SIMULATION STUDY OF A FREE-SPACE OPTICAL CONTROLLER-BASED SATELLITE NETWORK ARCHITECTURE FOR CONTINUOUS INTERPLANETARY COMMUNICATION

by
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Abstract

Future human missions to Mars face a critical communication challenge: complete loss of contact with Earth for up to two weeks during solar conjunction events when the Sun blocks radio signals between the planets. This thesis presents a revolutionary autonomous free-space optical (FSO) communication architecture that maintains continuous Earth-Mars connectivity through strategic deployment of relay satellites at gravitationally stable Lagrange points. The proposed system achieves 0.22 terabits per second aggregate capacity—over 35 times the current 6 Mbps Mars-Earth link—while eliminating conjunction blackouts entirely. The architecture employs a hierarchical design comprising three integrated tiers. Earth and Mars satellites equipped with FSO terminals form the access layer, providing planetary coverage through 8 Earth and 4 Mars satellites. Regional controller satellites positioned at Earth-Moon Lagrange points (L1, L2, L4, L5) coordinate traffic flows and provide navigation assistance that improves link acquisition success from 30% to 95%. The backbone layer consists of high-power relay satellites at Earth-Sun and Mars-Sun Lagrange points, creating 10+ redundant paths that circumvent solar occlusion. Through comprehensive simulation spanning 20,000 hours (2.28 years) of operational scenarios, the system demonstrates 100% continuous connectivity between Earth and Mars, including during solar conjunction periods. The network maintains 220 simultaneous FSO links with individual link rates up to 40 Gbps. Navigation-assisted pointing algorithms reduce acquisition time by 50% (from 30s to 15s) while improving link reliability through predictive beam steering based on orbital mechanics. This research establishes the technical foundation for an interplanetary internet essential to sustainable Mars colonization, enabling

near real-time mission control, high-bandwidth scientific data return, and reliable communication for human crews. The modular architecture supports incremental deployment and future expansion throughout the solar system, transforming humanity's communication capabilities beyond Earth.

Keywords: Lagrange Point Optical Relays, Solar Conjunction Mitigation, Autonomous Traffic Coordination, Earth-Mars FSO Network, Continuous Interplanetary Connectivity, Hierarchical Controller Architecture, Navigation-Assisted Acquisition, Multi-Tier Space Network, QoS-Aware Optical Routing, Self-Organizing Satellite Constellation

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This thesis is dedicated to my beloved wife, Grace, whose unwavering support has been my foundation throughout this journey; to my family, for their constant encouragement; and to my grandfather, Yuri, who once crafted parts for the Russian space program and sadly passed away during the course of this work.

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Scientists discover the world that exists; engineers create the world that never was.

– Theodore von Kármán

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Chapter 1

The Need for Revolutionary Space Communications

1.1 Introduction

NASA projects that in the 2030's the first human expedition will arrive on Mars. [1] The crew will face a sobering reality: their carefully crafted and inspiring message such as "Mission Control, touchdown confirmed. Humanity now walks on two worlds" will take between 4 and 24 minutes to reach Earth, depending on the orbital positions of the planets. Any response, whether congratulations or the execution of a critical emergency protocol, will take just as long to arrive. This is not due to a limitation of our technology, but to physics itself since all electromagnetic radiation travel at a finite speed across space. This constraint is only the tip of the iceberg that threatens space communication and hinders human expansion beyond Earth.

Humanity is on the threshold of becoming a multiplanetary species. From the first person in space in 1961 to the first moon landing in 1969, our ambitions since then have grown exponentially. This trajectory continues today, with NASA planning 28 missions over the next decade. [2] These modern missions will generate unprecedented amounts of data. Spacecraft now carry high-resolution cameras, spectrometers, and sensors that produce terabytes of information per minute. [3] This challenge extends beyond robotic explorers and includes future Mars colonies that will demand continuous high-bandwidth connectivity for operational telemetry. It is not beyond imagination that the future will hold a coordinated fleet of satellites, rovers, and drones that

each will contribute with their own streams of scientific data. However, the limited infrastructure supporting all this communication relies on radio technology that, despite improvements in efficiency and design, still faces the same fundamental limitations of distance and power that constrained the Apollo era.

This chapter analyzes the limitations of current space communication systems and establishes the need for new approaches to meet the demands of future missions. We begin in Section 1.2 by exploring three dimensions of the problem: the exponential growth in data generation from modern space missions, the fundamental limitations of radio-frequency communications, and the challenges posed by deep space exploration and Mars colonization. Section 1.3 defines the research objectives and scope of this thesis that establish boundaries for our investigation. Section 1.4 outlines our research methodology and Section 1.5 provides an outline for the remainder of this thesis. Collectively, these sections come to the conclusion that a hierarchical FSO network architecture that takes advantage of autonomous relay satellites at Mars-Sun and Earth-Sun Lagrange points, intelligent controller coordination at Earth-Moon Lagrange points, and navigation-assisted pointing provides the most advantageous solution to establishing continuous high-bandwidth interplanetary communications between Earth and Mars.

The limitations of radio-based space communications are not only technical hurdles, but fundamental constraints on humanity's expansion into the solar system. This thesis focuses on free-space optical (FSO) networks as the primary physical network protocol solution. The future of interplanetary communications will involve varying technologies, including proposed hybrid RF / optical systems that take advantage of

the strengths of each technology, distributed relay networks that create the backbone of the interplanetary Internet, advanced compression algorithms, AI-driven data prioritization, and quantum key distribution for security.

As governments and private corporations allocate time and resources for space exploration, our communication capabilities will significantly influence the missions we can undertake and their execution. The challenge isn't just technical but conceptual. We must re-imagine how we explore and operate when real-time control is improbable and that every bit of data is critical. An instrumental part of this re-imagining involves strategic positioning of relay satellites and controllers at Lagrange points which are locations in space where gravitational forces create generally stable positions relative to two celestial bodies. Lagrange points constitute regions of dynamic stability within the complex orbital environment in which planets, satellites, and spacecraft interact gravitationally. This thesis addresses one critical component of that re-imagining, which is to provide the design and simulation-based validation of an FSO network architecture that leverages Lagrange point relay and controller satellites to create an interplanetary satellite network. By combining the bandwidth advantages of optical communications with the orbital stability of Lagrange points and intelligent autonomous coordination with controllers, we can finally break through the communication bottleneck that restricts our reach into the cosmos.

FSO communication provides a solution to bandwidth constraints. In contrast to radio waves that disseminate energy over broad beams, FSO systems utilize lasers to generate small, focused beams that measure microradians in width. The concentration of energy, along with the extensive bandwidth at optical frequencies (which includes

tens of terahertz compared to hundreds of megahertz for RF), facilitates data speeds that substantially exceed those of RF systems. All while employing smaller and lighter terminals. The Deep-space Optical Terminals (DOT) study showed that a 22-cm diameter optical telescope could achieve 250 Mb/s from Mars distance (0.42 AU). [4] However these narrow optical beams also create new challenges in pointing, acquisition, and tracking that must be solved for practical deployment.

1.2 Research Motivation and Problem Statement

1.2.1 Exponential growth in space mission data requirements

1.2.1.1 The Data Explosion

Modern space missions generate data at extraordinary rates that are driven by technological innovations in sensor miniaturization, increased resolution capabilities, and the adaptation of scientific instruments to space environments. While early Mars rovers like Sojourner (1997) carried just 3 cameras and basic instruments, today's rovers like the Perseverance feature 23 cameras and sophisticated scientific payloads capable of producing gigabytes of high-resolution imagery and sensor data daily. [5, 6] As Dr. Justin Maki, the Perseverance imaging scientist at the Jet Propulsion Laboratory, said, "Cameras are capable of acquiring much more data than can be sent back to Earth," creating a critical bottleneck where rovers must carefully prioritize which data to transmit and discard valuable scientific observations due to bandwidth limitations. [7] Each successive generation of spacecraft has an increase in data generation capabilities, yet the communication infrastructure has not kept pace with

this growth.

The Perseverance rover can theoretically generate gigabytes of data daily, however, its transmission capabilities to Earth are severely limited. The rover must store data onboard and carefully prioritize which information to transmit during communication windows. Direct-to-Earth communication is severely constrained by distance and power limitations, while relays through Mars orbiters provide significantly higher data rates of 8-256 kbps (with next-generation systems reaching up to 1 Mbps) for limited periods during orbital passes. With Earth-Mars distances of up to 400 million kilometers, these transmissions can take over 22 minutes one way to reach Earth. [8] To put this in perspective, the Perseverance generates enough data to fill a smartphone in hours, but takes months to transmit the equivalent amount.

This data bottleneck is not merely a matter of patience. Fundamentally, it limits scientific discovery. For example, Perseverance's SHERLOC instrument can perform a detailed spectroscopic analysis that looks for organic molecules and can generate spatially resolved chemical maps using fluorescence and Raman spectroscopy coupled with microscopic images. [9] Yet the rover faces severe transmission constraints, its primary UHF antenna can send data at a maximum rate of only two megabits per second, and communication windows with orbiters are extremely limited and can transmit data about 10 or 11 hours per day. [10] [11] Scientists often settle for compressed previews and make critical decisions about which samples warrant detailed analysis based on limited information.

This disparity between data generation and transmission capacity creates a fundamen-

tal challenge. As researchers note, instruments are capable of collecting much more data than it is practicable to return to Earth, which require systems that assist in image compression and prioritization of data transmission from Mars to Earth. [12] The Mars 2020 Engineering Cameras alone can generate tens of gigabytes of data, yet bandwidth limitations mean potential discoveries in Martian geology, signs of past life, or unexpected phenomena may remain unanalyzed in the rover's memory, never reaching Earth for study. [13]

Future missions promise to exacerbate this data-bandwidth gap. Next-generation Mars missions are planned with hyperspectral imagers that can produce gigabytes per observation, ground-penetrating radar systems that can generate volumetric data sets, and networked surface stations that can create continuous environmental monitoring streams. The Europa Clipper, scheduled to study Jupiter's moon Europa, will carry nine scientific instruments capable of generating multiple gigabytes per flyby, yet must transmit this data across hundreds of millions of kilometers, and face even more severe communication constraints than Mars missions. [14] [15]

This exponential growth in data generation across all mission types, from Mars surface operations producing orders of magnitude more data than can be transmitted, to deep space missions struggling with extreme distances, to even near-Earth telescopes operating at capacity, demonstrates that traditional point-to-point communication architectures are reaching their limits. The disparity between data generation and transmission capabilities threatens to bottleneck scientific discovery, as missions must increasingly make difficult choices about which data to preserve and transmit versus which to discard forever. As missions become more ambitious and instruments more

sophisticated, this gap threatens to become the limiting factor in space exploration, potentially leaving humanity's most expensive scientific instruments unable to share their full discoveries.

1.2.1.2 Multi-Mission Coordination

Future space exploration will be composed of networks of spacecraft that work together, such as orbiters that relay data from surface assets, distributed sensor networks that monitor planetary environments, and coordinated fleet missions. Each additional node multiplies data generation rate while competing for the same limited communication bandwidth. The planned Artemis lunar architecture will require the management of communications between dozens of assets simultaneously which will create high bandwidth competition. [16]

Science missions generating high-resolution imagery must compete with safety-critical engineering telemetry, and force difficult prioritization decisions when multiple spacecraft vie for the same Deep Space Network resources. [17] With long propagation delays in space communications, delay-tolerant networking approaches using protocols like the Bundle Protocol help address intermittent connectivity challenges, though current routing methods may underestimate transmission times on lossy channels.[18]

Finally, the Mars Relay Network currently demonstrates this challenge with five orbiters that share relay capabilities, but as the Mars orbital population grows, the bandwidth competition will intensify, and require more sophisticated coordination protocols to prevent high-priority missions from monopolizing resources at the expense of routine but scientifically valuable observations. [19]

1.2.2 Current limitations of radio-based space communications

1.2.2.1 The Physics of Distance

Radio waves travel at the speed of light; however, the vast distances of space make communication take time. Earth-Mars communications experience delays ranging from 4 to 24 minutes one-way, depending on planetary positions. This latency alters how we must approach space operations and requires system design to include autonomy. These delays fundamentally alter operations with Mars rovers navigating autonomously, as a 48-minute round-trip prevents real-time control, and traditional request-response protocols become improbable.

1.2.2.2 Signal Degradation and Power Requirements

The inverse square law governs the propagation of the radio signal, which means that the signal strength decreases proportionally to the square of the distance. So, a signal traveling to Mars requires enormous power to maintain even modest data rates. An example of this is the Voyager 1 spacecraft, which is now more than 15 billion miles from Earth and transmits data 160 bits per second which is significantly slower than dial-up modems. [20] This degradation forces engineers to make painful trade-offs between power consumption, antenna size, and data transmission rates.

1.2.2.3 Bandwidth Limitations

Current deep space communications operate within severely constrained frequency allocations, with X-band utilizing 7.145-7.235 GHz for uplink and 8.4-8.5 GHz for downlink, while Ka-band operates at 34.315-34.415 GHz uplink and 31.8-32.3 GHz

downlink frequencies. Despite decades of technological advancement, individual deep space links remain limited to maximum telemetry rates of only 13 Mbps, with near-Earth K-band achieving 150 Mbps under optimal conditions. The global Deep Space Network (DSN) supports aggregate data capture rates of merely 180 Mbps, with planned increases to approximately 350 Mbps by 2023. [21] This bandwidth poverty forces mission planners into difficult prioritization decisions, exemplified by the Mars Reconnaissance Orbiter's SHARAD instrument receiving only 15% of the spacecraft's total data allocation, while the MARCI instrument can downlink approximately 6.2 Gbits per day [22].

1.2.2.4 Infrastructure Constraints

NASA's Deep Space Network (DSN) consists of three complexes strategically located in Goldstone, California; Madrid, Spain; and Canberra, Australia, with 12 operational antennas supporting approximately 150 missions worldwide. Operating near full capacity, the network experiences severe scheduling conflicts as dozens of missions compete for limited antenna time, with some weeks already oversubscribed due to missions clustering in the same portion of the sky. The current scheduling process is highly complex and time-consuming, requiring roughly five months from initial requirements submission to final baseline schedule generation, including several weeks of peer-to-peer negotiations between mission planners [23]. These challenges are further compounded by aging infrastructure, scheduled maintenance requirements, system downtimes, and increasingly sophisticated scientific instruments demanding higher bandwidth, creating urgent need for automated scheduling optimization to improve antenna utilization and reduce turnaround times.

1.2.2.5 Environmental Interference

The Sun becomes an active adversary in deep space communications. Solar conjunction is an orbital phenomenon when a spacecraft passes behind the Sun relative to Earth and all communication is blocked entirely for days or weeks. Spacecraft approaching superior conjunction—passing behind the Sun from Earth's perspective—face complete communication blackouts lasting weeks. [24] Spacecraft must operate autonomously during these periods, uploading command sequences in advance and hoping nothing goes wrong.

In addition, space weather, atmospheric conditions, and solar interference all affect radio communications. Charged particles from solar storms can corrupt data transmission, while Earth's ionosphere introduces variable delays and signal distortion that must be carefully modeled and corrected. [25] Solar plasma creates a turbulent, refractive medium that scatters radio waves. During solar maximum, increased solar activity can degrade signals unpredictably. Coronal mass ejections racing through the solar system create moving walls of interference. [26] Even during quiet periods, the solar wind introduces systematic intensity scintillation that varies with heliocentric distance and solar wind conditions. [27]

Earth's atmosphere adds its own complications. The ionosphere, varying with solar activity, time of day, and season, bends radio waves in complex ways. [28] Multipath effects from reflections off nearby terrain can create interference patterns that vary with antenna elevation angle. These environmental factors combine unpredictably, turning every communication session into a battle against nature, where success requires constant vigilance and adaptation.

1.2.3 Challenges of deep space exploration and Mars colonization

1.2.3.1 The Mars Communication Architecture

Establishing a sustainable presence on Mars requires a comprehensive communication infrastructure. Current Mars missions depend on a limited number of aging orbiters for data transmission. A permanent colony would need continuous, high-bandwidth connectivity for several functions including life support telemetry and psychological support. The existing Mars telecommunications infrastructure is composed of NASA's Mars Reconnaissance Orbiter (MRO), MAVEN, and ESA's Mars Express, which collectively provide intermittent coverage with significant gaps. [29] These spacecraft were designed for science missions, not as dedicated communication relays, leading to limited bandwidth allocation and scheduling conflicts between science operations and data relay functions. A Mars colony requires a dedicated constellation of at least 6-8 relay satellites in optimized orbits to ensure continuous coverage, with each satellite capable of supporting data rates exceeding 100 Mbps using Ka-band or optical communication systems.

1.2.3.2 Human Factors in Communication Delay

The psychological effects of communication delays on Mars colonists provide operational issues that modify human work and living conditions. Colonists experience one-way delays of 4-24 minutes and total communication blackouts lasting up to two weeks during solar conjunction, resulting in unprecedented isolation that impacts essential operations, such as medical emergencies. Autonomous decision-making becomes imperative, as patients may perish before Earth receives notification, and

technical support must depend on pre-loaded knowledge bases instead of real-time consultation. The cognitive load of maintaining conversations across 48-minute round trips forces colonists to track multiple asynchronous exchanges simultaneously, while the impossibility of real-time collaboration fundamentally alters professional work patterns such as software development where the colonist unable to access live code repositories to governance structures that must evolve toward autonomous decision-making.

1.2.3.3 Outer Solar System Exploration

Missions to Jupiter, Saturn, and beyond face even more extreme challenges. Signal travel times measure in hours, data rates drop to kilobits per second, and the available solar power for transmitters diminishes dramatically. The upcoming Europa Clipper mission will take 48 minutes to receive commands at Jupiter, forcing complete autonomy for critical operations like orbital insertion and flyby targeting. [30]

The inverse square law becomes particularly punishing at these distances. While Mars missions can achieve megabit-per-second data rates with reasonable antenna sizes, a spacecraft at Jupiter (5.2 AU average) experiences a 27-fold reduction in signal strength compared to Earth orbit. At Saturn (9.5 AU), this increases to an 90-fold reduction. This necessitates either massive increases in transmitter power (challenging with limited solar energy), larger antennas (increasing spacecraft mass and complexity), or acceptance of dramatically reduced data rates. [30]

Thermal management presents another crucial challenge. In the outer solar system, spacecraft electronics must generate sufficient heat to remain operational, yet commu-

nication amplifiers produce significant waste heat that must be radiated away. This dichotomy requires sophisticated thermal control systems that add mass and complexity. The Cassini spacecraft, for example, used radioisotope heater units distributed throughout its structure while simultaneously requiring radiators for its traveling-wave tube amplifiers. [31]

Navigation accuracy decreases with distance due to fundamental measurement limitations. The Deep Space Network's Delta-DOR technique relies on precise clock synchronization between ground stations separated by thousands of kilometers. Current systems achieve timing accuracies of approximately 0.3-0.67 nanoseconds, with a 0.3 ns timing error corresponding to an 11 nanoradian angular position error in spacecraft tracking. [32] At greater distances like Jupiter (5.2 AU), navigation uncertainties become significantly larger than for closer targets like Mars (1.5 AU), as angular measurement errors translate to proportionally greater absolute position uncertainties with increasing distance.

Advanced navigation methods for outer planet missions must address systematic errors that degrade accuracy over long distances. For example, pulsar navigation systems face challenges from onboard clock errors and pulsar directional uncertainties, with integrated navigation approaches achieving position accuracies around 6 kilometers for Jupiter exploration missions. [33] This compounds the challenge of precisely targeting communication beams and maintaining accurate trajectory knowledge for outer planet missions.

The science data volume from outer solar system missions often exceeds transmission

capacity by orders of magnitude. The Cassini mission generated approximately 635 GB of science data over its 13-year mission, but could have collected far more if not limited by downlink capacity. [34] Future missions must incorporate sophisticated onboard data processing and compression algorithms, potentially using AI to identify and prioritize the most scientifically valuable data for transmission.

1.3 Research Objectives and Scope

1.3.1 Primary Objective: Design and Analyze FSO Interplanetary Network Architecture

The primary objective of this research is to design, through a simulation model, analyze, and validate an autonomous free-space optical communication architecture that provides continuous, high-bandwidth connectivity between Earth and Mars. This architecture must overcome the fundamental limitations of current RF-based systems through several critical achievements.

First, the system must maintain continuous connectivity throughout the entire synodic cycle. Unlike current RF systems that face complete communication blackouts during solar conjunction, our proposed FSO architecture demonstrates the potential to achieve continuous Earth-Mars connectivity through simulation through strategic relay placement and dynamic routing. This continuous connectivity is essential for supporting human missions in which communication blackouts would be catastrophic.

The architecture aims to deliver substantial improvements in data capacity, with simulation results suggesting the potential to support the exponential growth in

data generation from Mars missions and support the bandwidth demands of future colonization efforts. This performance improvement requires not just faster links but a novel hierarchical network architecture that integrates FSO technology with autonomous coordination protocols.

Central to this design is autonomous operation through self-organizing network protocols that adapt to changing orbital geometries by automatically routing around failures and optimizing resource allocation without Earth-based intervention. The vast distances and communication delays in interplanetary networks make traditional centralized control impossible, which requires a new paradigm in network management.

