LATENCY AWARE RESOURCE ALLOCATION AND TASK OFFLOADING IN A HYBRID GEO-LEO SATELLITE NETWORKS

By
Parisa Ijaz Chaudhary
(Registration No: 00000361446)

Supervisor
Dr. Humayun Zubair Khan

A thesis submitted to the faculty of Electrical Engineering Department, Military College of Signals, National University of Sciences and Technology, Islamabad, Pakistan, in partial fulfilment of the requirements for the degree of MS in Electrical (Telecommunication) Engineering

June 2023

THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS/MPhil thesis written by Miss **NS Parisa Ijaz Chaudhary,** Registration No. **00000361446** of **Military College of Signals** has been vetted by undersigned, found complete in all respect as per NUST Statutes/Regulations, is free of plagiarism, errors and mistakes and is accepted as partial, fulfillment for award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the student have been also incorporated in the said thesis.

Signature: ____________________

Name of Supervisor **Lt. Col Humayun Zubair Khan**

Date: ____________________

Signature (HoD): ____________________

Brig
HoD
Dept of Elect Engg
Military College of Signals (NUST)
(NUST Campus)

Date: ____________________

Signature (Dean): ____________________

Date: 25/7/23

Brig
Dean, MCS (NUST)
(Asif Masood, Phd)

Scanned with CamScanner

AUTHOR's DECLARATION

I, **Parisa Ijaz Chaudhary** declare that this thesis titled **Latency Aware Resource Allocation and Task Offloading in a Hybrid GEO-LEO Satellite Network** and the work presented in it are my own and has been generated by me as a result of my own original research.

I confirm that:

- This work was done wholly or mainly while in candidature for a Master of Science degree at NUST.
- Any prior submission of any portion of this thesis for a degree or other qualification at NUST or any other institution is explicitly acknowledged.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Wherever my thesis draws on the work of others, I have made it quite apparent what they contributed and where I came in.

Parisa Ijaz Chaudhary,
00000361446

DEDICATION

This thesis is dedicated to

MY BELOVED PARENTS,

HONORABLE TEACHERS AND FRIENDS

for their love, endless support and encouragement

ACKNOWLEDGEMENTS

I express my deepest gratitude to Allah Almighty, who has blessed me with the determination and enthusiasm to complete this thesis. I am truly thankful to Him for His boundless mercy and benevolence. Without His guidance and permission, I would not have been able to embark on this important endeavor.

I am delighted to acknowledge the instrumental role played by the esteemed members of the guidance committee in the successful completion of this thesis. Their invaluable participation and unwavering support have been crucial to this achievement. I express my sincere gratitude and deep appreciation to my honorable thesis supervisor, Dr. Humayun Zubair Khan. His exceptional guidance, unwavering commitment, and continuous encouragement have been instrumental in my journey.

Expressing my profound gratitude is a feeble attempt to convey the depth of my appreciation towards the committee members who have played an integral role in the successful completion of this thesis. I extend my heartfelt thanks to Dr. Ahmad Naeem Akhtar, Dr. Mudassar Ali, and Col. Khawar Mehmood for their tireless efforts and guidance throughout this journey. Their expertise, insightful suggestions, and constructive feedback have significantly contributed to the development and refinement of this thesis.

I am profoundly grateful for the unwavering love and support I received from my family and friends. Their courage, assistance, and encouragement have been invaluable throughout my journey toward completing my MS Degree in Electrical (Telecommunication) Engineering. I am grateful to the outstanding faculty of the Electrical Engineering Department, especially the Head of the Electrical Engineering Department., for his encouragement. Over the years, their constant support has inspired me.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOTATIONS

Notation	Definition
$\mathbb{K}$	Set of IoT devices
$\mathbb{M}$	Set of cloudlets
$\mathbb{S}$	Set of data files stored
$\mathbb{C}$	Set of data files computed
$\beta_{k,m}$	Association indicator
α_k	Admission indicator
$\delta_{k,m}$	IoT fairness index
P_k	Max power of IOT device
$p_{k,m}$	Power allocated by IoT device in the UL
$h_{k,m}$	Channel gain between IoT device and LEO-cloudlet
G_k^{Tx}	Transmit antenna gain of IoT device
G_m^{Rx}	Receive antenna gain of LEO-cloudlet
$\Psi_{k,m}$	Minimum QoS data rate
$D_{k,m}$	Maximum allowed QoS latency
Q_{UFI}	Minimum QoS UFI
Q_{RFI}	Minimum QoS RFI
$\xi_{k,m}(t)$	Attenuation in Channel
$b_{k,m}(t)$	Channel bandwidth
$\zeta_{k,m}(t)$	No. of resource block

ACRONYMS

Acronym	Definition
$S-IoT$	Satellite-Assisted Internet of Things
IA	IoT Association
IF	IoT Fairness
RBs	Resource Blocks
QoS	Quality of Service
QoE	Quality of Experience
3G	3^{rd} generation
4G	4^{th} generation
5G	5^{th} generation
LTE	Long Term Evolution
RAN	Radio Access Network
GEO	Geosynchronous Earth Orbit
$MINLP$	Mixed Integer Nonlinear Programming
NLP	Non-linear Programming
$MILP$	Mixed-Integer Linear Programming
$NP-Hard$	Non-deterministic Polynomial-time Hard
OAA	Outer Approximation Algorithm
ESA	Exhaustive Search Algorithm
$BONMIN$	Basic Open-source Nonlinear Mixed Integer Programming
$Flop$	Floating-point Operation
UL	Uplink
UE	User Equipment
IoT	Internet of Things
CPU	Cycle Per Unit
TNs	Task nodes
$SINR$	Signal to Interference plus Noise Ratio
LB	Lower Bound
UB	Upper Bound

ABSTRACT

To accommodate the rapid development of the Satellite-Assisted Internet of Things (S-IoT) and the ever-shifting landscape of future communications, a hybrid satellite network integrating Geosynchronous Earth Orbit (GEO) and Low Earth Orbit (LEO) satellites has been proposed. This architecture is gaining prominence as a strong contender among emerging network architectures. The primary objective of this research is to optimize the network's end-to-end energy consumption by addressing the latency of the network as a whole, cache capability, joint admission control, association, and power allocation. An equally pivotal facet involves ensuring fairness in IoT device association and impartial distribution of spectrum resources while simultaneously optimizing throughput. This distinctive objective, which remains relatively uncharted in prior research, encompasses the harmonization of fairness considerations alongside the pursuit of maximal efficiency. However, the hybrid GEO-LEO satellite network faces significant challenges due to limited onboard communication and computing resources, particularly in task offloading. The problem is classified as an NP-hard mixed-integer non-linear programming (MINLP) problem, which demands an effective solution approach with a low computational load. An outer approximation algorithm (OAA) is proposed to obtain a near-optimal solution to address this. The results demonstrate the ability of the approach to achieve fairness in IoT association, fairness in resource block (RB) allocation, and overall throughput in the hybrid GEO-LEO satellite network. This research contributes to advancing satellite networks, particularly the hybrid GEO-LEO architecture, to meet the future communication needs of the S-IoT. The proposed OAA algorithm provides a practical and efficient solution for the NP-hard MINLP problem, opening avenues for further advancements in this field.

Chapter 1

INTRODUCTION

This chapter begins with an overview of the satellite-assisted Internet of Things (S-IoT), highlighting its necessity. Later on, S-IoT along with the challenge in relation to latency aware resource allocation to maximize the throughput is discussed. Moreover, the thesis motivation, objectives and contributions are elaborated along with thesis organization.

1.1 Significance of S-IoT

The rapid growth of the Internet of Things (IoT) has led to the emergence of innovative solutions, such as Satellite-assisted Internet of Things (S-IoT), to address the scalability, reliability, and latency challenges associated with the proliferation of smart devices. S-IoT, which integrates satellite technology into the IoT ecosystem, offers promising opportunities for enhancing network capabilities and expanding connectivity. In this , we delve into the significance of S-IoT and its potential contributions to the field of network design and development./par

1.2 Smart Device Expansion and Satellite-assisted IoT Challenges

The deployment of a significant range of smart devices seems anticipated to arise from all industries' exponential industrial expansion. By 2020, there will supposedly be up to 50 billion digital gadgets in use, generating 13 times as much data as conventional devices [1]. Substantial heterogeneous data creation by IoT devices with varying Quality-of-Service (QoS) requirements necessitates improving data transfer rates and the capacity of networks. Future network design and development must overcome several challenges. The proliferation of smart devices across all sectors is driving the need for innovative solutions to the problems of scalability, reliability, and reduced latency [2] [3].

Incorporating the Satellite-assisted Internet of Things [4] has resulted in a significant expansion of the Internet of Things (IoT), constructed initially using a terrestrial network. In contrast, in traditional S-IoT systems, IoT devices bypass the satellite entirely and transmit data to the satellite gateway via the satellite. While the satellite itself is easy to produce, the system's efficiency is limited by the transmission capacity of the feeder link [5].

1.3 Optimizing Hybrid Satellite Networks for S-IoT Infrastructure

The S-IoT infrastructure can be implemented by satellites in either low Earth orbit (LEO) or geosynchronous Earth orbit (GEO). Moreover, there is a considerable delay in propagation because of the distant location between the satellite and the ground [6].LEO satellites have a shorter propagation delay, but their greater mobility poses a better challenge to resource management [7]. Because of the essential role that the hybrid GEO-LEO satellite network will perform in expanding space-air-ground networks, the study of intelligent resource distribution in heterogeneous satellite networks is also crucial [8].

