Design of a Pricing Algorithm for Efficient Resource Management in an Integrated Terrestrial and Non-Terrestrial Network

Presented by:
Kwanele Mabanga

Prepared for:
A/Prof. Olabisi Falowo
Dept. of Electrical Engineering
University of Cape Town

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Student proposed?	*Y/N* *N*	*If Y, student name*
ID:	OF-4	
SUPERVISOR:	Olabisi Falowo	
TITLE:	**Design of a Pricing Algorithm for Efficient Resource Management in an Integrated Terrestrial and Non-Terrestrial Network**	
DESCRIPTION:	The integration of Terrestrial Networks (TN) and Non-Terrestrial Networks (NTN) is essential for achieving seamless global connectivity. However, existing pricing schemes for TN and NTN operate independently based of the different capabilities, cost structures, and deployment models of the two networks. This independent pricing schemes may force user to maintain multiple subscriptions and billing arrangements, which is not efficient for resource management in the integrated network. Thus, there is need to develop a unified pricing scheme for integrated terrestrial and non-terrestrial network so that users can maintain a single subscription and network operators can enhance resource management in the integrated network. The main objective of this project is to develop a unified pricing scheme for integrated terrestrial and non-terrestrial networks.	
DELIVERABLES:	A review of pricing schemes for terrestrial and not-terrestrial networks, a pricing scheme, simulation results, and report.	
SKILLS/REQUIREMENTS:	MATLAB, Python, or any other programming language, Knowledge of EEE4121F.	
GA 1: Problem solving: *Identify, formulate, analyse and solve complex* engineering problems creatively and innovatively*	The student is expected to develop and implement a pricing scheme for billing users in integrated terrestrial and non-terrestrial networks.	
GA 4**: Investigations, experiments and analysis: *Demonstrate competence to design and conduct investigations and experiments.*	The student is expected to investigate the performance of pricing scheme.	
GA 5: Use of engineering tools: *Demonstrate competence to create, select and apply and recognise limitations of appropriate techniques, resources and modern engineering and IT tools, including prediction and modelling, to complex engineering problems*	The student is expected to develop a network model, develop a pricing scheme, and implement the pricing scheme using MATLAB or any other programming language.	

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Abstract

The Integration of Terrestrial Networks (TNs) with Non-Terrestrial Networks (NTNs) is fundamental for achieving the global, seamless connectivity envisioned for 6G, promising to bridge the digital divide and provide ubiquitous service continuity. However, the differing characteristics and independent pricing schemes of these networks create inefficiencies for both users and network operators, such as the need for multiple subscriptions and suboptimal allocation of resources.

This project addresses these issues by designing, implementing, and evaluating a unified pricing algorithm for efficiently managing resources in an integrated TN-NTN environment.

The proposed algorithm dynamically adjusts access prices according to network load and available capacity, aiming to efficiently manage resources while minimising costs for the user. A network model incorporating a terrestrial base station (BS) and a Low Earth Orbit (LEO) satellite is designed to simulate user mobility and network performance. MATLAB simulations are conducted to assess the algorithm's performance, with key performance metrics including total user cost, operator revenue, call blocking probability, and call dropping probability. Based on these results, conclusions are drawn and recommendations for future work are made.

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Chapter 1

Introduction

1.1 Background to the study

The evolution of telecommunications has been defined by generational leaps, each bringing transformative capabilities that have reshaped global connectivity. From the analog voice of 1G to the high-speed, low-latency of 5G, each generation has expanded the boundaries of wireless communication in terms of speed, reliability, and service diversity. As the telecommunications industry shifts focus towards 6G and beyond, a new architectural vision emerges as central to its success: the seamless integration of Terrestrial Networks (TNs) and Non-Terrestrial Networks (NTNs).

In this integrated architecture, TNs form the backbone of connectivity in urban and suburban regions, offering high capacity and low latency. However, their coverage is limited by infrastructure availability and high deployment costs, making them less feasible in low-density or remote areas. NTNs, on the other hand, complement TNs by extending coverage to underserved or unserved areas, bridging the gaps left by terrestrial infrastructure.

While the TN-NTN integration promises ubiquitous, reliable, and high-speed connectivity, the two network types differ significantly in physical characteristics, cost structures, and Quality of Service (QoS). These differences have resulted in independent pricing schemes currently used by TN and NTN operators. This independence introduces significant inefficiencies, including multiple subscriptions (for users) and underutilised radio resources (for network operators). This results in a suboptimal user experience.

To address these inefficiencies, a unified pricing scheme is essential to support an integrated terrestrial and non-terrestrial network.

1.2 Problem Statement

The integration of Terrestrial Networks(TN) and Non-Terrestrial Networks is crucial for achieving seamless global coverage and bridging the digital divide. However, existing pricing schemes for TN and NTN operate independently based on different capabilities, cost structures, and deployment models of the two networks. This independence leads to multiple subscriptions and billing arrangements. Therefore, there's a need to develop a unified pricing scheme for an integrated terrestrial and non-terrestrial network (ITNTN).

1.3 Purpose of the study

.This project aims to review existing pricing schemes used in terrestrial and non-terrestrial networks. Based on the insights from this comprehensive review, a design and implementation of a unified pricing algorithm will follow. The primary objective of this algorithm is to eliminate the need for independent pricing schemes for TN and NTN, allowing users to maintain a single subscription while enabling network operators to manage radio resources within the integrated network efficiently.

1.4 Objectives of this study

The objectives of this study are:

- To review terrestrial and non-terrestrial networks as components of the envisioned 6G network.
- To review existing pricing schemes used in terrestrial and non-terrestrial networks.
- To design and implement a unified pricing algorithm for efficient resource management in an integrated terrestrial and non-terrestrial network.
- To evaluate the performance of the proposed pricing algorithm through numerical simulations

- To draw conclusions based on the performance of the algorithm
- To provide recommendations for future work.

1.5 Scope and Limitations

This project focuses on the design and implementation of a pricing algorithm for efficient radio resource management in an integrated terrestrial and non-terrestrial network. The proposed network model only considers an integration of cellular and LEO satellite networks. The study is limited to a single type of call service, and the Quality of Service (QoS) metrics used to evaluate the performance of the proposed pricing algorithm are call blocking and call dropping probabilities. Although 6G is envisioned to support Artificial Intelligence (AI) and Machine Learning (M) capabilities, this project does not include any AI or ML techniques.

1.6 Plan of development

The remainder of this report is organised as follows:

Chapter 2 provides an overview of both terrestrial and non-terrestrial networks. It discusses their architectures and operational characteristics. It also briefly discusses radio resource management (RRM).

Chapter 3 reviews existing pricing schemes used in terrestrial and non-terrestrial networks.

Chapter 4 presents the design of the proposed unified pricing scheme and the network model.

Chapter 5 presents the obtained simulation results and provides an evaluation and discussion of the results.

Chapter 6 draws conclusions based on the results of the project.

Chapter 7 provides the recommendations for future work.

Chapter 2

Literature Review on Terrestrial and Non-Terrestrial Networks

This chapter provides a technical overview of terrestrial and non-terrestrial networks, highlighting their architectures, capabilities, and limitations. It also briefly discusses radio resource management.

2.1 Terrestrial Networks

Terrestrial Networks (TNs) form the backbone of modern communications, delivering high-capacity, low-latency wireless access through virtualised and shareable infrastructure within 5G and future 6G systems [2][3]. TNs primarily serve densely populated areas, with infrastructure encompassing wireless local area networks, cellular mobile networks, and fixed broadband data networks [4]. Their performance is enhanced by advanced technologies such as Massive MIMO (M-MIMO), Distributed MIMO (D-MIMO), Reconfigurable Intelligent Surfaces (RISs), and sidelink communications, which together improve spectral efficiency and localisation accuracy [2]. However, their coverage is constrained by infrastructure costs and deployment feasibility, limiting access in sparsely populated or remote areas [2].

2.2 Non-Terrestrial Networks

NTNs complement TNs by enabling connectivity in remote, rural, airborne, and maritime areas where terrestrial infrastructure is unavailable or impractical to deploy [5][2]. Currently, wireless mobile coverage spans only about 15% of Earth's surface, underscoring the importance of NTNs [6].

2.2.1 Space-based NTNs

Space-based NTNs include satellites in Geosynchronous Earth Orbit (GEO), Medium Earth Orbit (MEO), and Low Earth Orbit (LEO), each offering distinct trade-offs between coverage, latency, and constellation size [2][7].

GEO satellites, positioned in a circular equatorial orbit at 35,786 km above sea level, match the Earth's rotational period and provide wide coverage footprints between 200 and 3,500 km. However, GEO satellites experience minimal Doppler shifts and high latency, leading to poor service in polar and high-latitude regions due to their altitude [2][7].

MEO satellites orbit at altitudes of 7,000–25,000 km with beam footprints between 100 and 1,000 km. MEO satellites experience moderate latency of around 70–80 ms and moderate Doppler shifts with about 12-hour orbital periods. MEO constellations require fewer satellites for global coverage compared to LEO systems [2][7].

LEO satellites orbit at altitudes between 200-2,000 km. Their relative proximity to Earth provides enhanced signal strength, lower latency, reduced propagation losses, and improved link budgets [8][6][9]. However, they require large constellations, often mega-constellations with hundreds or thousands of small satellites to provide continuous, global coverage [2][10]. These constellations are characterised by fast satellite movement, limited individual coverage, uneven distribution, and the need for inter-satellite coordination [11].

2.2.2 Aerial-based NTNs

Aerial-based NTNs include High-Altitude Platform Stations (HAPSs) and Unmanned Aerial Vehicles. HAPSs provide quasi-stationary wide-area service with minimal Doppler shifts, making them suitable for remote and rural areas [2][7]. They offer low latency, strong signal strength, and reduced launch costs compared to satellites, though they have smaller coverage areas and limited endurance due to refueling needs [7]. In contrast, UAVs provide agile and dynamic coverage, valuable in urban environments or emergency scenarios, but can introduce moderate Doppler effects due to rapid movement [2]. While offering the smallest coverage footprint, UAVs are notable for their low deployment cost, rapid setup, and operational flexibility [7].

2.2.3 NTN Evolution and Current Deployments

The evolution of NTNs has progressed through three phases. Initially, dedicated satellite systems operated independently of terrestrial networks; the second phase introduced satellite-based cell towers allowng direct device access with unmodified user equipment; and the current third phase focuses on co-designed satellite and user equipment (UE) for seamless TN-NTN integration [9]. This progression has enabled Software-Defined NTNs (SD-NTNs), which use SDN and NFV technologies, to provide centralised control, flexible resource management, and improved efficiency through network slicing [9].

Current deployments are led by major satellite network operators (SNOs), including SpaceX's Starlink, OneWeb, and Amazon's Kuiper [12][10][13]. GEO satellites are used for fixed broadband and IoT applications, while LEO satellites serve low-latency and enhanced link budget services [12].

2.2.4 NTN Challenges

Despite their benefits, NTNs face several challenges. The high mobility of LEO satellites complicates accurate channel state estimation and efficient beamforming [9]. Mobility management must address severe Doppler shifts and facilitate smooth handovers between terrestrial and non-terrestrial networks to maintain service continuity [9]. Traffic scheduling is constrained by the fixed nature of satellite constellations, which can lead to underutilised resources [9].

The diverse characteristics of TNs and NTNs require careful integration strategies to realize their combined potential. Section 2.3 examines these approaches and related technical challenges.

2.3 TN-NTN Integration

This section discusses the integration of TNs and NTNs, a foundational aspect of 5G-Advanced and 6G networks. It highlights standardisation efforts, use cases, technical challenges, and enabling architectures.

2.3.1 Standardisation Efforts

The 3rd Generation Partnership Project (3GPP) has progressively expanded support for TN-NTN integration through its standardisation releases. Release 15 enabled non-3GPP satellite access to coexist with LTE and 5G systems. Release 16 incorporated satellite access into 5G Standalone (SA) systems, exploring both mmWave and sub-6 GHz bands [14]. Release 17 marked the first global standard for NTN integration, introducing satellite-based Radio Access Network (RAN) solutions, mobility management, and QoS via satellite backhaul [12][5]. Release 18 enhanced mobility management, implementing power-saving techniques for user equipment (UE) under discontinuous satellite coverage, and integrating Artificial Intelligence (AI) to support network automation [5]. Looking forward, Release 19 is set to support more advanced satellite features, such as store-and-forward operations, direct UE-to-UE satellite communication, and AI/ML integration [5][2]. Release 20 will mark the beginning of 6G standardisation [2].

2.3.2 6G Vision and Capabilities

In 6G, NTNs are set to provide ubiquitous connectivity in rural, airborne, and maritime areas, ensure service continuity through extended terrestrial coverage, and enhance service scalability through data broadcast and multicast [14]. 5G-Advanced NTNs support eMBB-s, mMTC-s, and HRC-s. 6G NTNs are envisioned to deliver ultra-MBB, ultra-massive communications for large-scale sensing, immersive experiences such as holographic communications and AR/VR, ultra-critical communications, network sensing, and AI-driven resource optimization [12]. Collectively, these capabilities target 6G Key Performance Indicators (KPIs), such as 0.1 ms latency, 100-1000 Gbps data rates, and reliability above 99.99999% [15].

