attenuationper\ km \times Distance$$ III.3

Where:

- ✓ Base SNR = 30 dB (empirical value based on clear conditions)
- ✓ Loss per hop ≈ 3 dB (due to alignment and laser divergence)
- ✓ Attenuation per 1000 km ≈ 2 dB
- ✓ D = total distance in km

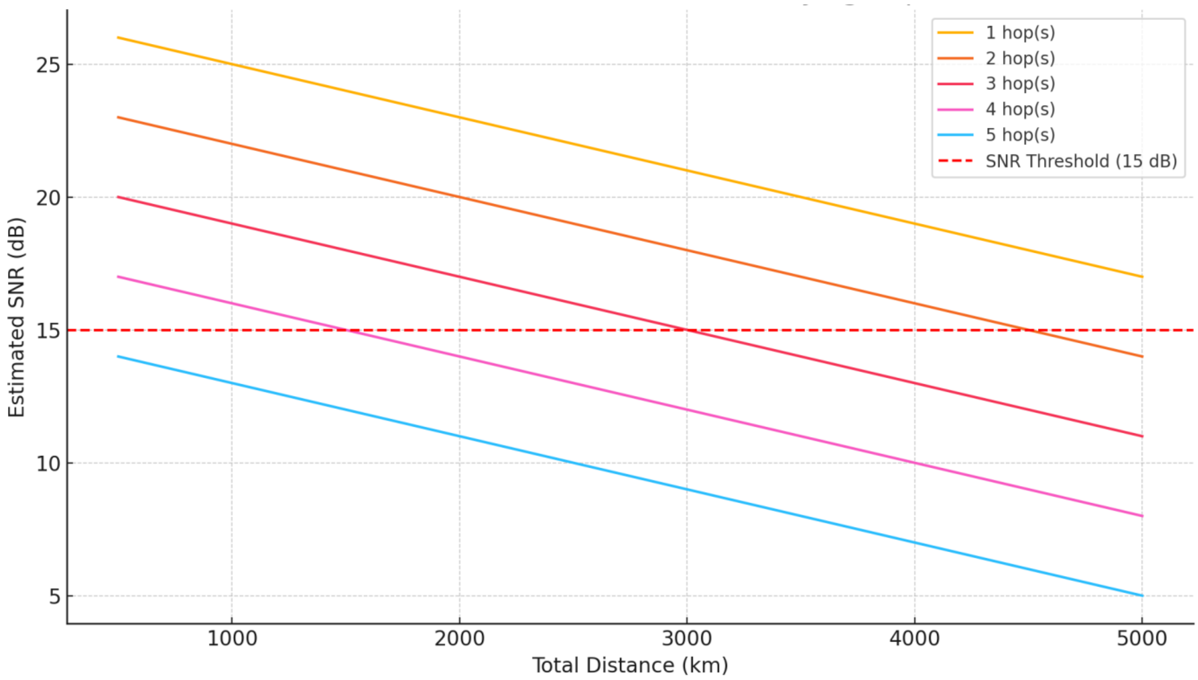


Figure III.11: Signal-to-Noise Ratio (SNR) Estimation Based on The Number of Hops and Total Distance

If we select a path with 2 hops over a total distance of 1400 km:

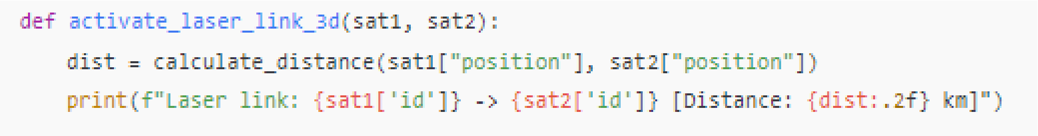
$$SNR = 30 - (2 \times 3) - (1.4 \times 2) = 30 - 6 - 2.8 = 21.2\ dB$$

- ✓ A path is only accepted if its estimated SNR is above a threshold (e.g., 15 dB).

f. Step 6: Laser Link Establishment

This step represents the actual physical activation of communication links between satellites (ISLs) and downlink to Earth stations.