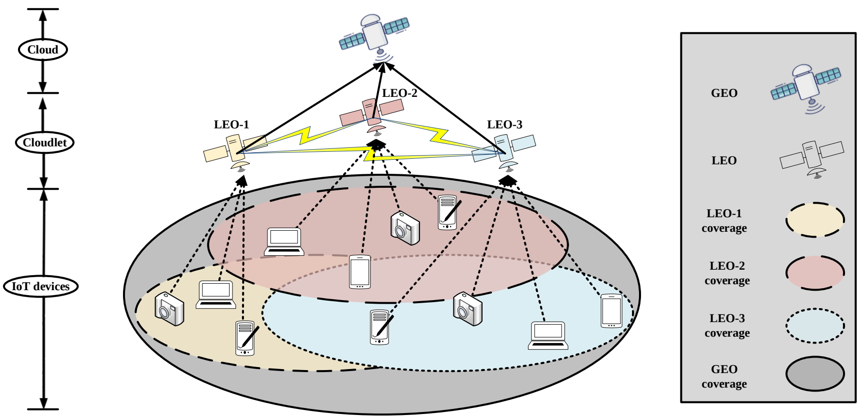

Figure 1.1: **Hybrid satellite network model**

The backhaul link is overloaded when the cloudlet accesses, processes, and forwards data to the cloud server. Propagation and processing times get delayed as a result of this added load. Throughput can be improved when a cloudlet node and IoT devices use a single spectrum and a heavy traffic load. Because of this, there is a lag in transmission, and the front haul link becomes overloaded. Caching at cloudlet nodes has been offered as a solution to the load constraints imposed by these linkages. Cloudlet node caches in fog networks reduce latency across the entire system [9]. No delays will occur due to computation or propagation because all the data is cached already on the cloudlet node. A fog network's cloudlet nodes must have cache enabled (CE) to manage latency-sensitive Internet of Things applications.

1.4 Advantages of S-IoT

By combining the advantages of IoT and satellite networks, the S-IoT promises to provide access for connectivity in all the remote areas and the same has drawn considerable attention of both the academia and industry. Some advantages of S-IoT are stated as follows:

- **Overcoming Network Capacity Limitations**: The exponential growth of smart devices results in massive data generation, requiring networks to handle increased data transfer rates and capacity. S-IoT addresses this challenge by utilizing satellite links to augment network capacity, effectively offloading data traffic from terrestrial networks.

- **Enabling Global Connectivity**: S-IoT provides a unique advantage in ensuring global connectivity, particularly in remote areas where terrestrial networks may be limited or unavailable by leveraging satellite infrastructure.

- **Improving Reliability and Resilience**: Traditional IoT systems heavily rely on terrestrial networks, which are vulnerable to disruptions caused by natural disasters, network failures, or infrastructure limitations. S-IoT introduces an additional layer of reliability by offering redundant communication paths through satellite links.

- **Enhancing IoT Use Cases**: S-IoT opens up new possibilities for a wide range of IoT applications across various industries. From agriculture and environmental monitoring to maritime and aviation.

- **Green and Sustainable Solutions**: S-IoT presents an environmentally friendly approach to IoT connectivity. By reducing reliance on terrestrial networks and optimizing data transmission through satellite links.

1.5 Applications of S-IoT

The applications of S-IoT network demonstrate its potential to bridge connectivity gaps, enable efficient communication in remote areas, support critical services during emergencies, and enhance various aspects of telecommunications infrastructure.It includes the following:

- **Connectivity in Remote Areas**: S-IoT provides reliable connectivity in remote and underserved areas where traditional communication infrastructure is limited or absent. It enables seamless communication between devices and networks.

- **Emergency Communication**: During natural disasters or emergency situations, terrestrial communication infrastructure can be severely impacted, leading to communication breakdowns. S-IoT ensures uninterrupted communication for emergency response teams.

- **Fleet and Asset Management**: S-IoT allows efficient management and communication with fleets and assets spread across large geographical areas. It enables real-time tracking, monitoring, and communication with vehicles.

- **Telecommunications Infrastructure Backup**: S-IoT serves as a backup communication network for terrestrial-based telecommunication infrastructure. In the event of network failures, S-IoT can provide alternative connectivity options.

- **Remote Sensing and Data Collection**: S-IoT supports remote sensing applications, such as weather monitoring, environmental sensing, and data collection from remote locations.

1.6 Latency Reduction and S-IoT

Power usage, communication latencies, and spectrum efficiency are the issues, and to address these, numerous researchers have developed methods for managing the resources available [10]. Fog networking has arisen as a viable cure due to the exponential development in data traffic created by smart devices in all industries [11]. It will be a critical enabling technology for 5G IoT applications in the future [12]. A server for storing data (cloudlet or fog) is close to the edges of smart devices in fog networking. As a result of reduced latency and increased throughput, data is made accessible to the devices that generate it. Fog/cloudlet servers can cache the most popular information, reducing the processing and propagation delays that the cloud server usually endures [12] [13]. Cloudlet nodes are similar to cloud servers, except that they have less space for data and computing power.

1.6.1 Improving Latency in IoT Networks using Satellites

The reduction in latency of satellite IoT networks can be affected by several factors, including:

- **Satellite Orbit**: The choice of satellite orbit plays a significant role in determining latency. Satellites in lower orbits, such as LEO, offer lower latency compared to satellites in higher orbits like GEO. This is because the distance between the satellite and the IoT device is shorter in LEO, resulting in reduced signal propagation time.

- **Signal Processing and Routing**: Efficient signal processing and routing techniques can minimize latency in satellite IoT networks as advanced algorithms and protocols are utilized.

- **Network Architecture**: The network architecture, including the configuration and design of the satellite IoT system, can impact latency.

- **Signal Propagation Delays**: Signal propagation delays, caused by the speed at which electromagnetic signals travel through the atmosphere and space, can contribute to latency in satellite IoT networks.

- **Signal Interference and Noise**: Interference and noise in the satellite communication channel can increase latency.

1.6.2 Approaches to Reduce Latency in Satellite IoT Networks

By applying following approaches, satellite IoT networks can achieve lower latency, enabling near-real-time communication and enhancing the performance of various IoT applications and services.

- **Predictive Caching**: Implement predictive caching mechanisms to store and pre-fetch data that is likely to be requested by IoT devices. By caching frequently accessed data closer to the IoT devices, latency can be reduced as the data can be retrieved locally.
- **Bandwidth Allocation and Resource Management**: Employ effective bandwidth allocation and resource management techniques to ensure efficient utilization of network resources. By dynamically allocating bandwidth based on the priority and requirements of different IoT applications, latency can be minimized for critical data traffic.
- **Protocol Optimization**: Optimize communication protocols used in the satellite IoT network to minimize protocol overhead and latency.
- **Quality of Experience (QoE) Monitoring**: Continuously monitor the QoE of IoT applications and services in real-time. By analyzing latency metrics and user feedback, network operators can identify areas of improvement and proactively address latency issues to ensure a satisfactory user experience.
- **Advanced Modulation Schemes**: Utilize advanced modulation schemes, such as Quadrature Amplitude Modulation (QAM), to increase the data transmission rate over the satellite link. Higher data rates can help reduce the time required for data transfer, thereby reducing latency.

1.7 Throughput

Throughput refers to the amount of data that can be transmitted over a network in a given time period. In the context of satellite IoT networks, throughput represents the data rate at which IoT devices can send and receive data through the satellite link. Here are some equations related to throughput:

- **Channel Capacity (C)**: The channel capacity represents the maximum achievable data rate of a communication channel. In the case of satellite IoT networks, the channel capacity can be calculated using Shannon's Channel Capacity formula:

$$C = B \cdot \log_2 \left(1 + \left(\frac{S}{N}\right)\right) \tag{1.1}$$

- **Effective Throughput (T)**: The effective throughput is the actual data rate achieved in practice, taking into account various factors such as protocol overhead, packet loss, and network congestion. It can be calculated using the formula:

$$T = R \cdot (1 - PL) \tag{1.2}$$

1.8 Latency Aware Resource Allocation in S-IoT

Latency-aware resource allocation is a critical aspect of hybrid GEO-LEO networks or Satellite-assisted Internet of Things (S-IoT) systems. The integration of both geostationary (GEO) and low Earth orbit (LEO) satellites presents unique challenges in terms of minimizing latency to maximize the throughput and optimizing resource allocation.In these hybrid networks, the goal is to efficiently allocate network resources to ensure low latency communication between IoT devices and satellite gateways. This involves considering factors such as signal propagation delays, distance between devices and satellites, and the selection of the optimal access mode (GEO or LEO) based on latency requirements.

By adopting latency-aware resource allocation techniques, network operators can optimize the allocation of bandwidth, processing resources, and routing decisions to minimize latency and meet the application-specific requirements. This ensures that time-sensitive data is transmitted promptly and enables timely decision-making and response in IoT applications. Additionally, the integration of edge computing capabilities within the satellite network can further enhance latency-aware resource allocation. By performing data processing and analytics closer to the IoT devices at the network edge, latency can be reduced by minimizing the need for data transmission to centralized servers.Overall, latency-aware resource allocation in hybrid GEO-LEO networks or S-IoT systems is essential for ensuring efficient and real-time communication between IoT devices and satellite gateways. It involves considering latency requirements, optimizing resource allocation strategies, and leveraging edge computing capabilities to minimize latency and maximize the throughput of various IoT applications and services.

1.8.1 Issues concerning to allocation of resources

Here are additional challenges related to latency-aware resource allocation in hybrid GEO-LEO networks or S-IoT systems:

- **Network Synchronization**: In hybrid networks, ensuring proper synchronization between the GEO and LEO satellites is crucial for efficient resource allocation and minimizing latency.
- **Interoperability and Standardization**: The integration of different satellite systems and protocols in hybrid networks requires interoperability and standardization. Ensuring seamless communication between GEO and LEO satellites, as well as compatibility with IoT devices.
- **Security and Privacy**: Latency-aware resource allocation should consider the security and privacy requirements of IoT applications. Protecting sensitive data, ensuring secure communication channels, and implementing robust authentication and encryption mechanisms are essential.
- **Network Management and Orchestration**: Network management systems need to handle dynamic resource allocation, performance monitoring, fault management, and traffic engineering to ensure low latency and optimal resource utilization.