2.3.3 Technical Challenges

NTNs experience signal degradation due to propagation delays, Doppler shifts, atmospheric attenuation, limited onboard processing, and obstruction and attenuation in urban areas [16][2].

Interference in integrated networks can be categorised as Inter-Beam Interference (IBI) within the same satellite, Inter-Satellite Interference (ISI) between different satellites, and LEO-Terrestrial infrastructure interference (LTI) [16]. Cross-tier and intra-tier interference are mitigated in part by using separate frequency bands [14]. Release 17 introduced timing and frequency compensation techniques, such as Global Navigation Satellite System (GNSS)-based UE pre-compensation [12].

Mobility management adds complexity through inter-beam, inter-satellite, and vertical handovers [16]. Additional challenges include spectrum sharing constraints, frequent handovers, high failure rates due to impairments and latency mismatches, overlapping coverage areas, increased signaling overhead, and increased UE power demands [6].

2.3.4 Enabling Architectures

To address these challenges, advanced network architectures leverage Software-Defined Networking (SDN) and Network Function Virtualization (NFV) for centralised control, adaptive network slicing, and real-time optimisation, giving rise to Software-Defined NTNs (SD-NTNs) [9]. Release 18 introduced multi-RAT resource control at the 5G Core (5GC), enabling dynamic load balancing across different radio technologies [17].

AI-based techniques, particularly Reinforcement Learning (RL), are increasingly explored to address the dynamic nature of service demands and environmental variability across space, air, and sea [4]. While RL supports intelligent network design and management, its limitations in multi-domain dynamics highlight the need for more adaptive solutions [4].

Efficient management of integrated TN-NTN systems relies on advanced radio resource management strategies, which are examined in the following section.

2.4 Radio Resource Management

Efficient Radio Resource Management (RRM) is essential in integrated TN–NTN systems to optimise performance, ensure fair resource allocation, and maintain consistent QoS. This section reviews key RRM objectives, challenges, and strategies proposed in the literature.

2.4.1 RRM Functions and Objectives

RRM focuses on effectively managing resources through spectrum sharing, interference management, load balancing, and seamless handover coordination. Techniques such as adaptive modulation and coding (AMC), dynamic scheduling, and power control improve spectral efficiency by adapting to network topology, signal propagation, and user distribution. Coordinated resource management ensures consistent QoS across multiple use cases [18].

2.4.2 Integration Challenges

Integrating satellite and terrestrial networks introduces several challenges due to their heterogeneous characteristics. Satellite links exhibit long propagation delays and asymmetry, while terrestrial links suffer from fading and interference. Maintaining continuous service requires effective handover management [18].

2.4.3 RRM Strategies and Techniques

Several strategies have been proposed to address these challenges. These include Joint Power and Bandwidth Allocation (JPBA) for energy-efficient QoS, Dynamic Resource Allocation (DRA) for adaptive resource use in response to traffic and channel variations [18], and Cognitive Radio (CR) for exploiting underutilised spectrum to improve coverage and mobility [18]. Beamforming and frequency reuse reduce interference, while multicast subgrouping clusters users within overlapping coverage areas to improve efficiency [8].

The BLASTER (Bandwidth SpLit, User ASsociaTion, and PowEr ContRol) framework proposed by Alam et al., coordinates bandwidth allocation, user association, and power control for TN-NTN integration, reducing terrestrial energy consumption by up to 67% and improving throughput and resource efficiency through multicast subgrouping [8].

Network slicing, enabled by SDN and NFV, creates virtual network segments for specific services [19]. Techniques combining multigroup precoding and resource allocation serve multiple UE groups via terrestrial or satellite base stations in different time slots, reducing interference [8].

Efficient spectrum use can be achieved through normal pairing, where NTN and TN share the same uplink (UL) and downlink (DL) spectrums, and reverse pairing, which swaps TN DL with NTN UL and TN UL with NTN DL [20].

Effective interference management techniques include power control, adaptive beamforming, frequency pattern reuse, bandwidth allocation, coordinated scheduling, and multiple access design [20]. These methods enable optimal radio resource sharing by using transmission paths with optimal bandwidth and signal strength through strategic antenna placement and power level control [18]. Additionally, integrating communication and sensing capabilities further optimizes spectrum efficiency in 6G NTN–TN networks [20].

Load balancing distributes resources to maintain performance under dynamic network conditions [18]. Integrated systems face interference at inter-beam, inter-satellite, and TN-NTN levels, especially in LEO-integrated terrestrial networks (LITNets). Effective mobility management uses handover strategies such as closest-satellite selection, maximum-visibility criteria, and SINR-based thresholds [16].

2.4.4 RRM Performance Metrics

RRM performance is evaluated using metrics such as spectrum efficiency, energy efficiency, load balancing, fairness, and intra- and inter-tier interference [21].

2.5 Conclusion

This chapter has provided a comprehensive technical overview of the components, challenges, and strategies inherent in the integration of terrestrial and non-terrestrial networks. It began by establishing the complementary relationship between TNs, which offer high-capacity yet geographically limited coverage, and NTNs, which provide the wide coverage necessary for global, seamless connectivity. To address these issues, the chapter examined the important role of Radio Resource Management (RRM). Building on this technical foundation, the next chapter reviews existing pricing schemes used in terrestrial and non-terrestrial networks.

Chapter 3

Literature Review on Existing Pricing Schemes

This chapter presents a review of existing pricing schemes used in terrestrial and non-terrestrial networks

3.1 Review of Terrestrial Network (TN) Pricing Schemes

In LTE networks, pricing is either static or dynamic. Static pricing applies a fixed fee irrespective of network conditions, while dynamic pricing adjusts costs based on network load and user demand. Service differentiation enhances the usability of dynamic pricing through parameters such as speed, bandwidth, and priority levels, allowing users to select plans matching their QoS requirements [22].

Mir and Nuaymi proposed a Subscriber Class-based Pricing (PSCP), dividing users into Gold, Silver, and Bronze tiers with per-PRB rates that increase during congestion. Compared with Network Load-based Pricing (NLP), QoS Profile and Bid-based Pricing (QPBP), Traffic Differentiated Pricing (TDP), Flat-Rate, and Fixed PRB models, PSCP improved multi-tier differentiation, dynamic congestion management, utilisation, and operator revenue, while maintaining access for lower-tier users at higher costs. [22].

Fu et al. proposed a two-level Stackelberg game for bandwidth allocation in HetNets, where operators set prices to maximise revenue, and users purchase bandwidth to maximise utility. To capture the suitability of networks for specific traffic types, the Match-

Degree was computed using Grey Relational Analysis and incorporated into users' utility functions, ensuring higher utility from networks better aligned with their traffic needs. The scheme quickly reaches equilibrium, improves user utility, and helps the operator to identify revenue-maximising prices [23].

Zhang et al. and Kang et al. also employed two-stage Stackelberg games to model the ISP-MU interactions. Zhang et al. proposed a uniform pricing scheme where an ISP sets a single access price and mobile users adjust demand to maximise the logarithmic utility. The Lagrange multiplier, representing the marginal utility, increases with user numbers, with the optimal price rising until marginal utility exceeds five [24]. In contrast, Kang et al. proposed a differentiated pricing scheme where an MNO tailors prices to users' QoS preferences and reward sensitivities, improving profit extraction and overall revenue [25].

Chen and Krishnamachari proposed a differential pricing scheme for 5G slices, grouping customers into latency and bandwidth classes, with uniform prices within each class. Each customer class has utility functions with different gain coefficients following normal distributions. Using a Drift-Plus-Penalty (DPP) algorithm for dynamic resource allocation, the model achieves efficiency comparable to complex auction-based mechanisms. Latency slices, being more profitable, command higher prices and attract more resources, achieving up to 86% of the maximum theoretical profit compared to 74% under uniform pricing [26].

Ndikumana et al. introduced a Vickrey-Clarke-Groves (VCG) auction-based pricing scheme to allocate virtualised bandwidth and caching resources between Infrastructure Providers (InPs) and Mobile Virtual Network Operators (MVNOs). InPs set reservation prices, while MVNOs submit bids specifying resource demands. Winners pay based on their impact on others' welfare. The scheme maximises social welfare, incentivises truthful bidding, and ensures individual rationality, while balancing costs and benefits, reducing operational complexity. [27].

Kumar et al. analysed pricing strategies for 5G networks that support multi-operator network sharing, focusing on profitability for InPs and MNOs. Using Nash equilibrium analysis, they compared three strategies within 5G neutral host networks (NHNs) enabled by network slicing: the Shapley Value Approach, which fairly allocates gains and costs but shifts risk to MNOs when subscriber numbers are low; Bargaining Games, involving per-user revenue sharing with higher risk for InPs; and Dynamic Pricing, which adjusts prices to market conditions, sharing costs, revenue, and risk between InPs and MNOs. Dynamic pricing delivered the highest payoff for both InPs and MNOs when subscribers exceeded 200, while Shapley value favoured InPs when subscribers are below 200, while

MNOs benefited when subscribers exceeded 280 [28].

Zhu et al. reviewed the application of game theory in network pricing, focusing on dynamic, cloud computing, and two-sided pricing. Dynamic pricing adjusts prices based on network demand and resource availability; cloud computing prices to optimise resource utilisation and latency; and two-sided pricing balances platform user groups to maximise revenue and market competitiveness [29].

3.2 Review of Non-Terrestrial Network (NTN) Pricing Schemes

Li et al. proposed a dynamic bargaining-based spectrum pricing mechanism between satellite and terrestrial network operators. The satellite network operator adjusts prices over multiple rounds, based on buyer utility and time discount factors, reaching a unique Nash Equilibrium in each round [30].

In a subsequent study, Li et al. introduced a Hotelling-model-based differential pricing scheme for multibeam satellite systems, dividing spectrum into quality-based channel. An iterative pricing algorithm was developed to reach a Nash equilibrium, ensuring stable allocation while balancing operator profits and user satisfaction. The spectrum pricing rises with spectrum quality and varies with user preference distributions, but excessive prices reduces demand and profits [31].

Li et al. proposed a dynamic game-based spectrum pricing scheme for 6G satellite networks, where non-LEO (NLEO) satellites have priority, and LEO satellites transmit opportunistically, shutting down in NLEO coverage to avoid interference. Service price depends on demand, latency, and allocation, solved through Bellman programming and Pontryagin's maximum principle, achieving open-loop Nash equilibria [32].

Akiyemi et al. proposed the Price-Restriction UAV-based System (PRUAV), which reduced infrastructure costs by optimising UAV deployment patterns, antenna configuration, and positioning. PRUAV integrated multi-mode antennas and adaptive positioning, achieving up to 32.5% cost reduction and 30.5% lower subscriber costs, with further savings through resource sharing [7].

Zhang et al.proposed a dynamic pricing strategy for LEO satellite IoT networks, ensuring revenue maximisation and fairness between two priority device classes. A Stackelberg-game-based price adjustment showed a 2:1 weight ratio generates higher operator revenue than 3:1, suggesting moderate service differentiation is most profitable [33].

Li et al. proposed an auction-based dynamic pricing scheme for LEO satellites, allocating bandwidth through competitive user bids. Users specify bandwidth, service duration, and delay penalties, while marginal pricing adjusts rates in real time, starting at a base rate and increasing exponentially as capacity limits are approached, improving resource utilisation and mitigating congestion[11].

The independent evolution of terrestrial and non-terrestrial pricing schemes highlights the need for unified approaches to manage resources across integrated networks.

3.3 Existing Work on Unified Pricing Scheme

Although pricing models for terrestrial networks (TN) and non-terrestrial networks (NTN) have been widely studied separately, research on unified pricing strategies remains limited. Such schemes are essential in ensuring seamless user experience, efficient spectrum utilisation, and fair cost distribution in integrated terrestrial and non-terrestrial networks.

Deng et al. proposed a Stackelberg game-based pricing scheme for data offloading in ultra-dense LEO satellite-terrestrial networks. The Satellite Operator (SO) sets prices for LEO-based small cells, and the Traditional Operator (TO) offloads users to maximise revenue. The algorithm converges to a Stackelberg Equilibrium, improving social welfare over centralised methods [34].

Shang et al. introduced a Nash equilibrium-based spectrum allocation framework for satellite–terrestrial network. The model defined separate utility functions for spectrum owners and tenants, with prices iteratively adjusted to maximise revenue while ensuring efficient spectrum use [35]. Although effective in balancing resource allocation, this framework primarily addresses spectrum-level and does not fully address service-level pricing across TN-NTN environments.