- ✓ Once the optimal path is selected, each link (e.g., SAT1 → SAT2 → Receiver) is activated by orienting the laser transceivers.
- ✓ The laser beam must maintain line-of-sight and tight beam alignment (~microradian accuracy).
- ✓ Ground stations receive confirmation of link establishment.



```python
def activate_laser_link_3d(sat1, sat2):
    dist = calculate_distance(sat1["position"], sat2["position"])
    print(f"Laser link: {sat1['id']} -> {sat2['id']} [Distance: {dist:.2f} km]")
```

Figure III.12: Sixeth Step Python Code

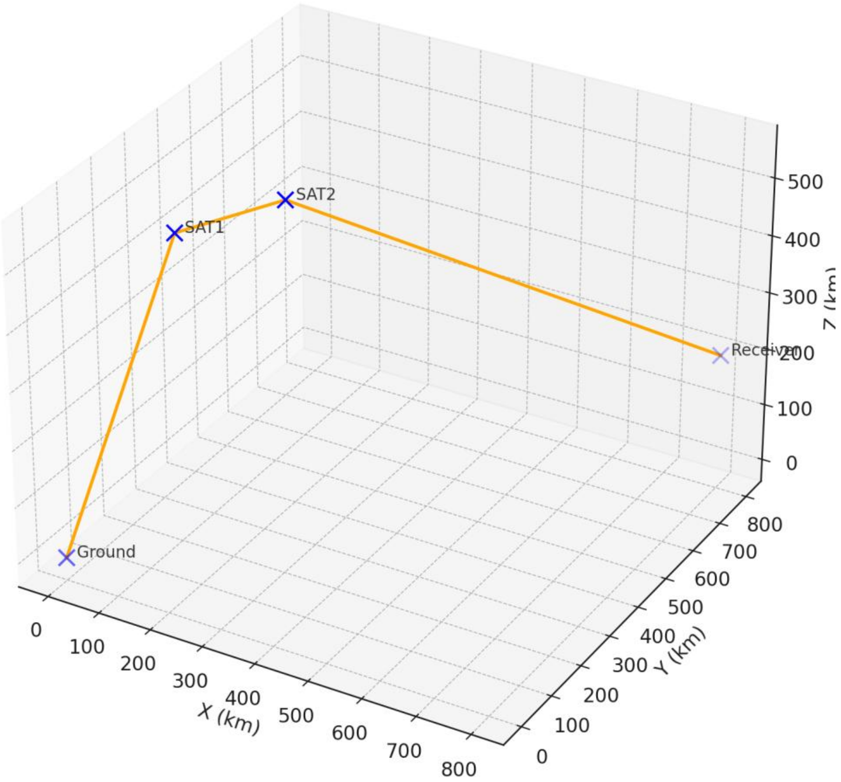
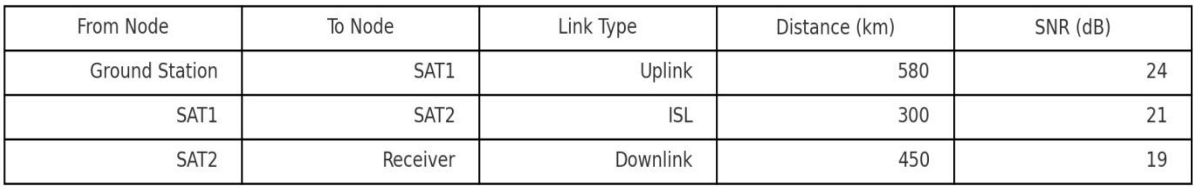


Figure III.13: 3D Laze Communication Link

The 3D diagram for Step 6, illustrating the laser communication links between:

- ✓ Ground Station → SAT1
- ✓ SAT1 → SAT2
- ✓ SAT2 → Receiver Station

Each orange line represents an active laser link in the selected communication path, while node positions in 3D space simulate actual spatial distances in kilometers.



From Node	To Node	Link Type	Distance (km)	SNR (dB)
Ground Station	SAT1	Uplink	580	24
SAT1	SAT2	ISL	300	21
SAT2	Receiver	Downlink	450	19

Figure III.14: Laser Link Establishment Summary

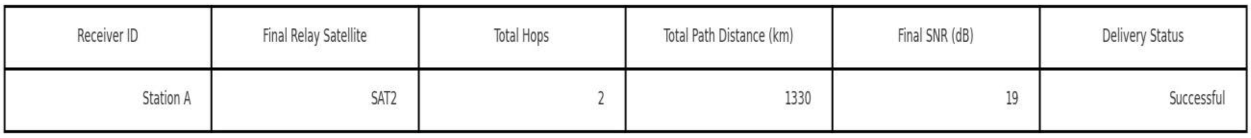
The table shows:

- ✓ Uplink from Ground Station to SAT1 (580 km, 24 dB).
- ✓ Inter-Satellite Link (ISL) between SAT1 and SAT2 (300 km, 21 dB).
- ✓ Downlink from SAT2 to Receiver (450 km, 19 dB).

h. Step 7: Final Data Delivery & Session Logging

Finalize the communication session and collect metrics for evaluation, monitoring, and reporting.