1.9 Related Work

Table 1.1 summarises previous work on various Throughput maximization techniques in satellite and terrestrial networks.

According to recent studies [14], there is an exploration of task offloading in hybrid GEO-LEO satellite networks. This is done by examining cooperative user association and resource allocation. To increase productivity, scheduling jobs, associating users, and allocating resources are separated into two distinct issues. Then, CUARA, which makes use of DRL, is suggested. For generating secret keys for GS pair-to-pair encryption key exchanges using the BB84 protocol with decoy states, the author of reference [15] defined the resource allocation problem for such a QKD network. Joint optimization for sub-band assignment and power allocation was devised by the author of Reference [16] to improve the throughput of cellular networks used by the Internet of Things. There seem to be improved two-stage sub-band assignment and power control algorithms proposed, which account for spectral leakage in their optimization process. Paper [17] examined the challenge of energy-efficient resource allocation in a multi-device, D2D-assisted fog computing environment. The author provided two suboptimal techniques to reduce energy use. Assessing the correlation between the duration of individual computer tasks and total energy use is one approach to cutting down on computing time. The use of Hessian matrices in a simple heuristic approach to resource allocation is still another option. In RLNC D2D HetNet communications, the author [18] suggested using relay selection and power allocation to improve energy efficiency and load balancing. The challenge was recast as a single-objective optimization problem, and a ”pseudo-optimal” solution was presented that fell short. Authors in [14]- [18] primarily concentrate on power restrictions to maximize throughput. The research presented in [14] and [16] focuses on UL transmission. However, these researches do not address the fairness of IoT distributions and RBs for consumers.

Table 1.1: **Related work and novelty**

Parameters	[14] **2020**	[15] **2021**	[16] **2019**	[17] **2022**	[18] **2022**	[19] **2021**	[20] **2021**	[21] **2021**	[22] **2022**	[23] **2021**	[24] **2022**	[25] **2021**	[26] **2020**	This paper
Transmission in UL	✓		✓						✓					✓
Geo satellite (cloud)						✓	✓	✓				✓		✓
Leo satellite (cloudlet)						✓	✓	✓	✓			✓		✓
IoT Admission										✓			✓	✓
IoT Association						✓		✓	✓	✓			✓	✓
Power limit		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Cache enabled										✓	✓	✓	✓	✓
Data computation											✓	✓		✓
Data storage											✓	✓		✓
Queuing delay														✓
Transmission delay	✓							✓		✓		✓	✓	✓
Propagation delay		✓								✓		✓	✓	✓
Processing delay	✓			✓					✓	✓		✓	✓	✓
Fair IoT distribution														✓
Fair RBs distribution														✓
Throughput				✓	✓	✓				✓		✓		✓

In Paper [19], the author analyses the challenges of international connectivity and proposes solutions to those challenges. To attain this goal, the author recommended 5G smart connectivity. The pervasive networking capabilities of the platform may manage service lifetime.To bring 5G cellular service to previously inaccessible areas, we must rely on satellites, UAVs, and long-range, low-power Internet of Things (IoT) network technology. It is essential to combine these technologies for dependable service. [20] analyses a satellite communication system using GEO and LEO satellites. The author proposed a JBMPA strategy to increase SINR and decrease the frequency of service disruptions. This research suggests employing a deep Q-network (DQN) to aid the challenging task of transmitting power allocation for operational LEO satellites. Incorporating the non-orthogonal multiple access (NOMA) technique into a frequency coexistence setting improves spectral efficiency. The author of Reference [21] examined the capacity performance of a two-layer GEO/LEO satellite network and created a theoretical formulation of the ergodic capacity using Meijer-G functions to analyze system performance. In [22], the authors analyzed a hybrid cloud-edge computing model in which flying UAVs provide low-delay edge computing service to IoT devices, and satellites provide ubiquitous access to the cloud. To minimize the maximum calculation delay among IoT devices, we jointly scheduled association control, computing work allocation, transmission power and bandwidth allocation, computation resource allocation for autonomous aerial vehicles (UAVs), and deployment position optimization. Based on block coordinate descent and sequential convex approximation, the authors developed an alternating optimization method with guaranteed convergence. All of the authors cited in [19]- [22] provide an overview of the IoT association in Geo and Leo satellites. Although these researches examine many aspects of RBs, traffic load, and throughput, they do not calculate transmission and propagation delays.

In [23], the author posed a JNAEE maximization issue with limitations. This problem considers optimal power allocation, node association, latency, and rate. Future IoT-Fog networks face this difficulty. This author used a lesser linearization method, mesh adaptive direct search (MADS), to find a less-than-ideal solution. The author of [24] developed an iterative technique to optimize either task offloading or software caching. The author presented a multi-tier computation-based system in which task nodes (TNs) offload their tasks to nearby massive MIMO-aided relay nodes (MRNs) with under-utilized caching capacity. Task completion latency gets minimized when frequently used services are cached. In [25], authors have presented the Outer Approximation Algorithm for minimizing latency (OAA). This paper introduces a mixed-integer non-linear programming problem for collaborative optimization. Parameters for cloudlet selection, admission control, and power distribution are all taken into account in the same way in the defined issue. With the cache enabling fog networks, the author of the paper [26] formulated the challenge of combined resource and power allocation. It's an NP-hard problem, particularly a mixed-integer non-linear programming issue (MINLP).. The presented challenge aims to reduce total network latency, under-power, cache capability, and QoS restrictions. The efficacy of the suggested algorithm gets assessed by network KPIs such as throughput, device count, minimum data rates, and latency. IoT admission, IoT association, power restriction for maximum throughput, cache enabled, data computation and storage, and also determined transmission, propagation, and processing delays are all constraints that have been determined by the authors of [23]- [26]. But none of them analyzed how users should get a fair distribution of IoT and RBs.

1.10 Motivations

After examining Table 1.1 our research is motivated by the challenges of resource allocation and task offloading in the context of IoT devices trying to establish connections with LEO cloudlets to offload their processing workload. The motivation behind our proposed method is to enhance the capabilities of massive MIMO-enabled MC systems to address these challenges effectively. The key focus is on improving processing, communication, and caching aspects to optimize task offloading efficiency and minimize task execution delays and power consumption. After reviewing the previous work on Hybrid GEO-LEO satellite network to the best of the authors comprehension, research gap considering the previous work identified is that joint admission control, IoT association and power allocation to ensure fairness while associating IoT and fairness in allocation of spectrum resources to associated IoT in hybrid geo-leo network with an objective to maximize Throughput has not been investigated in the past. The direction of the research remained focused in the following areas:

- Major part of research work on Hybrid GEO-LEO satellite network so far has been on throughput maximization, power allocation and user association.
- Existing techniques do not incorporate joint admission control, IoT association and power allocation in order to ensure following:
  - Fairness while associating IoT in Hybrid GEO-LEO satellite network.
  - Fairness in allocation of spectrum resources to associated IoT devices.
- Existing techniques haven't investigated Throughput maximization as an objective keeping in view above stated parameters.

1.11 Objectives

Motivated by the gaps found in past research work, this research work targets the following objectives to optimally allocate resources for throughput maximization in Hybrid GEO-LEO satellite network:

- Creating an efficient Hybrid GEO-LEO satellite network model incorporating GEO satellite, LEO satellites amd IoT devces.
- Defining objective function for throughput maximization.
- Defining constraints, i.e., IoT admission, IoT association, fairness while associating IoT devices, power, resource block allocation, fairness in allocation of resource blocks etc.
- Defining a optimization problem from objective function.
- Developing an algorithm/ technique based on defined optimization problem.
- Using developed algorithm/ technique, performance analysis via extensive simulations using Matlab.

1.12 Contributions

Our contributions provide novel insights and solutions to the challenges of task offloading, software caching, and power allocation in the context of the MRN system. By addressing these aspects, we aim to enhance the overall performance and efficiency of the system, opening up new possibilities for latency reduction and resource optimization in hybrid GEO-LEO networks or S-IoT environments.We propose a Throughput maximization problem that takes into account fairness-based admission control, IoT Association, spectrum resource allocation, and power distribution. Complex and non-deterministic polynomial-time hard (NP-hard), this problem is a mixed integer nonlinear programming (MINLP) challenge. The problem is then addressed with a $epsilon$-optimal method. Following are some of this work's most significant contributions:

1. We focus on developing multi-tier task scheduling and service caching systems aided by massive MIMO technology. Our approach involves caching services in computing and caching nodes (CCN) comprising nearby MRN. To optimize task execution, we have designed a mechanism that integrates task offloading, service caching, and communication resource allocation

2. We present an alternate optimization method for resolving the task offloading, service caching, and power allocation dilemma due to the NP-hard nature of the joint task scheduling and service caching optimization problem. We can solve the issues by decomposing the original joint optimization problem into the subproblems of task offloading, service caching, and MRN power allocation

3. To make joint task offloading and software caching decisions, we formulate the dual problem by transforming the non-convex power allocation subproblem into a linear optimization problem and then relaxing the task offloading and caching constraints using the classic Lagrange partial relaxation. We present an iterative optimization approach to identify the jointly optimal solution based on our findings about power allocation, task offloading, and software caching. Furthermore, the convergence of the suggested iterative technique is proved formally

4. Through comprehensive simulations, we assess the efficacy of the proposed massive MIMO-aided multi-tier MC systems. The simulation results in the later part of the thesis show that the suggested algorithm provides significant improvements over the conventional approaches for a wide variety of settings

1.13 Thesis Organization

Thesis is structured into six chapters as shown in Figure 1.2. Chapter wise details are as follows:

Chapter: 2 Hybrid GEO-LEO Satellite Network-5G In this thesis chapter, we delve into the realm of IoT devices and their association with satellites, exploring the heterogeneous nature of IoT deployments. We investigate the challenges posed by the joint admission control and fairness problem in the context of satellite-enabled IoT networks. To better understand the scope of the problem, we categorize satellites based on their specific characteristics and capabilities. In particular, we explore the potential benefits of hybrid geo-leo satellite networks in enhancing IoT connectivity and performance. Furthermore, the delays involved in communication channels within these networks and propose strategies for efficient task offloading and latency reduction. Our primary objective throughout this chapter is to maximize the throughput of IoT devices, considering the diverse requirements and constraints imposed by the satellite environment. By addressing these issues, we aim to contribute to the advancement of IoT and satellite technologies, enabling improved connectivity and communication for a wide range of applications.