Zhang et al. proposed a two-stage Stackelberg pricing game for mode selection and dynamic pricing in the Ultra Dense LEO Integrated Satellite-Terrestrial Network (ULISTN). The network operator sets optimal access prices for cellular and satellite access, while users respond by selecting their communication mode based on these prices. The evolutionary game converges quickly, but may oscillate with large variation factors. The operator's payoff increases with user density, with prices adjusted to shift some traffic to satellites when terrestrial networks are congested. Terrestrial access provides higher rates under light load, but degrades rapidly with higher user density, whereas satellite access remains stable. The scheme outperforms single-mode and random access approaches,by improving throughput and balance [36].

Zhang et al. later proposed the cybertwin-assisted Joint Mode Selection and Dynamic Pricing (JMSDP) scheme, where digital twins of physical entities facilitate decision-making. The scheme applies a two-stage game-theoretic model. In the first stage, a Stackelberg game enables the operator to set optimal access prices, thereby maximizing network throughput. In the second stage, an evolutionary game allows IoT users to select their communication mode based on access prices and transmission rates using replicator dynamics. The framework includes an operator cybertwin (O-CT) for network management and IoT cybertwins (IoT-CTs) representing user strategies. The JMSDP scheme achieved up to 167% higher transmission rates, and lower delays up to 117.61% compared to baseline methods such as random access (RA), max rate access (MRA) and swap matching algorithms (SMA) [37].

Qi et al. proposed a dynamic pricing scheme for the integrated satellite-terrestrial network (ISTN), where users access either satellite (Ka-band) or a relay station (RS) (C-band). To efficiently manage application server resources, the scheme encourages users to avoid peak usage periods. The server's operation time is divided into slots, with prices set according to three rules: (1) later slots are cheaper, (2) slots with higher computational demand are costlier, and (3) slots with limited computing power are priced higher. The total user expense combines uplink energy costs and server slot prices. Low terrestrial uplink bandwidth forces users to rely on satellites despite higher energy consumption, while sufficient bandwidth favours terrestrial access, which is cheaper but more sensitive to both congestion and location [1].

3.4 Comparative Analysis of Pricing Schemes

This section provides a comparative analysis of the pricing schemes reviewed in the previous sections.

3.4.1 Classification of Pricing Approaches

The reviewed pricing schemes can be classified into several categories based on their underlying mechanisms:

Game-theoretic approaches model operator-user intearactions, effectively managing competition and information asymmetry but involves high computational complexity. Non-cooperative games model competition among Mobile Network Operators (MNOs), where the Nash equilibrium represents stable pricing or spectrum allocation decisions. Stackelberg games extend this by adding leader-follower dynamics suitable for sequential resource management [21].

Auction-based schemes allocate resources through competitive bidding, promoting efficiency and, in some cases, truthful bidding. Ndikumana et al. [27] employ a VCG auction, while Li et al. [11] propose a dynamic auction, both aiming to Maximise social welfare but at the cost of signaling overhead and user complexity. Vickrey and VCG auctions promote truthful bidding, while combinatorial auctions allow bidding for bundles of heterogeneous resources but introduce NP-hard winner determination problems. Ascending clock auctions are simple but not fully truthful. Double auctions balance buyers' and sellers' bids for iterative spectrum allocation [21].

Dynamic pricing schemes adapt to network conditions and user demand but require real-time monitoring. Examples include the PSCP scheme by Mir et al. [22], the differential pricing approach by Chen and Krishnamachari [26], and the bargaining-based mechanism by Li et al. [30].

Utility-based schemes aim to balance user satisfaction and operator revenue. Zhang et al. [33] and Qi et al. [1] apply such schemes in LEO IoT and ISTN, respectively, focusing on user utility maximisation with fairness. Beyond game-theoretic methods, other pricing mechanisms include tiered pricing, Network Utility Maximization (NUM), and Paris Metro Pricing (PMP). Tiered pricing deters heavy usage through higher costs, NUM employs convex Optimisation to Maximise net utility under capacity limits, and

PMP differentiates services by QoS through pricing [21].

3.4.2 Performance Comparison

Table 3.1 provides a comparison analysis of schemes across network types, pricing strategies, goals, performance metrics, and limitations.

Table 3.1: Comparative Analysis of Pricing Schemes (Part 1: TN and NTN)

Authors	**Ref**	**Pricing Strategy**	**Optimisation Goal**	**Performance Metrics Used**	**Limitations of the Scheme**
Terrestrial Networks (TN)					
Mir and Nuaymi	[22]	Dynamic	Maximise operator revenue while ensuring user QoS	Number of PRBs, Operator revenue, Monthly user cost	Assumes fixed operator parameters, limiting adaptability
Fu et al.	[23]	Stackelberg Game	Maximise user utility and operator revenue	Total bandwidth, Price, Average match-degree, Revenue	Ignores inter-RAT interference; requires multiple iterations for convergence; assumes users support only one traffic category
Zhang	[24]	Stackelberg Game	Maximise operator revenue	Number of mobile users, Lagrange multiplier, Network service price	No discussion of fairness or scalability under varying traffic conditions
Kang	[25]	Stackelberg Game	Maximise MNO revenue and user utility	Reward value, Network capacity, Revenue, Service price	Assumes uniform user preference distribution; lacks comparison with alternative schemes
Chen and Krishnamachari	[26]	Differential	Maximise operator profit	Bandwidth sold, Price, Resources per slice, Profit, Time	No performance benchmark against existing pricing models
Ndikumana et al.	[27]	VCG Auction	Maximise social welfare	Price, Social welfare, Bandwidth, Profit, Revenue of InP, Caching payment	NP-hard problem; assumes MVNO resource demand is known a priori; no comparison with other allocation approaches
Non-Terrestrial Networks (NTN)					
Li et al.	[30]	Bargaining	Maximise satellite operator profit	Spectrum price, Actual and optimal utility	Lacks comparative evaluation with baseline pricing models
Li et al.	[32]	Dynamic	Maximise satellite operator revenue	Resource allocation and pricing strategy	No comparison with other allocation or pricing mechanisms
Li et al.	[31]	Differential	Maximise satellite profit	Spectrum price	Considers only uplink transmission; ignores cross-network interference

Table 3.2: Comparative Analysis of Pricing Schemes (Part 2: Integrated Networks)

Authors	**Ref**	**Pricing Strategy**	**Optimisation Goal**	**Performance Metrics Used**	**Limitations of the Scheme**
Akinyemi et al.	[7]	PRUAV	Minimize end-user equipment acquisition cost	System cost, Subscriber count, PPDE, Angular resolution	Does not account for operational costs or network dynamics
Zhang et al.	[33]	Dynamic	Maximise operator revenue while ensuring fairness	Active rate, Average delay, Arrival rate, Price	Uses fixed weight ratios; lacks comparison with other schemes
Li et al.	[11]	Auction-based	Maximise social welfare through fair bandwidth allocation	Social welfare, Allocated bandwidth	Critiques Stackelberg models for complexity but does not empirically compare results against them
Integrated Terrestrial and Non-Terrestrial (Unified)					
Zhang et al.	[36]	Stackelberg Game	Maximise operator revenue and user data rate	Average user payoff, User density, Average data rate	Claims superior transmission rates but provides no detailed baseline comparison
Zhang et al.	[37]	Stackelberg Game	Maximise average network throughput	SINR threshold, Outage probability, IoT density, Queue delay, Data generated per IoT user	Requires many iterations to reach stability, making it slow under rapidly changing conditions
Qi et al.	[1]	Dynamic	Minimize total user cost	Bandwidth, Arrival time, User location	Simplifies server load model; single-user decision framework; lacks benchmarking against other schemes
Shang et al.	[35]	Nash Equilibrium	Maximise total spectrum revenue	Preference distribution, Spectrum revenue metrics	No discussion of scalability or impact on user fairness
Deng et al.	[34]	Stackelberg Game	Maximise operator revenue	Unoccupied C-band spectrum, Optimal service price, Number of LEO satellites, Optimal revenue	Uses a simplified interference model and assumes negligible intersatellite interference

3.5 Research Gaps

Based on the comparative analysis presented in the previous sections, several key research gaps have been identified in the current literature on pricing schemes for integrated TN-NTN networks.

A major gap lies in the lack of comprehensive unified pricing schemes that can seamlessly manage resources across both terrestrial and non-terrestrial domains. Although TN and NTN pricing have been widely studied separately, only a few works propose unified approaches, which remain limited in scope. Current unified schemes address specific aspects of integration rather than offering a complete service-level pricing across both domains.

A core motivation for a unified scheme is to eliminate the inefficiency of multiple subscriptions. However, the reviewed unified pricing literature predominantly models the interaction between network operators [30] or presents the user with a choice between distinctly priced access modes [36] [1]. There is a lack of research into pricing frameworks designed from the ground up to support a single subscription, where the underlying network switching is transparent to the user and the pricing reflects the service delivered, not the access technology used.

Many of the sophisticated pricing mechanisms, particularly those based on game theory and auctions, suffer from high computational complexity [24][27][11].

The reviewed literature shows limited integration of artificial intelligence and machine learning techniques in pricing schemes, despite the increasing emphasis on AI-driven network management in 6G systems. Most current approaches rely on traditional Optimisation methods or game-theoretic frameworks without leveraging the adaptive capabilities that AI/ML could provide for dynamic pricing in highly variable TN-NTN environments.

3.6 Conclusion

This chapter examined the pricing schemes used in terrestrial and non-terrestrial networks. TN pricing has evolved toward dynamic and game-theoretic optimising operator revenue and user utility [22][23][26]. In contrast, NTN pricing schemes address satellite mobility, resource constraints, and dynamic coverage, using auction-based and game-theoretic approaches [34][27][11].

Research on unified pricing schemes remains fragmented, focusing mainly on spectrum sharing [30][35] or access mode selection [36][1], without providing a comprehensive framework for the integrated TN-NTN system envisioned for 6G. Key Gaps include the absence of QoS-driven, user-centric pricing schemes to enable a seamless single-subscription experience, scalable to the demands of 6G, and intelligent enough to adapt to highly dynamic environments.

Therefore, there is a clear need for holistic unified pricing algorithms that can efficiently manage the resources of integrated TN-NTN networks.

Chapter 4

Design

4.1 Introduction

Building on the insights from the previous chapter, this chapter presents the design of the network model of the Integrated Terrestrial and Non-Terrestrial Network (ITNTN) and the proposed unified pricing algorithm for efficient resource management.

4.2 Network Model

The network consists of a Terrestrial Network (TN) and a Non-Terrestrial Network (NTN). The TN comprises N cellular base stations (BSs) operating in the C-band, denoted as BS$-i$, where $i = 1, 2, \ldots, N$. Each BS provides coverage within a radius D and supports a maximum capacity of $C_{\text{Ter},i}$, measured in basic bandwidth units (bbu). The NTN includes M Low Earth Orbit (LEO) satellites operating in the Ka-band, denoted as LEO $- j$, where $j = 1, 2, \ldots, M$. Each LEO satellite operates at an orbital altitude H and offers a maximum capacity of $C_{\text{Sat},j}$. The network serves K mobile users with dual-connectivity capability, denoted as U $- k$, where $k = 1, 2, \ldots, K$.

Figure 4.1 illustrates the three-dimensional coordinate system of the ITNTN model. The BSs are positioned on the ground plane at $(b_x, b_y, 0)$, the LEO satellites are located at (s_x, s_y, H), and users are also situated on the ground at $(u_x, u_y, 0)$.

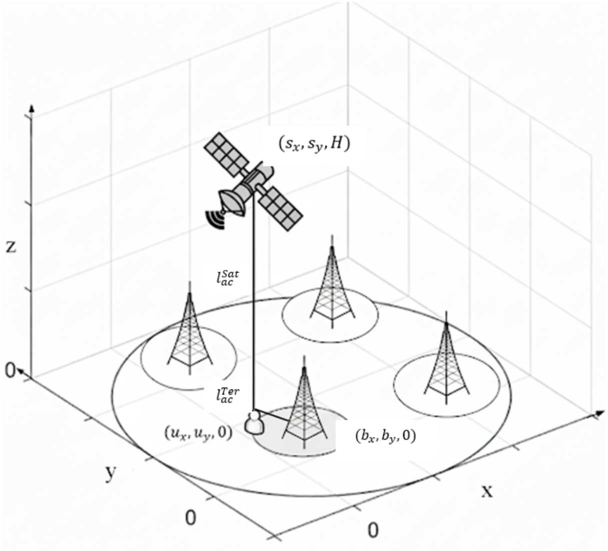

Figure 4.1: Integrated Terrestrial and Non-Terrestrial Network (ITNTN) Model [1]

The BS antenna height is assumed to be negligible ($z = 0$), as it is significantly smaller than the orbital altitude of LEO satellites.

As illustrated in Figure 4.2, within terrestrial coverage (LEO + Cellular), users can connect to either a BS or a LEO satellite, depending on pricing and resource availability. Outside terrestrial coverage (LEO only), users maintain connectivity through LEO satellites only.