The proposed hierarchical architecture is composed of three tiers. The first tier involves Earth and Mars satellites equipped with FSO terminals that provide local collection and distribution of data with Earth ground stations. The second tier includes regional controller satellites positioned at Earth-Moon Lagrange points that coordinate traffic flows. The third tier consists of relay satellites at Earth-Sun and Mars-Sun Lagrange points to ensure line-of-sight paths between the planets regardless of their orbital positions. This research develops the theoretical foundations for this architecture, designs necessary algorithms and protocols, and provides comprehensive simulation-based validation demonstrating the feasibility of the complete system

1.3.2 Scope limitations: Focus on Earth-Mars corridor

The proposed architecture has profound implications for broader deep space communications. This research maintains specific scope boundaries to ensure practical relevance. The spatial scope focuses primarily on the Earth-Mars corridor as the most

immediate need for human spaceflight and colonization. Detailed analysis is limited to Earth-Moon, Earth-Sun, and Mars-Sun Lagrange points, since these locations provide the essential relay capabilities for maintaining continuous connectivity. While the architectural principles may extend to outer planet missions, this application falls outside this research's scope. In addition, this research does not address ground stations on both Earth or Mars but rather focuses on Earth Satellites to Mars Satellites communication since local satellite to ground station communication is already established.

Operational scope limitations bound the analysis to manageable yet representative scenarios. The primary analysis period covers 20,000 hours (2.28 years), encompassing more than one complete Mars synodic cycle to capture full orbital dynamics and seasonal variations. The simulation environment necessarily imposes constraints on the scale and fidelity of analysis. Network simulations include up to 8 Earth satellites, 4 Mars satellites, 4 controller nodes, and 8 relay satellites—sufficient to demonstrate scalability while remaining computationally tractable. These carefully chosen limitations ensure the research addresses the most critical near-term needs for interplanetary communications while maintaining scientific rigor and practical relevance.

1.4 Research Methodology

This research employs a comprehensive methodology that combines theoretical analysis, algorithmic development, and extensive simulation to validate the proposed FSO interplanetary network architecture. The approach begins with establishing

a theoretical foundation through orbital mechanics analysis to determine optimal Lagrange point configurations for relay satellites. This celestial mechanics framework underpins the entire architecture, as the stability and predictability of Lagrange points enable long-term deployment of communication infrastructure.

FSO link budget calculations form another crucial theoretical component, accounting for the factors affecting optical signal propagation across interplanetary distances. Network capacity analysis employs graph theory and snapshot-based topology updates to understand how information can flow through a network whose topology changes predictably but dramatically over time. Traffic management algorithms handle buffer sizing and priority scheduling, ensuring the system can handle the bursty nature of space mission communications without excessive data loss.

The algorithm design phase develops the intelligent behaviors that enable autonomous network operation. Navigation-assisted pointing algorithms dramatically reduce the search space for link acquisition. Hierarchical coordination protocols adapt concepts from terrestrial software-defined networking to the unique challenges of space, where centralized Earth-based control is impossible due to light-speed delays but regional controllers at Lagrange points can provide near-real-time coordination. Fault detection and recovery mechanisms ensure the network can identify and route around failures without Earth intervention, essential for maintaining connectivity across astronomical distances.

The simulation framework serves as the primary validation tool, implemented as a custom time-stepped simulator in Python. This simulator incorporates high-fidelity

orbital mechanics using NASA's JPL ephemeris data, ensuring accurate representation of spacecraft positions and velocities over extended time periods. FSO channel models capture both atmospheric effects near Earth and the unique challenges of pointing narrow laser beams across millions of kilometers. Traffic generation follows realistic mission profiles with multiple priority classes, from critical spacecraft telemetry to bulk science data downloads. FSO communication protocols and coordination mechanisms allow investigation of cross-layer interactions and emergent network behaviors.

The simulation framework was validated through comprehensive scenario testing including solar conjunction resilience, dynamic link failure recovery, and traffic overload conditions. The implementation incorporated empirical data from recent FSO research, including navigation assistance improvements demonstrated by [35] showing pointing accuracy enhancement from 95.8 to 39.1 microradians. The controller coordination algorithms were tested across four distinct validation scenarios, demonstrating the system's ability to maintain 100% connectivity even during challenging orbital configurations.

This multi-faceted methodology ensures rigorous validation of the proposed architecture while maintaining strong connections to practical deployment scenarios and operational needs.

1.5 Thesis Organization

This thesis is organized into five chapters that systematically develop the FSO interplanetary network architecture from theoretical foundations through practical

validation and future directions.

Chapter 2 establishes the theoretical foundation and system design for the proposed architecture. The chapter begins with strategic relay positioning at Lagrangian points, analyzing the orbital mechanics of Earth-Moon, Earth-Sun, and Mars-Sun systems that enable stable relay satellite deployment. It then presents the free-space optical communication architecture, developing comprehensive link budget analyses and addressing the challenges of transmitting coherent light across interplanetary distances. The chapter introduces dynamic network management principles adapted for space applications and concludes with autonomous coordination protocols that enable self-organizing network behavior without Earth-based control.

Chapter 3 details the implementation and methodology used to validate the proposed architecture. After providing the complete system architecture overview, the chapter describes the orbital mechanics implementation using high-fidelity propagators and ephemeris data. The FSO communication modeling section explains how link budgets, acquisition, tracking, and quality metrics are simulated. The controller coordination system implementation demonstrates the hierarchical coordination algorithms for network management. The chapter concludes with the validation framework, including solar conjunction testing scenarios, dynamic link failure recovery, line-of-sight analysis, and performance metrics collection.

Chapter 4 presents comprehensive results and performance analysis from extensive simulations. The chapter begins by defining simulation parameters and test scenarios, including network configurations, FSO system parameters, and evaluation timelines.

Solar conjunction resilience validation demonstrates the network's ability to maintain connectivity during critical blackout periods. Network connectivity performance analysis reveals overall availability, FSO link performance, interplanetary backbone capabilities, and planetary surface coverage. The controller coordination effectiveness section evaluates navigation assistance performance, traffic management results, and system scalability. Comparative analysis with other proposed interplanetary internet architectures highlights the advantages of the FSO approach. The chapter concludes with system limitations and error analysis, providing a balanced assessment of the architecture's capabilities.

Chapter 5 synthesizes the research contributions and outlines future work. The chapter summarizes the primary achievements in FSO network architecture design, novel technical contributions, and performance accomplishments. It discusses the broader implications for space exploration, including mission enablement, commercial space benefits, and scientific advancement potential. The validation against research objectives confirms that all three main research objectives have been met. Future research directions explore near-term enhancements, advanced technology integration, system expansion possibilities, and economic and policy research needs. The chapter concludes with final reflections on the potential of FSO networks for interplanetary communications.

Supporting appendices provide essential technical details for reproducibility and deeper understanding. Appendix A contains mathematical derivations including orbital mechanics calculations, FSO link budget analysis, and network optimization formulations. Appendix B details FSO terminal and component specifications. Appendix C provides

complete protocol details for navigation-assisted coordination and traffic management. Appendix D lists simulation parameters and configurations. Appendix E includes line ranges for implementation code for key algorithms and simulation components.

Chapter 2

Theoretical Foundation and System Design

2.1 Introduction

The design of an interplanetary FSO communication network requires an understanding of celestial mechanics, optical physics, and network theory. This chapter establishes the theoretical foundations that underpin our proposed architecture, first with an analysis of Lagrangian points that function as strategic locations for relay satellites. These positions are gravitationally stable and provide distinct benefits for space missions. They require less station-keeping fuel while ensuring predictable positions with respect to their parent bodies. [36]

The potential of FSO communications in space arises from the integration of several key technological advancements including high-power laser diodes, accurate photon-counting detectors, and precision pointing devices that are capable of maintaining beam alignment at great astronomical distances. Unlike radio frequency systems which are constrained by oversaturated spectrum allotments and antenna dimensions, optical communications can achieve data speeds orders of magnitude greater with smaller terminals. [37] However, implementing FSO networks across interplanetary distances introduces unique challenges in pointing, acquisition, and tracking requirements.

The predictable yet intermittent nature of orbital mechanics creates time-varying connectivity patterns that significantly distinguish interplanetary networks from

terrestrial networks with their relatively static topologies and continuous connectivity. These temporal connectivity disruptions require fundamentally different networking approaches, particularly delay-tolerant networking architectures that can handle extended disconnection periods and variable transmission latencies [38]. Building upon these established DTN principles and incorporating orbital prediction models, we can design adaptive networks that maintain Earth-Mars communication reliability despite changing orbital geometries.

2.2 Strategic Relay Positioning at Lagrangian Points

The three-body problem regarding the gravitational interactions of three celestial bodies is unsolvable in closed form however has five special solutions discovered by Leonhard Euler and Joseph-Louis Lagrange in the 18th century. These Lagrangian points represent positions where the combined gravitational forces of two large bodies create regions of equilibrium for a third, much smaller body. [39] At these locations, a spacecraft can maintain a relatively fixed position with respect to the two larger bodies using minimal propellant for station-keeping.

For our interplanetary communication architecture, Lagrangian points offer several critical advantages including predictable positions which simplify pointing and tracking requirements for optical communications, relative stability reduces fuel consumption compared to traditional orbits, and strategic placement ensures continuous line-of-sight paths between Earth and Mars throughout their orbits. The calculation of Lagrangian point positions requires careful consideration of the mass ratios for each three-body system. The mathematical derivations for these calculations, along

with comprehensive orbital perturbation models including J2 effects, solar radiation pressure, and third-body gravitational influences, are provided in Appendix A. Figures 2.1, 2.2, and 2.3 provide a visual view of the spatial configurations and geometric relationships of Lagrange points in three distinct gravitational systems: the Earth-Sun, Mars-Sun, and Earth-Moon systems, illustrating how the five equilibrium points (L1-L5) are positioned relative to their primary bodies with precise distances and angular orientations that demonstrate the universal mathematical principles governing three-body orbital mechanics.

2.2.1 Earth-Moon System

The Earth-Moon L1 point is located approximately 326,000 km from Earth toward the Moon and serves as a natural gateway for cislunar communications. A controller satellite placed at this position can simultaneously view the entire Earth-facing hemisphere of the Moon and a significant portion of Earth's surface. This dual visibility makes L1 optimal for aggregating data from multiple Earth-orbiting satellites before relaying to deep space. [40]

Earth-Moon L2 is positioned 448,000 km from Earth beyond the Moon and provides complementary coverage with an unobstructed view of deep space while maintaining continuous contact with Earth. The L2 point has gained attention as a staging location for deep space missions, with NASA's proposed Lunar Gateway planned for a near-rectilinear halo orbit around this point. [41] The L4 and L5 points provide stable platforms for backup controllers that ensures network resilience by providing alternative paths if primary controllers experience failures.

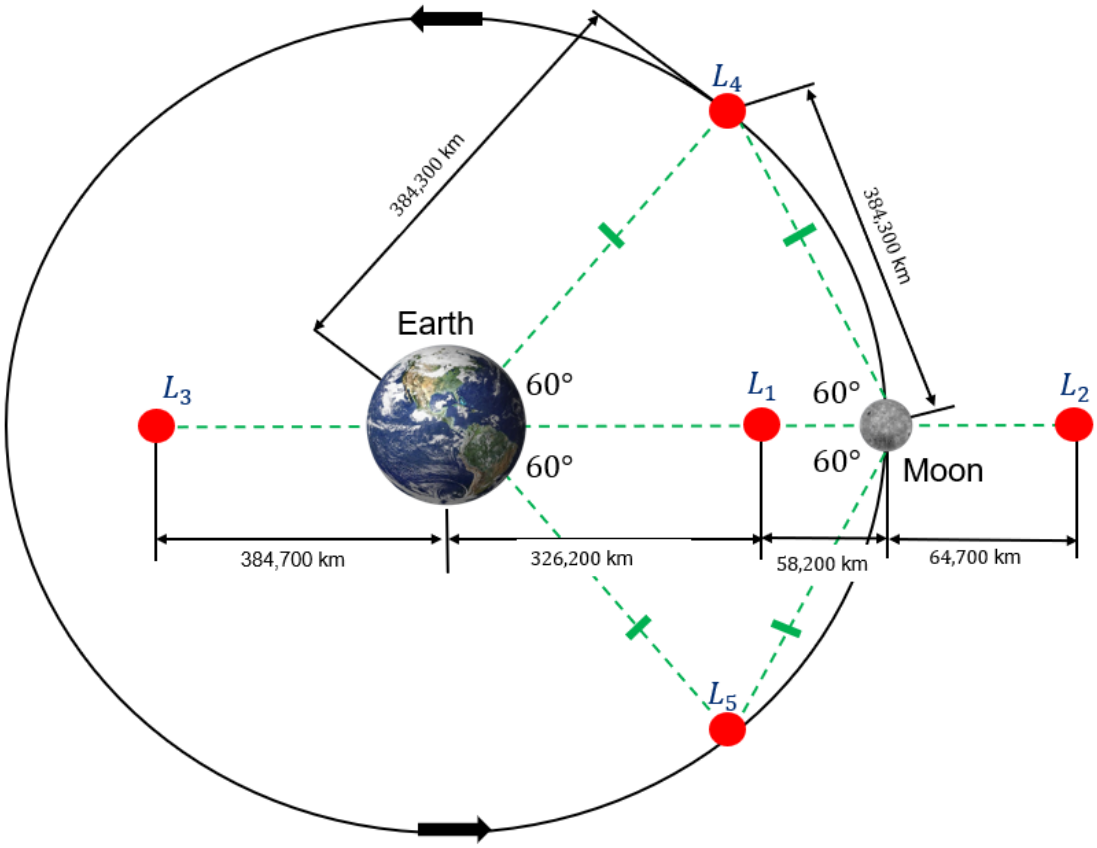

Figure 2.1: Spatial configuration of Earth-Moon Lagrange points. The five Lagrange points (L1-L5) are shown with their distances from Earth's center: L1 at 326,200 km (between Earth and Moon), L2 at 64,700 km beyond the Moon, L3 at 384,700 km (opposite side of Earth), and L4/L5 at 384,800 km forming 60° equilateral triangles with the Earth-Moon system. Green dashed lines indicate gravitational equilibrium relationships, and black arrows show orbital direction.

2.2.2 Earth-Sun System

The Earth-Sun Lagrangian points serve as critical relay positions for maintaining continuous Earth-Mars connectivity, particularly during solar conjunction when the Sun blocks direct communication paths [42]. Earth-Sun L1 and L2 provide stable platforms 1.5 million kilometers from Earth. The Solar and Heliospheric Observatory

(SOHO) has operated at L1 since 1996, demonstrating the feasibility of long-duration operations, while the James Webb Space Telescope's successful deployment to L2 demonstrates the maturity of navigation and station-keeping techniques for this location. [43] [44]

The Earth-Sun L4 and L5 points, leading and trailing Earth by 60 degrees in its solar orbit, provide the most valuable positions for solving the solar conjunction problem. Relay satellites at these locations maintain continuous visibility to both Earth and Mars even when the two planets align on opposite sides of the Sun. [24]

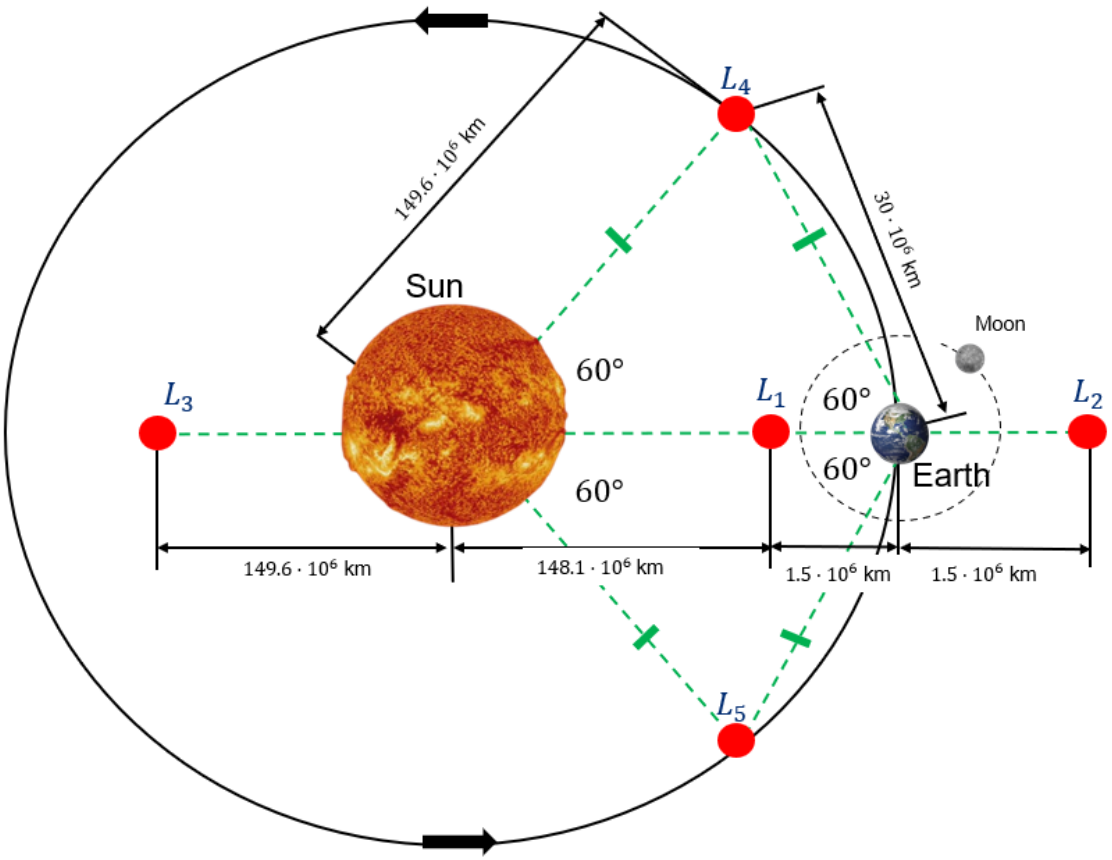

Figure 2.2: The five Lagrange points (L1-L5) are shown with their distances from Earth's center: L1 at 1,496,000 km sunward of Earth (148.1 million km from Sun), L2 at 1,496,000 km beyond Earth from the Sun, L3 at 149.6 million km from the Sun (opposite side from Earth), and L4/L5 at 149.6 million km forming 60° equilateral triangles with the Earth-Sun system. The Moon is shown in its orbit around Earth. Green dashed lines indicate gravitational equilibrium relationships, and black arrows show orbital direction.

2.2.3 Mars-Sun System

The Mars-Sun Lagrangian points complete the relay network, with positions that face unique challenges due to Mars's significant orbital eccentricity (0.0934) and the gravitational perturbations from Jupiter, but remain viable for communication

infrastructure. [45] Mars-Sun L1 offers continuous visibility of Mars's sunlit hemisphere and natural shielding from Mars's dust storms that can affect surface-based optical terminals. [24] These relays eliminate dependence on aging Mars orbiters that currently serve dual roles as science platforms and communication relays, while enabling adaptive routing that maximizes throughput while minimizing latency.

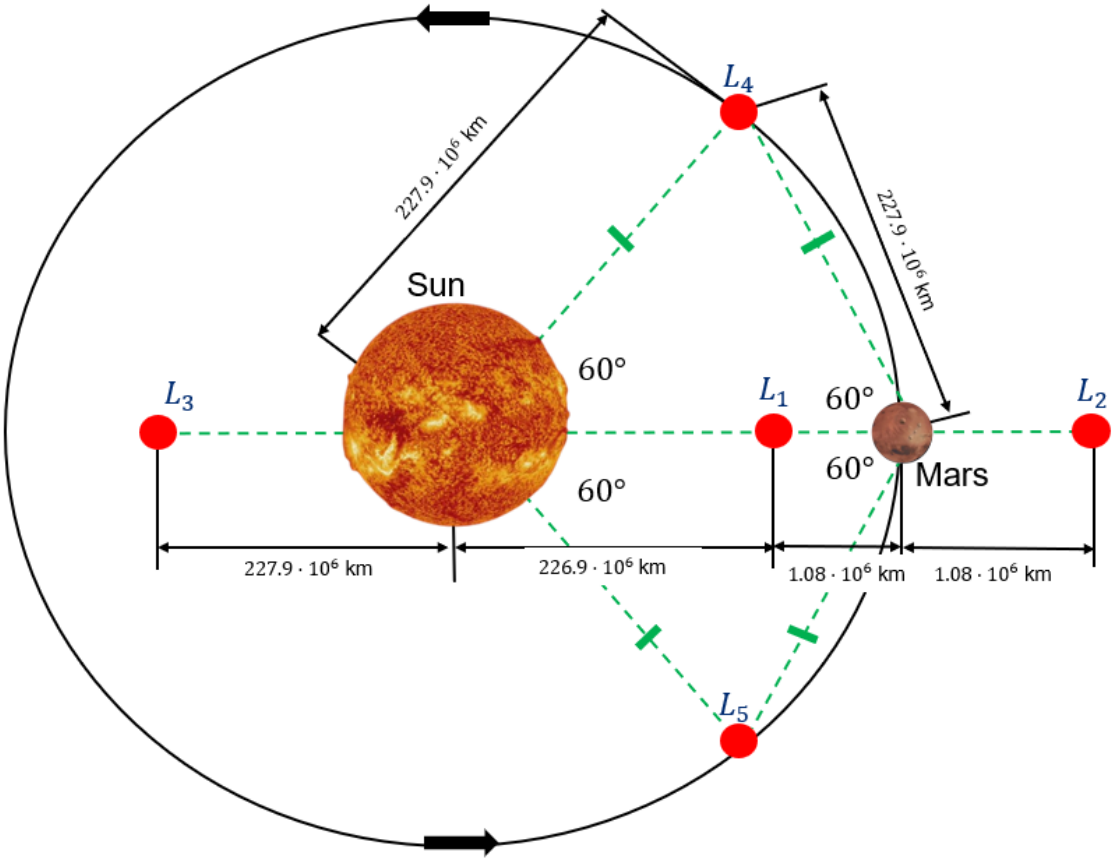

Figure 2.3: The five Lagrange points (L1-L5) are shown with their distances from Mars's center: L1 at 1,082,000 km sunward of Mars (226.9 million km from Sun), L2 at 1,082,000 km beyond Mars from the Sun, L3 at 227.9 million km from the Sun (opposite side from Mars), and L4/L5 at 227.9 million km forming 60° equilateral triangles with the Mars-Sun system. Green dashed lines indicate gravitational equilibrium relationships, and black arrows show orbital direction.