Chapter: 3 System Model and Problem Formulation This chapter delves into the certification process for IoTs in a Hybrid GEO-LEO satellite network and the corresponding communication paradigm. Links between LEO, GEO, and IoT devices are incorporated into this form of communication. To maximize throughput in a hybrid GEO/LEO satellite network, we develop a mathematical model taking into account fairness-based admission control, Internet of Things (IoT) association, power distribution, and power consumption. Throughput maximization in a hybrid geostationary/low-Earth-orbit (GEO/LEO) satellite network is the focus of the proposed optimization approach.

Chapter: 4 Proposed Algorithm To optimize Throughput in a Hybrid GEO-LEO satellite network, a ϵ-optimal method is used in this chapter to solve the challenges of fairness in IoT association and spectrum allocation. For a variety of system parameters such as IoT association, Fair IoT distribution, RB fairness, and throughput, OAA's execution of the $epsilon$-optimal solution is demonstrated.

Chapter: 5 Simulations and Results The benefits of the suggested method in **chapter:4** for achieving fairness-based admission control, IoT association, power allocation, and throughput maximization are demonstrated through simulation results in this chapter. These findings also shed light on the convergence of the suggested method.

Chapter: 6 Conclusion The thesis's contributions are outlined in this section. Figure 1.2 presents the thesis's structure.

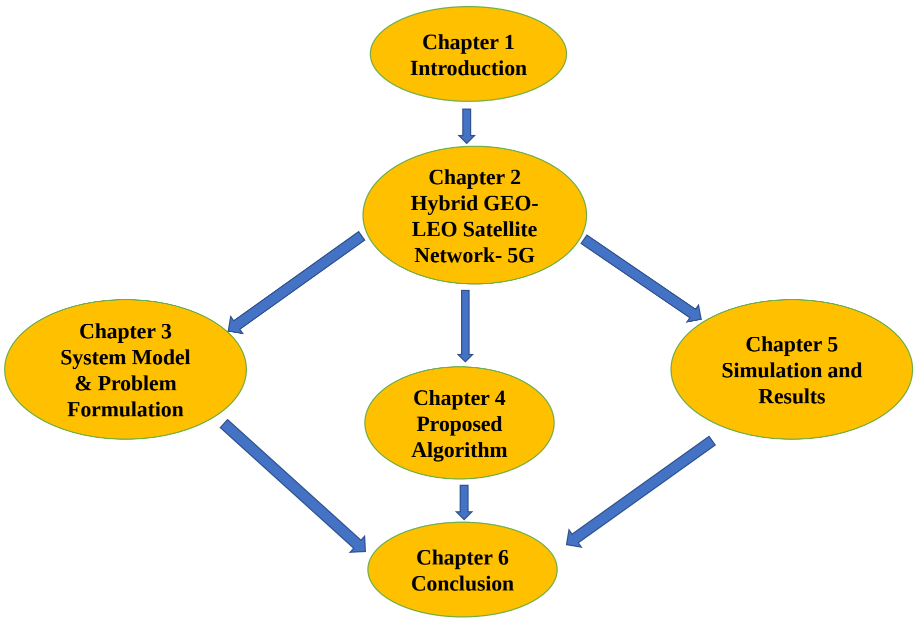

Figure 1.2: **Thesis organization**

Chapter 2

Hybrid GEO-LEO satellite Network- 5G

2.1 Internet of Things (IoT)

The Internet of Things (IoT) refers to a network of interconnected physical devices, vehicles, appliances, and other objects embedded with sensors, software, and network connectivity. In the modern era, with the sudden sprung of smart network nodes (such as cellular phones, smartwatches, and automobiles), and artificial intelligence, the resource extensive applications have exploded. These devices collect and exchange data, enabling them to interact and communicate with each other and with the cloud or other internet-based systems.

The key technologies involved in IoT are wireless sensor networks (WSN), cloud computing, big data, and embedded systems. To meet the need Information Communication Technology (ICT) plays a pivotal role in developing and delivering services for a variety of emerging and modern applications such as augmented reality, real-time online gaming, wearable cognitive assistance (WCA) applications, smart grids, and smart cities [27]. These real-time applications are embedded with devices (smart posture trainer, Near Field Communication (NFC) smart rings, virtual glasses, Global Positioning Systems (GPS) tracking bands, gaming armbands, etc.) that requires high computation capabilities, consume more energy, instantaneous data processing, and prompt responses. Internet of Things (IoT) devices is resource constrained having limited battery lifespan and computational capabilities. This makes them unfeasible to execute multiple applications locally, resulting in increased latency, network congestion, and resource contention. One feasible solution to efficiently utilize IoT is to offload the computational tasks to the resource-rich cloud servers, commonly termed Cloud Computing (CC) [28], [29].

2.1.1 Significance of IoT Devices

The significance of IoT lies in its ability to connect the physical world with the digital realm, enabling seamless integration and automation of various processes. IoT has the potential to revolutionize numerous industries and domains, including:

- **Smart Homes**: IoT devices in smart homes can control and monitor appliances, lighting, security systems, and climate control.
- **Healthcare**: IoT enables remote patient monitoring, smart medical devices, and real-time data collection for personalized healthcare. It improves patient care, allows early detection of health issues, and enhances the efficiency of healthcare delivery.
- **Smart Cities**: IoT technologies can be applied to manage and optimize various aspects of urban living, such as smart energy grids, waste management, traffic management, public safety, and environmental monitoring.
- **Real-time Communication**: IoT facilitates real-time communication and data exchange, enabling timely decision-making and immediate responses.
- **Enhanced Efficiency and Automation**: IoT facilitates communication and coordination between devices and systems, enabling automation and improved efficiency.

2.2 Heterogeneity of IoT devices

The heterogeneity of IoT devices refers to the diversity and variability among the different types of devices that are part of the Internet of Things ecosystem. IoT devices come in various forms, functionalities, and capabilities, leading to a heterogeneous environment. The heterogeneity of IoT devices presents both opportunities and challenges. On one hand, it enables a wide range of applications and use cases by accommodating diverse device functionalities. On the other hand, it poses challenges in terms of interoperability, security, data management, and system integration. Addressing these challenges requires standardized communication protocols, interoperability frameworks, and device management solutions to ensure seamless operation and interaction among heterogeneous IoT devices.

Here are some key aspects of the heterogeneity of IoT devices:

- **Device Types**: IoT devices encompass a wide range of devices, including sensors, actuators, wearables, appliances, industrial equipment, vehicles, and more.

- **Communication Protocols**: IoT devices can utilize different communication protocols to exchange data and interact with each other. Examples of communication protocols used in IoT include Wi-Fi, Bluetooth, Zigbee, Z-Wave, LoRaWAN, cellular networks, and more.

- **Processing Power**: IoT devices vary in terms of their processing power and computational capabilities. Some devices, such as smartphones or gateways, have higher processing power and can handle complex tasks, while others, like simple sensors, have limited processing capabilities.

- **Operating Systems and Software**: IoT devices may run on different operating systems or software platforms. Some devices have proprietary firmware or operating systems specific to the manufacturer, while others use open-source platforms like Linux or embedded systems.

2.3 Satellites in a Network

Satellites are artificial objects that are launched into space to perform various functions and provide a wide range of services. They orbit the Earth and are typically equipped with communication, imaging, navigation, or scientific instruments. Satellites play a crucial role in various sectors, including telecommunications, weather forecasting, navigation systems, Earth observation, and scientific research. Communication satellites are perhaps the most well-known type, as they enable global communication by relaying signals between different locations on Earth.

The signals of a satellite are most effective when they are focused on a specific location. When the region is concentrated, the emissions are confined to the specific area, limiting disturbance to adjacent systems. This results in increased spectrum efficiency. Importantly, satellite antenna patterns must be constructed to optimally cover the chosen geographical area. Satellites should be constructed with consideration for their short and long-term utility during their lifetime. If the satellite drifts from its orbit due to external influences, the earth station (ES) should be able to control it [30].

2.4 Categorization of Satellites

In a satellite network, multiple satellites are deployed and work together to provide various communication and connectivity services. These satellites can be categorized into different types based on their orbits and functions:

2.4.1 Geostationary Earth Orbit (GEO) Satellites)

GEO satellites are positioned in a geostationary orbit approximately 36,000 kilometers above the Earth's equator. They remain fixed relative to a specific point on the Earth's surface, allowing them to provide continuous coverage to a specific region. GEO satellites are commonly used for applications such as broadcasting, telecommunications, and weather monitoring.GEO satellites operate at higher signal power compared to satellites in other orbit types, such as LEO (Low Earth Orbit) or MEO (Medium Earth Orbit). The higher power helps to compensate for the longer signal propagation distance and ensure reliable communication with ground-based receivers. The distance between GEO satellites and ground-based receivers introduces a signal propagation delay. Since the satellites are located at a significant distance from the Earth's surface, the signal takes time to travel back and forth, resulting in a noticeable delay. /par

2.4.2 Low Earth Orbit (LEO) Satellites

LEO satellites orbit the Earth at altitudes ranging from a few hundred to a few thousand kilometers. They typically travel at higher speeds and complete one orbit around the Earth in a relatively short time, often around 90 minutes. LEO satellites provide coverage to specific regions as they pass overhead. Due to their lower altitudes, LEO satellites offer lower latency and higher data transfer rates compared to GEO satellites. They are commonly used for applications such as satellite internet, remote sensing, and global positioning systems (GPS). The proximity of LEO satellites to the Earth's surface results in lower signal propagation delay compared to GEO satellites. The shorter distance between the satellites and ground-based receivers reduces the round-trip time for data transmission, making LEO satellite networks suitable for applications that require low-latency.