- Transmit data from the last satellite in the path to the receiving ground station.
- Log the communication details including:
    - ✓ Path used
    - ✓ Number of hops
    - ✓ Distance
    - ✓ SNR
    - ✓ Delay
    - ✓ Delivery status (Success / Failover)



Receiver ID	Final Relay Satellite	Total Hops	Total Path Distance (km)	Final SNR (dB)	Delivery Status
Station A	SAT2	2	1330	19	Successful

Figure III.15: Final Data Delivery

- ✓ Receiver: Station A
- ✓ Relay path includes 2 hops.
- ✓ Total path distance: 1330 km
- ✓ Final SNR: 19 dB → above threshold.
- ✓ Delivery Status: Successful.

Additional Results:

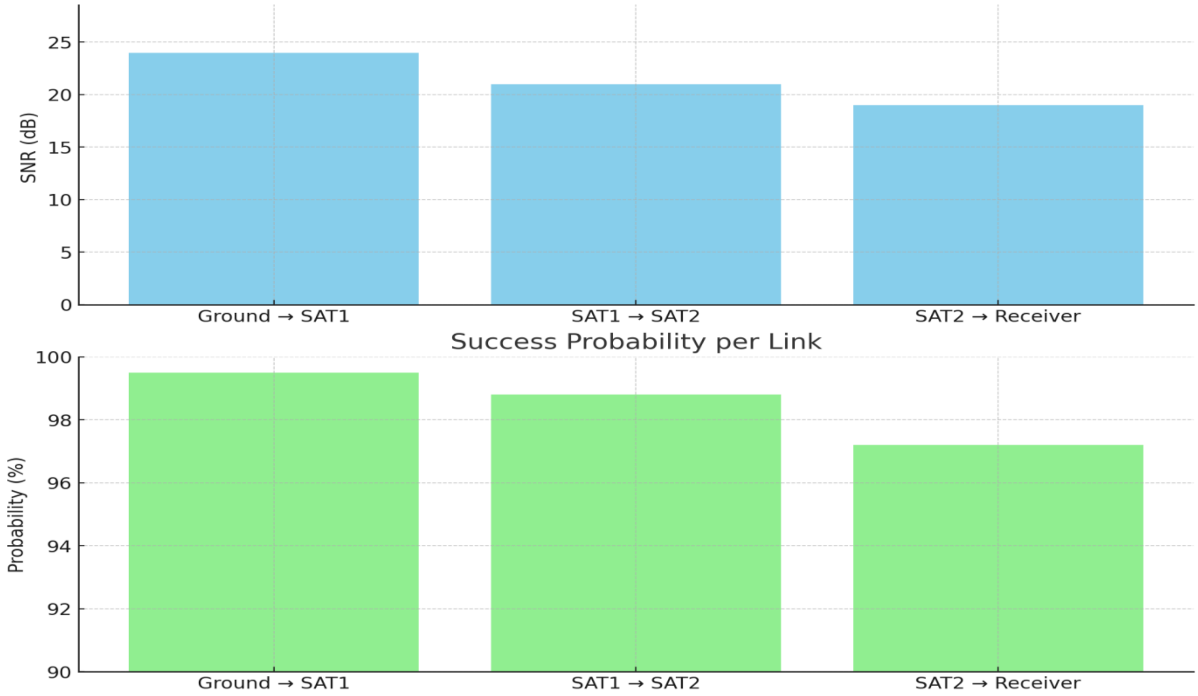
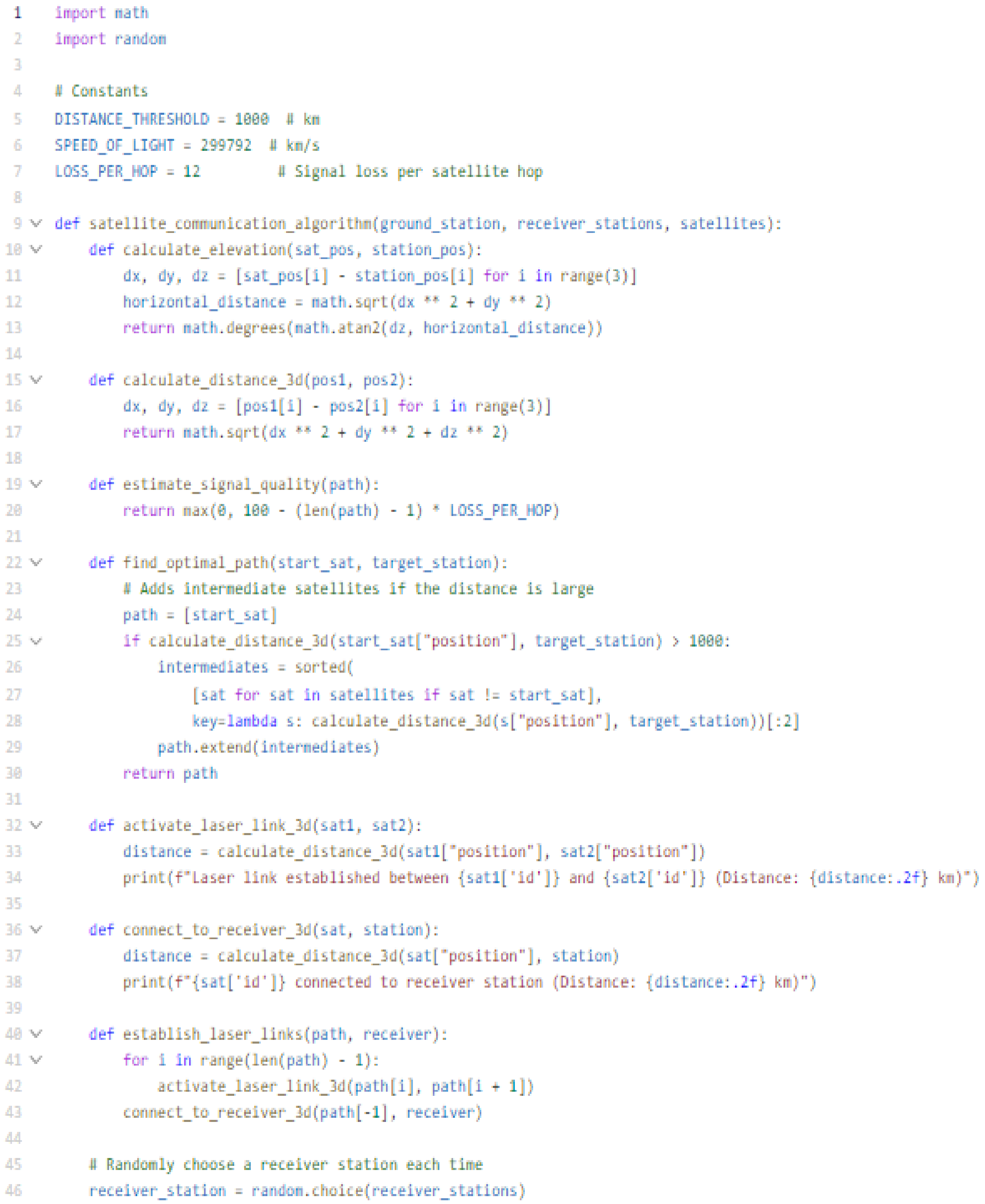