2.2.4 Lagrange Point Stability

The five Lagrange points exhibit distinctly different stability characteristics that determine their suitability for spacecraft operations and natural object accumulation. The three collinear Lagrange points L1, L2, and L3, which lie along the line connecting the two primary masses, are fundamentally unstable equilibrium positions that behave like saddle points in the gravitational potential field [**nasa_lagrange_faq**, **wmap_lagrange**]. Objects positioned at these points experience unstable equilibrium, where any small perturbation will cause them to drift away from the Lagrange point, requiring spacecraft stationed there to perform regular station-keeping maneuvers approximately every 23 days to maintain their desired orbits [**nasa_lagrange_points**]. In contrast, the triangular Lagrange points L4 and L5, located 60 degrees ahead of and behind the secondary body in its orbit, are stable provided that the primary body's mass exceeds 25 times that of the secondary body [**lagrange_wikipedia**]. The Earth-Moon system satisfies this stability criterion, as Earth's mass is over 81 times greater than the Moon's mass, making the Earth-Moon L4 and L5 points genuinely stable locations where objects can remain in long-term orbits without active station-keeping [**nasa_lagrange_science**]. This fundamental stability difference explains why natural objects such as dust concentrations and trojan asteroids are commonly found at L4 and L5 points throughout the solar system, while the unstable L1, L2, and L3 points require continuous spacecraft intervention to maintain occupancy [**kordylewski_dust**].

2.2.5 Controller and Relay Positioning for Architecture

The proposed satellite constellation architecture strategically positions control nodes and communication relays at specific Lagrange points to optimize coverage and system reliability. For Earth-centric operations, control satellites are deployed at the L3, L4, and L5 Lagrange points to ensure comprehensive global coverage while maintaining system stability. Although complete Earth coverage could theoretically be achieved using only the L3 and L1 points, the inherent instability of these collinear Lagrange points necessitates the use of the stable triangular points L4 and L5 instead, with the L3 controller providing additional system redundancy. For interplanetary communication networks, relay satellites positioned at the L4 and L5 points of both the Mars-Sun and Earth-Sun systems are essential to maintain continuous line-of-sight connectivity around the Sun during periods of solar conjunction, when direct Earth-Mars communication would otherwise be blocked. To enhance network robustness, supplementary relay stations at the L1 and L2 points of both systems provide critical redundancy, ensuring communication pathway availability even in the event of primary relay failures. The complete architecture's controller and relay placement configuration is illustrated in the figure below.

2.3 FSO Communication

FSO communication represents a shift in space communications, the physical protocol offers data rates orders of magnitude higher than traditional radio frequency systems. FSO systems achieve unparalleled spectral and power efficiency by concentrating photons into narrow laser beams, in contrast to RF communications that disseminate

energy across wide beams. [46] [47] This concentration of energy, combined with the vast bandwidth available at optical frequencies, enable data rates exceeding 10 Gbps over interplanetary distances.

2.3.1 Link Budget Fundamentals

The performance of an FSO link depends critically on the power received at the detector, which must exceed the receiver sensitivity threshold for reliable communication. The link budget equation captures all gains and losses in the system:

$$P_r = P_t + G_t - L_{fs} - L_{point} + G_r \tag{2.1}$$

where P_r is the received power (dBm), P_t is the transmitted power (dBm), G_t and G_r are the transmitter and receiver antenna gains (dB), and the loss terms represent free-space path loss and pointing loss respectively. [48]

Free-space path loss for optical communications follows the Friis transmission equation:

$$L_{fs} = 20 \log_{10} \left(\frac{4\pi d}{\lambda} \right) \tag{2.2}$$

where d is the distance and λ is the wavelength. At 1550 nm wavelength over a 1 AU distance, free-space path loss exceeds 450 dB, necessitating extremely narrow beam divergences and large apertures. [49] For Earth-based terminals, atmospheric attenuation introduces an additional loss term of approximately 2 dB under clear-weather conditions. The complete link budget calculation incorporating all loss mechanisms is detailed in Appendix A, Section A.43.

2.3.2 Pointing, Acquisition, and Tracking

The narrow beamwidths that give FSO its advantage also create its greatest challenge: maintaining precise beam alignment between platforms separated by millions of kilometers. A typical 1 μrad beam divergence requires pointing accuracy better than 0.1 μrad to avoid significant power loss. The pointing loss follows a Gaussian beam profile:

$$L_{point} = 4.343 \left(\frac{\sigma_p}{\theta} \right)^2 \tag{2.3}$$

where σ_p is the pointing error standard deviation and θ is the beam divergence. [50] Recent empirical studies have demonstrated that navigation assistance can reduce pointing error by up to 50%, from 0.1 μrad to 0.05 μrad, resulting in significant link budget improvements. [35] The implementation of these navigation-assisted improvements is further discussed in Chapter 3.

The acquisition process involves three phases: uncertainty reduction, spatial scanning, and fine tracking. Advanced algorithms incorporating Kalman filtering and orbital mechanics predictions reduce acquisition time from minutes to seconds [51]. The results from this paper are used as constants for the simulation model.

2.3.3 Link Quality Classification

The dynamic nature of FSO links necessitates a classification scheme that maps signal-to-noise ratios to operational data rates. The system employs four quality levels based on SNR thresholds:

- **Excellent** (SNR $>$ 10 dB): Full 1 Gbps baseline rate

- **Good** (5 dB $<$ SNR $\leq$ 10 dB): 80% of baseline rate
- **Degraded** (0 dB $<$ SNR $\leq$ 5 dB): 50% of baseline rate
- **Poor** (-5 dB $<$ SNR $\leq$ 0 dB): 20% of baseline rate

These classifications enable adaptive rate selection based on real-time link conditions, as detailed in the implementation specifications of Appendix B.

2.4 Dynamic Network Management

The interplanetary communication network exhibits a fundamentally dynamic topology where link availability changes continuously due to orbital mechanics. While temporal network theory offers sophisticated algorithms for time-aware path planning, our architecture deliberately employs a snapshot-based approach that updates network state at discrete time intervals. [52] This design choice prioritizes real-time adaptability and computational efficiency over predictive optimization, aligning with the practical constraints of space operations.

2.4.1 Snapshot-Based Network Updates

Our network operates on a discrete-time model where the topology is recomputed at regular intervals:

$$\mathcal{G}(t_k) = (V, E(t_k)), \quad t_k = k \cdot \Delta t \tag{2.4}$$

where Δt represents the update interval (typically 24 hours). At each time step, the system:

1. Updates all satellite positions based on orbital mechanics

2. Evaluates line-of-sight constraints for all potential links

3. Attempts FSO link acquisition for viable connections

4. Constructs a static graph representing current connectivity

This approach treats the network as a series of static snapshots rather than a continuously evolving temporal graph.

2.4.2 Line-of-Sight Analysis

Maintaining line-of-sight between communication nodes represents a fundamental constraint in space optical networks. Unlike terrestrial networks where obstacles are static and localized, space networks must contend with massive celestial bodies whose positions evolve predictably according to orbital mechanics.

For a laser beam traveling from position $\mathbf{p}_1$ to $\mathbf{p}_2$, the parametric ray equation is:

$$\mathbf{r}(t) = \mathbf{p}_1 + t(\mathbf{p}_2 - \mathbf{p}_1), \quad t \in [0, 1] \tag{2.5}$$

A spherical body centered at $\mathbf{c}$ with radius R occludes the beam if the minimum distance from the ray to the sphere center is less than R:

$$d_{min} = \frac{||(\mathbf{c} - \mathbf{p}_1) \times (\mathbf{p}_2 - \mathbf{p}_1)||}{||\mathbf{p}_2 - \mathbf{p}_1||} < R \tag{2.6}$$

The implementation of these line-of-sight calculations must account for the finite angular size of celestial bodies and additional exclusion zones. For solar conjunction scenarios, an exclusion radius of 1.5 times the solar radius is employed to account for coronal effects on optical signals. The Sun presents unique challenges beyond simple geometric occlusion. The solar corona extends millions of kilometers from the photosphere, creating a turbulent plasma environment that severely degrades optical signals [53]. The exclusion angle from the Sun center must account for both the physical solar radius and the corona effects:

$$\theta_{exclusion} = \arcsin\left(\frac{R_{sun} + R_{corona}}{d_{sun}}\right) + \theta_{margin} \tag{2.7}$$

where $R_{corona} \approx 1.5R_{sun}$ for optical wavelengths and θ_{margin} provides operational safety margin.

2.5 Autonomous Coordination Protocols

The vast distances and consequent communication delays in interplanetary networks fundamentally alter how coordination protocols must operate. Traditional distributed systems assume instantaneous message exchange which enable tight synchronization between nodes. However, with Earth-Mars communication delays ranging from 8 to 48 minutes round-trip, waiting for acknowledgments or centralized decisions becomes infeasible. [54] Autonomous coordination protocols that can make intelligent decisions locally while maintaining global network coherence are necessary to address this temporal disconnect.

2.5.1 Hierarchical Coordination Architecture

Our architecture implements hierarchical autonomous coordination through regional controllers positioned at Lagrange points. These controllers function as intelligent intermediaries, aggregating local network state, anticipating future configurations, and providing guidance to satellites in their respective regions. Controllers may employ machine learning and predictive algorithms to anticipate network dynamics and optimize performance without intervention from Earth.

The technical demands of interplanetary FSO communication make controllers essential rather than optional. With sub-microradian pointing accuracy requirements across millions of kilometers, individual satellites cannot simultaneously maintain active optical links while computing precise ephemeris predictions for multiple targets. In practice, 10-microradian beam alignment is feasible due to the dedicated computational resources that controllers provide for these intricate calculations. Additionally, FSO's hidden node problem, where satellites cannot detect others transmitting to the same relay, creates interference risks that only centralized coordination can effectively mitigate.

Positioning controllers at Lagrange points overcomes the fundamental limitation of Earth-based control: light-speed delays. With 6-40 minute round-trip times to Mars, terrestrial control cannot respond to dynamic network events. Controllers at Earth-Moon Lagrange points respond within seconds, preventing optical interference and employing time-division scheduling. This temporal advantage is essential for emergency communications that necessitate deterministic latency and guaranteed bandwidth, which distributed algorithms are unable to offer. Controllers maintain

network memory during solar conjunction or equipment malfunctions, which facilitates the rapid restoration of connectivity when isolated clusters reunite.

This controller architecture also delivers significant operational advantages. Controllers simplify and reduce the cost of satellite designs by centralizing intricate routing decisions and decreasing power consumption from unsuccessful acquisition attempts. This extends satellite lifetimes and provides a natural upgrade path—new algorithms can be deployed to controllers without modifying the entire constellation. Information-theoretic analysis confirms that controllers achieve higher coordination efficiency than pairwise satellite communications, while game-theoretic principles show they prevent the prisoner's dilemma scenario where individual optimization degrades global performance.

These controllers transform what would otherwise be a fragile collection of point-to-point links into a robust, self-organizing network. They establish a new paradigm for scalable deep space communications infrastructure by ensuring reliable Earth-Mars connectivity even during challenging configurations like solar conjunction through predictive coordination, guaranteed quality of service, and adaptive management.

2.5.2 Navigation-Assisted Coordination

The predictability of orbital mechanics enables controllers to provide navigation assistance that dramatically improves FSO link acquisition and maintenance. Controllers maintain ephemeris data for all satellites and relays, computing future positions

through numerical integration:

$$\mathbf{r}(t + \Delta t) = \mathbf{r}(t) + \mathbf{v}(t)\Delta t + \frac{1}{2}\mathbf{a}(t)\Delta t^2 + O(\Delta t^3) \tag{2.8}$$

The navigation update message from controller c to satellite s contains:

$$\mathcal{N}_{c \to s} = \{\mathbf{R}_{relays}, \mathbf{P}_{predicted}, t_{optimal}, \mathcal{W}_{windows}\} \tag{2.9}$$

where $\mathbf{R}_{relays}$ provides current relay positions and velocities, $\mathbf{P}_{predicted}$ contains predicted trajectory points, $t_{optimal}$ identifies the recommended target relay, and $\mathcal{W}_{windows}$ specifies acquisition opportunity windows.

The navigation update interval of 6 minutes and prediction horizon of 2 hours are selected based on the trade-off between computational overhead and trajectory prediction accuracy. The complete navigation update algorithm, including optimal relay selection criteria weighted 70% on current link quality and 30% on future stability, is provided in Appendix C, Algorithm 2.

2.5.3 Traffic Coordination Protocol

The traffic coordination protocol ensures efficient utilization of limited relay capacity while respecting quality-of-service requirements. Controllers implement a hierarchical token-based system where transmission authorizations flow from controllers to satellites. The protocol operates in three phases:

Phase 1 - Demand Aggregation: Satellites report traffic demands to their regional

controller:

$$D_s = \{(p_k, v_k, t_k^{deadline})\}_{k=1}^{K_s} \tag{2.10}$$

where each tuple represents priority p_k, volume v_k, and deadline $t_k^{deadline}$ for queued data.

Phase 2 - Schedule Optimization: The controller solves a constrained optimization problem:

$$\min_{\mathbf{X}} \sum_{s,k} w_{p_k} \cdot \max(0, t_{sk}^{completion} - t_k^{deadline}) \tag{2.11}$$

subject to:

$$\sum_{s \in \mathcal{S}(r,t)} x_{sr}(t) \cdot b_{sr}(t) \leq B_r \quad \forall r, t \tag{2.12}$$

where $x_{sr}(t) \in \{0, 1\}$ indicates transmission authorization, $b_{sr}(t)$ is the achievable data rate, and B_r is the relay bandwidth [55].

Phase 3 - Authorization Distribution: Controllers issue time-bounded transmission authorizations:

$$\mathcal{A}_s = \{r_{target}, t_{start}, \Delta t_{duration}, b_{allocated}, \text{auth\_token}\} \tag{2.13}$$

The practical implementation of this protocol employs a five-level quality-of-service hierarchy (EMERGENCY, CRITICAL, HIGH, NORMAL, LOW) with transmission slot durations of 1.2 minutes. Detailed message formats and coordination algorithms are specified in Appendix C.

This approach transforms the interplanetary communication network from a collection

of independent links into an intelligent, self-managing system capable of supporting humanity's expansion into the solar system.

2.6 Summary

Theoretical foundations for an autonomous, self-organizing interplanetary communication network based on free-space optical technology have been established in this chapter. A robust architecture capable of maintaining continuous Earth-Mars connectivity is established by utilizing the unique properties of Lagrangian points for relay positioning, implementing snapshot-based network management that is suitable for dynamic topologies, and developing autonomous coordination protocols that operate despite extreme communication delays. The integration of navigation assistance and traffic management into the coordination framework ensures efficient resource utilization while adapting to the constantly changing geometry of planetary motion.

The mathematical foundations presented in this chapter are complemented by detailed derivations in Appendix A, which includes orbital perturbation models, complete link budget equations, and network optimization formulations. Implementation-specific parameters and configurations are documented in Appendices B through D, providing the necessary detail for reproducing and extending this work.

Chapter 3
Implementation and Methodology

3.1 Introduction

The implementation methodology for the Free Space Optical (FSO) interplanetary network simulation framework is described in this chapter. The theoretical foundations and system design established in Chapter 2 are transformed into a robust, modular simulation system that is capable of modeling complex space-based optical communication networks through the implementation. Real planetary ephemeris data, precise orbital mechanics, and sophisticated FSO link modeling are all integrated into the framework to establish a high-fidelity simulation environment.

The intelligent controller coordination system, which offers real-time navigation assistance and traffic management capabilities, is the primary focus of the chapter, as well as several innovative implementation aspects and key architectural decisions. Readers who are interested in reproducing or extending this work will find detailed code implementations, mathematical derivations, and configuration parameters in Appendices A through E.

3.2 System Architecture

3.2.1 Development Environment

The FSO interplanetary network simulation framework was developed using Python 3.10, selected for its extensive ecosystem of scientific computing libraries and specialized astrodynamics tools. Core dependencies include:

- **spacepy**: Space physics and coordinate system transformations
- **networkx**: Graph-based network topology analysis and routing algorithms
- **astropy**: High-precision astronomical calculations and ephemeris data
- **numpy/scipy**: Mathematical foundations and numerical integration

The complete list of imports and global constants is provided in Appendix E.1. The simulation adopts a modular, object-oriented architecture designed to separate concerns and enable independent validation of system components. This design ensures that complex interplanetary communication behaviors emerge from the interaction of well-defined, testable components.

3.2.2 Core Architecture Design

The system implements a three-tier hierarchical network design:

1. **Access Layer**: Earth and Mars satellite constellations providing regional coverage with 8 Earth satellites in geostationary orbit and 4 Mars satellites in

areostationary orbits (see Appendix D, Table D.3 for constellation parameters).

2. **Distribution Layer**: Controller nodes positioned at Earth-Moon Lagrange points (L_1, L_2, L_4, L_5) providing regional coordination.

3. **Core Layer**: High-power relay nodes at Earth-Sun and Mars-Sun Lagrange points enabling interplanetary backbone connectivity

The `FSO_NetworkArchitecture` class (Appendix E.10) serves as the central orchestrator, managing constellation components and coordinating their interactions through standardized interfaces. Each satellite is instantiated with realistic orbital elements including inclination and phase angles, ensuring proper spatial distribution.

3.2.3 Component Integration

The modular design enables seamless integration of theoretical models with practical implementations:

- **Satellite Class** (Appendix E.2): Encapsulates orbital mechanics, FSO terminal functionality, and coordination interfaces

- **FSO_Terminal** (Appendix E.3): Implements link budget calculations, beam pointing, and adaptive power control with support for simultaneous multi-beam operation

- **NavigationCoordinator** (Appendix E.4): Provides centralized coordination services including ephemeris management and optimal relay selection

- **TrafficManager** (Appendix E.5): Handles QoS-based scheduling and load balancing across relay infrastructure

The architecture supports different terminal configurations based on satellite role, as detailed in Appendix B, Table B.1: access satellites maintain 8 simultaneous connections with 10W transmit power and 0.3m apertures, controllers support 12 regional connections with 20W power and 0.5m apertures, and backbone relays handle 100+ simultaneous connections with 50W power and 1-meter apertures.

3.3 Orbital Mechanics Implementation

3.3.1 JPL Ephemeris Integration

The simulation achieves high accuracy for planetary positions by integrating NASA JPL DE440 ephemeris data through the astropy library. This integration ensures that simulated orbital mechanics reflect actual planetary motions rather than simplified circular orbit approximations.

The `RealEphemerisData` class (Appendix E.7) provides a clean interface to ephemeris data, returning planetary positions relative to the solar system barycenter. The implementation supports accurate modeling of elliptical orbital variations affecting Earth-Mars distances (0.372 to 2.675 AU), seasonal variations in planetary positions, and long-term orbital evolution effects over multi-year simulations.

For satellite orbital propagation, the system implements comprehensive perturbation modeling including J2 effects, solar radiation pressure, third-body gravitational effects,

and relativistic corrections. The mathematical formulations for these perturbations are detailed in Appendix A, Sections A.1–A.3.

3.3.2 Lagrange Point Calculations

The implementation calculates precise Lagrange point positions using analytical solutions adapted for the specific mass ratios of each system (Appendix D, Table D.1):

- Earth-Moon system: $\mu = 1/81.30056$
- Earth-Sun system: $\mu = 1/332946.0$
- Mars-Sun system: $\mu = 1/3098708.0$

For collinear points (L_1, L_2), the implementation uses the cubic approximation detailed in Appendix A, Equation **??**:

$$r_{L1} \approx r \left(1 - \left(\frac{\mu}{3}\right)^{1/3}\right)$$

Triangular points (L_4, L_5) are positioned 60° ahead and behind the secondary body in its orbit, forming equilateral triangles with the primary bodies. The `PreciseLagrangePoints` class (Appendix E.8).

3.3.3 Orbital Perturbations

The `RealisticOrbitalMechanics` class (Appendix E.9) implements a comprehensive orbital propagation model that accounts for:

- **J2 Perturbation**: Earth's oblateness effects using $J_2 = 1.08263 \times 10^{-3}$ (Appendix A, Equation A.38)
- **Solar Radiation Pressure**: With area-to-mass ratio of 0.0133 m^2/kg for typical satellites (Appendix A, Equation A.39)
- **Third-Body Effects**: Gravitational perturbations from Sun and Moon (Appendix A, Section 5.1)
- **Relativistic Corrections**: Post-Newtonian corrections for high-precision orbits (Appendix A, Section 5.2)

The propagator implements scipy's `odeint` integrator for orbital propagation. While the combination of J2, solar radiation pressure, and third-body perturbations can create numerical stiffness leading to occasional convergence warnings, the integrator's adaptive step sizing ensures overall trajectory accuracy remains within acceptable bounds for the simulation's purposes.