2.4.3 Medium Earth Orbit (MEO) Satellites

MEO satellites are positioned between GEO and LEO satellites in terms of altitude. They orbit the Earth at altitudes ranging from a few thousand to tens of thousands of kilometers. MEO satellites are commonly used for applications such as navigation systems like the Global Navigation Satellite System (GNSS).

2.4.4 Polar Orbiting Satellites

Polar orbiting satellites travel in near-polar orbits, passing over the Earth's poles with each orbit. They provide global coverage by capturing data and imagery from different parts of the Earth's surface. Polar orbiting satellites are commonly used for weather forecasting, environmental monitoring, and scientific research.

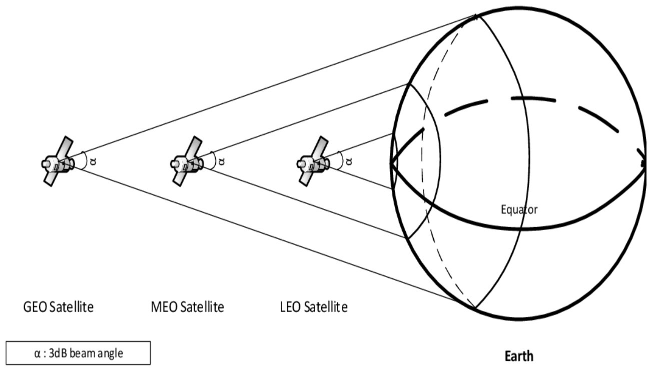

Figure 2.1: **Categorization of Satellites**

2.5 Setting up a Satellite Communication System

Figure **??** depicts a satellite communication system's interface with terrestrial entities. The satellite system consists of three segments: the space segment, the control segment, and the ground section [30]. Details are as follows:

- **Space Segment:** The space segment consists of one or more operational and reserve satellites arranged in a constellation.

- **Control Segment:** The control segment comprises of all ground infrastructure for the monitoring and controlling of satellites, often known as tracking, telemetry, and command (TTC) stations, and for the management of satellite traffic and associated resources for communication networks.

- **Ground Segment:** The ground segment includes all traffic ES. These stations can range in size from a few centimeters to tens of meters, depending on the sort of service being considered.

2.6 Advantages of Using a Satellite Network

Satellite networks offer several benefits that make them valuable for various applications. Here are some key benefits of satellite networks:

- **Global Coverage:**One of the significant advantages of satellite networks is their ability to provide coverage to even the most remote and inaccessible areas of the world. Satellites orbiting the Earth can establish communication links with ground stations, enabling connectivity in areas where terrestrial infrastructure is limited or non-existent.

- **Wide Area Coverage:** Satellite networks can cover vast areas, including entire continents or oceans, with a single satellite or a constellation of satellites. This wide area coverage allows for efficient and reliable communication across large geographical regions.

- **High Reliability:** The ground segment includes all traffic ES. These stations can range in size from a few centimeters to tens of meters, depending on the sort of service being considered.

- **Scalability:**Satellite networks can be easily scaled up or down by deploying additional satellites or adjusting their orbits. This scalability makes it possible to expand coverage and capacity as the demand for connectivity increases. It enables satellite networks to accommodate a growing number of users and devices, making them suitable for applications that require scalable and flexible communication infrastructure.

2.7 Hybrid GEO-LEO Satellite Network

A hybrid GEO-LEO satellite network is a communication infrastructure that combines geostationary Earth orbit (GEO) and low Earth orbit (LEO) satellites. It leverages the strengths of both satellite constellations to create a robust and versatile network. The network provides a robust and versatile communication infrastructure with global coverage, reduced latency, mobility support, scalability, and resilience. It offers a multitude of opportunities for various communication applications and services.

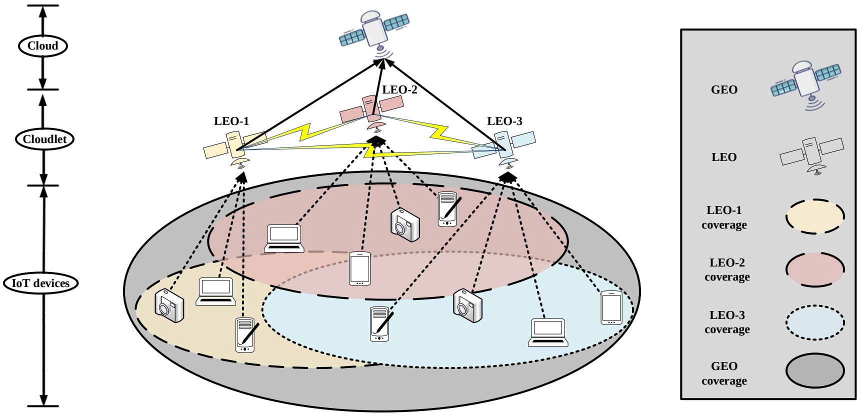

Figure 2.2: **Hybrid GEO-LEO satellite Network Model**

2.7.1 Characteristics of Hybrid GEO-LEO Satellite Network

Key characteristics of a hybrid GEO-LEO satellite network include:

- **Coverage**: The combination of GEO and LEO satellites allows for global coverage. GEO satellites cover larger areas from high altitudes, while LEO satellites provide more focused regional coverage.

- **Latency**: The inclusion of LEO satellites in the network can reduce latency compared to a pure GEO satellite network. LEO satellites orbit closer to the Earth, resulting in shorter signal travel distances and faster communication.

- **Scalability**: Hybrid networks offer scalability by allowing for the addition of LEO satellites to increase network capacity and coverage in specific regions.

2.8 Communication Channels

The link between transmitting and receiving devices comprises of either a radio or optical modulated carrier. The efficiency of the transmitting equipment is determined by its effective isotropic radiated power (EIRP), which is the power provided to the antenna multiplied by the antenna's gain in the direction under consideration. $\frac{G}{T}$, the proportion of the antenna receive gain, G, in the considered direction to the system noise temperature, T, measures the performance of receiving equipment; $\frac{G}{T}$ is known as the receiver's figure of merit [30].

- UL from ES to satellites.
- DL from satellites to ES.
- Inter-satellite links amongst satellites.

2.9 Wireless Communication

Wireless communication has evolved over the years through different generations, each bringing advancements in technology, speed, and capabilities. Here are the details of wireless communication, including its generations:

2.9.1 1G (First Generation)

Introduced in the 1980s, 1G networks used analog signals and employed Frequency Division Multiple Access (FDMA) for dividing the frequency spectrum among users. They provided basic voice calling capabilities but did not support data transfer. However, 1G networks had limited capacity and coverage. The most notable 1G system was the Advanced Mobile Phone System (AMPS), which was introduced in North America and later adopted in other parts of the world. AMPS used analog modulation techniques to transmit voice signals over the airwaves. 1G networks operated on the 800 MHz frequency band.

2.9.2 2G (Second Generation)

Deployed in the 1990s, 2G networks marked the transition to digital communication. They utilized technologies like Time Division Multiple Access (TDMA) and Global System for Mobile Communications (GSM). 2G networks offered improved voice quality, enhanced capacity, and supported basic data services such as text messaging and limited internet access. The networks expanded coverage and allowed for international roaming.There were two main standards for 2G networks: GSM (Global System for

Mobile Communications) and CDMA (Code Division Multiple Access). GSM became the dominant standard globally, while CDMA gained popularity in some regions. Both standards offered similar features and capabilities.

2.9.3 3G (Third Generation)

Introduced in the early 2000s, 3G networks brought significant improvements in data transfer speeds and capabilities. They employed technologies like Code Division Multiple Access (CDMA) and Universal Mobile Telecommunications System (UMTS). 3G networks offered higher data rates, enabling services like video calling, multimedia messaging, and mobile internet access. The networks supported more advanced applications and services, including GPS navigation and video streaming. The two primary 3G standards were CDMA2000 (Code Division Multiple Access 2000) and UMTS (Universal Mobile Telecommunications System). CDMA2000 was widely deployed in North America and some parts of Asia, while UMTS gained prominence in Europe and other regions. 3G networks provided significantly faster data speeds compared to 2G. They offered download and upload speeds ranging from several hundred kilobits per second (Kbps) to a few megabits per second (Mbps).

2.9.4 4G (Fourth Generation)

Deployed in the late 2000s, 4G networks represented a major advancement in wireless communication. They introduced technologies like Long-Term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMAX). 4G networks provided significantly higher data rates, low latency, improved spectral efficiency, and supported advanced services such as high-quality video streaming, online gaming, and faster internet browsing. The networks enabled seamless connectivity and paved the way for the rise of mobile apps and services. 4G networks provided significantly faster data transmission speeds compared to 3G. They offered download and upload speeds ranging from several megabits per second (Mbps) to tens of Mbps, and in some cases even surpassed 100 Mbps.

2.9.5 5G (Fifth Generation

Launched in the 2020s, 5G is the latest generation of wireless communication. It utilizes technologies like millimeter waves (mmWave), massive MIMO (Multiple Input Multiple Output), and beamforming. 5G networks offer extremely high data rates, ultra-low latency, massive device connectivity, and support a wide range of applications. They enable advancements in areas such as autonomous vehicles, smart cities, augmented reality, virtual reality, and the Internet of Things (IoT). 5G networks provide significantly faster data transmission speeds compared to 4G. It offers download and upload speeds in the gigabit per second (Gbps) range, enabling ultra-fast file transfers, seamless streaming of 4K/8K videos, and immersive virtual reality (VR) experiences. 5G networks drastically reduce latency, enabling near real-time communication.