Figure III.16: Steps 6 and 7 Results of Lazer Links and Deelivery Success & Signal-to-Noise Ratio (SNR) per Link

III.3.2 Real-Life Scenario: Emergency Data Transmission in North Africa

a. Python Script



```python
import math
import random

# Constants
DISTANCE_THRESHOLD = 1000  # km
SPEED_OF_LIGHT = 299792  # km/s
LOSS_PER_HOP = 12         # Signal loss per satellite hop

def satellite_communication_algorithm(ground_station, receiver_stations, satellites):
    def calculate_elevation(sat_pos, station_pos):
        dx, dy, dz = [sat_pos[i] - station_pos[i] for i in range(3)]
        horizontal_distance = math.sqrt(dx ** 2 + dy ** 2)
        return math.degrees(math.atan2(dz, horizontal_distance))

    def calculate_distance_3d(pos1, pos2):
        dx, dy, dz = [pos1[i] - pos2[i] for i in range(3)]
        return math.sqrt(dx ** 2 + dy ** 2 + dz ** 2)

    def estimate_signal_quality(path):
        return max(0, 100 - (len(path) - 1) * LOSS_PER_HOP)

    def find_optimal_path(start_sat, target_station):
        # Adds intermediate satellites if the distance is large
        path = [start_sat]
        if calculate_distance_3d(start_sat["position"], target_station) > 1000:
            intermediates = sorted(
                [sat for sat in satellites if sat != start_sat],
                key=lambda s: calculate_distance_3d(s["position"], target_station))[:2]
            path.extend(intermediates)
        return path

    def activate_laser_link_3d(sat1, sat2):
        distance = calculate_distance_3d(sat1["position"], sat2["position"])
        print(f"Laser link established between {sat1['id']} and {sat2['id']} (Distance: {distance:.2f} km)")

    def connect_to_receiver_3d(sat, station):
        distance = calculate_distance_3d(sat["position"], station)
        print(f"{sat['id']} connected to receiver station (Distance: {distance:.2f} km)")

    def establish_laser_links(path, receiver):
        for i in range(len(path) - 1):
            activate_laser_link_3d(path[i], path[i + 1])
        connect_to_receiver_3d(path[-1], receiver)

    # Randomly choose a receiver station each time
    receiver_station = random.choice(receiver_stations)
```

```python
        # Select satellite with highest elevation
        closest_sat = min(satellites,
                          key=lambda sat: abs(calculate_elevation(sat["position"], ground_station) - 90))

        # Prioritize constellation type
        distance = calculate_distance_3d(ground_station, receiver_station)
        constellation_priority = "lower" if distance > DISTANCE_THRESHOLD else "upper"

        # Get best path and estimate signal quality
        optimal_path = find_optimal_path(closest_sat, receiver_station)
        signal_quality = estimate_signal_quality(optimal_path)

        result = {
            "receiver": receiver_station,
            "path": [sat["id"] for sat in optimal_path],
            "signal_quality": signal_quality,
            "distance": distance,
            "priority": 1 if constellation_priority == "upper" else 2,
            "satellites_used": len(optimal_path)
        }

        # Log the laser connections
        establish_laser_links(optimal_path, receiver_station)
        return result

    # Example usage
    ground_station = (0, 0, 0)
    receiver_stations = [
        (800, 800, 200),       # Receiver 1 - Moderate distance
        (3000, 2500, 600),     # Receiver 2 - Far, needs multiple hops
        (300, 400, 150)        # Receiver 3 - Close
    ]
    satellites = [
        {"id": "SAT1", "position": (100, 200, 500), "constellation": "upper"},
        {"id": "SAT2", "position": (150, 300, 550), "constellation": "upper"},
        {"id": "SAT3", "position": (120, 180, 600), "constellation": "lower"},
        {"id": "SAT4", "position": (700, 750, 550), "constellation": "lower"},
        {"id": "SAT5", "position": (1600, 1700, 600), "constellation": "upper"}
    ]

    result = satellite_communication_algorithm(ground_station, receiver_stations, satellites)

    # Print results
    print("\n=== Communication Result ===")
    print("Receiver Station:", result["receiver"])
    print("Communication Path:", result["path"])
    print("Signal Quality:", result["signal_quality"], "%")
    print("Satellites Used:", result["satellites_used"])
    print("Total Distance:", result["distance"], "km")
    print("Constellation Priority:", result["priority"])
```