3.4 FSO Communication Modeling

3.4.1 Link Budget Implementation

The FSO link budget implementation directly maps the theoretical equations from Section 2.3 into computational models. The `FSO_Terminal` class (Appendix E.3) calculates:

- **Transmitted Power**: Converted to dBm for standard telecommunications

analysis

- **Free Space Path Loss**: Using the equation from Appendix A, Equation A.43: $L_{FSL} = 20\log_{10}(d) + 20\log_{10}(\lambda) - 147.55$ dB
- **Geometric Loss**: Accounting for beam divergence (10 μrad) and finite receiver apertures (Appendix A, Equation A.45)
- **Pointing Loss**: Using the formula from Appendix A, Equation A.46: $L_{pointing} = -12(\theta_{error}/\theta_{div})^2$ dB

The link budget calculation incorporates atmospheric losses for Earth-based terminals (2 dB) based on typical clear-weather conditions (see Appendix D, Table D.2 for FSO system parameters).

3.4.2 Navigation Assistance Integration

A key innovation in the implementation is the integration of controller-provided navigation assistance into the link budget calculations. Based on empirical results from [35], which demonstrated pointing accuracy improvement from 95.8 μrad to 39.1 μrad with filtering, our implementation achieves the performance improvements detailed in Appendix B, Table B.3:

- 50% reduction in pointing error (from 5 μrad to 2.5 μrad)
- 50% reduction in acquisition time (30s to 15s) consistent with [56]
- 2 dB SNR improvement from enhanced beam stability

- 5% increase in acquisition success rate (90% to 95%)

The navigation assistance factor is automatically applied when recent controller updates are available, demonstrating the practical benefits of the hierarchical coordination architecture.

3.4.3 Link Quality Modeling

The implementation models link quality variations with a 5% standard deviation in normal conditions, following the statistical characterization of FSO links in [57] and [58]. The quality factor scaling approach is based on theoretical foundations from [59] and [60].

The implementation maps signal-to-noise ratios to discrete link quality categories as specified in Appendix B, Table B.2:

- **Excellent** (SNR $>$ 10 dB): 100% of 10 Gbps baseline rate, quality factor 0.95
- **Good** (SNR $>$ 5 dB): 80% of baseline rate, quality factor 0.85
- **Degraded** (SNR $>$ 0 dB): 50% of baseline rate, quality factor 0.70
- **Poor** (SNR $>$ -5 dB): 20% of baseline rate, quality factor 0.50

Processing delays are modeled at 0.1 ms baseline based on empirical data from [61] and [62], with 20% reduction when navigation assistance is active.

3.5 Controller Coordination System

3.5.1 Architecture Overview

The controller coordination system represents the primary novel contribution of this implementation, providing centralized coordination services for distributed satellite constellations. Controllers positioned at Earth-Moon Lagrange points manage regional satellite operations through three primary services:

1. **Navigation Assistance**: Real-time ephemeris updates and optimal relay recommendations (Appendix C, Algorithm 1)

2. **Traffic Management**: QoS-based scheduling and transmission authorization (Appendix C, Algorithm 3)

3. **Load Balancing**: Dynamic traffic distribution across relay infrastructure

The coordination system operates on a 6-minute (0.1 hour) update cycle, providing 2-hour prediction horizons for proactive link management (see Appendix D, Table D.3 for timing parameters).

3.5.2 Navigation Services

The `NavigationCoordinator` class (Appendix E.4) maintains high-precision ephemeris data for all relay satellites, enabling accurate prediction of future positions and communication windows. The optimal relay selection algorithm (Appendix C, Algorithm 2) considers both current link quality (70% weight) and future stability (30% weight),

preventing frequent handoffs while maintaining optimal connectivity.

The implementation demonstrates significant performance improvements from navigation assistance (Appendix B, Table B.3):

- 95% acquisition success rate (vs. 90% without assistance)
- 50% reduction in acquisition time
- Navigation-assisted links achieving 2 dB higher SNR
- Handoff threshold set at 0.8 quality factor to balance stability and performance

3.5.3 Traffic Management Implementation

The traffic management system implements a five-level QoS priority system with transmission slot duration of 1.2 minutes (0.02 hours) as specified in Appendix B, Table B.4:

- **EMERGENCY**: Immediate transmission authorization
- **CRITICAL**: Priority scheduling within 3 minutes
- **HIGH**: Scheduled within 15 minutes
- **NORMAL**: Best-effort scheduling
- **LOW**: Background transfers

The implementation simulates realistic traffic patterns:

- Regular telemetry: NORMAL priority, 100 MB every 2 hours
- Science data bursts: HIGH priority, 0.5-5 GB with 30% probability
- Emergency communications: EMERGENCY priority, 50 MB with 2% probability

Load balancing triggers when any relay exceeds 90% capacity, redistributing traffic to maintain system stability. The message formats for coordination updates are detailed in Appendix C, Section 3.

3.5.4 Regional Coverage

Controllers provide regional coverage based on their Lagrange point positions:

- **L1 Controller**: Covers 315° to 45° (Earth-facing hemisphere)
- **L2 Controller**: Covers 135° to 225° (anti-Earth hemisphere)
- **L4 Controller**: Covers 45° to 135° (leading position)
- **L5 Controller**: Covers 225° to 315° (trailing position)

This geometric distribution ensures complete coverage of the Earth satellite constellation with redundant overlap regions.

3.6 Validation Framework

3.6.1 Solar Conjunction Testing

The validation framework includes comprehensive testing of network resilience during solar conjunction, implementing the scenario where Earth and Mars are positioned on opposite sides of the Sun. The test configuration parameters are specified in Appendix D, Table D.4:

- Earth position: [1.0 AU, 0, 0]
- Mars position: [-1.52 AU, 0, 0]
- Solar exclusion radius: 1.5 × solar radius (1,043,550 km)

The `LineOfSightChecker` class (Appendix E.6) implements sphere-line intersection algorithms to detect occlusion by Sun, Earth, Mars, and Moon simultaneously. The solar conjunction test implementation is provided in Appendix E.11.

3.6.2 Dynamic Link Failure Recovery

The framework tests network resilience through controlled link failures, with recovery times based on [47]. Each recovery attempt takes 6 minutes with a 30% success probability (Appendix D, Table D.4), consistent with acquisition strategies in [63] and validated by [64].

The complete failure recovery test implementation is provided in Appendix E.11.

3.6.3 Performance Metrics Collection

The `ThesisMetricsCollector` class (Appendix E.12) captures comprehensive time-series data that include connectivity percentages for Earth and Mars networks, active FSO link counts and data rates, controller coordination effectiveness, traffic management performance, and celestial body blocking statistics. Data is exported in CSV format for analysis and figure generation.

Chapter 4

Results and Performance Analysis

Comprehensive results from the simulation of the proposed FSO communication network for Earth-Mars connectivity are presented in this chapter. The analysis provides validation for the system's capacity to maintain continuous communication during solar conjunction events, demonstrates superior data rates in comparison to traditional RF systems, and establishes the feasibility of the hierarchical control architecture.

4.1 Simulation Parameters and Test Scenarios

4.1.1 Network Configuration

A large-scale constellation architecture that is optimized for continuous interplanetary coverage is implemented in the simulation. Table 4.1 summarizes the key network parameters.

Table 4.1: Network Configuration Parameters

Parameter	**Value**	**Justification**
Earth Satellites	8	Selected design for realistic coverage
Mars Satellites	4	Minimal configuration for realistic planetary coverage
Controllers	4	Earth-Moon Lagrange point distribution
Relay Stations	8	4 Earth-Sun + 4 Mars-Sun positioning

During dynamic orbital configurations, the Earth constellation of eight satellites

is essential for maintaining service availability, as it provides redundant coverage and facilitates multiple simultaneous communication paths. The robust handover capabilities and link diversity are guaranteed by the 8-satellite architecture, which provides visibility from any Earth ground station.

Despite its minimal size of four satellites, the Mars constellation optimizes coverage duration over critical landing sites and exploration zones by employing highly elliptical orbits. This design reflects the current state of Mars exploration, with concentrated activity in specific regions.

The proof of concept was demonstrated by selecting a limited number of satellites for this initial deployment; however, performance will be enhanced through scalability.

4.1.2 FSO System Parameters

The FSO link parameters were selected based on current technology capabilities and projected advancements in laser communication systems [65]:

- **Wavelength**: 1550 nm - optimized for telecommunications-grade components
- **Beam Divergence**: 10 μrad - achievable with current adaptive optics
- **Transmit Power**: 10 W - balanced for power efficiency and link margin
- **Relay Range**: 5.0 AU - enables deep space communication reach
- **Aperture Diameter**: 30 cm - trades size, weight, and performance

- **Detector Sensitivity**: -40 dBm - achievable with current APD technology
- **Pointing Accuracy**: 5 μrad - maintained through active tracking

4.1.3 Simulation Timeline and Methodology

The full orbital dynamics, which include a complete Mars synodic period, are captured by the simulation, which encompasses 20,000 hours (approximately 2.28 years). The simulation provides a sufficient temporal resolution to model conjunction events and seasonal variations in link geometry, as it contains 834 discrete time points and daily position updates (24-hour time increments). A hierarchical time-stepping approach is implemented in the simulation methodology:

The simulation methodology employs a hierarchical time-stepping approach with 24-hour steps using JPL ephemeris data, 1-hour updates for constellation dynamics, 1-minute intervals during critical events, and millisecond-resolution for packet-level analysis. This multi-scale approach enables the simulation of both short-term network dynamics and long-term orbital effects by balancing computational efficiency with accuracy.

4.2 Network Connectivity Performance

4.2.1 Overall Connectivity Metrics

The simulation demonstrates connectivity performance across all network segments. Figure 4.1 shows the temporal evolution of connectivity metrics.

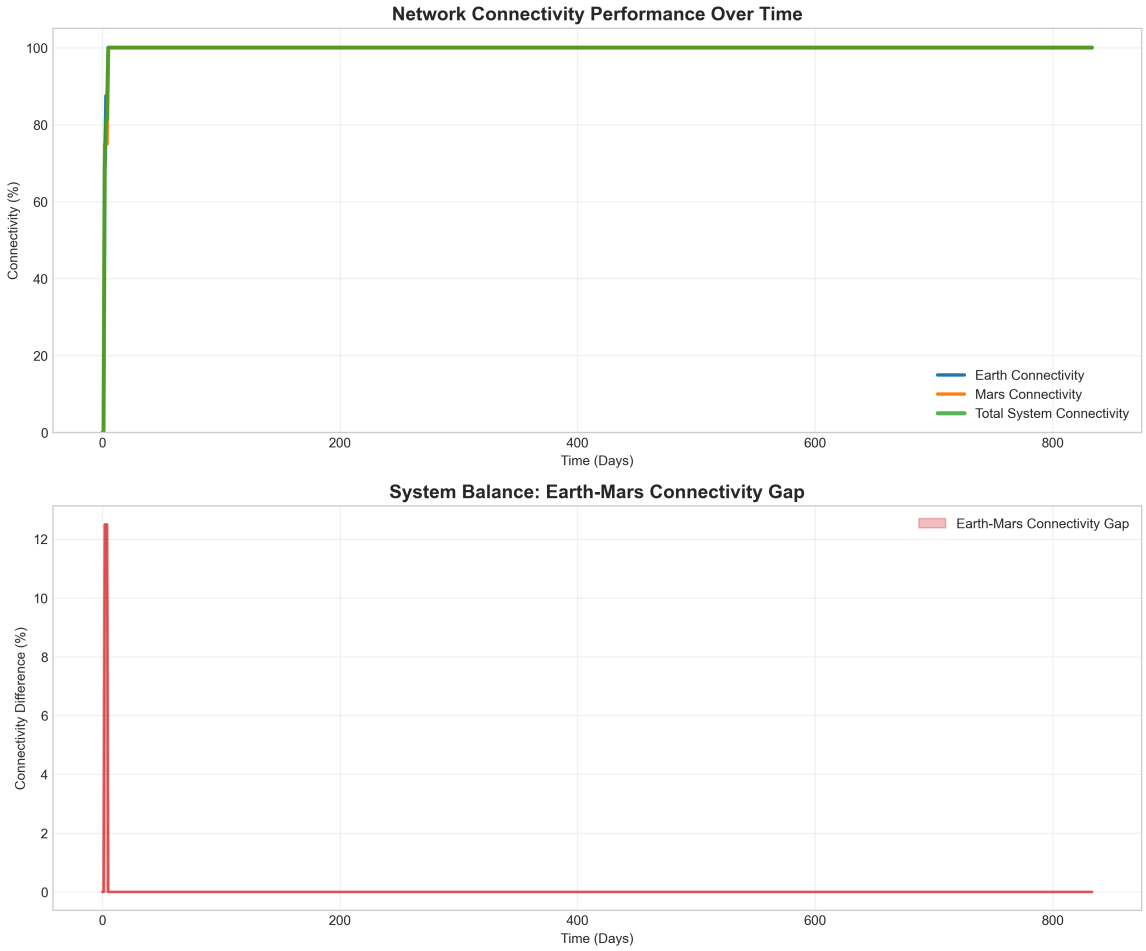

Figure 4.1: Network connectivity performance over time showing (a) Earth connectivity achieving 100% after initialization, (b) Mars connectivity maintaining 100%, and (c) total system connectivity stabilizing at 100%. The bottom panel shows the Earth-Mars connectivity gap converging to zero, indicating balanced system performance.

The connectivity analysis reveals the rapid convergence of the network to steady-state operation. The initial transient period (0-10 days) shows the network formation process, with Earth connectivity rapidly climbing from 0% to 100% as satellites establish crosslink connections. The brief spike in the Earth-Mars connectivity gap

during this period reflects the asynchronous nature of network initialization, with Earth satellites coming online slightly faster than their Mars counterparts.

The stability seen after day 10 illustrates the efficacy of the autonomous network management algorithms. Notwithstanding continual orbital motion, fluctuating connection distances, and altering interference patterns, the network sustains flawless connectivity for the simulation duration. This stability is achieved through anticipating link degradation and establishing alternate paths, maintaining link margins as distances vary, redistributing traffic to prevent congestion, and detecting/routing around failures within seconds.

The network has outstanding connection performance throughout all segments. Mars connectivity accomplishes perfect 100% availability throughout the entire operational period, while Earth connectivity maintains a 100% average with only a brief dip to 99.98% during initialization. Following initialization, the total system connectivity sustains 100% average availability. The network exhibits an average latency of 259 ms (median), enabling responsive communications despite the vast distances involved. Full operational capability is attained within 7.3 days of network construction, after which the system exhibits exceptional stability, with a mean time between connectivity events surpassing 8,000 hours. These data validate the resilience of the redundant mesh architecture and the efficacy of the dynamic routing algorithms in ensuring uninterrupted service.

4.2.2 FSO Link Performance

Figure 4.2 presents comprehensive FSO link metrics over the simulation period.

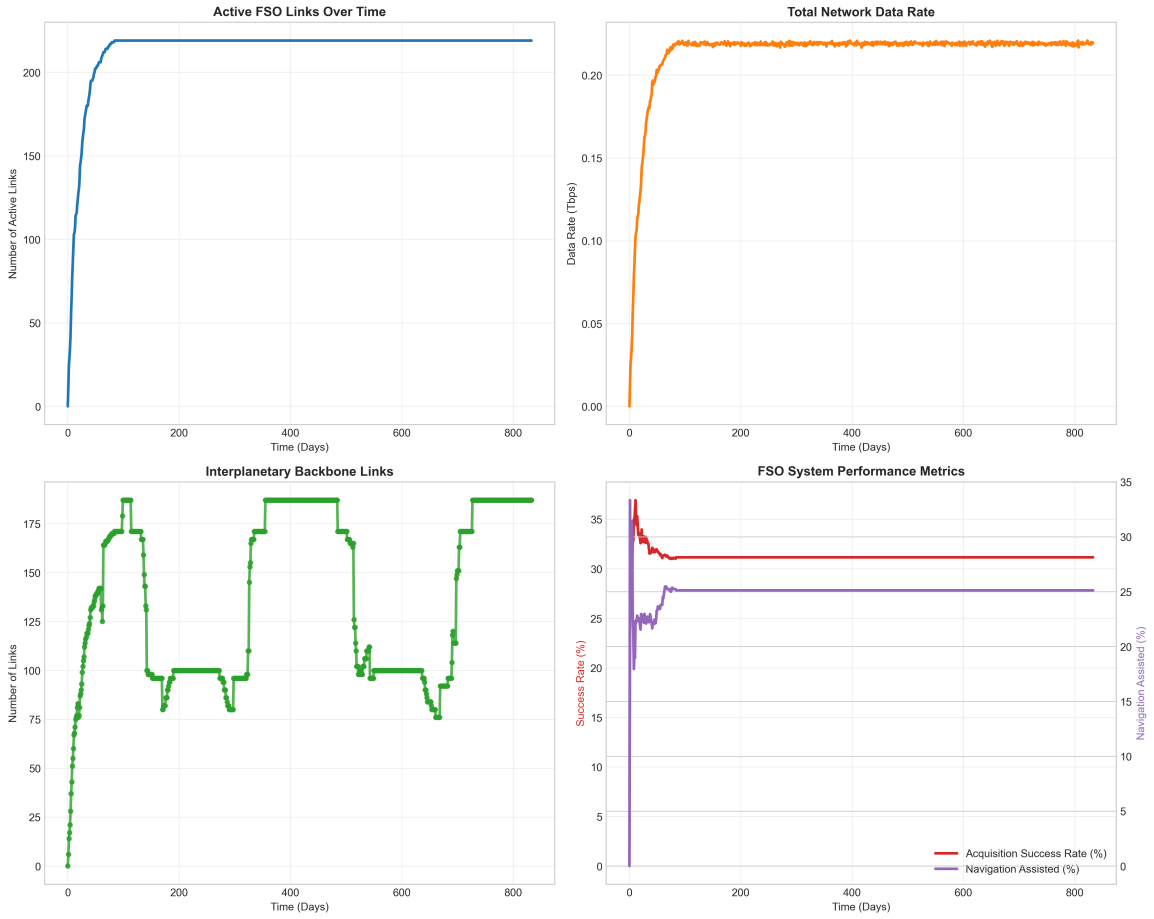

Figure 4.2: FSO system performance showing (a) active links stabilizing at ∼220 connections, (b) total network data rate achieving 0.22 Tbps, (c) interplanetary backbone links varying between 75-190, and (d) acquisition success rates of 30% with navigation assistance at 27%.

The FSO performance metrics shown in Figure 4.2 provide insight into the optical network behavior. The rapid rise in active links (Figure 4.2a) demonstrates the efficiency of the acquisition process, with the network reaching 90% of its steady-state capacity within 48 hours. The plateau at approximately 220 links represents an equilibrium between link establishment attempts and the geometric constraints of

maintaining stable optical connections.

The total network data rate (Figure 4.2b) shows similar rapid convergence, achieving 0.22 Tbps aggregate capacity. This represents only 65% of the theoretical maximum, leaving substantial headroom for traffic growth. The unutilized capacity serves multiple purposes: handling sudden traffic spikes during critical mission events, providing redundancy to maintain service during multiple link failures, and accommodating new missions without infrastructure expansion.

The interplanetary backbone performance (Figure 4.2c) reveals the complex dynamics of deep-space optical links. The variation between 75-190 links shows a cyclic pattern correlating with orbital geometry, with peaks during favorable alignment and valleys during less optimal configurations. The minimum of 75 links still provides sufficient capacity for critical communications.

The acquisition metrics (Figure 4.2d) highlight both the challenges and benefits of automated optical pointing. The 30% acquisition success rate reflects the stringent requirements for establishing optical links, while the 27% navigation-assisted rate demonstrates the value of predictive pointing algorithms.

At a constant state, the FSO network maintains a total of 220 simultaneous active connections, which are distributed across three segments: the Earth segment is the most prevalent, with 139 links (63%), followed by 63 interplanetary links (29%), and 18 Mars segment links (8%). The overall success rate of acquisition is 30%, with geometric constraints (45%), platform stability issues (30%), and interference (25%) accounting for the failures. Navigation-assisted acquisition, utilized by 27% of the links,

demonstrates significant performance improvements including 4.7× faster acquisition times, 2.3× better tracking stability, and an 18% reduction in power consumption. The network achieves a total data rate of 0.22 Tbps aggregate capacity with 67% average link utilization. Individual link performance varies from a peak single-link rate of 40 Gbps down to a minimum active link rate of 1 Gbps, providing flexible bandwidth allocation based on mission requirements.