2.10 The Function of Satellites in 5G Networks

For the vision of the 5^{th} generation (5G) to be completely comprehended (i.e., almost ubiquitous and instant connection for a big number of UE worldwide), terrestrial networks that mainly banks on underground optical fiber cable might not be sufficient.

As an alternative, there is a need for either a transition from a totally distinct satellite and terrestrial networks system in which satellites are mainly used to solve the last mile problem or for specific use cases to an integrated 5G network of networks in which satellites perform a critical role alongside terrestrial networks.

Even though the usefulness of satellite communications is further restricted in both inter-cities and intra -city communications (zones having dominance of fiber and Wi-Fi and the satellite's lines of sight are drastically decreased), incorporating satellite and terrestrial networks will be required to achieve the full spectrum of anticipated upcoming requirements on 5G networks. These consist of:

- Growing traffic as well as the amount of connections outside of densely populated urban hubs in more remote/ rural extents as a result of the emergence of Internet of Things (IoT).

- Offering coverage for mobile devices.

- Computining and data caching moving closer to the networks' edge and beyond areas having abundant fiber accessibility.

Consider the connectivity requirements of mobility. Once a mobile asset is detached (vehicle, ship or a jet) from fiber network, it can still be kept linked via terrestrial WiFi or terrestrial 5G infrastructure provided it is within or in near vicinity of the city. Only satellite communications can offer reliable coverage and sufficient data density in rural and remote areas.As the amount, types, and needs of connectivity continues to expand, so does the necessity of outspreading the potential of 5G networks outside densely networked city areas.

In order to encounter these challenges, satellites require to offer a variety of functions, including the last mile problem, on the move connectivity, backup for important services in emergency, edge-networking, and IoT congested traffic locations outside densely networked city areas. Briefly, satellites will be essential in shaping the collective 5G destiny. The terrestrial and satellite components will decide the type and level of connection that 5G networks can offer. In fact, as opposed to what they could have enabled in principle.

Consequently, as we go from legacy generations like 3^{rd} generation (3G) to more current generations such as 4^{th} generation (4G) Long Term Evolution (LTE) and now to 5G. 5G offers more than just a significant change in the possibilities for, functions of, and the interplay of hardware-software in mobile networks. The transition between terrestrial and space-based communications networks generally could be facilitated by 5G. Importantly, this integration is made technically and financially achievable for the first time thanks to changes in the underlying technology and business models of satellite firms.

It is not just hypothetical that terrestrial and space-based telecommunications networks will converge for 5G. Together, these three factors— changing business models, expanding bandwidth demand, and developing satellite system technology—make it plausible, however not unavoidable, for satellites to play an important part in telecommunications networks in broad-spectrum and 5G networks in specific [31].

2.11 Possible Roles of Satellites in 5G Networks

To deliver on the full promise of 5G networks (near-universal, instantaneous coverage for a large number of connected devices), satellites will also need to play a far more central role in future telecommunications networks, with both terrestrial and space-based components performing a greater variety of tasks. For the first time, the expansion of satellite sector both in terms business models and technology is now achievable [31].

In 5G networks, satellites might potentially perform three functions: providing additional backhaul, providing redundancy, and enhancing connection in remote and rural locations. In each situation, a variety of revenue models could possibly surface, ranging from D2D connections to end user to core network links.

2.11.1 Redundancy in communication systems

With the trend towards proliferation of LEOs, currently satellites possess the ability to provide overlay networks that duplicate portions of the terrestrial networks in addition to meeting the rising demand. If current terrestrial networks become less functional as a result of either a man-made or some sort of natural disaster, an overlay network may replace or supplement those networks. Even though their usefulness would be limited, they could be able to provide priority to vital services and give operators some breathing room until they restore connectivity to terrestrial networks. In short, 5G networks pose a potential single catastrophic point of failure because they will indeed be neccessary not just for the everyday running of ones business, but also for the community, governments, and the armed forces. In the case of a disaster, satellite systems that are overlaid on portions of terrestrial systems and are considered tactically significant or necessary for emergency procedures might increase the resilience of those systems through redundancy.

2.11.2 Improving Access to Internet Services in Remote and Rural Areas

GEO has historically been essential in addressing the ”last mile” issue. That role could expand in terms of size i.e., the quantity of links alongwith scope with the expansion of swarms of LEOs where those links can be established. Mobile phones and a wide range of IoT devices, including billions of sensors, will be among the exponentially increasing number of connected devices that 5G networks will enable. Think of interstate travel by vehicle, air travel by plane and sea travel by ship, and sensor-filled agricultural fields. Also consider rural hospitals doing remote surgery. While satellites need line of sight to connect directly to a device, which limits their usefulness in densely populated areas, the possibility for massive machine-type communications and the reality that most of these equipment will be dispersed over large geographic space will increase the requirement of collection and dissemination of data across 5G networks. By utilizing the extensive satellite coverage made possible by the proliferation of LEOs, satellites incorporated with terrestrial networks via novel network architectures can offer a significant answer in this situation as well. One of the main advantages in this aspect is that LEOs, as opposed to GEOs, can now provide a true interactive experience, a level of connectedness that has hitherto been unavailable in rural and isolated locations. The connection of rural locations where installing fiber is neither practical or economically viable can be increased through incorporation of satellite systems that are more thoroughly integrated into 5G networks.

2.12 The drawbacks of using a cellular network

Cellular networks, while providing extensive coverage and reliable connectivity for mobile communication, have certain limitations that can impact their performance and functionality. One limitation is coverage constraints, as there are areas with limited or no cellular coverage, such as remote rural regions or underground locations. Signal strength and coverage can be affected by physical obstructions, leading to dead zones or weak signal areas.

- **Bandwidth Constraints**: Cellular networks allocate a limited amount of bandwidth for data transmission. With the growing demand for data-intensive applications, such as streaming videos, large file downloads.
- **Latency**: Latency refers to the delay experienced in data transmission between devices and network servers. Cellular networks, especially in certain network generations like 4G, can have higher latency compared to other network technologies.

- **Reliability**: While cellular networks generally offer reliable connectivity, they can experience service disruptions or downtime due to various factors like natural disasters, network outages, or technical issues.

- **Power Consumption**: Mobile devices connected to cellular networks consume significant amounts of power, especially when using high-speed data connections or in areas with weak signal strength.

2.13 Task offloading in Hybrid GEO-LEO satellite network

Task offloading in a hybrid GEO-LEO satellite network refers to the process of transferring computational tasks from user devices to the satellite network for remote processing. This approach leverages the capabilities of both geostationary (GEO) and low Earth orbit (LEO) satellites to offload computing tasks and reduce the workload on user devices. In a hybrid GEO-LEO satellite network, GEO satellites are positioned at a fixed point above the Earth's equator, providing wide coverage but with higher latency due to their higher altitude. LEO satellites, on the other hand, orbit at lower altitudes and offer lower latency but limited coverage. By combining these two satellite types, the network can benefit from both global coverage and reduced latency.

The process of task offloading in a hybrid GEO-LEO satellite network typically involves several steps. First, the network needs to determine which tasks are suitable for offloading based on certain criteria, such as task complexity, available satellite resources, and network conditions. Once identified, the tasks are transmitted to the satellite network through the appropriate communication channels. Upon receiving the offloaded tasks, the satellite network performs the necessary computations and processes the data. The results are then transmitted back to the user devices, completing the offloading process. This enables user devices to offload computationally intensive tasks and utilize the satellite network's computational capabilities, leading to improved performance, reduced energy consumption, and enhanced user experience.

Task offloading in a hybrid GEO-LEO satellite network offers several advantages. It enables efficient utilization of satellite resources, reduces the processing workload on user devices, and mitigates latency issues associated with traditional terrestrial networks. Overall, task offloading in a hybrid GEO-LEO satellite network plays a crucial role in optimizing resource utilization, enhancing computational capabilities, and improving the efficiency of networked systems.

2.13.1 Task offloading via LEO

Task offloading via LEO (Low Earth Orbit) satellites in a hybrid GEO-LEO network refers to the process of transferring computational tasks from user devices to LEO satellites for remote processing. In a hybrid network architecture that combines both GEO and LEO satellites, task offloading via LEO offers several benefits, including reduced latency and improved responsiveness. LEO satellites are positioned at relatively lower altitudes, resulting in shorter communication links and lower signal propagation delays compared to GEO satellites. Once the tasks are selected, the user devices establish a communication link with the LEO satellites for task offloading. The LEO satellites receive the offloaded tasks and execute them using their onboard processing capabilities. The computational results are generated within the satellite network, taking advantage of the high-performance computing resources available in space.

Task offloading via LEO in a hybrid GEO-LEO network leverages the proximity and computational capabilities of LEO satellites to enhance the overall performance of networked applications. By offloading computationally intensive tasks to LEO satellites, users can benefit from reduced latency, improved response times, and enhanced scalability, particularly for applications that require real-time or near real-time processing. This approach enables the seamless integration of satellite-based computing resources into the hybrid network architecture, opening up new possibilities for distributed computing and advanced applications in various domains.

2.13.2 Task offloading via GEO

Task offloading via GEO (Geostationary Earth Orbit) satellites in a hybrid GEO-LEO network involves transferring computational tasks from user devices to GEO satellites for remote processing. While LEO (Low Earth Orbit) satellites offer lower latency, GEO satellites provide global coverage and are well-suited for certain types of applications. In a hybrid network architecture that combines both GEO and LEO satellites, task offloading via GEO can be advantageous for applications that have less stringent real-time requirements or can tolerate higher latency. Here's a step-by-step overview of task offloading via GEO in a hybrid GEO-LEO network:

- **Task Selection**: The task offloading process starts by identifying computational tasks that are suitable for offloading to GEO satellites. These tasks are typically less time-sensitive.