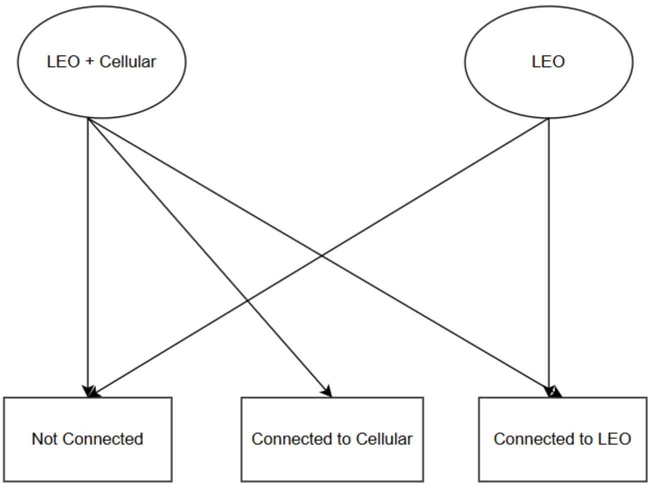

Figure 4.2: User Connectivity Options in ITNTN

4.2.1 Channel Models

Terrestrial Access Channel

The terrestrial access channel experiences multipath effects due to buildings and other obstructions between the user and the BS, resulting in Rayleigh fading [1]. The channel gain G^{Ter} is given by:

$$G^{\text{Ter}} = \frac{|g|^2}{10^{\frac{PL_{\text{dB}}}{10}}} \tag{4.1}$$

where PL_{dB} is the path loss in dB:

$$PL_{\text{dB}} = 52.44 + 20 \log_{10} l_{\text{ac}}^{\text{Ter}} + 20 \log_{10} f_{\text{ac}}^{\text{Ter}} \tag{4.2}$$

Here, $l_{\text{ac}}^{\text{Ter}}$ is the communication distance between the user and the BS (in km), $f_{\text{ac}}^{\text{Ter}}$ is the carrier frequency (C-band) (in MHz), and $|g|^2$ is the squared magnitude of the Rayleigh fading coefficient. The complex fading coefficient g follows complex normal distribution, i.e, $g \sim \mathcal{CN}(0, 1)$ [1].

The communication distance is computed as:

$$l_{\text{ac}}^{\text{Ter}} = \sqrt{(u_x - b_x)^2 + (u_y - b_y)^2} \tag{4.3}$$

Using the Shannon capacity theorem, the achievable transmission rate (in bps) is:

$$R_{\text{tx}}^{\text{Ter}} = W^{\text{Ter}} \log_2 \left(1 + \frac{P_{\text{tx}}^{\text{Ter}} G^{\text{Ter}}}{W^{\text{Ter}} N_0^{\text{Ter}}} \right) \tag{4.4}$$

where $P_{\text{tx}}^{\text{Ter}}$ is the transmission power (in W), W^{Ter} is the channel bandwidth (in Hz), and N_0^{Ter} denotes the noise power spectral density (in W/Hz) [1].

Satellite Access Channel

In contrast to terrestrial channels, satellite channels are dominated by a strong line-of-sight (LoS) between the satellite and the user. While a Rician fading model often provides a more precise representation of this condition [36], this work adopts a simplified distance-based path loss model for simplicity and to focus on the impact of large-scale fading. Satellite access channels experience more severe path loss than their terrestrial counterparts due to the significantly longer transmission distances involved [1].

The channel gain for satellite access G^{Sat} is therefore primarily determined by this distance:

$$G^{\text{Sat}} = (l_{\text{ac}}^{\text{Sat}})^{-\eta} \tag{4.5}$$

where $l_{\text{ac}}^{\text{Sat}}$ is the communication distance between the user and satellite (in km):

$$l_{\text{ac}}^{\text{Sat}} = \sqrt{(u_x - s_x)^2 + (u_y - s_y)^2 + H^2} \tag{4.6}$$

and η is the path loss exponent ($\eta > 0$) [1].

The achievable transmission rate (in bps) is:

$$R_{\text{tx}}^{\text{Sat}} = W^{\text{Sat}} \log_2 \left(1 + \frac{P_{\text{tx}}^{\text{Sat}} G^{\text{Sat}}}{W^{\text{Sat}} N_0^{\text{Sat}}} \right) \tag{4.7}$$

where $P_{\text{tx}}^{\text{Sat}}$ is the transmission power (in W), W^{Sat} is the channel bandwidth (in Hz), and N_0^{Sat} denotes the noise power spectral density (in W/Hz) [1].

4.2.2 Multi-User File Upload Model

The network supports K users, each uploading a file. The file upload for each user is characterised by file size O_k, and allocated bandwidth $b_{k,n}$, which is assumed to remain constant for the duration of the user's connection.

4.2.3 Energy Consumption

Energy consumption is a critical factor for the user, influencing both the device battery life and the overall cost of service. The energy consumed during data transmission is given by:

$$E^n = P_{\text{tx}}^n \cdot T_{\text{tx}}^n \tag{4.8}$$

where P_{tx}^n is the transmission power and T_{tx}^n is the transmission time ($n \in \{\text{Ter}, \text{Sat}\}$) [1].

Here, the transmission time is given by:

$$T_{\text{tx}}^n = \frac{O}{R_{\text{tx}}^n} \tag{4.9}$$

where O is the file size (in bits).

Due to the longer communication distance ($l_{\text{ac}}^{\text{Sat}} \gg l_{\text{ac}}^{\text{Ter}}$), satellite access consumes more energy than terrestrial access [1].

4.2.4 Network Capacity

The total network capacity represents the maximum number of basic bandwidth units (bbu) that can be allocated across all network nodes:

$$C_{\text{Total}} = \sum_{i=1}^{N} C_{\text{Ter},i} + \sum_{j=1}^{M} C_{\text{Sat},j} \tag{4.10}$$

where $C_{\text{Ter},i}$ denotes the capacity of the i-th base station and $C_{\text{Sat},j}$ represents the capacity of the j-th LEO satellite.

When considering a single BS and LEO satellite case, this simplifies to:

$$C_{\text{Total}} = C_{\text{Ter}} + C_{\text{Sat}} \tag{4.11}$$

Each network type $n \in \{\text{Ter}, \text{Sat}\}$ is characterised by the following parameters:

- **Maximum Capacity (C_n):** The total resources available (in bbu).
- **Allocated User Bandwidth ($b_{k,n}$):** The bandwidth resources (in bbu) allocated to user-k when connected to network n.
- **Current Network Load (L_n):** Percentage of capacity utilised, expressed as:

  $$L_n = \frac{\sum_{k \in \mathcal{K}_n} b_{k,n}}{C_n} \tag{4.12}$$

  where $\mathcal{K}_n$ denotes the set of users connected to network n. $\sum_{k \in \mathcal{K}_n} b_{k,n}$ represents total bandwidth allocated to active users.
- **Available Capacity ($C_{n,\text{avail}}$):** Percentage of available resources for new user allocations, computed as:

  $$C_{n,\text{avail}} = 1 - L_n \tag{4.13}$$

As users are admitted to the network and allocated resources, the network load and available capacity are updated as:

$$L_n = L_n + \frac{b_{k,n}}{C_n} \tag{4.14}$$

$$C_{n,\text{avail}} = 1 - L_n \tag{4.15}$$

Bandwidth Reservation

To maintain quality of service (QoS) and ensure user satisfaction, the network implements a threshold-based admission control mechanism. The use of this mechanism allows the system to reserve a portion of capacity to accommodate handoff calls, acknowledging that users are more sensitive to handoff calls (call dropping) than new calls (call blocking) [38].

For each network type n, two key thresholds are defined:

- $t_{m,n}$: Admission threshold for new calls, where $0 < t_{m,n} < C_n$.
- C_n: Maximum network capacity

The reserved bandwidth for network n is:

$$C_n^{\text{res}} = C_n - t_{m,n} \tag{4.16}$$

Admission Control

A new call from user k is admitted to network n if and only if the projected network load does not exceed the predefined admission threshold for new calls:

$$L_n + \frac{b_{k,n}}{C_n} \leq t_{m,n} \tag{4.17}$$

where L_n is the current network load, $b_{k,n}$ is the bandwidth allocated to the new user, and C_n is the total network capacity.

In contrast, a handoff call is admitted from user k if and only if the projected network load does not exceed the maximum network capacity:

$$L_n + \frac{b_{k,n}}{C_n} \leq 1 \tag{4.18}$$

4.3 State Space and Admissible States

4.3.1 State Space

The state space is given by:

$$\Omega = (m_{i,j}, h_{i,j} : i = 1, \ldots, I, j = 1, \ldots, J) \tag{4.19}$$

where $m_{i,j}$ denotes new class-i calls in RAT-j and h_n denotes handoff class-i calls admitted to RAT-j n [38]. Since this work only considers one type of service and two RAT, the state space will be:

$$\Omega = (m_{1,1}, h_{1,1}, m_{1,2}, h_{1,2}) \tag{4.20}$$

4.3.2 Admissible States

The set of admissible states, $\mathcal{S}$, is a subset of Ω satisfying the capacity and threshold constraints:

$$\begin{aligned} \mathcal{S} = \Big\{ \Omega = (m_{i,j}, h_{i,j} : i = 1, \ldots, I, j = 1, \ldots, J) : \\ \sum_{i=1}^{I} (m_{i,j} \cdot \mathrm{b}_i) \leq t_{m_{i,j}} \forall j \wedge \\ \sum_{i=1}^{I} (m_{i,j} + h_{i,j}) \cdot \mathrm{b}_i \leq C_j, \forall j \Big\} \end{aligned} \tag{4.21}$$

where b_i is the bandwidth allocated to class-i calls (in bbu) [38].

4.4 Quality of Service Performance Metrics

The network performance and user satisfaction are evaluated using standard telecommunications Quality of Service (QoS) metrics, namely Call Blocking Probability and Call Dropping

Probability.

4.4.1 Network Load Factor

The network load factor for new class-i calls in RAT-j is given by

$$\rho_{new_{i,j}} = \frac{\lambda_{new_{i,j}}}{\mu_{new_{i,j}}} \tag{4.22}$$

where $\lambda_{new_{i,j}}$ is the arrival rate and $\mu_{new_{i,j}}$ is the departure rate for handoff class-i calls in RAT-j [38]

Similarly for handoff class-i calls in RAT-j [38]:

$$\rho_{han_{i,j}} = \frac{\lambda_{han_{i,j}}}{\mu_{han_{i,j}}} \tag{4.23}$$

4.4.2 Steady State Probability, $P(s)$

The steady-state probability of being in state s ($s \in \mathcal{S}$) is given by:

$$P(s) = \frac{1}{G}\prod_{i=1}^{I}\prod_{j=1}^{J}\frac{(\rho_{\text{new}_{i,j}})^{m_{i,j}}(\rho_{\text{han}_{i,j}})^{h_{i,j}}}{m_{i,j}!\,h_{i,j}!} \tag{4.24}$$

where G is a normalisation constant given by [38]:

$$G = \sum_{s\in S}\prod_{i=1}^{I}\prod_{j=1}^{J}\frac{(\rho_{\text{new}_{i,j}})^{m_{i,j}}(\rho_{\text{han}_{i,j}})^{h_{i,j}}}{m_{i,j}!\,h_{i,j}!} \tag{4.25}$$

4.4.3 New Call Blocking Probability

The new call blocking probability $P_{B_{i,j}}$ represents the probability that a new call to network n is blocked due to insufficient resources to accommodate it. It is given by:

$$P_{B_{i,j}} = \sum_{s\in S_{B_{i,j}}} P(s) \tag{4.26}$$

where $S_{B_{i,j}}$ is the set of blocking states for new class-i calls in RAT-j [38]:

$$S_{B_{i,j}} = \left\{ s \in S : \left(b_i + \sum_{i=1}^{I} m_{i,j} \cdot b_{i,j} > t_{m_{i,j}} \right) \vee \left(b_i + \sum_{i=1}^{I} (m_{i,j} + h_{i,j}) \cdot b_i > C_j \right) \right\} \tag{4.27}$$

4.4.4 Handoff Call Dropping Probability

The call dropping probability $P_{D_{i,j}}$ represents the probability that an ongoing call is dropped during handoff when the total network capacity is reached. It is given by [38]:

$$P_{D_{i,j}} = \sum_{s \in S_{D_{i,j}}} P(s) \tag{4.28}$$

where $S_{D_{i,j}}$ is the set of dropping states for handoff class-i calls in RAT-j [38]:

$$S_{D_{i,j}} = \left\{ s \in S : \left(b_i + \sum_{i=1}^{I} (m_{i,j} + h_{i,j}) \cdot b_i > C_j \right) \right\} \tag{4.29}$$

4.5 Dynamic Pricing Mechanism

4.5.1 Unit Network Price

The unit price for accessing network type n is given by:

$$p_n = \alpha_n + \beta_n \cdot L_n + \frac{\gamma_n}{C_{n,\text{avail}}} \tag{4.30}$$

where α_n is the base price for network n, β_n converts the network load L_n into price, and γ_n converts the available network capacity $C_{n,\text{avail}}$ into price [1].