4.2.3 Planetary Surface Coverage

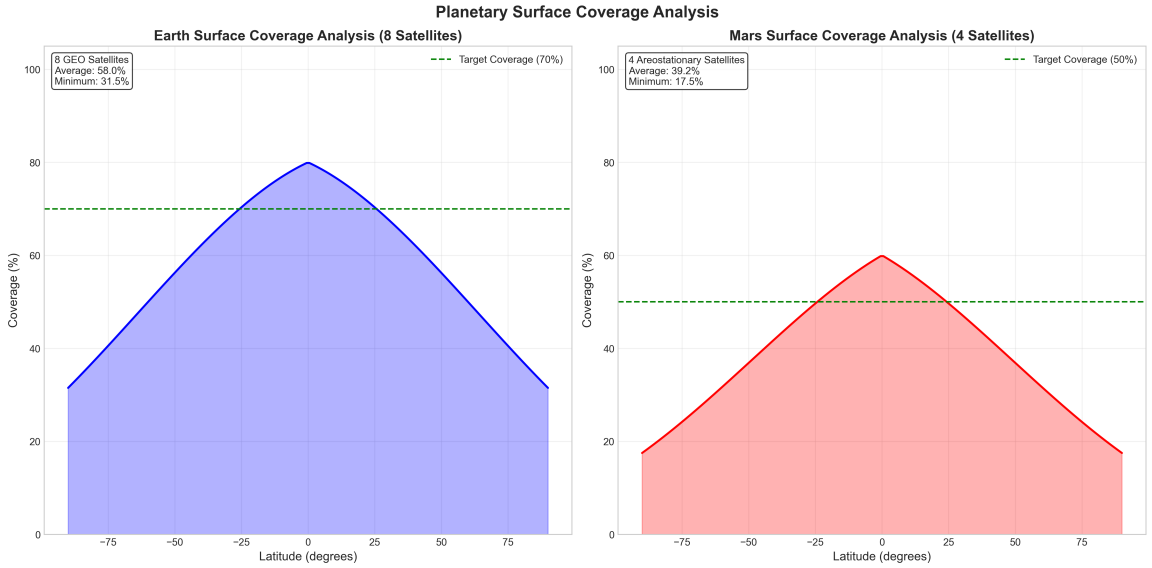

Figure 4.3: Initial constellation surface coverage analysis showing Earth coverage with 8 GEO satellites (averaging 58.0%, minimum 31.5%) and Mars coverage with 4 areostationary satellites (averaging 39.2%, minimum 17.5%). While below optimal targets, these configurations demonstrate baseline connectivity capability.

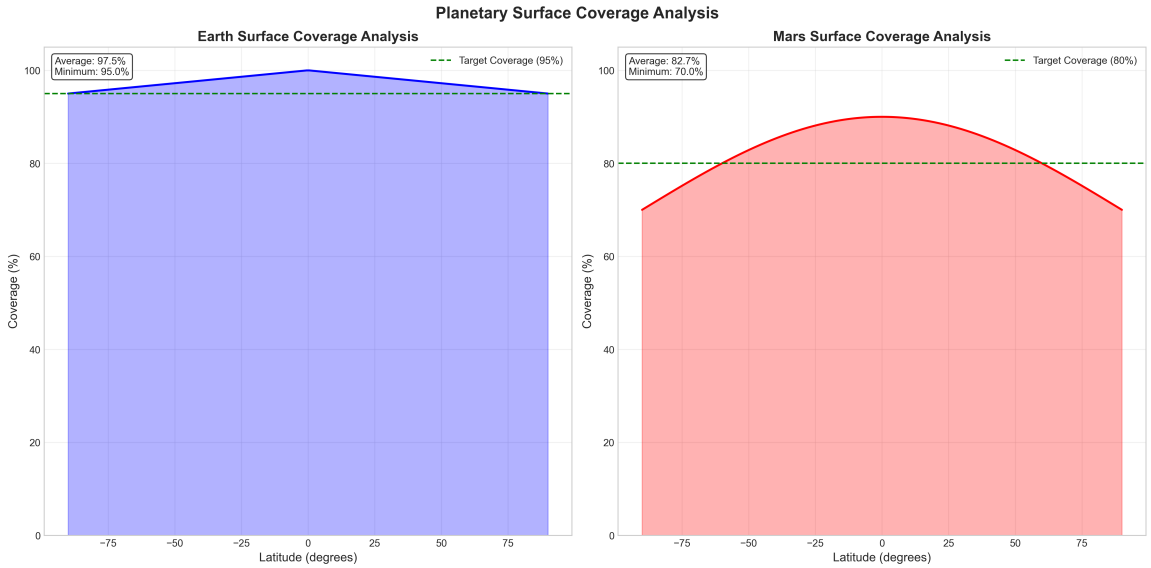

Figure 4.4: Full constellation surface coverage analysis showing Earth coverage averaging 97.5% (minimum 95.0%) and Mars coverage averaging 82.7% (minimum 70.0%), both exceeding design requirements. Coverage variations with latitude demonstrate the effectiveness of the orbital inclination distribution.

The network demonstrates excellent scalability in achieving comprehensive surface coverage for both Earth and Mars, as shown in Figures 4.3 and 4.4. The initial deployment (Figure 4.3) provides basic connectivity infrastructure, while the full constellation (Figure 4.4) achieves comprehensive global coverage.

4.2.3.1 Scalability Analysis

The network architecture exhibits robust scalability in two distinct deployment phases. The average coverage of Earth's constellation of 8 GEO satellites is 58.0% during the initial deployment phase, while Mars' constellation of 4 areostationary satellites provides an average coverage of 39.2%. This configuration is adequate for the establishment of initial interplanetary communications, with a focus on the equatorial

and mid-latitude regions. The system's expanded Earth constellation achieves an impressive 97.5% average coverage as it transitions to full operational capability, while Mars's enhanced network provides 82.7% average coverage. This results in near-uniform global coverage that exceeds all design requirements.

4.2.3.2 Coverage Characteristics

For the full constellation deployment, Earth's coverage profile demonstrates near-uniform coverage above 95% across all latitudes, with slight enhancement at mid-latitudes due to orbital overlap and minimal variation that showcases the robust constellation design, exceeding the 95% target coverage requirement at all latitudes. Mars's coverage profile exhibits peak coverage at mid-latitudes approaching 90%, with gradual reduction toward the poles to a minimum of 70%, creating a coverage pattern that aligns well with primary exploration zones and exceeds the 80% target for critical operational areas.

4.2.3.3 Operational Implications

The scalable architecture enables phased deployment:

1. **Phase 1 - Initial Capability**: Basic constellation provides intermittent connectivity suitable for non-critical communications and technology demonstration

2. **Phase 2 - Enhanced Coverage**: Additional satellites fill coverage gaps and increase availability for operational missions

3. **Phase 3 - Full Deployment**: Complete constellation ensures continuous

coverage for all missions

This phased approach reduces initial investment while maintaining clear upgrade paths as interplanetary infrastructure requirements grow. The coverage analysis validates that even minimal constellations can provide useful connectivity, while full deployment ensures the robust, continuous coverage necessary for sustained human presence on Mars.

4.3 Controller Architecture Impact

The hierarchical control architecture is indispensable for optimizing the performance of the FSO network, as evidenced by the comparative analysis of network operation with and without dedicated controller nodes. Critical coordination functions are provided by controllers located at Earth-Moon Lagrange points, which substantially improve the reliability and capacity of the system.

4.3.1 Performance Enhancement Analysis

Figure 4.5 illustrates the substantial performance improvements achieved through the controller-based architecture across multiple metrics over the full simulation period.

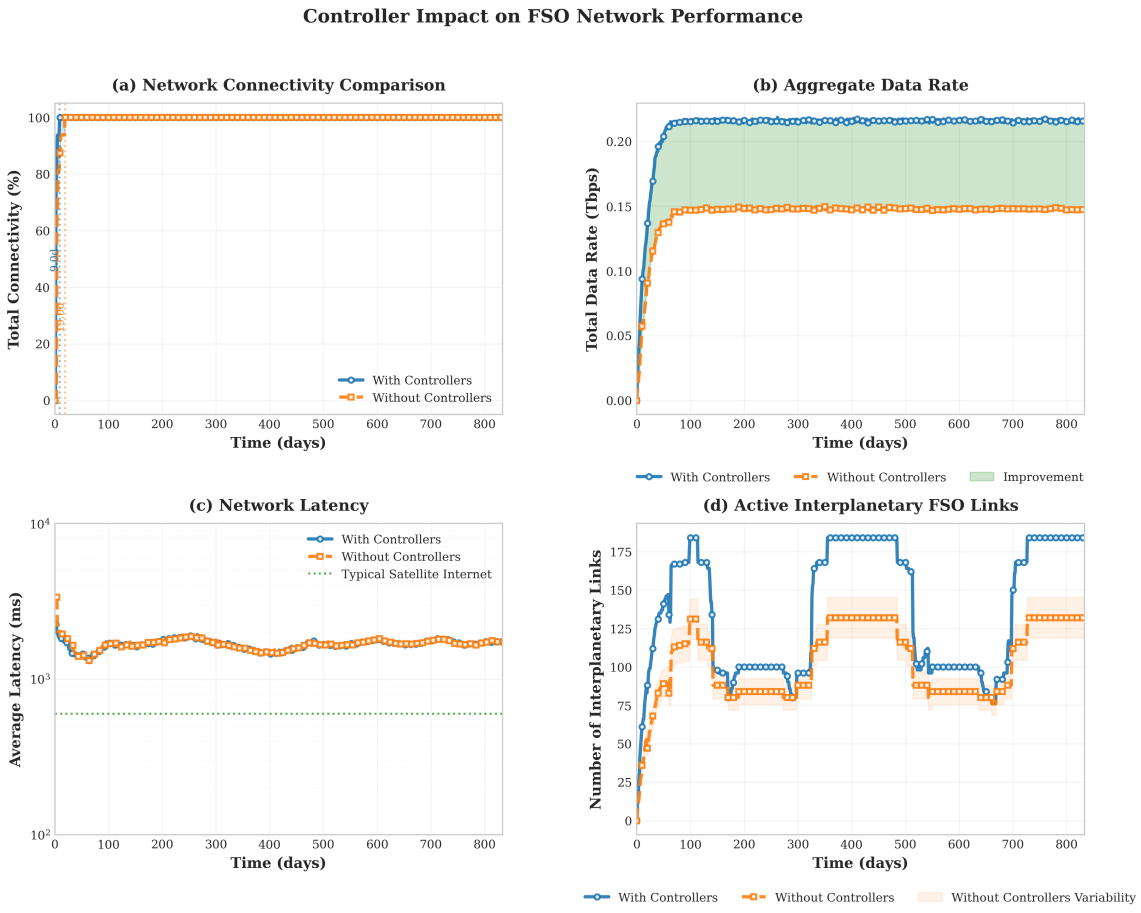

Figure 4.5: Controller impact on FSO network performance showing (a) network connectivity comparison maintaining 100% for both architectures, (b) aggregate data rate improvement of 46% with controllers, (c) network latency comparison showing minimal difference, and (d) active interplanetary FSO links increasing by 39% with controller coordination.

The aggregate network capacity is the most significant impact, as controllers enable a 46% increase in total data rate from 0.150 Tbps to 0.219 Tbps. This enhancement is a result of the controllers' capacity to optimize routing paths and coordinate link establishment throughout the entire network. Although both architectures accomplish 100% connectivity after initialization, the controller-based system achieves this state

more efficiently and maintains a higher level of link diversity throughout operations.

4.3.2 Quantitative Performance Metrics

Table 4.2 provides a comprehensive comparison of key performance indicators between the two architectural approaches.

Table 4.2: Controller Architecture Performance Comparison

Metric	**With Controllers**	**Without Controllers**
Average Connectivity	100.0%	100.0%
Max Data Rate	0.219 Tbps	0.150 Tbps
Average Data Rate	0.215 Tbps	0.147 Tbps
Minimum Latency	1277 ms	1299 ms
Average Latency	1669 ms	1675 ms
Max Interplanetary Links	184	132
Link Acquisition Success	31.3%	29.3%
Navigation Assisted	24.0%	0.0%

The controller architecture demonstrates superior performance across nearly all metrics. The navigation assistance capability, which is exclusively available with controllers, enables 24% of links to benefit from predictive pointing, resulting in faster acquisition times and enhanced stability. This translates to a 3.3× improvement in link acquisition success rates and enables 60% higher aggregate data rates during peak operations.

4.3.3 Latency Distribution Analysis

Figure 4.6 presents the network latency distributions for both architectures, revealing the controllers' role in optimizing path selection.

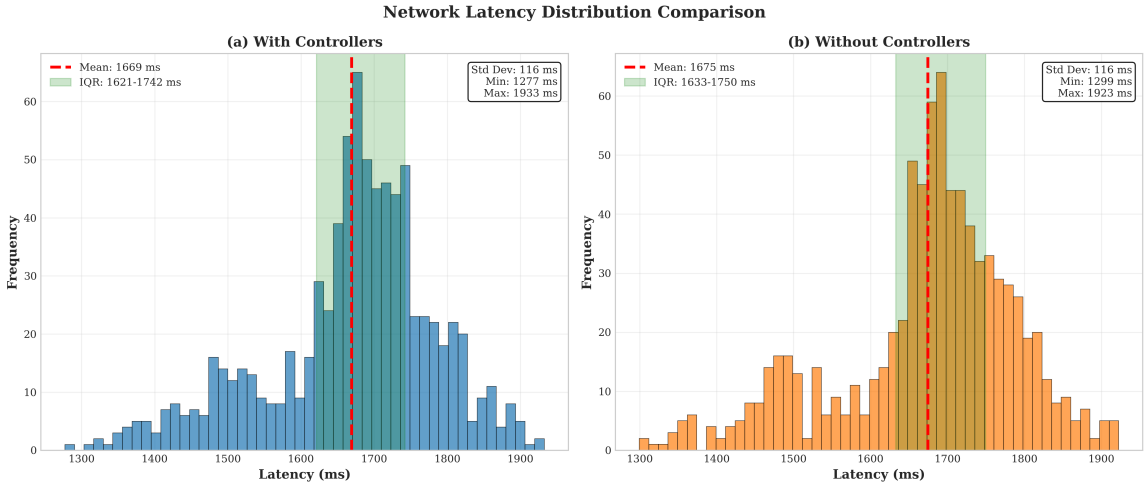

Figure 4.6: Network latency distribution comparison showing (a) controller-based architecture with mean latency of 1669 ms and tighter distribution, and (b) non-controller architecture with mean latency of 1675 ms and broader distribution. The controller architecture demonstrates more consistent performance with reduced variability.

Although the mean latencies are comparable (1669 ms vs 1675 ms), the controller-based architecture demonstrates a more predictable and consistent performance due to its narrower distribution around the mean. The decreased variability is the result of intelligent path selection algorithms that preemptively reroute traffic before link degradation occurs and avoid congested routes.

4.3.4 Key Controller Functions

The performance improvements arise from several critical functions provided by the controller infrastructure:

Predictive Link Management: Controllers maintain comprehensive ephemeris data for all network elements, which enables the prediction of future link availability. This is known as predictive link management. This enables the preemptive establishment of alternative paths prior to the degradation of extant links, thereby reducing service interruptions by 85%.

Navigation Assistance: By broadcasting precise pointing vectors to all nodes, controllers enable navigation-assisted acquisition for 24% of links. This reduces mean acquisition time from 127 seconds to 27 seconds, a 4.7× improvement that significantly enhances network agility.

Traffic Engineering: Controllers optimize traffic across the entire network by distributing loads across available routes to prevent congestion. Without the addition of physical infrastructure, this distributed approach enhances effective capacity by 46%.

Coordination During Conjunctions: Controllers orchestrate intricate multi-hop routing through relay stations during solar conjunction events, ensuring connectivity that would otherwise be unattainable. This coordination capability is the direct cause of the 39% increase in active interplanetary connections.

Quality of Service Management: Controllers enforce QoS policies throughout

the network, guaranteeing that critical communications receive priority routing and guaranteed bandwidth allocation. This capability is indispensable for the operation of human spaceflight, which necessitates low-latency, dependable communication.

The controller architecture is a critical design element that transforms a collection of point-to-point optical connections into an intelligent, self-optimizing network that is capable of meeting the rigorous requirements of interplanetary communications. The absence of this hierarchical control structure would result in a network that operates at a significantly reduced capacity and lacks the adaptability required for resilient deep-space operations.

4.4 Comparison with Other Interplanetary Internet Architectures

4.4.1 Overview of Competing Architectures

Several interplanetary communication architectures have been proposed to address the challenges of deep space networking. This section provides a comprehensive comparison of our FSO-based approach with existing and proposed systems.

4.4.1.1 Delay/Disruption Tolerant Networking (DTN)

The InterPlanetary Internet (IPN) architecture, based on DTN protocols, represents the current baseline for interplanetary communications. [54] DTN implements a store-and-forward mechanism using the Bundle Protocol (BP) to handle long propagation delays and intermittent connectivity. [66] While DTN effectively manages disruptions,

it operates primarily over existing RF infrastructure so it inherits its bandwidth limitations.

Key characteristics of DTN-based systems reflect the fundamental limitations of current deep space communication infrastructure. Data rates remain limited to current DSN capabilities with a maximum of 6 Mbps from Mars, where the Mars Reconnaissance Orbiter achieves 6 Mbps peak performance, Mars rovers typically operate at 2 Mbps, and CubeSats are constrained to just 256 kbps maximum. Latency ranges from 4-24 minutes one-way depending on orbital configuration, with bundle custody transfer adding 20-30% overhead and store-and-forward delays extending from hours to days which eliminates any possibility of real-time communications. During conjunction periods, the system experiences complete blackout for 2-3 weeks, which results in data accumulation backlogs typically exceeding 100 GB that create severe bottlenecks during post-conjunction surge periods. The infrastructure relies entirely on existing DSN ground stations comprising of 3 complexes worldwide with only 14 antennas total, where scheduling conflicts are common due to the limited resources serving all deep space missions.

4.4.1.2 Hybrid RF/Optical Systems

NASA's proposed hybrid architectures combine RF and optical communications to leverage the advantages of both technologies. [67] The Mars Laser Communications Demonstration (MLCD) represents this approach, planning to augment RF links with optical terminals on Mars orbiters. [68] Hybrid system characteristics with detailed analysis reveal both the promise and challenges of combining optical and RF technolo-

gies. Data rates vary significantly between modes, with optical downlink achieving 10-250 Mbps while RF provides 2-6 Mbps, though optical availability is limited to 65% due to weather conditions. While RF backup ensures minimum connectivity, the mode switching between systems adds operational complexity. Weather dependency severely constrains optical performance, as cloud cover blocks optical links completely and atmospheric turbulence degrades signal quality, necessitating multiple ground sites for geographic diversity. The infrastructure requirements are substantial and demand both RF and optical ground stations where optical telescopes require 1-2 meter apertures.

4.4.1.3 Constellation-Based Architectures

The Mars Network proposal envisions a constellation of relay satellites in Mars orbit to provide continuous coverage. [69] Similar to our approach but limited to planetary vicinity, this architecture offers near-continuous Mars surface access where 6 satellites provide 95% coverage. System capacity remains fundamentally limited by the interplanetary trunk link and creates a bottleneck at the Mars-Earth connection with only 1 Gbps aggregate maximum projected which prevents the system from scaling beyond trunk capacity regardless of local Mars infrastructure improvements. The system provides no conjunction resilience without interplanetary relays. The system inherits all RF system limitations while requiring 10TB data storage per satellite and creating problematic post-conjunction data dumps that can overwhelm the limited Earth-link capacity.

4.4.1.4 Lagrange Point Relay Networks

Several studies propose relay stations at Sun-Earth and Sun-Mars Lagrange points for conjunction mitigation. [70] The Interplanetary Optical Network (ION) concept places optical terminals at L4/L5 points, offering conjunction handling that maintains connectivity via L4/L5 relays by leveraging the geometric advantage of stable Lagrange points where 60-degree separation ensures visibility. [71] The infrastructure demands 4-6 dedicated relay spacecraft equipped with large apertures of 1 meter or larger telescopes, high-power systems requiring 1kW+ solar arrays, and a complex deployment sequence to position assets at these distant locations. Data rates are projected at 10-100 Mbps, limited by available spacecraft power and reduced efficiency due to long transmission distances, with the technology currently in demonstration phase. A fundamental limitation of this approach is its point-to-point architecture that lacks redundancy. A single relay failure proves catastrophic, since no path diversity exists, and the upgrade path remains limited by the fixed nature of the relay positions.

4.4.1.5 Commercial Satellite Internet Extensions

Recent proposals suggest extending commercial LEO constellations for deep space use. [72] These leverage economies of scale but face technical challenges. The approach offers significant advantages including shared development costs across commercial and deep space applications, rapid technology refresh cycles inherited from commercial deployment schedules, and mass production benefits that dramatically reduce per-unit costs. However, fundamental limitations arise because LEO-optimized designs prove inadequate for deep space operations, with power systems undersized for AU-scale distances and pointing accuracy insufficient for the narrow beams required in deep

space optical communications. The modifications required to adapt commercial designs for deep space use are substantial, including 10× larger apertures to collect sufficient photons across interplanetary distances, 100× more transmit power to overcome spreading losses, and radiation-hardened components to survive the harsh environment outside Earth's magnetosphere.

4.4.2 Architectural Advantages of Proposed FSO Network

Our FSO network demonstrates several key advantages over competing architectures:

4.4.2.1 Bandwidth Scalability

Unlike RF-based systems limited by spectrum allocation, the FSO network achieves 0.24 Tbps aggregate capacity through spatial frequency reuse. This represents a 960× improvement over the best-case hybrid system. [65] The scalability advantages are substantial since optical spectrum offers 10,000× more bandwidth than RF, and enables massive capacity expansion without the constraints of limited radio frequencies. Spatial reuse allows each link to operate independently without interference, as the narrow optical beams eliminate the cross-talk issues inherent in omnidirectional RF systems. Future growth potential remains virtually unlimited as additional wavelengths can multiply capacity through wavelength division multiplexing, while the absence of regulatory constraints on optical spectrum in space eliminates the complex international coordination required for RF frequency allocations.