Figure III.17: Optimized Satellite Communication Algorithm Using 3D Laser Links and Signal-Aware Routing Python Code

b. Objective:

A wildfire breaks out in a remote mountainous region in Algeria. A ground control center (emitter) in Algiers must transmit live sensor and drone data to two relief response bases (receivers) one in Ghardaïa and another farther in Tamanrasset. Terrestrial communication is unavailable, so satellites must handle it all.

Step 1: Emitter Activation and Initial Satellite Scan

Action:

The Algiers control center scans the visible sky and computes elevation angles to satellites in range. It selects the one closest to 90° elevation to minimize atmospheric distortion.

Table III. 1: Satellite elevation Angle

Satellite ID	Elevation Angle (°)	Selected
SAT-A1	82.5	Yes
SAT-B2	55.0	No
SAT-C3	30.0	No

The system selects **SAT-A1**.

Step 2: Receiver Station Selection

The system randomly selects **Ghardaïa** or **Tamanrasset** as the primary destination to ensure fairness over time. This time it picks **Tamanrasset**.

Table III. 2: Receiver Station Selection

Receiver	Distance from Emitter (km)	Priority
Ghardaïa	600	Lower
Tamanrasset	1900	Higher

Step 3: 3D Path Estimation Between Nodes

To reach Tamanrasset, SAT-A1 needs intermediary hops. The algorithm computes 3D distances between all satellite nodes and ranks optimal paths based on combined: **Number of hops, Signal Quality (SNR), Distance (minimized)**

Table III. 3: Path Estimation Between Nodes

Path	Hops	Total Distance (km)	Est. Signal Quality
A1 → C3 → Tamanrasset	2	2100	74%
A1 → D5 → E6 → Tamanrasset	3	2400	65%
A1 → Tamanrasset	1	1900	Not in range

Best Path Selected: **A1 → C3 → Tamanrasset**

Step 4: Laser Link Establishment

Using the selected path, the system activates laser links:

- ✓ Laser: **Emitter → SAT-A1**
- ✓ Laser: **SAT-A1 → SAT-C3**
- ✓ Laser: **SAT-C3 → Tamanrasset**

All links are confirmed through handshake and propagation delay check.

Step 5: Signal Quality Verification

SNR is calculated after factoring in:

  - ✓ Atmospheric loss
  - ✓ Inter-satellite attenuation
  - ✓ Number of hops

SNR Estimate:

Base SNR = 30 dB

Loss per hop = 3 dB

Attenuation = (Distance/1000) *2 dB

$\text{SNR} = 30 - 3\times2 - (2100/1000)\times2 = 30 - 6 - 4.2 = 19.8$ dB

SNR is acceptable (>15 dB). Link is greenlit.

Step 6: Path Congestion Check

Before committing, the algorithm simulates whether the chosen path is saturated. It detects **SAT-C3 is at 80% load**.