4.6 Unified Cost Optimisation

4.6.1 Network Selection Decision

The network selection decision for each user is represented by an access strategy matrix $\mathbf{X} = [x_1, x_2]$, where $x_1, x_2 \in \{0, 1\}$ with $x_1 + x_2 = 1$ [1]:

- $x_1 = 1, x_2 = 0$: The user connects to a terrestrial network.
- $x_1 = 0, x_2 = 1$: The user connects to a LEO satellite network.

4.6.2 Network Access Cost

Each user's mobility path consists of K position updates, where the user's position at update k is given by $(u_x^k, u_y^k, 0)$.

Once the network selection is made, the access cost incurred at position update k depends on the pricing of the selected network and bandwidth allocated:

$$C_{k,n}^A = p_n \cdot b_{k,n} \tag{4.31}$$

The access cost vector for both networks is:

$$\mathbf{C}_k^A = \begin{bmatrix} C_{k,\mathrm{Ter}}^A \\ C_{k,\mathrm{Sat}}^A \end{bmatrix} \tag{4.32}$$

4.6.3 Energy Consumption Cost

The energy consumption cost C^E is:

$$\mathbf{C_k^E} = \theta \cdot \begin{bmatrix} E^{\mathrm{Ter}} \\ E^{\mathrm{Sat}} \end{bmatrix} \tag{4.33}$$

where θ is the energy-to-cost conversion factor [1].

4.6.4 Total User Cost

The total cost incurred by a user at position update k is a weighted sum of network access cost $C^A_{n,k}$ and energy consumption cost $C^E_{n,k}$, where $n \in \{\mathrm{Ter}, \mathrm{Sat}\}$:

$$C_k^T = \mathbf{X}^\mathbf{T}(\xi_a \cdot \mathbf{C}_k^A + \xi_b \cdot \mathbf{C}_\mathbf{k}^\mathbf{E}) \tag{4.34}$$

The total user cost accumulated over K position updates is:

$$C^T = \sum_{k=1}^{K} C_k^T \tag{4.35}$$

4.6.5 Network Operator Revenue

The total revenue generated by the network operator from all users over the service period is:

$$R_{\text{total}} = \sum_{u=1}^{U} C_u^T \tag{4.36}$$

where U is the total number of users served during the period.

4.6.6 Optimisation Objective

The network selection decision aims to minimise the total user cost at each position update k by optimally choosing between terrestrial and satellite access. The optimisation objective is formulated as:

$$\min_{\mathbf{X}} C_k^T \tag{4.37}$$

Chapter 5

Simulation Results and Discussions

This chapter presents the results obtained through a series of numerical simulations conducted in MATLAB to evaluate the performance of the proposed unified pricing algorithm. The metrics used include the network operator's revenue, call blocking probability, and call dropping probability. The simulation models a single terrestrial base station (BS) and one LEO satellite, each with distinct capacity and cost characteristics. The MATLAB code used to produce these results can be found in Appendix C.

5.1 Simulation Parameters

Table 5.1 presents the parameters used to conduct the simulations.

Parameter	**Symbol**	**Value**
LEO Satellite Altitude	H	450 km [1]
BS Coverage Radius	D	2 km [1]
Carrier Frequency (C-band)	f_{ac}^{Ter}	6 GHz [1]
Channel Bandwidth (Ter, Sat)	$W^{\text{Ter}}, W^{\text{Sat}}$	5 MHz, 30 MHz [1]
Noise (C-band, Ka-band)	$N^{\text{Ter}}, N^{\text{Sat}}$	0.8, 0.8 [1]
Path Loss Exponent	η	2.2 [1]
Base Prices (Ter, Sat)	$\alpha_{\text{Ter}}, \alpha_{\text{Sat}}$	0.5, 0.85
Load-to-Cost Factor (Ter, Sat)	$\beta_{\text{Ter}}, \beta_{\text{Sat}}$	1.5, 1.2
Capacity-to-Cost Factor (Ter, Sat)	$\gamma_{\text{Ter}}, \gamma_{\text{Sat}}$	0.05, 0.03
Energy-to-Cost Factor	θ	1.5 [1]
Total Cost Weights	ξ_a, ξ_b	0.5, 0.5 [1]
Max Network Capacity (Ter, Sat)	$C_{\text{Ter}}, C_{\text{Sat}}$	45, 50
Admission Threshold (Ter, Sat)	$t_{m,\text{Ter}}, t_{m,\text{Sat}}$	35, 30
Departure Rate – New Calls (Ter, Sat)	$\mu_{m,\text{Ter}}, \mu_{m,\text{Sat}}$	1, 1
Departure Rate – Handoff (Ter, Sat)	$\mu_{h,\text{Ter}}, \mu_{h,\text{Sat}}$	0.5, 0.5
File Size	O	1 Mbit

Table 5.1: Proposed Simulation Parameters

5.2 Total User Cost Evaluation

This section evaluates how the user's total cost varies as a function of the user's position relative to the terrestrial BS and satellite coverage. The total user cost, defined in Equation (4.34), is a weighted sum of two key factors: the network access cost and the energy-consumption cost.

To explore the sensitivity of the total cost to user priorities, three configurations of the cost weights were considered:

1. **Balanced Weights:** $\xi_a = 0.5$, $\xi_b = 0.5$
2. **Network Access Cost (Dominant):** $\xi_a = 0.7$, $\xi_b = 0.3$
3. **Energy Consumption Cost (Dominant):** $\xi_a = 0.3$, $\xi_b = 0.7$

Figure 5.1 illustrates the cost dynamics within the terrestrial network.

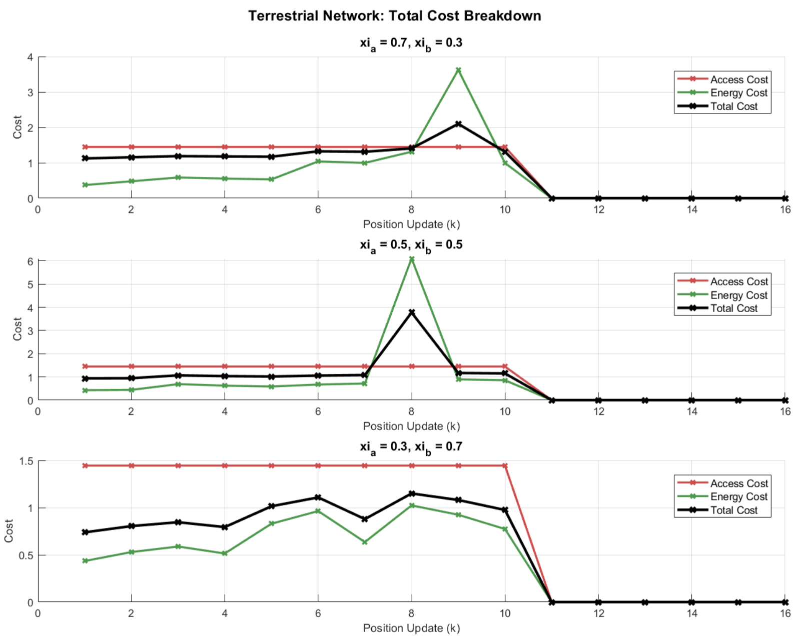

Figure 5.1: Total Cost Breakdown for Terrestrial Network

Results Interpretation:
The network access cost remains constant, as it is determined by the network load rather than the user's distance from the BS. In contrast, the energy consumption cost shows a clear dependency on distance, increasing as the user moves away from the BS. This is a direct consequence of the greater transmission rate, R_{tx}^{Ter}, required to maintain the connection.

At position update $k = 11$, he user moves beyond the BS coverage radius, causing both cost components to drop to zero as the connection is handed over to the satellite network.

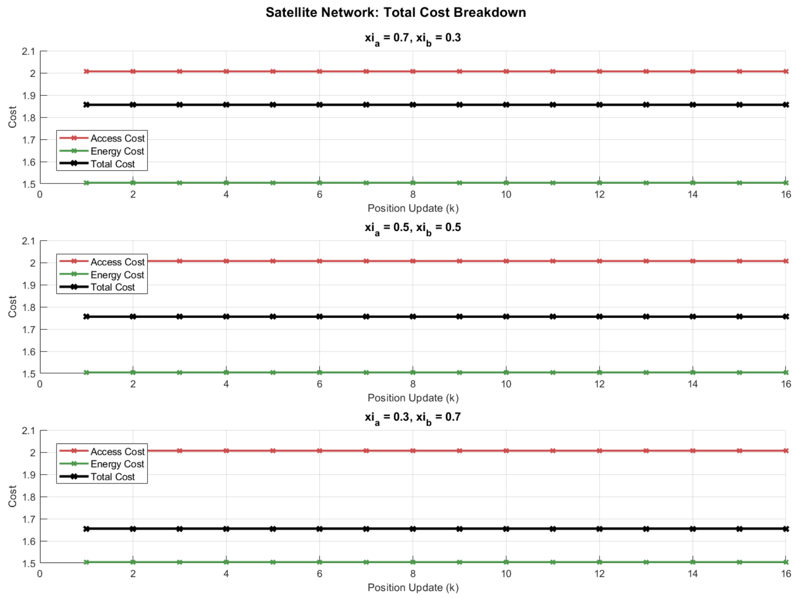

Figure 5.2: Total Cost Breakdown for Satellite Network

Results Interpretation:
Conversely, as shown in Figure 5.2, both the network access and energy consumption costs for the satellite network remain nearly constant regardless of the user's mobility. This stability is due to the high orbital altitude of the LEO satellite, which renders the user's horizontal displacement negligible. As a result, the total communication distance, and therefore the required transmission rate, experiences negligible variation, leading to a consistent cost profile across all position updates.

Effect of Cost Weights:
The choice of cost weights (ξ_a, ξ_b) significantly influences the total user cost. When ξ_a is dominant, the total cost is primarily determined by the constant network access pricing, resulting in a relatively flat cost curve. Conversely, when ξ_b is dominant, the total cost curve shows a steeper gradient as the communication distance increases. The balanced weight configuration provides an intermediate scenario where both network access and

energy consumption costs contribute equally.

5.3 Network Selection and Total User Cost Evaluation

This section evaluates the core functionality of the optimisation objective defined in Chapter 4: its ability to select the most cost-effective network for the user as they move between different coverage areas. The evaluation focuses on how the user's position relative to the terrestrial base station influences the decision between terrestrial and satellite network access, and how this dynamic selection minimises overall total user costs.

Figure 5.3 illustrates the evolution of both total user cost and the corresponding network selection over position updates. The upper subplot shows the network selection outcome, and the lower subplot presents the total user cost associated with each cost. The terrestrial and satellite costs are plotted individually, along with the selected total cost corresponding to the network chosen at each position update.

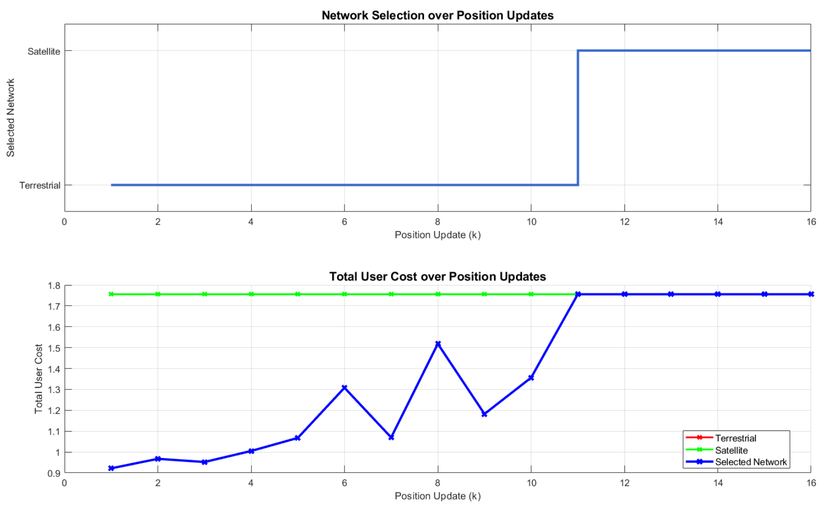

Figure 5.3: Network Selection and Total Cost over Position Updates

Results Interpretation:
Initially, when the user is close to the BS, the terrestrial network's low energy requirement makes it the clear optimal choice. As the user moves towards the edge of the terrestrial coverage area, its associated energy cost rises steadily. The algorithm continuously compares this rising terrestrial cost against the stable, although higher, cost of satellite access. At position update $k = 11$, the algorithm triggers a handover. This seamless transition ensures a continuous connection for the user.