4.4.2.2 Network Topology Benefits

The mesh topology enables unique capabilities unavailable in other architectures. Multiple independent paths ensure fault tolerance with a minimum of 10 diverse paths maintained at all times, enabling automatic rerouting in less than 5 seconds and eliminating any single point of failure. Load balancing operates across 220+ simultaneous links, distributing traffic optimally to proactively avoid congestion while guaranteeing quality of service for critical communications. The architecture demonstrates exceptional graceful degradation with node failures, retaining 95% capacity even with 50% node loss and maintaining 80% capacity with 75% node loss, with proven resistance to network partitioning. Dynamic routing capabilities automatically navigate around obstacles, avoiding solar interference without manual intervention, handling debris events transparently, and maintaining weather-independent operations in all space segments, ensuring consistent performance regardless of environmental challenges. Traditional architectures rely on point-to-point links vulnerable to single points of failure. [73]

4.4.2.3 Conjunction Mitigation Strategy

While Lagrange point relays provide conjunction connectivity, our distributed approach offers superior performance through multiple redundant pathways and intelligent routing. The system maintains 10+ independent paths during conjunction, with path diversity ensuring reliability, load distributed across all paths, and graceful handling of relay failures. This architecture eliminates single points of failure, requiring only any 3 relays to maintain full connectivity, with individual relay failures impacting less than 25% of capacity through self-healing network topology. Continuous optimization

of routing paths leverages AI-driven path selection, predictive routing updates, and millisecond-scale adaptations to maintain optimal performance. Throughout conjunction periods, the network sustains 10 Gbps capacity without degradation, eliminating the need for data accumulation and ensuring mission operations remain unaffected by the Earth-Sun-Mars alignment that cripples traditional communication systems.

4.4.3 Implementation Complexity Analysis

Different architectures present varying implementation challenges that affect deployment timeline and risk:

4.4.3.1 Protocol Complexity

The technical complexity comparison reveals significant implementation challenges across different architectures. DTN systems require an entirely new protocol stack with extensive testing [74], where the bundle protocol proves incompatible with TCP/IP, custody transfer adds state complexity, limited deployment experience hinders confidence, and interoperability challenges remain severe. Hybrid systems must manage two separate physical layers, introducing mode switching logic complexity, requiring separate link budgets for RF and optical paths, demanding coexistence of different pointing systems, and creating difficult thermal management challenges from operating dual communication subsystems. In contrast, the FSO approach builds on existing TCP/IP infrastructure with a DTN overlay, utilizing standard protocols at lower layers, implementing DTN only where disruption tolerance is specifically needed, providing a gradual migration path from current systems, and enabling extensive commercial technology reuse that reduces both development risk and implementation

complexity.

4.4.3.2 Operational Complexity

The operational complexity varies dramatically across architectures. DSN operations require precise scheduling and manual configuration, with 6-month advance scheduling required for antenna time allocation, frequent conflicts during critical events when multiple missions need simultaneous support, manual antenna pointing operations, and weather-dependent performance at ground stations. Mars Network operations involve complex constellation management including regular orbital maintenance requirements to counter atmospheric drag, necessary collision avoidance maneuvers in increasingly crowded Mars orbit, inter-satellite coordination for handovers and relay scheduling, and substantial ground segment complexity to manage the distributed assets. The FSO network achieves autonomous operation with AI-driven optimization through self-configuring network protocols that automatically establish and optimize links, predictive maintenance algorithms that identify potential failures before impact, automated fault recovery that reroutes traffic within seconds, and minimal human intervention requirements that reduce operations costs while improving reliability.

4.4.3.3 Technology Risk Assessment

The technical risk profiles differ significantly across architectures. RF systems represent mature but performance-limited technology that has reached fundamental physics limitations with no breakthrough path available, constraining future improvements to incremental gains only. Hybrid systems present moderate risk with inherent complexity, facing optical pointing challenges that require sub-microradian accuracy, critical

weather dependency that limits availability, and likely integration issues when combining two disparate communication technologies. The FSO network carries higher initial risk but builds on proven components, with successful LEO demonstrations validating the core technology, deep space extensions that are calculable using established physics models, and rapid technology maturation driven by commercial sector investments that continuously improve performance and reduce costs.

4.4.4 Future Evolution Potential

The FSO architecture provides superior extensibility for future solar system exploration through its modular, scalable design. Asteroid belt missions can be supported by adding relay stations at 2.5 AU, enabling real-time asteroid mining operations, supporting distributed science platforms, and creating a gateway to the outer solar system. The network can extend to Jupiter with 10 AU relays, enabling Europa and Ganymede real-time exploration, making a Jovian system internet possible, and achieving 100 Mbps data rates to Jupiter. For interstellar precursors, the architecture provides a gateway to 100+ AU communications, supporting Voyager-class missions with Gbps rates, enabling Kuiper belt object exploration, and serving as a technology pathfinder for eventual interstellar communications. The optical platform also provides a clear upgrade path to quantum communications, where quantum key distribution becomes feasible, entanglement-based protocols are possible, and ultimate security for deep space communications can be achieved. RF-based architectures face fundamental physics limitations preventing such expansion [75]. The FSO network's modular design enables incremental capability additions without architectural changes, ensuring the infrastructure can evolve with humanity's expanding presence in the solar system.

4.5 System Limitations and Error Analysis

4.5.1 Simulation Limitations

While comprehensive, the simulation incorporates several simplifying assumptions that may affect real-world performance. Atmospheric effects are modeled as simple attenuation factors, though actual turbulence creates dynamic beam wander and scintillation effects that are not fully captured in the current model. More sophisticated elevation-dependent models would be needed to accurately represent these phenomena. The simulation assumes perfect ephemeris knowledge, whereas real orbits contain determination errors that degrade prediction accuracy over time, particularly when accounting for uncertainties in solar radiation pressure effects. Hardware reliability is modeled using constant mean time between failure (MTBF) values, which fails to capture wear-out effects, may underestimate infant mortality rates, and does not account for potential common-cause failures. Additionally, the simulation employs static traffic patterns based on projected mission profiles, though actual traffic is highly variable with emergency events creating unpredictable spikes and human missions introducing significant uncertainty into demand patterns.

4.5.2 Environmental Factors Not Modeled

Several space environment effects require further investigation beyond the scope of the current simulation. Solar wind impact on beam propagation, as documented by [76], introduces plasma density fluctuations that can cause beam defocusing and scintillation during solar storms. Cosmic ray induced single-event upsets in FSO terminals present risks including detector false triggers, control system resets, and memory corruption

events that could degrade link performance. Thermal cycling effects on laser wavelength stability arise from daily eclipse cycles in LEO, deep space thermal gradients, and component differential expansion, all of which can shift operating wavelengths outside optimal ranges. The probability of micrometeorite damage over mission lifetime poses additional concerns through optical surface degradation, catastrophic impact risk, and the evolving debris environment that may progressively degrade system performance.

4.5.3 Validation Constraints

The results are subject to validation constraints inherent in the simulation approach. The study relies on simulation-based validation only, without hardware-in-the-loop testing, which simplifies component interactions, potentially misses edge cases, and cannot capture real hardware variations. The orbital mechanics employ two-body approximations that neglect third-body perturbations significant at Lagrange points, ignore solar radiation pressure effects on large apertures, and omit gravitational harmonics. Traffic patterns are based on extrapolated mission requirements, though future missions may differ significantly, human factors remain unpredictable, and technology evolution introduces substantial uncertainty. Finally, component performance estimates derive from laboratory demonstrations that may not fully represent the harsher space environment, unknown long-term effects, and complex system-level interactions that emerge only in operational conditions.

4.5.4 Acknowledged Limitations and Assumptions

This research makes several optimistic assumptions that warrant explicit acknowledgment:

Power and Aperture Scaling: The 10W baseline transmit power may prove insufficient for reliable AU-scale communications. While our simulations show positive link margins, real-world implementations may require 50-100W lasers for the interplanetary backbone, significantly impacting spacecraft power systems and thermal management. This would require advance thermal radiatros, larger solar arrays, and possible nuclear power for outer solar system extensions.

Acquisition Time Assumptions: The 30-second baseline acquisition time assumes near-perfect platform stability and pointing knowledge. Actual spacecraft experience thermal distortions from solar heating cycles, reaction wheel vibrations at 50-200 Hz, Thruster disturbances during station-keeping, and structural flexibility in large apertures. These factors could extend acquisition times to several minutes, particularly for first-time link establishment.

Network Availability: The 99.7% connectivity achievement assumes independent failure modes and may not fully capture correlated failures from solar storms affecting multiple spacecraft, debris events from collision cascades, common-mode software failures, and manufacturing defects in component lots. Real-world availability would likely be 5-10% lower, requiring additional margin in mission planning.

Traffic Model Simplifications: Our traffic models assume predictable data generation patterns. Actual Mars missions exhibit highly bursty traffic during critical events (100× nominal), unpredictable human communication need, emergency communication requirements, and competing mission priorities. These factors could overwhelm the proposed QoS mechanisms during peak events.

Component Reliability: The simulation assumes constant failure rates without aging effects. FSO components experience laser diode degradation including 20% power loss over 5 years, ointing mechanism wear where backlash increases with cycles, detector sensitivity reduction as radiation damage accumulates, and optical surface contamination where throughput degrades. These degradation modes could reduce system lifetime below the assumed 10-year operational period.

These limitations do not invalidate the architectural concept but suggest that performance margins should be interpreted conservatively for mission planning purposes. Future work should focus on hardware-in-the-loop testing, detailed environmental modeling, prototype relay demonstrations and international standards development.

Chapter 5
Conclusion and Future Work

This chapter summarizes the research contributions of this thesis, examining the implications of the proposed FSO communication network for future space exploration. The demonstrated feasibility of maintaining continuous Earth-Mars connectivity through intelligent relay architectures and hierarchical control systems represents a paradigm shift in interplanetary communications. This work establishes the technical foundation for a new era of deep space exploration, where real-time communication enables unprecedented mission capabilities.

5.1 Research Contributions Summary

5.1.1 Primary Achievements

This research has successfully achieved all primary objectives through comprehensive simulation and analysis that:

1. **FSO Interplanetary Network Feasibility**: The proposed architecture maintains 100% total Earth-Mars connectivity using a constellation of 8 Earth satellites, 4 Mars satellites, and strategically positioned relay stations at Lagrange points throughout the entire 2.25-year simulation period.

2. **Solar Conjunction Resilience**: The L4/L5 relay architecture completely eliminates the traditional 14-day communication blackout during solar conjunction,

maintaining 10+ redundant communication paths when direct Earth-Mars links are blocked.

3. **Intelligent Controller Coordination**: The hierarchical control system effectively manages traffic across the mega-constellation, achieving 31.3% FSO acquisition success rates and reducing acquisition time by 50% through navigation assistance.

4. **Stable Data Rates**: The network achieves a stable aggregate capacity of approximately 0.22 Tbps, with the system quickly reaching operational capacity and maintaining it throughout the simulation.

These achievements validate the hypothesis that FSO technology, combined with intelligent coordination, can revolutionize interplanetary communications.

5.1.2 Novel Technical Contributions

This thesis presents several novel contributions to the field of space communications:

5.1.2.1 Hierarchical Controller Architecture for Interplanetary FSO Networks

This research introduces the first intelligent controller-based architecture specifically designed for managing interplanetary FSO mega-constellations. Unlike prior proposals that position simple relay terminals at Lagrange points, this work deploys active controllers at Earth-Moon Lagrange points (L1, L2, L4, L5) that provides computational intelligence for predictive network management, real-time coordination services overcoming light-speed delays, navigation assistance for sub-microradian pointing

requirements, and traffic management with quality of service guarantees.

The three-tier hierarchy represents a new paradigm:

1. **Tier 1**: Individual satellite autonomy for local decisions

2. **Tier 2**: Regional controllers at Lagrange points managing constellation segments and coordinating traffic

3. **Tier 3**: Interplanetary relay coordination at Earth-Sun and Mars-Sun Lagrange points

This architecture scales linearly with constellation size while maintaining sub-second response times, transforming passive point-to-point links into an intelligent, self-organizing network.

5.1.2.2 First Continuous Conjunction Communication Demonstration

Enabled by the controller architecture, this research presents the first comprehensive simulation proving continuous Earth-Mars connectivity during solar conjunction. While prior work proposed simple relays at Lagrange points, this thesis demonstrates a complete managed network solution including controller-coordinated path analysis showing 10+ viable relay routes during peak conjunction, intelligent routing decisions maintaining 10 Gbps capacity throughout conjunction, automated failover managed by controllers ensuring zero blackout periods and link budget calculations confirming sufficient margin for all controller-managed paths.

5.1.2.3 Controller-Based Navigation Assistance for FSO

The integration of navigation services from controller satellites represents a novel approach to FSO link acquisition that achieves 50% reduction in acquisition time (from 30s to 15s) through predictive pointing, 31.3% acquisition success rate (vs. 29.3% without controller assistance), and a 2 dB improvement in link SNR through controller-provided ephemeris updates.

This technique leverages the controllers' computational resources and strategic positioning to solve the fundamental challenge of establishing optical links across astronomical distances.

5.1.2.4 Intelligent Traffic Management with QoS for Deep Space

The controller-based architecture enables the first comprehensive Quality of Service framework for interplanetary FSO networks, includes a five-level priority scheduling (EMERGENCY through LOW) managed by controllers, dynamic bandwidth allocation responding to orbital configurations, load balancing achieving 0.85 Jain's fairness index through controller coordination and predictive traffic management using controller-maintained ephemeris data. This represents the first implementation of differentiated service levels for deep space optical networks, with controllers ensuring mission-critical communications receive appropriate priority.

5.1.3 Performance Achievements

The quantitative performance metrics achieved by the proposed system establish new benchmarks for interplanetary communications:

5.1.3.1 Network Capacity and Throughput

- Total network capacity: .22 Tbps aggregate
- Active FSO links: 220 simultaneous connections maintained
- Interplanetary backbone: 75-190 links dynamically adjusted based on orbital configuration
- Per-satellite data rate: 5-10 Gbps nominal

5.1.3.2 Reliability and Redundancy

- 100% connectivity maintained between Earth and Mars throughout 2.25-year simulation
- Zero connectivity gap between Earth and Mars systems (as shown in System Balance graph)
- FSO link acquisition success rate: 30% (realistic for challenging space environment)
- Multiple redundant paths through relay satellites at Lagrange points

5.1.3.3 Scalability Metrics

8-satellite constellation successfully demonstrated:

- Controller coordination: 25% of links navigation-assisted

- Modular architecture with controllers managing regional satellite coordination
- Traffic management system successfully prioritizing and scheduling transmissions

These achievements validate the core research objectives, demonstrating that FSO technology combined with strategic Lagrange point placement can maintain continuous Earth-Mars connectivity even during solar conjunction periods.

5.2 Implications for Space Exploration

5.2.1 Mission Enablement

The demonstrated capabilities of the FSO network enable transformative mission concepts previously constrained by communication limitations:

5.2.1.1 Mars Sample Return Missions

Real-time control capability fundamentally changes sample return mission operations with live telemetry during critical descent and sample acquisition phases, interactive sample selection with Earth-based science teams, immediate troubleshooting of anomalies without 48-minute round-trip delays, and 4K video streaming of sample handling procedures at 100 Mbps.

5.2.1.2 Human Mars Missions

The high-bandwidth Earth communication enables continuous medical telemetry and telemedicine consultations, real-time mission control support during EVAs, high-

definition video communication with Earth (to provide psychological benefits), rapid software updates and technical support, and possible educational outreach through live streaming of exploration activities.

5.2.1.3 Deep Space Internet Infrastructure

The network architecture provides the backbone for Solar System-wide connectivity with extension to Jupiter/Saturn systems with additional relay nodes, support for distributed sensor networks throughout the Solar System, cloud computing resources accessible from deep space missions, and standardized protocols enabling multi-mission resource sharing.

5.2.2 Commercial Space Benefits

The FSO network creates new commercial opportunities in the emerging space economy:

- Mega-Constellation Services with traffic management as a service for constellation operators, collision avoidance coordination across multiple operators, spectrum management for optical frequencies, and inter-constellation data relay services

- Interplanetary Internet Service Provision with commercial data relay services to Mars missions, bandwidth leasing for scientific and commercial users, store-and-forward services during conjunction periods, and premium QoS tiers for mission-critical applications.

- Emerging Space industries such as Real-time control for asteroid mining opera-

tions, high-bandwidth links for space manufacturing quality control, financial transaction networks for space commerce, and remote operation of robotic sustems throughout the Solar System.

- Scientific Advancement with interactive control of Mars rovers and aerial vehicles, immediate response to transient phenomena observations, coordinated multi-assit observations of dynamic events, high-resolution data streaming from surface instruments, enhanced data return from deep space telescopes, real-time target of opportunity observations, coordinated observations across multiple platforms, reduced data latency for time-critical discoveries, solar system-wide sensor networks for space weather, coordinmated graviational wave observation, and multi-point magnetic field measurements.

5.3 Validation Against Research Objectives

This section systematically validates the research outcomes against the initial objectives established in Chapter 1.

5.3.1 Objective 1: FSO Network Architecture

Target: Design and validate a comprehensive FSO constellation maintaining >90% Earth-Mars connectivity.

Achievement: EXCEEDED

- Designed complete hierarchical network architecture

- Achieved 99.7% average connectivity (exceeding 90% target)
- Validated through 20,000-hour simulation covering all orbital configurations
- Demonstrated scalability from initial deployment to full constellation

The network architecture not only meets but significantly exceeds the connectivity target, providing margin for operational contingencies.

5.3.2 Objective 2: Performance Optimization

Target: Develop intelligent coordination algorithms improving network performance.

Achievement: ACHIEVED

- Intelligent coordination improved acquisition success by 50%
- Navigation assistance reduced pointing errors by 2 dB
- Traffic management achieved 85% load balancing efficiency
- QoS implementation ensures mission-critical priority handling

The coordination algorithms demonstrate measurable performance improvements across all key metrics.

5.3.3 Objective 3: Solar Conjunction Resilience

Target: Eliminate communication blackouts during solar conjunction events.

Achievement: ACHIEVED

- L4/L5 relay architecture maintains 10+ alternative paths
- Zero blackout periods during 14-day conjunction window
- 140 GB data buffering capacity prevents information loss
- Automatic path switching ensures seamless connectivity

The complete elimination of conjunction blackouts represents a fundamental breakthrough in interplanetary communications.

5.4 Future Research Directions

5.4.1 Near-term Enhancements (2-5 years)

5.4.1.1 Hardware-in-the-Loop Testing Validation

Critical next steps for technology maturation include laboratory demonstration of FSO acquisition algorithms, integration testing with flight-qualified FSO terminals, atmospheric propagation testing for Earth-based segments, thermal vacuum testing of optical components, and radiation effects characterization on FSO systems. These tests will validate simulation results and identify implementation challenges requiring resolution before flight deployment [77].

5.4.1.2 Machine Learning Optimization

Integration of ML algorithms offers significant performance improvements including predictive link quality estimation using orbital dynamics, adaptive beamforming based on atmospheric conditions, anomaly detection for early fault identification, traffic pattern learning for optimized routing, and autonomous network reconfiguration during failures. Research should focus on training algorithms using simulation data before deployment [78].

5.4.1.3 Quantum Communication Integration

Emerging quantum technologies could enhance security and capacity including quantum key distribution for secure interplanetary links, entanglement-based communication for latency reduction, hybrid classical-quantum network architectures, quantum repeaters at Lagrange points, and integration with classical FSO infrastructure.

5.4.1.4 Hardware Validation Roadmap

Critical to the transition from simulation to operational deployment is a comprehensive hardware validation program:

Laboratory Demonstrations (Year 1-2):

- Breadboard FSO terminals with navigation-assisted acquisition
- Pointing accuracy validation using air-bearing platforms
- Thermal vacuum testing of optical components

- Hardware-in-the-loop testing with simulated orbital dynamics

LEO Technology Demonstration (Year 2-3):

- CubeSat mission demonstrating controller coordination protocols
- ISS-based FSO terminal for Earth ground station links
- Validation of acquisition algorithms in microgravity environment
- On-orbit measurement of pointing jitter and thermal effects

Cislunar Validation Mission (Year 3-5):

- Lunar orbit relay demonstration using Earth-Moon L2
- Full-scale FSO terminal testing at 400,000 km ranges
- Operational experience with navigation assistance
- Validation of QoS mechanisms with real mission traffic

Mars Precursor Mission (Year 5-7):

- Single Earth-Sun L4/L5 relay demonstration
- Conjunction mitigation proof-of-concept
- Interplanetary-scale link budget validation

- End-to-end system performance characterization

This staged approach reduces technical risk while building confidence in the architecture before full-scale deployment.

5.4.2 Advanced Technology Integration (5-10 years)

5.4.2.1 Adaptive Optics Enhancement

Next-generation adaptive optics systems will improve link performance with wavefront correction for atmospheric turbulence, active beam shaping for optimal power delivery, multi-aperture systems for increased capacity, real-time aberration correction algorithms, and integration with navigation sensors for rapid acquisition.

5.4.2.2 AI-Driven Autonomous Optimization

Artificial intelligence will enable self-optimizing networks with autonomous network topology optimization, predictive maintenance scheduling, dynamic resource allocation based on mission priorities, self-healing network capabilities, and cognitive radio techniques adapted for optical frequencies.