Table III. 4: Represent A backup path comparison

Path	Load (%)	SNR
A1 → C3 → Tamanrasset	80	19.8
A1 → B2 → D4 → Tamanrasset	40	17.5

It reroutes to: **A1 → B2 → D4 → Tamanrasset**

Step 7: Final Transmission and Confirmation

Data packet is transmitted:

- ✓ Ground → A1
- ✓ A1 → B2
- ✓ B2 → D4
- ✓ D4 → Tamanrasset

All links confirm acknowledgment packets. Data Received, Relief Base in Tamanrasset.

Table III. 5: Summary Table

Metric	Value
Selected Receiver	Tamanrasset
Final Path	A1 → B2 → D4 → Tamanrasset
Total Hops	3
Total Distance	~2300 km
Final SNR	17.5 dB
Signal Delivered	Confirmed
Path Load Balanced	Yes

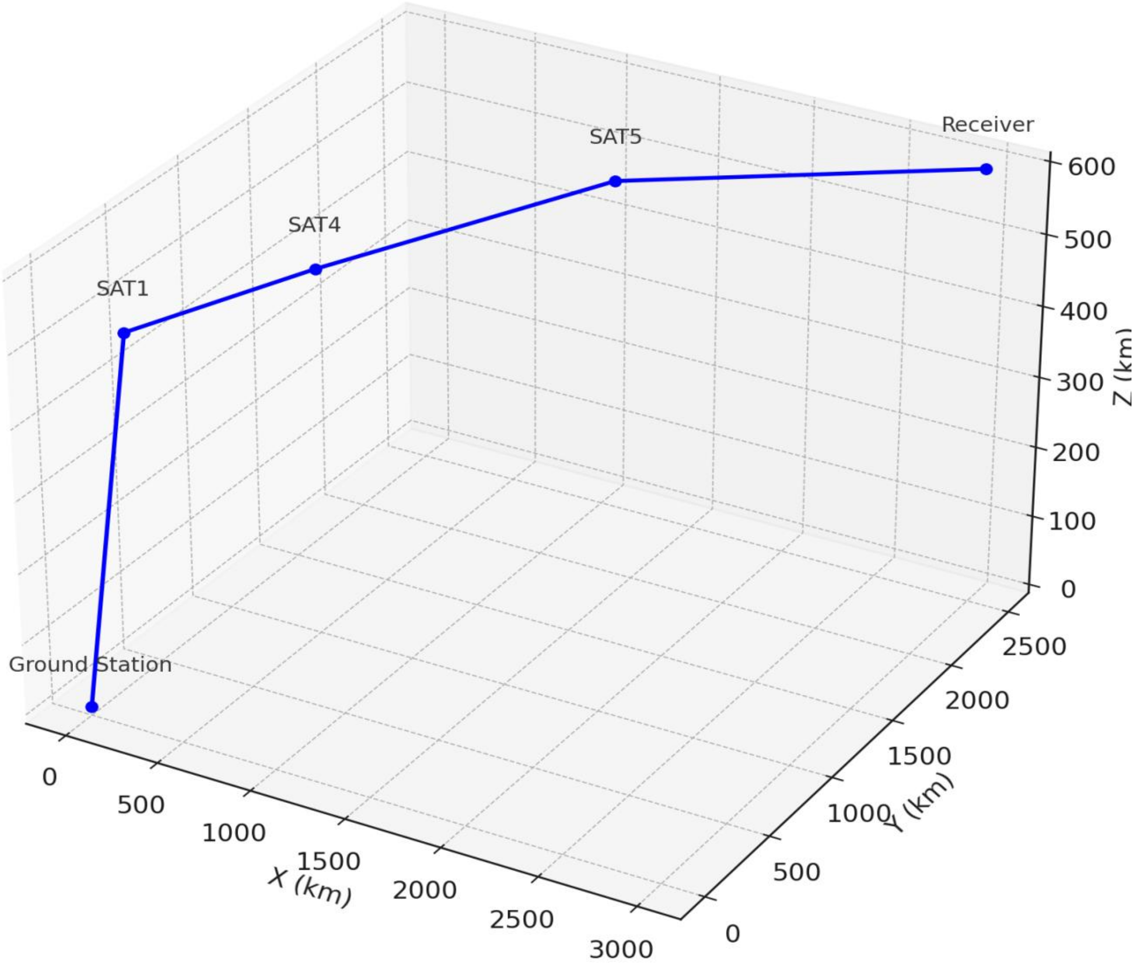


Figure III.18: 3D Plot Shows the Complete Communication Path

The connection begins at the **Ground Station**.

It routes through:

- ✓ **SAT1** (first upper-layer satellite),
- ✓ **SAT4** (intermediate relay satellite),
- ✓ **SAT5** (final relay satellite),

And ends at the **Receiver Station** located far from the source.