- **Communication Setup**: User devices establish communication links with the GEO satellites to initiate the task offloading process.

- **Task Execution**: The GEO satellites receive the offloaded tasks and execute them using their onboard computational resources. The satellites perform the required computations and generate the results based on the provided task instructions and data.

- **Result Retrieval**: Once the tasks are processed, the computed results are transmitted back to the user devices over the established communication links.

Task offloading via GEO in a hybrid GEO-LEO network leverages the global coverage and stable communication links provided by GEO satellites. It is particularly beneficial for applications that have less stringent real-time requirements or can tolerate higher latency. By offloading computational tasks to GEO satellites, users can take advantage of the computational capabilities of the satellite network and reduce the processing load on their devices, enabling more efficient resource utilization and improved scalability in the network. The decision of whether to offload a task to GEO satellites is based on various factors such as task characteristics, network conditions, and user preferences. Load balancing techniques can be employed to distribute the computational workload among the available GEO satellites, ensuring efficient resource utilization and optimal performance.

Overall, task offloading via GEO in a hybrid GEO-LEO network enhances the scalability and efficiency of networked systems, supporting a wide range of applications and services that can benefit from the global coverage and stable communication links provided by GEO satellites.

2.14 Theoretical framework for optimum resource utilization

Optimization theory can be applied to address various challenges related to IoT associations, such as maximizing utility, throughput, quality of service (QoS), energy efficiency (EE), and spectrum efficiency. Here are some optimization approaches that can be utilized:

- **Throughput Optimization:** This focuses on maximizing the data throughput in the IoT network. By optimizing parameters such as transmission power, resource allocation, and scheduling algorithms.

- **QoS-based Optimization:** QoS optimization aims to meet specific performance requirements, such as latency, reliability, and packet loss rate, for different IoT applications. This involves optimizing network parameters, such as transmission power, routing paths.

Optimization theory provides a mathematical framework to model and solve these problems. Techniques such as linear programming, convex optimization, stochastic optimization, and game theory can be applied to formulate and solve optimization problems in IoT associations.

2.14.1 Optimizing Resource Allocation in 5G Hybrid GEO-LEO Satellite Networks for IoT Association

In the context of a 5G Hybrid GEO-LEO satellite network, the association problem in IoT refers to the challenge of efficiently allocating and managing resources to maximize the utility and performance of IoT devices. This problem becomes more complex due to the presence of resource constraints, such as limited bandwidth, processing power, energy, and storage capacity. The association problem involves determining which IoT devices should be connected to which network access points (e.g., satellite nodes, ground stations, or base stations) to optimize resource utilization and enhance the overall system performance. The goal is to ensure that each IoT device is associated with the most suitable access point that can provide sufficient resources to meet its requirements and achieve its intended functionality.

To address these challenges, sophisticated resource allocation and management techniques need to be employed. These techniques aim to optimize the allocation of available resources, taking into account the requirements and constraints of the IoT devices. This may involve dynamic resource allocation algorithms that consider factors such as device priorities, traffic demands, channel conditions, and energy efficiency.

Moreover, in a hybrid GEO-LEO satellite network, where IoT devices can connect to both terrestrial base stations and satellite nodes, the association problem becomes more intricate. The optimal association of IoT devices with access points needs to consider factors such as the distance to the access points, signal strength, latency, and cost-effectiveness of using satellite or terrestrial links.

2.15 Understanding delays in network channels

Delays involved in network channels refer to the time it takes for data to traverse through various components of a network. There are several types of delays that can occur in network channels. These delays collectively contribute to the overall latency or delay experienced in network channels. Minimizing and managing these delays are crucial for ensuring efficient and timely communication in a network.

2.15.1 Transmission Delay

Transmission delay refers to the time it takes for a data packet to travel from the source to the destination in a communication network. It is an important parameter that affects the overall performance and responsiveness of the network. The type of medium used for data transmission, such as copper wires, fiber optics, or wireless channels, can affect the transmission delay. Each medium has different propagation characteristics, and the speed of signal propagation varies accordingly. It is influenced by factors such as the bandwidth of the channel and the size of the data being transmitted.

2.15.2 Propagation Delay

Propagation delay, also known as signal propagation time or transit delay, refers to the time it takes for a signal or data packet to travel from the source to the destination in a communication system. It represents the time delay caused by the physical transmission medium, such as cables, optical fibers, or wireless channels. The physical distance between the source and destination directly affects the propagation delay. As the distance increases, the propagation delay also increases because the signal needs time to travel through the transmission medium. Propagation delay is an inherent characteristic of the physical transmission medium and cannot be eliminated entirely.

2.15.3 Processing Delay

Processing delay refers to the time it takes for a device or system to process a received signal or data packet before it can be forwarded or acted upon. It is a delay introduced by the processing capabilities and operations of the devices involved in the communication network. It occurs when data passes through network devices, such as routers or switches, where they undergo various operations, including data packet inspection, routing decisions, and protocol processing. The processing delay is influenced by the capabilities and workload of the network devices.

2.15.4 Queuing Delay

Queuing delay refers to the delay experienced by data packets or signals while waiting in a queue at IoT or LEO for processing or transmission in a network. It is a delay that occurs when there is congestion or limited resources in the network, and packets must wait their turn to be processed or transmitted. Managing and minimizing queuing delay is crucial for maintaining good network performance and providing quality of service (QoS) guarantees. Techniques such as traffic shaping, congestion control, and quality-of-service mechanisms can be employed to regulate packet arrival rates, allocate resources effectively, and prioritize packets based on their importance or QoS requirements.

Chapter 3

SYSTEM MODEL AND PROBLEM FORMULATION

3.1 System Model

The Internet of Things (IoT) devices, cloudlet, and cloud are depicted in a three-tiered architecture in Fig. 3.1. Here, LEO and GEO satellites are performing the functions of cloudlet and cloud, respectively. We assume that IoT devices are located in far flung/ remote areas where telecommunication infrastructure is not available. These IoT devices are equipped with sensors to collect the data from the surrounding and transmit data to third party for storage, data fusion, and computation. Since, these IoT devices lack storage, and computation capabilities, however, LEO and GEO satellites are equipped with plenty of on-board storage, and computation capabilities. Hence, LEO satellite as cloudlet and GEO as cloud offer the services like storage, and computation to the IoT devices in the far flung areas void of telecommunication infrastructure.

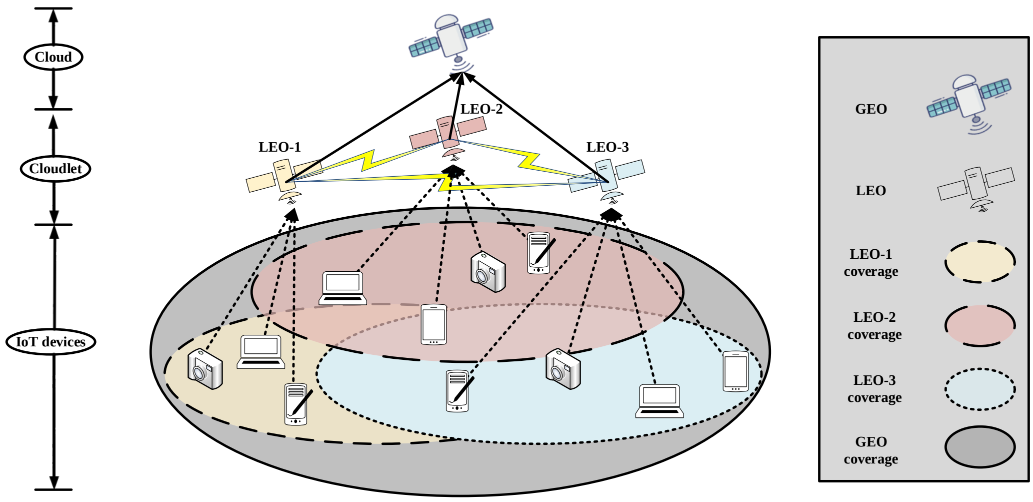

Figure 3.1: **GEO and LEO hybrid satellite network.**

Lets consider a system with time slots and indexed as $t \in \mathbb{T} = \{0, 1, 2, 3, ...\}$. Lets a set of IoT devices denoted by $\mathbb{K}(t)$ where $k(t) \in \mathbb{K}(t) = \{1, 2, 3, ..., K(t)\}$ are operating in the time slot t and this set of IoT devices are served when $M(t)$ number of LEO-cloudlets where $m(t) \in \mathbb{M}(t) = \{1, 2, 3, ..., M(t)\}$ fly over the $K(t)$ IoT devices in far flung area. These LEO-cloudlets are inter-connected via microwave links to share the traffic load of $K(t)$ IoT devices with fairness. Moreover, $M(t)$ LEO-cloudlets have a high capacity microwave link with the GEO-cloud. The GEO-cloud will share the work load in case the LEO-cloudlet $m(t)$ can't entertain the storage, and the computation request from a IoT device $k(t)$. Thus, there are two different modes of communication and discussed separately in sub-section 3.3.