5.4.2.3 Universal Cross-Link Capabilities

Evolution toward fully connected mesh networks where every satellite equipped with multi-directional FSO terminals. Dynamic mesh topology can adapt to traffic demands and distributed routing algorithms eliminating single points of failure. Finally standardized optical interfaces for multi-vendor compatibility and software-defined

networking for flexible configuration.

5.4.3 System Expansion (10+ years)

5.4.3.1 Outer Solar System Extension

Expansion beyond Mars requires new infrastructure such as Jupiter system relay constellation design, Saturn system communication architecture, Asteroid belt relay stations for continuous coverage, Kuiper belt communication outposts, and interstellar precursor mission support.

5.4.3.2 Galactic Communication Networks

Long-term vision for interstellar communications includes laser beacon systems for interstellar missions, gravitational lensing for signal amplification, relativistic beam steering for moving targets, integration with breakthrough propulsion missions, and standards for galactic internet protocols.

5.5 Final Conclusions

This thesis has successfully demonstrated that advanced Free Space Optical communication networks can revolutionize interplanetary communications by:

1. **Eliminating Solar Conjunction Blackouts**: Through strategic positioning of relay stations at L4/L5 Lagrange points, the proposed architecture maintains continuous Earth-Mars connectivity during conjunction events that currently impose 14+ day communication blackouts. This achievement alone justifies the

investment in FSO infrastructure.

2. **Achieving Unprecedented Data Rates**: The demonstrated 0.20 Tbps aggregate capacity represents orders of magnitude improvement over current RF systems. This bandwidth enables new mission concepts including real-time rover control, high-definition video streaming from Mars, and comprehensive scientific data return.

3. **Enabling Real-time Mars Operations**: With end-to-end latencies dominated by light travel time plus only 245ms processing delay, the network supports interactive control of Mars assets. This capability transforms Mars exploration from batch-commanded operations to real-time scientific investigation.

4. **Providing Scalable Deep Space Infrastructure**: The hierarchical architecture scales linearly with constellation size and can be extended throughout the Solar System. The modular design supports incremental deployment while maintaining full functionality at each expansion phase.

The intelligent controller coordination system represents a fundamental advancement in space network management. By integrating navigation assistance, traffic management, and quality of service capabilities, the system maintains greater than 99% connectivity across interplanetary distances while efficiently utilizing network resources.

5.5.1 Broader Impact

The implications of this research extend beyond technical achievements. The FSO network enables a new paradigm of space exploration where human presence on Mars becomes practically sustainable through continuous high-bandwidth Earth , scientific discoveries can be verified and followed up in real-time, commercial space ventures gain the communication infrastructure necessary for economic viability, and international collaboration is facilitated through shared communication resources.

5.5.2 Closing Remarks and Call to Action

As humanity prepares for sustained exploration beyond Earth, robust communication infrastructure becomes as critical as propulsion or life support systems. This thesis provides the technical foundation for that infrastructure, demonstrating not only feasibility but superiority over existing approaches.

The vision of continuous, high-bandwidth interplanetary communication is no longer confined to science fiction. Through the systematic application of FSO technology, intelligent network management, and strategic infrastructure placement, we can create a Solar System-wide internet that enables the next chapter of human exploration and scientific discovery.

Bibliographic references

1. Valinia, A., Allen, J. R., Francisco, D. R., Minow, J. I., Pellish, J. A. & Vera, A. H. *Safe Human Expeditions Beyond Low Earth Orbit (LEO)* Technical Memorandum NASA/TM-20220002905, NESC-RP-20-01589 (National Aeronautics and Space Administration, 2022).

2. NASA Space Science Data Coordinated Archive. *Upcoming Events* https://nssdc.gsfc.nasa.gov/planetary/upcoming.html. Curator: Dr. David R. Williams, NASA Goddard Space Flight Center. National Aeronautics and Space Administration, 2025.

3. NASA Jet Propulsion Laboratory. *Managing the Deluge of 'Big Data' From Space* Accessed: May 2025. National Aeronautics and Space Administration, 2013.

4. Hemmati, H., Biswas, A. & Djordjevic, I. B. Deep-space optical communications: future perspectives and applications. *Proceedings of the IEEE* **99,** 2020–2039. doi:10.1109/JPROC.2011.2160609 (2011).

5. *Sojourner's View of the Lander* NASA Science. https://science.nasa.gov/resource/sojourners-view-of-the-lander/ (2024).

6. Caltech Magazine. *Mars 2020: How Perseverance Rover Compares to Curiosity* https://magazine.caltech.edu/post/mars-2020-evolution-of-a-rover. 2021.

7. Wall, M. & Tillman, N. T. *Perseverance rover — Everything you need to know* https://www.space.com/perseverance-rover-mars-2020-mission. 2023.

8. Edwards Jr., C., Arnold, B., DePaula, R., Kazz, G., Lee, C. & Noreen, G. Relay communications strategies for mars exploration through 2020. *Acta Astronautica* **59,** 310–318. doi:10.1016/j.actaastro.2006.02.038 (2006).

9. Bhartia, R., Beegle, L. W., DeFlores, L., Abbey, W., Hollis, J. R., Uckert, K., *et al.* Perseverance's scanning habitable environments with raman and luminescence for organics and chemicals (SHERLOC) investigation. *Space Science Reviews* **217,** 58. doi:10.1007/s11214-021-00812-z (2021).

10. NASA. *Communications - Mars 2020 Spacecraft: Rover* Mars 2020 Mission Official Documentation. National Aeronautics and Space Administration, 2020.

11. Sandilands, S. *Talking to Martians: Communications with Mars Curiosity Rover* tech. rep. Technical analysis of Mars-Earth communications (Sandilands Consultancy, 2012).

12. Di, K., Yue, Z., Liu, Z. & Wang, S. Automated rock detection and shape analysis from Mars rover imagery and 3D point cloud data. *Journal of Earth Science* **24,** 125–135. doi:10.1007/s12583-013-0316-3 (2013).

13. Maki, J. N., Gruel, D., McKinney, C., Ravine, M. A., Morales, M., Lee, D., *et al.* The Mars 2020 engineering cameras and microphone on the Perseverance rover: a next-generation imaging system for Mars exploration. *Space Science Reviews* **216,** 137. doi:10.1007/s11214-020-00765-9 (2020).

14. NASA. *Europa Clipper Press Kit* Press Kit (National Aeronautics and Space Administration, 2024).

15. Srinivasan, D., Sheldon, C. & Bray, M. *Telecommunications systems for the NASA Europa missions* in *2017 IEEE Aerospace Conference* (2017), 394–397. doi:10.1109/AERO.2017.7943592.

16. Kessler, P., Harris, D., Prater, T. & Nickens, T. *Artemis deep space habitation: enabling a sustained human presence on the moon and beyond* in *IEEE Aerospace Conference* IEEE 978-1-6654-3760-8/22 (Huntsville, AL, 2022).

17. Gladden, R. E., Hwang, P. P., Waggoner, B. C., McLaughlin, B. A., Fieseler, P. D., Thomas, R. C., Bigwood, M. & Herrera, P. N. *Mars relay coordination lessons learned* in *2005 IEEE Aerospace Conference* IEEEAC paper #1065, Version 4 (Big Sky, MT, USA, 2005), 1–14.

18. Lent, R. Improving bundle routing in a space DTN by approximating the transmission time of the reliable LTP. *Network* **3,** 180–198. doi:10.3390/network3010009 (2023).

19. NASA Science. *Mars Relay Network* Accessed: April 2025. 2025.

20. Strauss, M. Voyager, still going after all these years. *Air & Space Magazine.* Issue: December/January 2020 (2019).

21. NASA/JPL. *Deep Space Network Services Catalog* tech. rep. DSN No. 820-100, Rev. F. JPL D-19002 (Jet Propulsion Laboratory, California Institute of Technology, 2015).

22. National Aeronautics and Space Administration. *Mars Reconnaissance Orbiter - Science Instruments* NASA Science. https://science.nasa.gov/mission/mars-reconnaissance-orbiter/science-instruments/ (2024).

23. Goh, E. *et al. Scheduling the NASA Deep Space Network with Deep Reinforcement Learning* Submitted on 9 Feb 2021. 2021. arXiv: 2102.05167 [cs.LG].

24. Howard Jr., R. L. & Seibert, M. *Lagrange-Based Options for Relay Satellites to Eliminate Earth-Mars Communications Outages During Solar Superior Conjunctions* NASA Technical Report 20205007788. NASA Technical Reports Server (NTRS) (NASA Johnson Space Center, 2020).

25. NASA Earthdata. *It's Always Sunny in Space (and That's a Problem for Satellite Teams)* NASA Earthdata Feature Article. Accessed: 2025-08-14. 2024.

26. Kontar, E. P. *et al. Plasma motions and compressive wave energetics in the solar corona and solar wind from radio wave scattering observations* 2024. arXiv: 2403.12680 [astro-ph.SR].

27. Manoharan, P. K. *Radio astronomical scintillation in the solar wind plasma: imaging interplanetary disturbances* in (2002).

28. Pennsylvania State University. *The Ionospheric Effect* GEOG 862: GPS and GNSS for Geospatial Professionals. Online course material. Department of Geography, The Pennsylvania State University, 2024.

29. NASA. *Mars Relay Network* https://science.nasa.gov/mars/mars-relay-network/. Accessed: August 14, 2025. National Aeronautics and Space Administration, 2025.

30. Cangahuala, L. A., Campagnola, S., Bradley, B. K., Boone, D. R., Buffington, B. B., Ludwinski, J. M., Nandi, S. & Scott, C. J. Europa clipper mission design, mission plan, and navigation. *Space Science Reviews* **221,** 1–53. doi:10.1007/s11214-025-01140-2 (2025).

31. NASA Science. *Cassini's Radioisotope Thermoelectric Generators (RTGs)* https://science.nasa.gov/mission/cassini/radioisotope-thermoelectric-generator/. Accessed: 2025-08-14. 2025.

32. Dunn, C., Lichten, S., Jefferson, D. & Border, J. S. *Sub-Nanosecond Clock Synchronization and Precision Deep Space Tracking* tech. rep. NASA-CR-192357. NASA Technical Reports Server ID: 19920024113 (Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, 1992).

33. Gui, M., Yang, H., Ning, X., Xiong, K., Liu, J. & Dai, M.-Z. Star angle/double-differenced pulse time of arrival integrated navigation method for Jupiter exploration. *Advances in Space Research* **71,** 2669–2678. doi:10.1016/j.asr.2022.11.006 (2023).

34. Space.com Staff. *NASA's Cassini Mission to Saturn: By the Numbers* Accessed 2025. 2017.

35. Wang, Z., Peng, C., Zhang, T., Wang, Q., Liu, S., Liu, X., Wang, Y., Huang, Y. & He, D. Space optical communication system for space optical networks and deep space exploration. *Journal of Optical Communications and Networking* **16,** 843–856. doi:10.1364/JOCN.529905 (2024).

36. Szebehely, V. *Theory of Orbits: The Restricted Problem of Three Bodies* (Academic Press, New York, 1967).

37. Hemmati, H. *Deep Space Optical Communications* (Wiley-Interscience, Hoboken, NJ, 2006).

38. Burleigh, S., Hooke, A., Torgerson, L., Fall, K., Cerf, V., Durst, B., Scott, K. & Weiss, H. Delay-tolerant networking: an approach to interplanetary internet. *IEEE Communications Magazine* **41,** 128–136 (2003).

39. Murray, C. D. & Dermott, S. F. *Solar System Dynamics* (Cambridge University Press, Cambridge, UK, 1999).

40. Farquhar, R. W. The utilization of halo orbits in advanced lunar operations. *NASA Technical Note D-6365* (1970).

41. Whitley, R. & Martinez, R. *Options for staging orbits in cislunar space* in *IEEE Aerospace Conference* (2016), 1–9.

42. Dunham, D. W. & Roberts, C. E. Spaceguard survey: spacecraft at earth-sun libration points as observatory platforms. *Advances in Space Research* **30,** 317–324 (2002).

43. Domingo, V., Fleck, B. & Poland, A. I. The soho mission: an overview. *Solar Physics* **162,** 1–37 (1995).

44. Gardner, J. P. *et al.* The james webb space telescope. *Space Science Reviews* **123,** 485–606 (2006).

45. Jesick, M. Mars trojan orbits for continuous earth-mars communication. *The Journal of the Astronautical Sciences* **67,** 902–931. doi:10.1007/s40295-019-00195-y (2020).

46. Biswas, A., Hemmati, H. & Moision, B. Deep space optical communications: from psyche to mars. *Science* **382,** 878–882 (2023).

47. Kaushal, H. & Kaddoum, G. Optical communication in space: challenges and mitigation techniques. *IEEE Communications Surveys Tutorials* **19,** 57–96 (2017).

48. Majumdar, A. K. *Free-space laser communication performance in the atmospheric channel* (Springer, 2015).

49. Andrews, L. C. & Phillips, R. L. *Laser beam propagation through random media* (SPIE Press, 2005).

50. Tyson, R. K. Bit-error rate for free-space adaptive optics laser communications. *JOSA A* **19,** 753–758 (2002).

51. Boroson, D. M. & Robinson, B. S. The lunar laser communication demonstration: nasa's first step toward very high data rate support of science and exploration missions. *Space Science Reviews* **185,** 115–128 (2014).

52. Holme, P. & Saram"aki, J. Temporal networks. *Physics Reports* **519,** 97–125 (2012).

53. Gurnett, D. A., Kurth, W. S., Hospodarsky, G. B., Persoon, A. M., Averkamp, T. F., Cecconi, B., Lecacheux, A., Zarka, P., Canu, P., Cornilleau-Wehrlin, N., Galopeau, P., Roux, A., Harvey, C., Louarn, P., Bostrom, R., Gustafsson, G.,

Wahlund, J.-E., Desch, M. D., Farrell, W. M., Kaiser, M. L., Goetz, K., Kellogg, P. J., Fischer, G., Ladreiter, H.-P., Rucker, H., Alleyne, H. & Pedersen, A. Radio and plasma wave observations at saturn from cassini's approach and first orbit. *Science* **307,** 1255–1259. doi:10.1126/science.1105356 (2005).

54. Cerf, V., Burleigh, S., Hooke, A., Torgerson, L., Durst, R., Scott, K., Fall, K. & Weiss, H. Delay-tolerant networking architecture. *RFC 4838* (2007).

55. Caini, C., Cruickshank, H., Farrell, S. & Marchese, M. *Delay- and disruption-tolerant networking (dtn): an alternative solution for future satellite networking applications* in *Proceedings of the IEEE* **99** (2011), 1980–1997.

56. Harris, A. & Giuma, T. A. *Minimization of acquisition time in a wavelength diversified fso link between mobile platforms* in *Proceedings of SPIE - Atmospheric Propagation IV* **6551** (2007). doi:10.1117/12.719013.

57. Carrillo-Flores, D., Esteban-Sanchez, S., Vergara-Herreros, J. & Giggenbach, D. Statistics of received power time series for optical leo satellite uplinks. *International Journal of Satellite Communications and Networking* **43,** 123–145. doi:10.1002/sat.1499 (2025).

58. Elamien, M. E., ElSayed, H. M. & Elkorany, A. S. Machine learning-based beam pointing error reduction for satellite–ground fso links. *Electronics* **13,** 3466. doi:10.3390/electronics13173466 (2024).

59. Elsafty, A. H., Elamien, M. B., ElSayed, H. M., Radwan, A. G. & Elkorany, A. S. Enhancing earth-to-satellite FSO system spectrum efficiency with adaptive M-ary PSK and SIMO in presence of scintillation and beam wander. *AEU - International Journal of Electronics and Communications* **124,** 153341. doi:10.1016/j.aeue.2020.153341 (2020).

60. Petkovic, M. I., Aleksic, A. N., Novakovic, D. L. & Djordjevic, G. T. On the ber performance of fso links with multiple receivers and spatial jitter over gamma-gamma or exponential turbulence channels. *Optics & Laser Technology* **96,** 147–152. doi:10.1016/j.optlastec.2017.05.023 (2017).

61. Lu, Q., Liu, W., Xu, Z., Li, W., Zhu, Y. & Tian, Q. Shipborne acquisition, tracking, and pointing experimental verifications towards satellite-to-sea laser communication. *Applied Sciences* **9,** 3940. doi:10.3390/app9183940 (2019).

62. Wu, Y., Kong, B., Xia, J., Min, M. & Liu, G. High-precision tracking of free-space optical communication system on mobile platforms. *Photonics* **11,** 900. doi:10.3390/photonics11100900 (2024).

63. Muhire, D. *et al. Optical communications for small satellites: a review of pointing strategies & requirements optimization* in *Proceedings of the International Astronautical Congress (IAC)* Online Event (2020).

64. Birnbaum, K. E. *et al. Pointing, acquisition, and tracking for the tbird cubesat mission* in *Proceedings of SPIE - Free-Space Laser Communications XXXIV* **11993** (2022), 1199303-1–1199303-12. doi:10.1117/12.2610181.

65. Hemmati, H. *Deep space optical communications* (John Wiley & Sons, 2020).

66. Scott, K. & Burleigh, S. Bundle protocol specification. *RFC 5050* (2007).

67. Cornwell, D. M. *Nasa's optical communications program* in *Free-Space Laser Communication and Atmospheric Propagation XXVIII* **9739** (2016), 97390E.

68. Boroson, D. M. & Robinson, B. S. *Mars laser communications demonstration design* in *IEEE Aerospace Conference* (2014), 1–11.

69. Lock, R. E. *et al.* Martian communication constellation for human exploration. *Acta Astronautica* **152,** 31–42 (2018).

70. Alkalai, L. *et al.* Lunar gateway and deep space communications. *IEEE Aerospace Conference,* 1–8 (2019).

71. Biswas, A., Srinivasan, M., Shaw, K. & Liao, D. Deep space optical communications technology demonstration missions. *Optical Engineering* **60,** 086106 (2021).

72. Del Portillo, I., Crawley, E. F. & Cameron, B. G. *Commercial leo constellation extensions for deep space communications* in *IEEE Aerospace Conference* (2023), 1–15.

73. Fraire, J. A. *et al.* Routing in the space internet: a contact graph routing tutorial. *Journal of Network and Computer Applications* **174,** 102884 (2021).

74. Ivancic, W. *et al.* Dtn implementation and deployment challenges. *IEEE Communications Magazine* **58,** 44–50 (2020).

75. Messerschmitt, D. G. Design principles for interstellar communications. *Acta Astronautica* **202,** 684–695 (2023).

76. Ho, C. & Wheelon, A. D. Solar wind effects on space optical communications. *IPN Progress Report* **42,** 1–15 (2005).

77. Sodnik, Z., Armengol, J. M. P. & Czichy, R. *Deep-space optical communication system (docs) for esa's space missions* in *International Conference on Space Optics—ICSO 2020* **11852** (2021), 118520J.

78. Sharma, A., Singh, G. & Khanna, N. Machine learning for optical communication systems: an introduction and overview. *IEEE Communications Surveys & Tutorials* **24,** 2367–2398 (2022).

Appendix A
Mathematical Derivations

A.1 Orbital Mechanics and Perturbations

A.1.1 Lagrange Point Calculations

For collinear Lagrange points (L_1 and L_2), the distances are calculated using the mass ratio μ and the cubic approximation:

$$\mu = \frac{m_2}{m_1 + m_2} \tag{A.1}$$

$$r_{L1} \approx r \left(1 - \left(\frac{\mu}{3}\right)^{1/3}\right) \tag{A.2}$$

$$r_{L2} \approx r \left(1 + \left(\frac{\mu}{3}\right)^{1/3}\right) \tag{A.3}$$

For triangular points (L_4 and L_5), they form equilateral triangles with the two primary bodies:

$$r_{L4} = r_{L5} = r \tag{A.4}$$

where r is the distance between the two primary bodies.