5.4 Network Operator Revenue Evaluation

This section examines the network operator's revenue variation as users connect between the terrestrial and satellite networks. Twenty users were simulated - even-numbered users (User 2, 4, 6, ..., 20) moved from within terrestrial coverage to outside the coverage area, while odd-numbered users (User 1, 3, 5, ..., 19) moved from outside to within terrestrial coverage.

Figures 5.4 and 5.5 illustrate how the network operator's revenue changes over position updates and the cumulative revenue, respectively

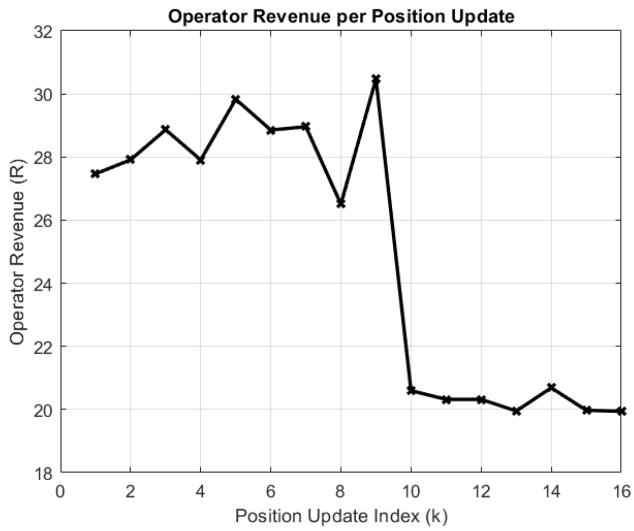

Figure 5.4: Network Operator Revenue

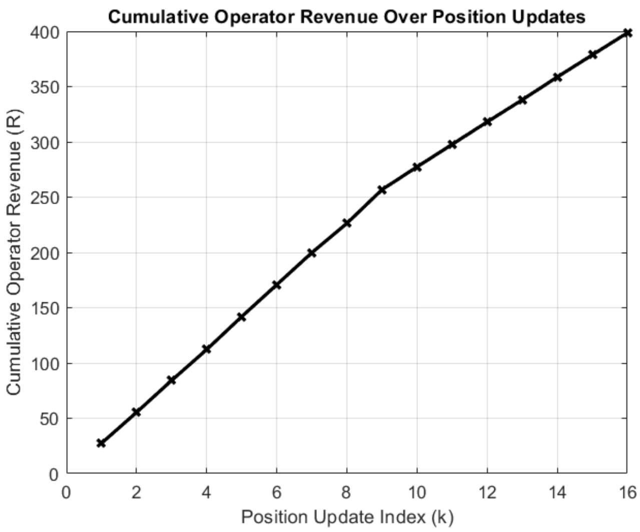

Figure 5.5: Cumulative Network Operator Revenue

Results Interpretation:
The network operator's revenue fluctuates with user mobility as users switch between terrestrial and satellite networks. When more users are within BS coverage, revenue from terrestrial access dominates due to lower pricing. Conversely, when more users rely on satellite access, revenue temporarily increases due to higher pricing, but later stablises as the network capacity constraint is approached.

5.5 Quality of Service (QoS) Performance Evaluation

This section presents how the QoS performance of the proposed pricing algorithm was assessed in terms of call blocking probability and call dropping probability. The call blocking probability quantifies the likelihood that a new call is blocked due to insufficient capacity, while the dropping probability reflects the likelihood that an ongoing call is dropped during handoff.

5.5.1 Effect of Arrival Rate

Figure 5.6 illustrates the effect of arrival rate on both call blocking and call dropping probabilities.

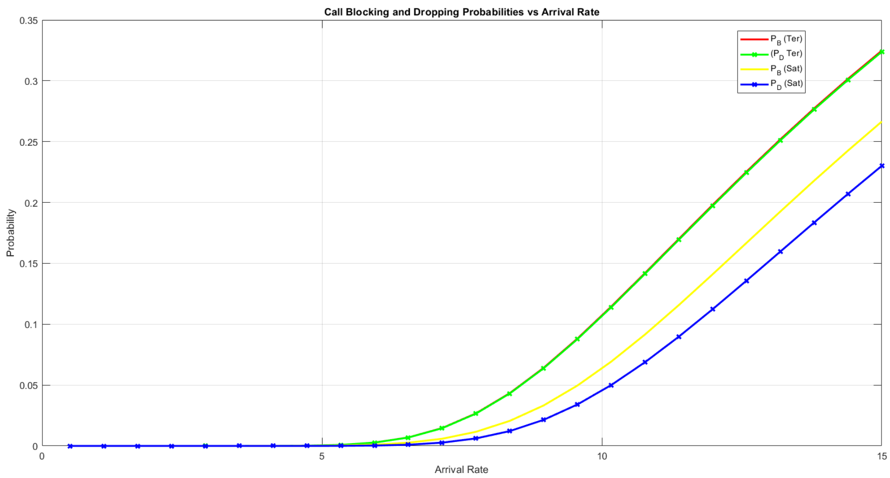

Figure 5.6: Call Blocking and Call Dropping Probabilities Under Varying Arrival Rates

5.5.2 New Call Blocking Probability and Handoff Call Dropping Probability over Position Updates

Figure 5.7 illustrates the call blocking and call dropping probabilities over position updat.

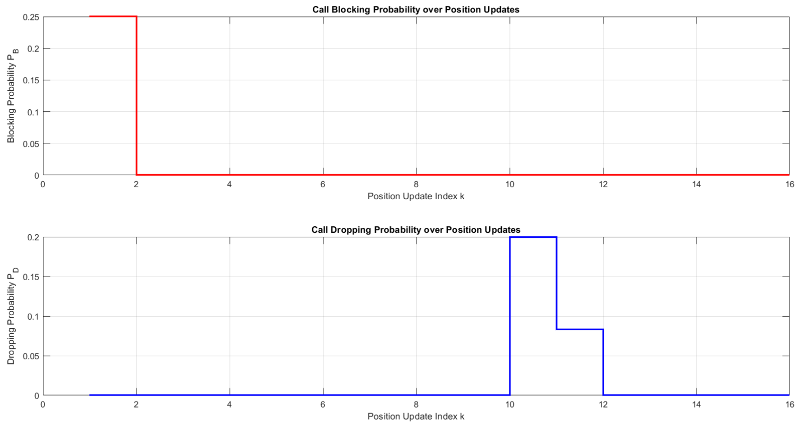

Figure 5.7: Call Blocking Probability and Call Dropping Probability over Position Updates

At the initial position update ($k = 0$), all 20 users attempt to establish new calls. The admission control logic evaluates each call based on the projected network load as defined in Equation (4.14). New calls are admitted if their addition does not cause the projected load to exceed the admission threshold, $t_{m,n}$. After each successful new call admission, the network load and available capacity are updated accordingly. The admission control logic governed by the threshold $t_{m,n}$ immediately blocks 5 of these calls, resulting in an initial call blocking probability of 25%.

Throughout the remainder of the simulation, as users move and trigger handoffs, the call dropping probability remains at zero until a high-congestion scenario forces a dropped call.

Chapter 6

Conclusions

The objective of this project design and implement a unified pricing algorithm for efficient resource management in an integrated terrestrial and non-terrestrial network.

A comprehensive literature review, presented in Chapter 3, examined existing pricing schemes in both terrestrial and non-terrestrial networks and identified key research gaps.

Based on the results and discussions in Chapter 5, the following conclusions have been drawn:

The proposed unified pricing algorithm outlined in Chapter 4 successfully enables dynamic network selection, allowing users to seamlessly switch between terrestrial and satellite networks to minimise their total cost, which is a weighted sum of network access and energy consumption costs.

The weighting between access and energy costs significantly influences total user cost, allowing for the prioritisation of either affordability or energy efficiency, or a balance of the two.

The dynamic pricing algorithm efficiently manages network resources, as reflected in the analysis of call blocking and dropping probabilities under varying network loads. The admission control mechanism successfully reserves capacity for handoff calls, thereby improving the Quality of Service (QoS) for mobile users.

Chapter 7

Recommendations

Based on the conclusions presented in Chapter **??**, the following recommendations are proposed:

Expand the Network Model: The current network model considers a single type of call service and a simplified network with one base station and one LEO satellite. Future work could extend this to incorporate multiple service types, each with distinct Quality of Service (QoS) requirements. Additionally. A more complex network model featuring multiple base stations and LEO satellites could provide a more realistic evaluation of the network performance.

Investigate Different Pricing Schemes: This work focuses on a specific dynamic pricing algorithm adapted from Qi et al. [1]). Future work could perform a comparative analysis of different pricing schemes, including game-theoretic or auction-based schemes, within a unified TN-NTN environment. Such analysis could provide valuable insights into the most effective approaches for different network scenarios.

Integrate Machine Learning and Artificial Intelligence: Future work could explore the use of Artificial Intelligence (AI) and Machine Learning (ML) techniques to develop more adaptive and predictive pricing schemes. These schemes could learn from real-time network traffic patterns and user behaviour to dynamically optimise resource allocation and pricing decisions, improving efficiency and user satisfaction.

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Appendix A

Graduate Attribute Tracking Form

GA	Requirement	Evidence and report section
1	Problem-solving	The focus of this project is on the inefficiencies caused by independent pricing in terrestrial and non-terrestrial networks, which lead to multiple subscriptions and bills for users, reducing the overall experience. To address this, a detailed literature review was conducted, examining technical aspects of both network types and the resource management techniques employed (Chapter 2). Existing pricing schemes for TN and NTN were analyzed to identify limitations of independent pricing models, along with a review of integrated TN-NTN pricing schemes to highlight gaps (Chapter 3). Based on these findings, a unified pricing algorithm and network model were designed (Chapter 4), and MATLAB simulations were conducted to assess its performance (Chapter 5).
4	Investigations, experiments, and data analysis	MATLAB simulations were used to evaluate the unified pricing algorithm, measuring metrics such as call blocking probability, call dropping probability, and operator revenue (Chapter 5).
5	Use of engineering tools	MATLAB was employed to implement and simulate the unified pricing scheme under various network conditions (Chapter 5).
6	Professional and technical communication	The report follows academic writing standards and proper referencing conventions, ensuring that all external sources are correctly credited.
8	Individual work	This work is entirely my own. I independently reviewed the literature, designed and implemented the unified pricing algorithm. I have attended weekly research meetings to discuss progress. (Chapters 1 - 6).
9	Independent learning ability	I conducted the literature review and implemented the proposed unified pricing algorithm independently, following proper referencing practices (Chapters 1 - 6).

Appendix B

Ethics Clearance

UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

PRE-SCREENING QUESTIONNAIRE OUTCOME LETTER

STU-EBE-2025-PSQ001900
2025/08/27

Dear Kwanele Mabanga,

Your Ethics pre-screening questionnaire (PSQ) has been evaluated by your departmental ethics representative. Based on the information supplied in your PSQ, it has been determined that you do not need to make a full ethics application for the research project in question.

You may proceed with your research project titled:

Design of a Pricing Algorithm for Efficient Resource Management in an Integrated Terrestrial and Non-Terrestrial Network

Please note that should aspect(s) of your current project change, you should submit a new PSQ in order to determine whether the changed aspects increase the ethical risks of your project. It may be the case that project changes could require a full ethics application and review process.