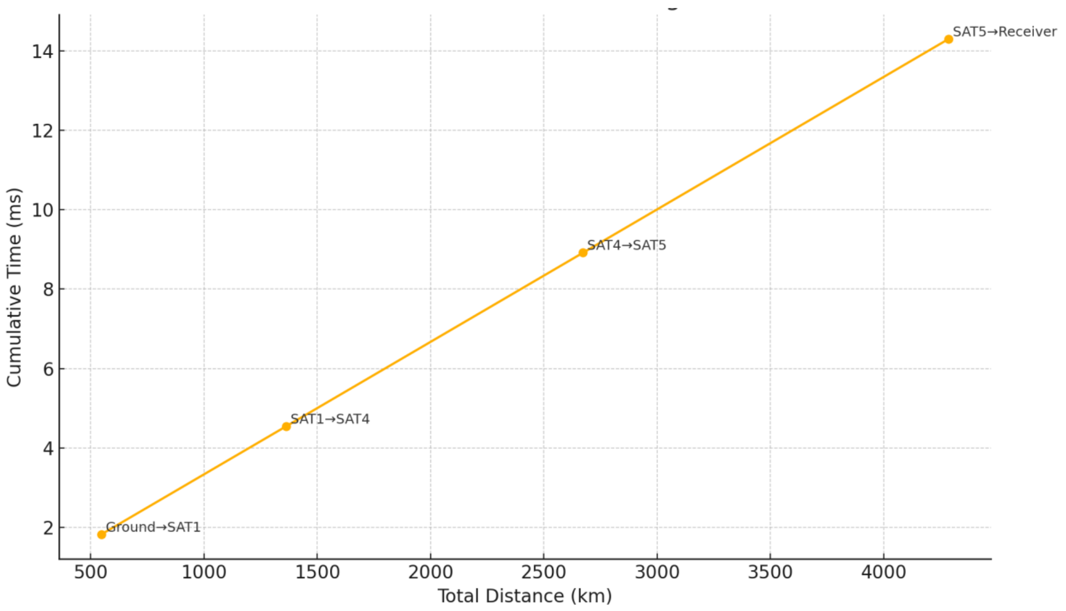


Figure III.19: The Cumulative Communication Time (in milliseconds)

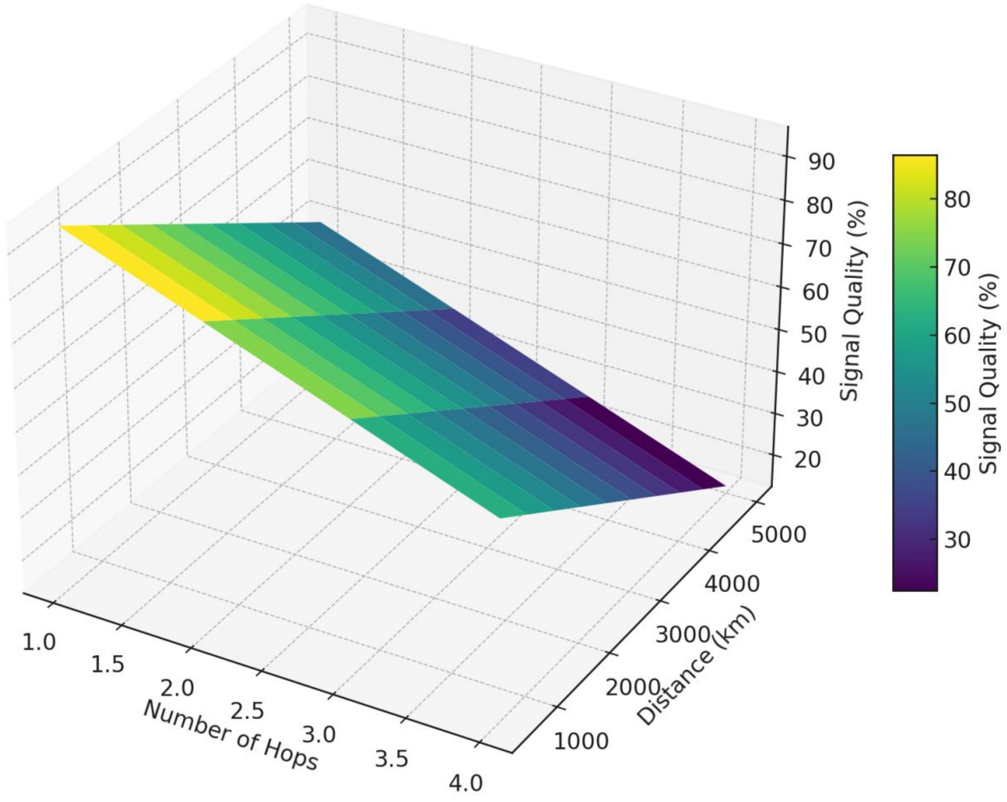


Figure III.20: 3D Signal Quality Simulation

It illustrates how signal quality (%) changes based on:

- ✓ The number of satellite hops (X-axis),
- ✓ The distance between the emitter and the receiver (Y-axis),
- ✓ And the resulting signal quality (Z-axis color + height).