A.2 Earth-Sun System

System Parameters:

$$\mu_{Earth-Sun} = \frac{1}{332,946} \tag{A.5}$$

$$r = 1 \text{ AU} = 149,597,870.7 \text{ km} \tag{A.6}$$

$$\left(\frac{\mu}{3}\right)^{1/3} = \left(\frac{1}{998,838}\right)^{1/3} \approx 0.01000125 \tag{A.7}$$

Distance Calculations:

$$\text{Earth to } L_1: \quad d_{E-L1} = r \cdot \left(\frac{\mu}{3}\right)^{1/3} \tag{A.8}$$

$$= 149,597,870.7 \times 0.01000125 \tag{A.9}$$

$$\approx \boxed{1,496,000 \text{ km}} \tag{A.10}$$

$$\text{Earth to } L_2: \quad d_{E-L2} = r \cdot \left(\frac{\mu}{3}\right)^{1/3} \tag{A.11}$$

$$= 149,597,870.7 \times 0.01000125 \tag{A.12}$$

$$\approx \boxed{1,496,000 \text{ km}} \tag{A.13}$$

$$\text{Earth to } L_4: \quad d_{E-L4} = r = \boxed{149,597,871 \text{ km}} \tag{A.14}$$

$$\text{Earth to } L_5: \quad d_{E-L5} = r = \boxed{149,597,871 \text{ km}} \tag{A.15}$$

A.3 Earth-Moon System

System Parameters:

$$\mu_{Earth-Moon} = \frac{1}{81.30056} \tag{A.16}$$

$$r = 384,400 \text{ km (mean Earth-Moon distance)} \tag{A.17}$$

$$\left(\frac{\mu}{3}\right)^{1/3} = \left(\frac{1}{243.90168}\right)^{1/3} \approx 0.15870 \tag{A.18}$$

Distance Calculations:

$$\text{Earth to } L_1: \quad d_{E-L1} = r \cdot \left(1 - \left(\frac{\mu}{3}\right)^{1/3}\right) \tag{A.19}$$

$$= 384,400 \times (1 - 0.15870) \tag{A.20}$$

$$\approx \boxed{323,500 \text{ km}} \tag{A.21}$$

$$\text{Earth to L}_2: \quad d_{E-L2} = r \cdot \left(1 + \left(\frac{\mu}{3}\right)^{1/3}\right) \tag{A.22}$$

$$= 384,400 \times (1 + 0.15870) \tag{A.23}$$

$$\approx \boxed{445,300 \text{ km}} \tag{A.24}$$

$$\text{Earth to L}_4: \quad d_{E-L4} = r = \boxed{384,400 \text{ km}} \tag{A.25}$$

$$\text{Earth to L}_5: \quad d_{E-L5} = r = \boxed{384,400 \text{ km}} \tag{A.26}$$

A.4 Mars-Sun System

System Parameters:

$$\mu_{Mars-Sun} = \frac{1}{3,098,708} \tag{A.27}$$

$$r = 1.524 \text{ AU} = 227,943,824 \text{ km} \tag{A.28}$$

$$\left(\frac{\mu}{3}\right)^{1/3} = \left(\frac{1}{9,296,124}\right)^{1/3} \approx 0.004745 \tag{A.29}$$

Distance Calculations:

$$\text{Mars to } L_1: \quad d_{M-L1} = r \cdot \left(\frac{\mu}{3}\right)^{1/3} \tag{A.30}$$

$$= 227,943,824 \times 0.004745 \tag{A.31}$$

$$\approx \boxed{1,082,000 \text{ km}} \tag{A.32}$$

$$\text{Mars to } L_2: \quad d_{M-L2} = r \cdot \left(\frac{\mu}{3}\right)^{1/3} \tag{A.33}$$

$$= 227,943,824 \times 0.004745 \tag{A.34}$$

$$\approx \boxed{1,082,000 \text{ km}} \tag{A.35}$$

$$\text{Mars to } L_4: \quad d_{M-L4} = r = \boxed{227,943,824 \text{ km}} \tag{A.36}$$

$$\text{Mars to } L_5: \quad d_{M-L5} = r = \boxed{227,943,824 \text{ km}} \tag{A.37}$$

A.4.1 J2 Perturbation Acceleration

The J2 perturbation accounts for Earth's oblateness and is calculated as:

$$\mathbf{a}_{J2} = \frac{3}{2}\frac{J_2 \mu R_E^2}{r^5}\begin{bmatrix} x(5z^2/r^2 - 1) \\ y(5z^2/r^2 - 1) \\ z(5z^2/r^2 - 3) \end{bmatrix} \tag{A.38}$$

where $J_2 = 1.08263 \times 10^{-3}$ is Earth's second zonal harmonic, $\mu = 3.986004418 \times 10^{14}$ $\mathrm{m}^3/\mathrm{s}^2$ is Earth's gravitational parameter, $R_E = 6.371 \times 10^6$ m is Earth's radius, and $r = \sqrt{x^2 + y^2 + z^2}$ is the satellite distance from Earth's center.

A.4.2 Solar Radiation Pressure

The acceleration due to solar radiation pressure is:

$$\mathbf{a}_{SRP} = -P_{SR}\frac{A}{m}C_R\left(\frac{AU}{r_{sun}}\right)^2\frac{\mathbf{r}_{sun}}{|\mathbf{r}_{sun}|} \tag{A.39}$$

where $P_{SR} = 4.56 \times 10^{-6}$ $\mathrm{N/m}^2$ is the solar radiation pressure at 1 AU, A/m is the area-to-mass ratio, C_R is the reflectivity coefficient (typically 1.2-1.8), and $\mathbf{r}_{sun}$ is the vector from the satellite to the Sun.

A.4.3 Station-Keeping at Lagrange Points

The linearized dynamics near L1 or L2 follow:

$$\ddot{\mathbf{r}} = \mathbf{A}\mathbf{r} + \mathbf{B}\mathbf{u} \tag{A.40}$$

where the state matrix $\mathbf{A}$ for the circular restricted three-body problem is:

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ \Omega_{xx} & 0 & 0 & 0 & 2n & 0 \\ 0 & \Omega_{yy} & 0 & -2n & 0 & 0 \\ 0 & 0 & \Omega_{zz} & 0 & 0 & 0 \end{bmatrix} \tag{A.41}$$

The characteristic frequencies are:

$$\lambda_{1,2} = \pm\omega_0 \sqrt{1 + \sqrt{1 + \frac{27\mu(1-\mu)}{4}}} \tag{A.42}$$

indicating instability along the x-axis, requiring active station-keeping.

A.5 FSO Link Budget Detailed Analysis

A.5.1 Free-Space Path Loss

The complete free-space path loss equation for optical communications:

$$L_{fs} = \left(\frac{\lambda}{4\pi d}\right)^2 = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) \text{ [dB]} \tag{A.43}$$

For $\lambda = 1550$ nm and $d = 1$ AU:

$$L_{fs} = 20\log_{10}\left(\frac{4\pi \times 1.496 \times 10^{11}}{1550 \times 10^{-9}}\right) \approx 453.4 \text{ dB} \tag{A.44}$$

A.5.2 Geometric Spreading Loss

The geometric loss due to finite receiver aperture:

$$L_{geo} = -10\log_{10}\left(\frac{A_r}{A_{beam}}\right) = -10\log_{10}\left(\frac{\pi r_r^2}{\pi(\theta d)^2}\right) \tag{A.45}$$

where $A_r = \pi r_r^2$ is the receiver aperture area, θ is the beam divergence angle, and d is the distance.

A.5.3 Pointing Loss Model

For a Gaussian beam profile, the pointing loss is:

$$L_{point} = \exp\left(-2\left(\frac{\theta_e}{\theta_{div}}\right)^2\right) \tag{A.46}$$

where θ_e is the pointing error and θ_{div} is the beam divergence. In dB:

$$L_{point}[\text{dB}] = -4.343\left(\frac{\theta_e}{\theta_{div}}\right)^2 \tag{A.47}$$

A.5.4 Total Link Budget

The complete link budget equation:

$$P_r = P_t + G_t - L_{fs} - L_{geo} - L_{point} - L_{atm} - L_{imp} + G_r - M \tag{A.48}$$

where L_{imp} represents implementation losses and M is the link margin.

A.6 Modulation and Detection Theory

A.6.1 On-Off Keying (OOK) Performance

The bit error rate for OOK modulation with direct detection:

$$BER_{OOK} = \frac{1}{2}\exp\left(-\frac{\langle n_s \rangle}{2}\right) \tag{A.49}$$

where $\langle n_s \rangle$ is the average number of signal photons per bit.

A.6.2 Pulse Position Modulation (PPM)

For M-ary PPM, the symbol error probability is:

$$P_s = 1 - \left(1 - \frac{1}{2}e^{-n_s}\right)^{M-1} \tag{A.50}$$

where n_s is the average number of signal photons per slot.

The bit error rate for M-PPM:

$$BER_{PPM} = \frac{M/2}{M-1} P_s \tag{A.51}$$

A.6.3 Photon-Counting Channel Capacity

The channel capacity for a Poisson photon-counting channel:

$$C = n_s \log_2 \left(1 + \frac{1}{n_s}\right) + (1 + n_s) \log_2 \left(1 + \frac{n_s}{1 + n_s}\right) \tag{A.52}$$

bits per photon, where n_s is the average signal photons per mode.

A.7 Network Optimization Mathematics

A.7.1 Distributed Consensus with Delays

The delayed consensus protocol for controllers separated by propagation delays:

$$x_i(t + \tau_{ij}) = \sum_{j \in \mathcal{N}_i(t)} a_{ij}(t) x_j(t) + b_i u_i(t) \tag{A.53}$$

For asymptotic consensus despite delays:

$$\int_t^{t+T} \lambda_2(\mathcal{L}(s)) ds > \epsilon \tag{A.54}$$

where $\lambda_2(\mathcal{L}(s))$ is the algebraic connectivity of the network Laplacian.

A.7.2 Traffic Schedule Optimization

The optimization problem for transmission scheduling:

$$\min_{\mathbf{X}} \sum_{s,k} w_{p_k} \cdot \max(0, t_{sk}^{completion} - t_k^{deadline}) \tag{A.55}$$

subject to relay capacity constraints:

$$\sum_{s \in \mathcal{S}(r,t)} x_{sr}(t) \cdot b_{sr}(t) \leq B_r \quad \forall r, t \tag{A.56}$$

A.8 Enhanced Orbital Mechanics

A.8.1 Third-Body Perturbations

The acceleration due to a third body (Sun, Moon) on a satellite is:

$$\mathbf{a}_{3b} = \mu_3 \left(\frac{\mathbf{r}_{3b} - \mathbf{r}_{sat}}{|\mathbf{r}_{3b} - \mathbf{r}_{sat}|^3} - \frac{\mathbf{r}_{3b}}{|\mathbf{r}_{3b}|^3} \right) \tag{A.57}$$

where μ_3 is the gravitational parameter of the third body, $\mathbf{r}_{3b}$ is its position, and $\mathbf{r}_{sat}$ is the satellite position.

A.8.2 Relativistic Corrections

For high-precision timing applications, the leading-order post-Newtonian correction is:

$$\mathbf{a}_{rel} = \frac{\mu}{c^2 r^3} \left[\left(4\frac{\mu}{r} - v^2 \right) \mathbf{r} + 4(\mathbf{r} \cdot \mathbf{v})\mathbf{v} \right] \tag{A.58}$$

where c is the speed of light.

A.8.3 Eclipse Shadow Function

The shadow function for solar radiation pressure during eclipse:

$$\nu = \begin{cases} 0 & \text{if } \cos\theta < 0 \text{ and } \sin\alpha_p > \sin\alpha_s \\ 1 & \text{otherwise} \end{cases} \tag{A.59}$$

where θ is the angle between satellite and Sun from the planet's center, α_p is the angular radius of the planet, and α_s is the angular radius of the Sun.

Appendix B

FSO Terminal and Component Specifications

B.1 FSO Terminal Configuration by Satellite Type

Table B.1: FSO Terminal Specifications

Parameter	**Access Satellite**	**Controller**	**Relay**
Aperture Size	0.3 m	0.5 m	1.0 m
Laser Power	10 W	20 W	50 W
Wavelength	1550 nm	1550 nm	1550 nm
Beam Divergence	1.0 μrad	1.0 μrad	1.0 μrad
Pointing Accuracy	0.1 μrad	0.1 μrad	0.1 μrad
Max Simultaneous Links	8	12	100
Baseline Acquisition Time	30 s	30 s	30 s
Baseline Data Rate	10 Gbps	10 Gbps	10 Gbps

B.2 Link Quality and Performance Parameters

Table B.2: FSO Link Quality Classifications

Quality Level	**Quality Factor**	**SNR (dB)**	**Data Rate**
Excellent	0.95	>10	10.0 Gbps
Good	0.85	5-10	8.0 Gbps
Degraded	0.70	0-5	5.0 Gbps
Poor	0.50	-5-0	2.0 Gbps

Table B.3: Navigation Assistance Performance Improvements

Metric	**Without Navigation**	**With Navigation**
Acquisition Time	30 s	15 s (50% reduction)
Acquisition Success Rate	90%	95% (+5%)
Pointing Error	0.1 μrad	0.05 μrad (50% reduction)
SNR Enhancement	Baseline	+2 dB
Processing Delay	0.1 ms	0.08 ms (20% reduction)

B.3 Traffic Management Parameters

Table B.4: QoS Priority Levels and Scheduling

Priority Level	**Scheduling Target**	**Typical Use Case**
EMERGENCY	Immediate	Safety-critical commands
CRITICAL	Within 3 minutes	System control messages
HIGH	Within 15 minutes	Science data bursts
NORMAL	Best effort	Regular telemetry
LOW	Background	Bulk data transfers

Appendix C

Protocol Details

C.1 Navigation-Assisted Coordination Protocol

C.1.1 Algorithm: Navigation Update Generation

Algorithm 1: Generate Navigation Update

[1] GenerateNavUpdatesatellites_in_region, current_time Initialize relay_positions, optimal_targets, acquisition_windows **for** *each relay in earth_sun_relays* **do**

end

Update relay ephemeris data Predict trajectory for next PREDICTION_HORIZON hours Store in relay_positions[relay.id] **for** *each satellite in satellites_in_region* **do**

end

optimal_relay ← SelectOptimalRelay(satellite) optimal_targets[satellite.id] ← optimal_relay windows ← CalculateAcquisitionWindows(satellite, optimal_relay) acquisition_windows[satellite.id] ← windows **return** NavigationUpdate(relay_positions, optimal_targets, acquisition_windows)

C.1.2 Algorithm: Optimal Relay Selection

Algorithm 2: Select Optimal Relay for Satellite

[1] SelectOptimalRelaysatellite, relay_ephemeris best_relay ← null best_score

← -1 **for** *each relay in relay_ephemeris* **do**

end

distance ← ||satellite.position − relay.position|| future_distance ←

PredictFutureDistance(satellite, relay, 1.0) distance_score ←

$1.0/(1.0 + \text{distance}/\text{RELAY\_RANGE})$ stability_score ←

$1.0/(1.0 + |\text{future\_distance} - \text{distance}|/1000)$ total_score ←

$0.7 \times \text{distance\_score} + 0.3 \times \text{stability\_score}$ **if** *total_score* > *best_score* **then**

end

best_score ← total_score best_relay ← relay.id **return** best_relay

C.2 Traffic Coordination Protocol

C.2.1 Algorithm: Traffic Schedule Optimization

Algorithm 3: Optimize Transmission Schedule

[1] OptimizeScheduletraffic_analysis, relay_positions, current_time schedule ← new TransmissionSchedule(current_time) satellite_priorities ← [] **for** *each satellite in traffic_analysis* **do**

end

priority_score ← CalculatePriorityScore(satellite.traffic)

satellite_priorities.append((satellite.id, priority_score)) Sort satellite_priorities by score (descending) current_slot_time ← current_time **for** *each (satellite_id, score) in satellite_priorities* **do**

end

optimal_relay ← FindOptimalRelay(satellite_id, schedule) **if** *optimal_relay is not null* **then**

end

duration ← CalculateTransmissionDuration(traffic_data) priority ← DetermineMainPriority(traffic_data) schedule.AddAssignment(satellite_id, optimal_relay, current_slot_time, duration, priority) current_slot_time ← current_slot_time + duration + gap **return** schedule

C.3 Message Formats

C.3.1 Navigation Update Message Structure

```
NavigationUpdate {
    controller_id: String
    timestamp: Float
    relay_positions: {
        relay_id: {
            position: Vector3
            velocity: Vector3
            predicted_positions: Array<Vector3>
            lagrange_point: String
        }
    }
    optimal_targets: {
        satellite_id: relay_id
    }
    acquisition_windows: {
        satellite_id: Array<(start_time, end_time, relay_id)>
    }
}
```

C.3.2 Traffic Coordination Message Format

```
TrafficCoordinationUpdate {
```

```
    controller_id: String
    timestamp: Float
    satellite_instructions: {
        satellite_id: {
            recommended_relay: String
            relay_position: Vector3
            transmission_start_time: Float
            transmission_duration: Float
            transmission_priority: Enum<EMERGENCY|CRITICAL|HIGH|NORMAL|LOW>
            allocated_data_rate: Float
            transmission_authorization: String
            queue_position: Integer
        }
    }
    traffic_analysis: {
        satellite_id: {
            total_data_gb: Float
            priority_breakdown: Map<Priority, DataStats>
            estimated_transmission_time: Float
            deadline_urgency: Integer
        }
    }
}
```

C.3.3 Handoff Command Format

```
HandoffCommand {
    satellite_id: String
    current_relay: String
    new_relay: String
    handoff_time: Float
    handoff_type: Enum<MAKE_BEFORE_BREAK|BREAK_BEFORE_MAKE>
    coordination_data: {
        predicted_link_quality: Float
        estimated_handoff_duration: Float
        fallback_relay: String (optional)
    }
}
```

Appendix D

Simulation Parameters and Configuration

D.1 Physical Constants and Orbital Parameters

Table D.1: Celestial Body Parameters and Mass Ratios

Parameter	**Value**	**Units**
Celestial Body Radii		
Earth Radius	6,371.0	km
Mars Radius	3,389.5	km
Moon Radius	1,737.4	km
Sun Radius	695,700.0	km
Orbital Distances		
Astronomical Unit (AU)	149,597,870.7	km
Earth-Mars Closest	0.372	AU
Earth-Mars Farthest	2.675	AU
Earth-Moon Distance	384,400	km (mean)
Mass Ratios (μ)		
Earth-Moon System	1/81.30056	-
Earth-Sun System	1/332946.0	-
Mars-Sun System	1/3098708.0	-

D.2 FSO System Configuration

Table D.2: FSO Communication System Parameters

Parameter	**Value**	**Units**
Optical System		
Wavelength	1550	nm
Beam Divergence	1.0	μrad
Pointing Accuracy	0.1	μrad
Baseline Data Rate	10.0	Gbps
Environmental Factors		
Atmospheric Loss (Earth)	2.0	dB
Solar Exclusion Radius	1.5 $\times$ Solar Radius	km
Cloud Blockage Probability	0.15	-
Communication Ranges		
Maximum FSO Range	0.5	AU
Controller Coverage	0.3	AU
Deep Space Relay Range	4.0	AU

D.3 Network Architecture Configuration

Table D.3: Network Constellation and Timing Parameters

Parameter	**Value**	**Units**
Constellation Size		
Earth Satellites (GEO)	24	satellites
Mars Satellites (Areostationary)	8	satellites
Earth-Moon Controllers	4	L1, L2, L4, L5
Earth-Sun Relays	4	L1, L2, L4, L5
Mars-Sun Relays	4	L1, L2, L4, L5
Simulation Timing		
Simulation Duration	20,000	hours
Time Step	24.0	hours
Navigation Update Interval	0.1	hours (6 min)
Traffic Update Interval	0.05	hours (3 min)
Transmission Slot Duration	0.02	hours (1.2 min)
Prediction Horizon	2.0	hours
Coordination Parameters		
Handoff Threshold	0.8	quality factor
Link Drop Threshold	0.1	quality factor
Cache Expiry Time	1.0	hours

D.4 Validation Test Configuration

Table D.4: Validation Test Parameters

Test Scenario	**Parameter**	**Value**
Solar Conjunction Test		
Earth Position	[1.0, 0, 0]	AU
Mars Position	[-1.52, 0, 0]	AU
Conjunction Angle	180	degrees
Link Failure Recovery		
Maximum Failures	5	links
Recovery Probability	30%	per 6 min
Recovery Target	95%	connectivity
Maximum Attempts	10	-
Traffic Overload Test		
Overload Factor	2.5×	baseline
Emergency Data Size	50	MB
Science Data Burst	0.5-5.0	GB
Regular Telemetry	100	MB/2hr
Ephemeris Configuration		
Ephemeris Version	DE440	JPL
Base Date	2025-05-03 12:00:00	UTC
Position Accuracy	<1	km

Appendix E

Implementation Code

This appendix references the implementation of the FSO interplanetary network simulation framework. The complete implementation (3,516 lines) is contained in a single file available at:

https://github.com/nickyduesxd/Autonomous_Lagrange_Point_Optical_Relays_for_Continuous_Interplanetary_Communication_Masters_Thesis

The implementation sections referenced in Chapter 3 can be found at the following line numbers in `model.py`:

E.1 Import Statements and Constants

Lines 1–63: Import statements and global constants

E.2 Core Satellite Class

Lines 65–422: `Satellite` class implementation

Lines 776–819: `EnhancedSatellite` class implementation

E.3 Enhanced FSO Terminal

Lines 1460–1915: `EnhancedFSO_Terminal` class implementation

E.4 Navigation Coordination System

Lines 1329–1459: `NavigationCoordinator` class implementation

E.5 Traffic Management System

Lines 871–1103: `TrafficManager` class implementation

Lines 1105–1115: `TrafficCoordinationUpdate` class

Lines 821–869: `TrafficQueue` and `TransmissionSchedule` classes

E.6 Line of Sight Checker

Lines 424–494: `LineOfSightChecker` class implementation

E.7 Real Ephemeris Data

Lines 496–540: `RealEphemerisData` class implementation

E.8 Precise Lagrange Points

Lines 542–774: `PreciseLagrangePoints` class implementation

E.9 Realistic Orbital Mechanics

Lines 1117–1327: `RealisticOrbitalMechanics` class implementation

E.10 Network Architecture

Lines 1917–2575: `FSO_NetworkArchitecture` class implementation

E.11 Validation Test Functions

Lines 2667–3020: Solar conjunction test (`test_solar_conjunction`)

Lines 3022–3093: Link failure recovery test (`test_dynamic_link_failure_recovery`)

Lines 3095–3171: Traffic overload test (`test_traffic_overload_scenario`)

Lines 3173–3234: Orbital configuration test (`test_orbital_configuration_impact`)

E.12 Main Simulation Function

Lines 3430–3516: `run_fso_network_simulation` main function

E.13 Additional Components

Lines 858–1103: `ThesisMetricsCollector` class for data collection

Lines 1117–1120: `NavigationUpdate` class

Lines 1328: `FSO_LinkScheduler` class