Regards,

Faculty Research Ethics Committee

Appendix C

Code Used for Simulation

```
%% ver4
% ITNTN Simulation
% Multi-User Integrated Terrestrial and Non-Terrestrial Network

%% Clears workspace, command window and closes all figures
clear; clc; close all;

%% Simulation Parameters
% Altitude of LEO satellite (m)
H = 450 * 10^3;
% Coordinate of LEO satellite (m)
s_x = 0; s_y = 0; s_z = H;

% Coverage radius of BS (m)
D = 2000;
% Coordinates of BS (m)
b_x = 0; b_y = 0; b_z = 0;

% Carrier frequency (C-band) (Hz)
f_Ter_ac = 6 * 10^9;

% Channel Bandwidths (Hz)
W_Ter = 5 * 10^6; W_Sat = 30 * 10^6;

% Transmission Powers (dBm to W)
P_Ter_tx = 10^((42-30)/10); % 42 dBm to 15.85 W
P_Sat_tx = 10^((60-30)/10); % 60 dBm  to 1000 W
```

```

% Noise Figures (dB)
N_Ter = 0.8; N_Sat = 0.8;
% Noise Spectral Density (W/Hz)
% N0 = kB * T0 * NF where kB = 1.38 * 10^-23 J/K and T0 = 290K
N0_Ter = 1.38e-23 * 290 * 10^(N_Ter/10);
N0_Sat = 1.38e-23 * 290 * 10^(N_Sat/10);

% Path loss exponent
eta = 2.2;

% Base prices
alpha_Ter = 0.5; alpha_Sat = 0.85;

% Load sensitivity factors
beta_Ter = 1.5; beta_Sat = 1.2;

% Available capacity sensitivity factors
gamma_Ter = 0.05; gamma_Sat = 0.03;

% Energy to-cost conversion factor
theta = 1.5;

% Total cost weights
% C_T = xi_a * C_A + xi_b * C_E
% xi_a + xi_b = 1
% Equal weighting between network access and energy consumption costs
xi_a = 0.5; xi_b = 0.5;

%% Network Capacity
% Maximum capacity (bbu)
C_Ter = 45; C_Sat = 50;

% Admission thresholds for new calls (bbu)
t_m_Ter = 35; t_m_Sat = 30;

% Reserves capacity for handoff calls (pioritises handoff calls)
% Reserved capacity = Maximum capacity - Admission threshold

fprintf('Network Capacity:\n');
```

```
fprintf('  Terrestrial: C = %d bbu, t_m = %d bbu\n', C_Ter, t_m_Ter);
fprintf('  Satellite:   C = %d bbu, t_m = %d bbu\n', C_Sat, t_m_Sat);

%% Initial Network State
% Initial programmatic loads (bbu)
L_Ter = 5; L_Sat = 5;

% Available capacity (%)
C_Ter_avail = 1 - (L_Ter / C_Ter); C_Sat_avail = 1 - (L_Sat / C_Sat);

fprintf('\nInitial Network State:\n');
fprintf('  Terrestrial: Network Load = %.2f%%, Available Capacity = %.2f%%\n', ...
    (L_Ter/C_Ter) * 100, C_Ter_avail * 100);
fprintf('  Satellite:   Network Load = %.2f%%, Available Capacity = %.2f%%\n', ...
    (L_Sat/C_Sat) * 100, C_Sat_avail * 100);

%% Multi-User Configuration
% Number of users
U = 20;
% Number of position updates
K = 16;

% File size (bits)
file_size = 1e6;
% Allocated bandwidth per call (bbu)
b_user = 2;

% Assigns same file size and allocated bandwidth to all users
O_k = file_size * ones(1, U); b_k = b_user * ones(1, U);

%% User Mobility Paths
user_paths = cell(U, 1);
for u = 1:U
    if mod(u, 2) == 1
        % Odd users: Start within BS coverage, move outward
        ux_path = linspace(0, 3000, K);
```

```
        uy_path = (u - 1) * 50 + 200;
    else
        % Even users: Start outside BS coverage, move inward
        ux_path = linspace(3000, 0, K);
        uy_path = (u - 1) * 50 + 250;
    end
    user_paths{u} = [ux_path; uy_path * ones(1,K); zeros(1,K)];
end

%% QoS Parameters
% New call arrival rates
lambda_m_Ter = 2.0; lambda_m_Sat = 1.8;
% Handoff call arrival rates
lambda_h_Ter = 0.8; lambda_h_Sat = 0.6;

% New call departure rates
mu_m_Ter = 1; mu_m_Sat = 1;
% Handoff call departure rates
mu_h_Ter = 0.5; mu_h_Sat = 0.5;

%% Result Arrays
% Stores network selection
% 0 = blocked, 1 = Ter, 2 = Sat, -1 = dropped
all_decisions = zeros(U, K);

% Stores total cost for selected network
all_costs = zeros(U, K);
% Stores per-network total costs
all_costs_Ter = zeros(U, K); all_costs_Sat = zeros(U, K);

% Stores the coverage status
% 1 = Within BS coverage, 0 = outside Ter coverage)
all_coverage = zeros(U, K);

% Stores per-network admission status
% 'feasible', 'blocked', 'dropped'
all_status_Ter = cell(U, K); all_status_Sat = cell(U, K);

% Initialises number of handoff calls
handoff_calls = 0;

```

```
% Initialises number of dropped calls
dropped_call = 0;

% Initialises number of blocked calls
blocked_calls = 0;

%% Multi-User Simulation Loop
fprintf('\nSimulation: \n');

% Outer loop: Iterates over users
for u = 1:U
    % Gets current user's file size (bits)
    O = O_k(u);
    % Gets current user's allocated Bandwidth (bbu)
    b_user = b_k(u);
    % Gets currrent user's mobility path
    path = user_paths{u};

    % Initialises previous network selection
    X_prev = [];

    % Initialises flag to check if call was blocked or dropped
    isCallBlockedOrDropped = false;

    % Inner loop: Iterates over position updates
    for k = 1:K
        % Get current user position
        u_x = path(1,k); u_y = path(2,k); u_z = path(3,k);

        %% Terrestrial Access
        % Computes communication distance between user and BS
        l_Ter_ac = sqrt((u_x - b_x)^2 + (u_y - b_y)^2 + (u_z - b_z)
            ^2);

        % Checks coverage status
        % Return 1 if user within BS coverage, else 0
        all_coverage(u,k) = (l_Ter_ac <= D);

        % Computes path loss
        PL_dB = 52.44 + 20 * log10(l_Ter_ac / 10^3) + 20 * log10(
            f_Ter_ac / 10^6);
```

```
    % Generates complex Rayleigh fading coefficient (g ~ CN(0,1)
        )
    g = (randn(1) + 1i * randn(1)) / sqrt(2);

    % Computes Channel gain
    G_Ter = abs(g)^2 / 10^(PL_dB/10);

    % Computes achievable transmission rate (Shannon Capacity
        Theorem)
    R_Ter_tx = W_Ter * log2(1 + (P_Ter_tx * G_Ter)/(W_Ter *
        N0_Ter));

    % Computes transmission time
    T_Ter_tx = O / R_Ter_tx;

    %% Satellite Access
    % Compuutes communication distance between user and LEO
        satellite
    l_Sat_ac = sqrt((u_x - s_x)^2 + (u_y - s_y)^2 + (u_z - s_z)
        ^2);

    % Computes channel gain
    G_Sat = (l_Sat_ac / 10^3)^(-eta);

    % Computes achievable transmission rate (Shannon Capacity
        Theorem)
    R_Sat_tx = W_Sat * log2(1 + (P_Sat_tx * G_Sat)/(W_Sat *
        N0_Sat));

    % Computes transmission time
    T_Sat_tx = O / R_Sat_tx;

    % Initialises total costs
    C_T_Ter = 0; C_T_Sat = 0;

    %% At k = 1, New calls
    if k == 1
        % Checks if networks can admit new calls
        % Returns admission status and updated network load and
            available capacity
```

```
        [status_Ter, L_Ter, C_Ter_avail] = ...
            check_admission(L_Ter, C_Ter_avail, b_user, C_Ter,
               t_m_Ter, 'new');

        [status_Sat, L_Sat, C_Sat_avail] = ...
            check_admission(L_Sat, C_Sat_avail, b_user, C_Sat,
               t_m_Sat, 'new');

        % Compute costs if feasible
        if strcmp(status_Ter, 'feasible')
            % Computes unit price (based on network load and
               available capacity)
            p_Ter = alpha_Ter + beta_Ter * (L_Ter / C_Ter) +
               gamma_Ter / C_Ter_avail;

            % Computes network access cost
            C_A_Ter = p_Ter * b_user;

            % Computes energy consumption
            E_Ter = P_Ter_tx * T_Ter_tx;

            % Computes energy cost
            C_E_Ter = theta * E_Ter;

            % Computes total cost = Weighted sum of network
               access and energy consumption costs
            C_T_Ter = xi_a * C_A_Ter + xi_b * C_E_Ter;
        end

        if strcmp(status_Sat, 'feasible')
            % Computes unit price (based on network load and
               available capacity)
            p_Sat = alpha_Sat + beta_Sat * (L_Sat/C_Sat) +
               gamma_Sat / C_Sat_avail;

            % Computes network access cost
            C_A_Sat = p_Sat * b_user;

            % Computes energy consumption
            E_Sat = P_Sat_tx * T_Sat_tx;
            % Computes Eenergy consumption cost
```

```
            C_E_Sat = theta * E_Sat;

            % Computes total cost = Weighted sum of network
               access and energy consumption costs
            C_T_Sat = xi_a * C_A_Sat + xi_b * C_E_Sat;
        end

        % Store per-network total costs
        all_costs_Ter(u,k) = C_T_Ter; all_costs_Sat(u,k) =
           C_T_Sat;

        %% Network Selection
        % If the user is outside BS coverage
        if (all_coverage(u,k) == 0)
            % If the satellite network is feasible
            if (strcmp(status_Sat, 'feasible'))
                X = [0; 1]; selected_network = 2;
            % If the satellite network is not feasible - blocks
               the call
            else
                X = [0; 0]; selected_network = 0;

                % Increments number of blocked calls
                blocked_calls = blocked_calls + 1;

                % Sets the flag to true
                isCallBlockedOrDropped = true;
            end
        end

        % If the user is within BS coverage
        if (all_coverage(u, k) == 1)
            % Case 1: if both networks are feasible
            if (strcmp(status_Ter, 'feasible') && strcmp(
               status_Sat, 'feasible'))
                % Compares total costs
                if C_T_Ter < C_T_Sat
                    X = [1; 0]; selected_network = 1;
                else
                    X = [0; 1]; selected_network = 2;
                end
```

```
            % Case 2: If only terrestrial network is feasible
            elseif (strcmp(status_Ter, 'feasible'))
                X = [1; 0]; selected_network = 1;

            % Case 3: If only satellite network is feasible:
            elseif (strcmp(status_Sat, 'feasible'))
                X = [0; 1]; selected_network = 2;

            % Case 4: If both networks are not feasible - block
               the call
            else
                X = [0; 0]; selected_network = 0;

                % Increments number of blocked calls
                blocked_calls = blocked_calls + 1;

                % Sets the flag to true
                isCallBlockedOrDropped = true;
            end
        end

        % Stores the selected network
        all_decisions(u,k) = selected_network;

        % Stores the selected network total cost
        all_costs(u,k) = X' * [C_T_Ter; C_T_Sat];

        % Stores the admission status
        all_status_Ter{u,k} = status_Ter; all_status_Sat{u,k} =
           status_Sat;

        % Updates previous network selection
        X_prev = X;

    %% At k = 2..K, Handoff calls
    else
        % If the call was blocked or dropped, skip remaining
           position updates
        % Carries forward previous network selection decision (B
            or D)
        if isCallBlockedOrDropped
```

```
                all_decisions(u, k) = all_decisions(u, k-1);
                all_costs(u,k) = 0;
                continue;
            end

            % Terrestrial:
            % If the user is within terrestrial coverage
            if (all_coverage(u,k) == 1)
                % If the terrestrial network is feasible
                if (strcmp(all_status_Ter{u,1}, 'feasible'))
                    % Computes unit price (based on network load and
                        available capacity)
                    p_Ter = alpha_Ter + beta_Ter * (L_Ter / C_Ter) +
                        gamma_Ter / C_Ter_avail;

                    % Computes network access cost
                    C_A_Ter = p_Ter * b_user;

                    % Computes energy consumption
                    E_Ter = P_Ter_tx * T_Ter_tx;
                    % Computes energy consumption cost
                    C_E_Ter = theta * E_Ter;

                    % Computes total cost = Weighted sum of network
                       access and energy consumption costs
                    C_T_Ter = xi_a * C_A_Ter + xi_b * C_E_Ter;
                end
            end

            % Satellite:
            % if the satellite is feasible
            if (strcmp(all_status_Sat{u,1}, 'feasible'))
                % Computes unit price (based on network load and
                   available capacity)
                p_Sat = alpha_Sat + beta_Sat * (L_Sat / C_Sat) +
                   gamma_Sat / C_Sat_avail;
                % Computes network access cost
                C_A_Sat = p_Sat * b_user;

                % Computes energy consumption
                E_Sat = P_Sat_tx * T_Sat_tx;
```

```
            % Computes energy consumption cost
            C_E_Sat = theta * E_Sat;

            % Computes total cost = Weighted sum of network
               access and energy consumption costs
            C_T_Sat = xi_a * C_A_Sat + xi_b * C_E_Sat;
        end

        % Stores per-network total costs
        all_costs_Ter(u,k) = C_T_Ter; all_costs_Sat(u,k) =
           C_T_Sat;

        %% Network Selection
        % Initialise current network selection
        X = [];

        % If the user is within terrestrial coverage
        if (all_coverage(u,k) == 1)
            % Case 1: If both networks are feasible
            if (strcmp(all_status_Ter{u,1}, 'feasible') &&
               strcmp(all_status_Sat{u,1}, 'feasible'))
                % Compare total costs
                if (C_T_Ter < C_T_Sat)
                    X = [1; 0];
                else
                    X = [0; 1];
                end

            % Case 2: If only terrestrial network is feasible
            elseif (strcmp(all_status_Ter{u,1}, 'feasible'))
                X = [1; 0];

            % Case 3: If only satellite network is feasible
            elseif (strcmp(all_status_Sat{u,1}, 'feasible'))
               X = [0; 1];
            end

        % if the user is outside BS coverage
        else
            % if the satellite network is feasible
            if (strcmp(all_status_Sat{u,1}, 'feasible'))
```

```
                X = [0; 1];
            end
        end

        %% Handoff Execution
        % Checks if the current network selection (X) is the same as
        % previous network selection (X_prev)
        if isequal(X_prev, X)
            % Yes: Stay on the same network (No handoff needed)
            selected_network = all_decisions(u, k-1);
        else
            % No: Attempt handoff
            % Handoff to Terrestrial
            if isequal(X, [1; 0])
                % Checks admission for handoff call
                [status_Ter, L_Ter_temp, C_Ter_avail_temp] = ...
                    check_admission(L_Ter, C_Ter_avail, b_user, C_Ter, t_m_Ter, 'handoff');

                % If the terrestrial Libra is feasible - Handoff successful
                if (strcmp(status_Ter, 'feasible'))
                    % Updates network state
                    L_Ter = L_Ter_temp; C_Ter_avail = C_Ter_avail_temp;

                    % Releases resources from previous network
                    L_Sat = L_Sat - b_user; C_Sat_avail = 1 - (L_Sat / C_Sat);

                    selected_network = 1;

                    % Increments the number of handoff calls
                    handoff_calls = handoff_calls + 1;

                % If the terrestrial network is not feasible - Handoff failed
                else
                    X = [0; 0]; selected_network = -1;