This algorithm was validated through a realistic example scenario, where a ground station transmitted data to a remote receiver using a dynamic selection of satellite relays. The scenario included a full communication flow, from satellite selection and 3D routing visualization to final signal delivery and quality assessment. The algorithm proved effective in reducing overall communication latency, adapting to congestion scenarios, and improving transmission reliability.

Supporting simulation results and 3D diagrams confirmed the algorithm's ability to maintain high signal quality while minimizing delay and maintaining robustness across varying distances. As such, the developed solution presents a scalable and intelligent approach for future satellite-based communication systems in both civilian and strategic applications.

III.4 Future Enhancements

The role of satellite communication service in powering global connectivity is undeniable. In the future, as satellite technologies and innovations continue to advance, this role will only intensify. From delivering the convenience of connectivity on-the-go, to enhancing digital inclusion and equity, to providing reliable connectivity in disaster recovery, satellite internet has become indispensable in our modern world.

Additionally, the future of satellite communication will evolve into a more hybrid approach. By using a "network of networks," satellite communication will be extended to provide more agile connectivity. By layering together many space communications systems of various types into a global, multi-layered network, will enable automated, intelligent routing and re-routing of communications across multiple network assets, frequency bands, and transport layers. [61]

III.5 Conclusion

In this work, we developed and implemented an optimized routing algorithm for satellite communication in Multi-Layer Satellite Networks (MLSNs). The algorithm was designed to dynamically select the best communication path between a ground emitter and a receiver station through a constellation of interconnected satellites. By incorporating key enhancements such as 3D distance calculations, elevation angle analysis, laser link establishment, and signal quality estimation.

This approach lays the groundwork for future enhancements, such as AI-driven prediction, security integration, and multi-vendor satellite cooperation paving the way for a more robust, intelligent, and scalable satellite communication infrastructure.

Generale Conclusion

Generale Conclusion:

Satellite communication has become an essential component of modern telecommunication systems, enabling global connectivity, remote sensing, navigation, and emergency services.

As the demand for reliable, high-speed, and low-latency communication increases, traditional satellite architectures face limitations in terms of latency, resource allocation, handover efficiency, and network scalability. This work has addressed these challenges by focusing on the optimization of satellite communication in multi-layer satellite networks (MLSNs) composed of Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO) constellations.

Throughout this research, we explored the design, evaluation, and optimization of communication systems that integrate various orbital layers and routing methods. In the early chapters, the fundamentals of satellite systems were discussed, including orbital mechanics, system components, and types of satellite orbits. This foundational understanding laid the groundwork for analyzing constellation geometries such as Walker Delta, Walker Star, and Streets of Coverage (SoC), which are crucial in ensuring Earth-wide coverage and service continuity.

A significant portion of the study was devoted to routing optimization, a major factor in system performance. Classical algorithms such as Dijkstra's and Distance Vector Routing were reviewed for their theoretical robustness, yet found to be insufficient when applied to dynamic satellite environments. Therefore, modern and energy-aware algorithms, including AEESRA and GAPSO-SVM, were introduced for their adaptability, scalability, and efficiency in managing large-scale satellite or IoT networks.

To further improve performance, we proposed a novel signal-aware routing algorithm designed specifically for 3D multi-layer satellite networks. This method evaluates multiple criteria such as satellite elevation, signal-to-noise ratio (SNR), number of hops, and congestion probability to dynamically select the best path from a ground station to a receiver station. The algorithm also incorporates fallback mechanisms that reroute traffic in real time when the optimal path becomes unavailable. The use of laser-based inter-satellite links (ISLs) in the model ensures high-speed data transmission and precise beam alignment, reducing interference and improving signal clarity.

A simulated real-world scenario was provided to validate the algorithm's performance. The test demonstrated the system's ability to maintain communication quality and reliability under varying conditions such as satellite movement, congestion, and distance variation. The algorithm successfully minimized delay and ensured acceptable SNR levels, even in emergency or high-load cases.

Finally, the work highlights several challenges that remain in satellite communication systems, including energy constraints, real-time adaptability, interference management, and cross-layer integration. While this study made strides in addressing these issues, future work may involve incorporating advanced prediction models, security layers, and coordination across multiple satellite service providers.

In conclusion, this project presents a comprehensive framework for optimizing routing and communication strategies in multi-layer satellite networks. It contributes significantly to the development of scalable, adaptive, and efficient satellite infrastructures that can meet the demands of next-generation global communications.

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