```

```
                % Increments number of dropped calls
                dropped_call = dropped_call + 1;

                % Sets the flag to true
                isCallBlockedOrDropped = true;

                % Releases resources from previous network
                if isequal(X_prev, [1; 0])
                    L_Ter = L_Ter - b_user; C_Ter_avail = 1 - (L_Ter / C_Ter);
                elseif isequal(X_prev, [0; 1])
                    L_Sat = L_Sat - b_user; C_Sat_avail = 1 - (L_Sat / C_Sat);
                end
            end

        % Handoff to Satellite
        elseif isequal(X, [0; 1])
            % Checks admission for handoff call
            [status_Sat, L_Sat_temp, C_Sat_avail_temp] = ...
                check_admission(L_Sat, C_Sat_avail, b_user, C_Sat, t_m_Sat, 'handoff');

            % If the satellite network is feasible - Handoff successful
            if (strcmp(status_Sat, 'feasible'))
                % Updates network state
                L_Sat = L_Sat_temp; C_Sat_avail = C_Sat_avail_temp;

                % Releases resources from previous network
                L_Ter = L_Ter - b_user; C_Ter_avail = 1 - (L_Ter / C_Ter);

                selected_network = 2;

                % Increments number of handoff calls
                handoff_calls = handoff_calls + 1;
            else
                % If the terrestrial network is not feasible - Handoff failed
```

```
                        %
                        X = [0; 0]; selected_network = -1;

                        % Increments the number of dropped calls
                        dropped_call = dropped_call + 1;

                        % Sets the flag to true
                        isCallBlockedOrDropped = true;

                        % Releases resources from previous network
                        if (isequal(X_prev, [1; 0]))
                            L_Ter = L_Ter - b_user; C_Ter_avail = 1
                                - (L_Ter / C_Ter);
                        elseif (isequal(X_prev, [0; 1]))
                            L_Sat = L_Sat - b_user; C_Sat_avail = 1
                                - (L_Sat / C_Sat);
                        end
                    end

                % If both networks are not feasible - Handoff failed
                else
                    X = [0; 0]; selected_network = -1;

                    % Increments the number of dropped calls
                    dropped_call = dropped_call + 1;

                    isCallBlockedOrDropped = true;
                    % Release resources from previous network
                    if (isequal(X_prev, [1; 0]))
                        L_Ter = L_Ter - b_user; C_Ter_avail = 1 - (
                            L_Ter / C_Ter);
                    elseif (isequal(X_prev, [0; 1]))
                        L_Sat = L_Sat - b_user; C_Sat_avail = 1 - (
                            L_Sat / C_Sat);
                    end
                end
            end

            % Stores the selected network
            all_decisions(u,k) = selected_network;

```

```
                % Store the selected network total cost
                all_costs(u,k) = X' * [C_T_Ter; C_T_Sat];

                % Updates previous network selection
                X_prev = X;
            end
        end
end

%% Dynamic Call Blocking and Dropping Probabilities (Subplots)
% Compute probabilities per position update
P_B_over_k = zeros(1,K); P_D_over_k = zeros(1,K);

for k = 1:K
    if k == 1
        % New calls
        total_new_calls = U;
        blocked_calls_k = nnz(all_decisions(:,k) == 0);
        P_B_over_k(k) = blocked_calls_k / total_new_calls;
        P_D_over_k(k) = 0;
    else
        % Handoff calls
        total_handoff_k = 0;
        dropped_calls_k = 0;
        for u = 1:U
            prev_net = all_decisions(u,k-1);
            curr_net = all_decisions(u,k);
            if prev_net > 0
                total_handoff_k = total_handoff_k + 1;
                if curr_net == -1
                    dropped_calls_k = dropped_calls_k + 1;
                end
            end
        end
        P_B_over_k(k) = 0;
        P_D_over_k(k) = dropped_calls_k / (total_handoff_k + eps);
    end
end

figure;

```

```
% Blocking Probability
subplot(2,1,1);
stairs(1:K, P_B_over_k, 'r-', 'LineWidth', 2, 'MarkerSize', 6);
xlabel('Position Update Index k');
ylabel('Blocking Probability P_B');
title('Call Blocking Probability over Position Updates');
grid on;

% Dropping Probability
subplot(2,1,2);
stairs(1:K, P_D_over_k, 'b-', 'LineWidth', 2, 'MarkerSize', 6);
xlabel('Position Update Index k');
ylabel('Dropping Probability P_D');
title('Call Dropping Probability over Position Updates');
grid on;

%% Network Operator Revenue Per Position Update and Cumulative
% Computes the operator revenue per position update
R_over_time = sum(all_costs, 1);

% Computes the cumulative operator revenue
R_cumulative = cumsum(R_over_time);

% Figure 1: Operator revenue per position update
figure;
plot(1:K, R_over_time, 'k-x', 'LineWidth', 2, 'MarkerSize', 6);
xlabel('Position Update Index (k)');
ylabel('Operator Revenue (R)');
title('Operator Revenue per Position Update');
grid on;

% Figure 2: Cumulative operator revenue
figure;
plot(1:K, R_cumulative, 'k-x', 'LineWidth', 2, 'MarkerSize', 6);
xlabel('Position Update Index (k)');
ylabel('Cumulative Operator Revenue (R)');
title('Cumulative Operator Revenue Over Position Updates');
grid on;

%% QoS Performance Metrics: Call Blocking and Dropping Probability

```

```
fprintf('\n--- QoS Performance Metrics ---\n');

% Markov Model
% Arrival rates
lambda_m_vals = linspace(0.5, 15, 25);
lambda_h_vals = 0.5 * lambda_m_vals;

% Initialise probabilities
P_B_Ter = zeros(size(lambda_m_vals));
P_D_Ter = zeros(size(lambda_m_vals));
P_B_Sat = zeros(size(lambda_m_vals));
P_D_Sat = zeros(size(lambda_m_vals));

for i = 1:length(lambda_m_vals)
    % Arrival rates
    lambda_m_Ter = lambda_m_vals(i); lambda_m_Sat = lambda_m_vals(i)
        ;
    lambda_h_Ter = lambda_h_vals(i); lambda_h_Sat = lambda_h_vals(i)
        ;

    % Network load factors
    rho_m_Ter = lambda_m_Ter / mu_m_Ter; rho_h_Ter = lambda_h_Ter /
        mu_h_Ter;
    rho_m_Sat = lambda_m_Sat / mu_m_Sat; rho_h_Sat = lambda_h_Sat /
        mu_h_Sat;

    % Initialize state probabilities
    ST_Ter = 0; SB_Ter = 0; SD_Ter = 0;
    ST_Sat = 0; SB_Sat = 0; SD_Sat = 0;

    % Terrestrial Network
    for m = 0:t_m_Ter
        for h = 0:C_Ter
            if (b_user * m <= t_m_Ter) && (b_user * (m + h) <= C_Ter
                )

                P = (rho_m_Ter^(m) * rho_h_Ter^(h)) / (factorial(m)*
                    factorial(h));

                ST_Ter = ST_Ter + P;

```

```
                % Blocking state: new call rejected
                if ((b_user * m  > t_m_Ter) || (b_user + b_user * (m + h) > C_Ter))
                    SB_Ter = SB_Ter + P;
                end

                % Dropping state: handoff rejected
                if (b_user + b_user * (m + h) > C_Ter)
                    SD_Ter = SD_Ter + P;
                end
            end
        end
    end

    % Satellite Network
    for m = 0:t_m_Sat
        for h = 0:C_Sat
            if (b_user * m <= t_m_Sat) && (b_user * (m + h) <= C_Sat)
                P = (rho_m_Sat^(m)  * rho_h_Sat^(h)) / (factorial(m)*factorial(h));
                ST_Sat = ST_Sat + P;
                if ((b_user*m > t_m_Sat) || (b_user +  b_user * (m + h) > C_Sat))
                    SB_Sat = SB_Sat + P;
                end
                if (b_user +  b_user * (m + h) > C_Sat)
                    SD_Sat = SD_Sat + P;
                end
            end
        end
    end

    % Compute Probabilities
    P_B_Ter(i) = SB_Ter / ST_Ter;  P_D_Ter(i) = SD_Ter / ST_Ter;
    P_B_Sat(i) = SB_Sat / ST_Sat; P_D_Sat(i) = SD_Sat / ST_Sat;
end

%% Network Operator Revenue
% Total cost per user
total_user_costs = sum(all_costs, 2);
```

```
% Network operator revenue
R_total = sum(total_user_costs);

%% Results
fprintf('Results:\n');
fprintf('Total Operator Revenue: %.2f\n', R_total);
fprintf('Total Handoffs: %d\n', handoff_calls);

% Count network selections
ter_selections = nnz(all_decisions(:) == 1);
sat_selections = nnz(all_decisions(:) == 2);

fprintf('Network Selection Statistics:\n');
fprintf('Terrestrial Selections: %d\n', ter_selections);
fprintf('Satellite Selections: %d\n', sat_selections);
fprintf('Blocked Calls (at k = 1): %d\n', blocked_calls);
fprintf('Dropped Calls (at k = 2..K): %d\n', dropped_call);

%% Network Selection History Per User
fprintf('Network Selection History: \n');
fprintf('Selection Sequence: (T = Terrestrial, S = Satellite, B =
   Blocked, D = Dropped) \n')

for u = 1:U
    fprintf('User %d:\n', u);
    fprintf(' File Size: %.2f Mbits, BW: %d bbu\n', ...
        O_k(u) / 10^6, b_k(u));
    fprintf(' Total Cost: %.2f\n', total_user_costs(u));

    % Count network usage
    user_ter = nnz(all_decisions(u,:) == 1);
    user_sat = nnz(all_decisions(u,:) == 2);
    user_blocked = nnz(all_decisions(u,:) == 0);
    user_dropped = nnz(all_decisions(u,:) == -1);

    fprintf(' Network Usage: Terrestrial = %d, Satellite = %d,
       Blocked = %d, Dropped = %d\n', ...
        user_ter, user_sat, user_blocked, user_dropped);

    % Display selection sequence
    fprintf(' Selection Sequence: ');
```

```
    for k = 1:K
        switch all_decisions(u,k)
            case 0
                fprintf('B '); % Blocked
            case -1
                fprintf('D '); % Dropped
            case 1
                fprintf('T '); % Terrestrial
            case 2
                fprintf('S '); % Satellite
        end
    end


    % Count number of handoffs for current user
    user_handoffs = 0;
    for k = 2:K
        if (all_decisions(u, k) ~= all_decisions(u, k - 1) && all_decisions(u, k) > 0 && all_decisions(u, k - 1) > 0)
            user_handoffs = user_handoffs + 1;
        end
    end
    fprintf('  \n Handoffs: %d\n\n', user_handoffs);
end


%% Helper Functions
% Check Admission
function [status, L_n, C_n_avail] = check_admission(L_n, C_n_avail, b_k, C_n, t_m_n, call_type)
    % Projected network load
    L_proj = L_n + b_k;

    % New call: Check if the projected load <= new calls admission threshold
    if strcmp(call_type, 'new')
        if L_proj <= t_m_n
            % Mark the network as feasible
            status = 'feasible';
            % Update network state
            L_n = L_proj; C_n_avail = 1 - (L_proj / C_n);
```

```
        else
            % Network not feasible - block the call
            status = 'blocked';
        end
    end

    % Handoff call: Check if the projected load <= total network
        capacity
    if strcmp(call_type, 'handoff')
        if L_proj <= C_n
            % Mark network as feasible
            status = 'feasible';
            % Update network state
            L_n = L_proj; C_n_avail = 1 - (L_proj / C_n);
        else
            % Network not feasible - drop the call
            status = 'dropped';
        end
    end
end
```

Listing C.1: ITNTN Simulation — Multi-User Integrated Terrestrial and Non-Terrestrial Network (ver4)