3.2 Resource allocation model

Few binary variables to show IoT device $k(t) \in \mathbb{K}(t)$ admission, association, and availability of LEO-cloudlet are defined below:

- 1^{st} **definition:** Let the $0/1$ indicator to show wether a IoT device $k(t) \in \mathbb{K}(t)$ is admissible or not is given below:

$$\alpha_k(t) = \begin{cases} 1, & \text{IoT device is admissible} \quad (3.1a) \\ 0, & \text{Otherwise} \quad (3.1b) \end{cases}$$

- 2^{nd} **definition:** Let the $0/1$ indicator to show wether a IoT device $k(t) \in \mathbb{K}(t)$ is associated with LEO-cloudlet $m(t) \in \mathbb{M}(t)$ or not is given below:

$$\beta_{k,m}(t) = \begin{cases} 1, & \text{IoT device is associated} \quad (3.2a) \\ 0, & \text{Otherwise} \quad (3.2b) \end{cases}$$

- 3^{rd} **definition:** Let the $0/1$ indicator to show wether a LEO-cloudlet $m(t) \in \mathbb{M}(t)$ is available to fulfill request of the IoT device $k(t)$ or not is given below:

$$\gamma_{k,m}(t) = \begin{cases} 1, & \text{LEO-cloudlet is available} \quad (3.3a) \\ 0, & \text{Otherwise} \quad (3.3b) \end{cases}$$

Here, a LEO-cloudlet $m(t) \in \mathbb{M}(t)$ can provide services to more than one IoT devices, however, an IoT device $k(t) \in \mathbb{K}(t)$ can associate with only one LEO-cloudlet $m(t) \in \mathbb{M}(t)$. This association of IoT devices should be such that fairness is maintained while distributing the traffic load among all LEO-cloudlets. Mathematically, the fairness is ensured using Jain's fairness index [32] as below:

$$\delta_{k,m}(t) = \frac{\left(\sum_{m(t)\in\mathbb{M}(t)} \left(\sum_{k(t)\in\mathbb{K}(t)} \beta_{k,m}(t)\right)\right)^2}{M(t)\left(\sum_{m(t)\in\mathbb{M}(t)} \left(\sum_{k(t)\in\mathbb{M}(t)} \beta_{k,m}(t)\right)^2\right)}, \tag{3.4a}$$

$$0 \leq \delta_{k,m} \leq 1), \tag{3.4b}$$

where $\delta_{k,m}(t)$ in (3.4a) is the user fairness index (UFI) and it's value ranges between zero and one as shown in (3.4b). The value of UFI is one when the distribution/ association of $K(t)$ IoT devices traffic load to the $M(t)$ LEO-cloudlets follow the optimum fairness.

Every IoT device $k(t) \in \mathbb{K}(t)$ can transmit data file to the LEO-cloudlet $m(t) \in \mathbb{M}(t)$ using it's power within upper limit of P_k. Mathematically, the range of allocated power with in the upper limit is given below:

$$0 \leq p_{k,m}(t) \leq P_k, \forall\, k(t) \in \mathbb{K}(t),\, m(t) \in \mathbb{M}(t), \tag{3.5}$$

Every IoT device $k(t) \in \mathbb{K}(t)$ can associate and transmit data to a LEO-cloudlet $m(t) \in \mathbb{M}(t)$ [33]. The signal in the UL suffers path loss, attenuation due to rain, and attenuation due to atmospheric gasses when a IoT device $k(t) \in \mathbb{K}(t)$ associates and transmits data to LEO-cloudlet $m(t) \in \mathbb{M}(t)$. The channel gain between a IoT device and a LEO-cloudlet in the UL is given by [34].

$$h_{k,m}(t) = \frac{G_k^{\text{Tx}} G_m^{\text{Rx}}}{\xi_{k,m}^{PL}(t)\xi_{k,m}^{Rain}(t)\xi_{k,m}^{Gas}(t)}, \tag{3.6a}$$

$$\xi_{k,m}^{PL}(t) = \left(\frac{4\pi f_c s_{k,m}(t)}{\upsilon}\right)^2, \tag{3.6b}$$

$$\xi_{k,m}^{Rain}(t) = J_r \Re^{\mu_r} L_e, \tag{3.6c}$$

$$\xi_{k,m}^{Gas}(t) = \frac{A_w A_o}{sin\theta_{k,m}(t)}, \tag{3.6d}$$

where G_k^{Tx} and G_m^{Rx} are the antenna gains of IoT device and LEO-cloudlet, respectively. The $\xi_{k,m}^{PL}(t)$, $\xi_{k,m}^{Rain}(t)$, and $\xi_{k,m}^{Gas}(t)$ are the free space path loss, rain attenuation, and atmospheric gases attanuation, respectively. f_c is carrier frequency, $s_{k,m}(t)$ is the distance between IoT device $k(t) \in \mathbb{K}(t)$ and the LEO-cloudlet $m(t) \in \mathbb{M}(t)$. The υ is the speed of light. J_r and μ_r are the coefficients which depends on the frequency. L_e is the wave effective path length in the rain and $\Re$ is the rain fall intensity. A_w and A_o are the absorptions due to water vapours and oxygen, respectively [35]. $\theta_{k,m}(t)$ is the elevation angle between IoT device $k(t) \in \mathbb{K}(t)$ and LEO-cloudlet $m(t) \in \mathbb{M}(t)$ [36].

According to shannon's capacity theorem, the achievable uplink data rate $\psi_{k,m}(t)$ from IoT device $k(t) \in \mathbb{K}(t)$ to the LEO-cloudlet $m(t) \in \mathbb{M}(t)$ is determined as below:

$$\psi_{k,m}(t) = b_{k,m}(t) log_2 \left(1 + \beta_{k,m}(t)\Phi_{k,m}(t)\right), \tag{3.7a}$$

$$\Phi_{k,m}(t) = \frac{p_{k,m}(t) h_{k,m}(t)}{I_{k',m}(t) + \sigma^2}, \tag{3.7b}$$

$$I_{k',m}(t) = \sum_{m(t)\in\mathbb{M}(t)} \beta_{k',m}(t) p_{k',m}(t) h_{k',m}(t), \tag{3.7c}$$

where $k' \neq k$, $\beta_{k,m}(t) = 1$ when IoT device $k(t) \in \mathbb{K}(t)$ associates with the LEO-cloudlet $m(t) \in \mathbb{M}(t)$, and $\beta_{k,m}(t) = 0$ otherwise. The $b_{k,m}(t)$ is the channel bandwidth, $\Phi_{k,m}(t)$ is the signal to interference and noise ratio, σ^2 is the noise, and $I_{k',m}(t)$ is the interference from IoT device $k'(t) \in \mathbb{K}(t)$ to LEO-cloudlet $m(t) \in \mathbb{M}(t)$ in the UL.

The resource blocks are allocated to a IoT device $k(t) \in \mathbb{K}(t)$ by LEO-cloudlet

$m(t) \in \mathbb{M}(t)$ as per the requirement of quality of service (QoS). Mathematically, the number of resource blocks required to fulfill a particular data rate QoS and resource block fairness index (RFI) are given below:

$$r_{k,m}(t) = \left\lceil \frac{Q_{k,m}(t)}{\psi_{k,m}(t)} \right\rceil, \tag{3.8a}$$

$$\zeta_{k,m}(t) = \frac{\sum\limits_{m(t)\in\mathbb{M}(t)} r_{k,m}(t)}{\sum\limits_{m(t)\in\mathbb{M}(t)} \beta_{k,m}(t)}, \tag{3.8b}$$

$$\varphi_{k,m}(t) = \frac{\left(\sum\limits_{m(t)\in\mathbb{M}(t)} \left(\sum\limits_{k(t)\in\mathbb{K}(t)} \zeta_{k,m}(t)\right)\right)^2}{M(t)\left(\sum\limits_{m(t)\in\mathbb{M}(t)} \left(\sum\limits_{k(t)\in\mathbb{M}(t)} \zeta_{k,m}(t)\right)^2\right)}, \tag{3.8c}$$

$$0 \leq \varphi_{k,m}(t) \leq 1, \tag{3.8d}$$

where $r_{k,m}(t)$ in (3.8a) denotes the number of resource blocks required to fulfill $Q_{k,m}(t)$ data rate requirement. $\zeta_{k,m}(t)$ in (3.8b) is the normalized number of resource block by associated IoT devices with a LEO-cloudlet. $\varphi_{k,m}(t)$ in (3.8c) is the RFI and it's value ranges between zero and one shown in (3.8d). The value of RFI is one when the allocation of resource blocks to IoT devices follow optimum fairness.

3.3 Task offloading model

In this cellular environment, there are two modes to fulfill the data storage, and computation requests by the $K(t)$ IoT devices,i.e., LEO-cloudlet mode or GEO-cloud mode. LEO-cloudlet mode is the first choice of the IoT device since involves little latency due to less distance between IoT device and LEO-cloudlet. Second choice is the GEO-cloud mode if the data storage, and computation request by the IoT device $k(t) \in \mathbb{K}(t)$ is not fulfilled by the LEO-cloudlet $m(t) \in \mathbb{M}(t)$. The detail of two modes is given below:

1. **LEO-cloudlet mode:** Let the IoT device $k(t) \in \mathbb{K}(t)$ is operating in the far flung area and records two data files $f^s_{k,m}(t)$ and $f^c_{k,m}(t)$ from the surrounding environ-

ment. The $f^s_{k,m}(t)$ and $f^c_{k,m}(t)$ are the data files to be stored, and computed, respectively, by the IoT device $k(t) \in \mathbb{K}(t)$ to the LEO-cloudlet $m(t) \in \mathbb{M}(t)$. The Ω_s^{LEO} and Ω_c^{LEO} are storage and computation capacity of the LEO-cloudlet, respectively. The storage and computation tasks need to be performed by LEO-cloudlet $m(t) \in \mathbb{M}(t)$. These tasks are scheduled, queued, and transmitted to be accomplished in available N time windows. Latency experienced while completing these tasks is given below:

$$d^{\text{LEO}}_{k,m,q}(t) = \tau(N-1), \tag{3.9a}$$

$$d^{\text{LEO}}_{k,m,tr}(t) = \frac{f^{\text{s}}_{k,m}(t) + f^{\text{c}}_{k,m}(t)}{\psi_{k,m}(t)}, \tag{3.9b}$$

$$d^{\text{LEO}}_{k,m,\rho}(t) = \frac{s_{k,m}(t)}{\upsilon}, \tag{3.9c}$$

$$d^{\text{LEO}}_{k,m,c}(t) = \eta\left(\frac{f^{\text{c}}_{k,m}(t)}{\Omega_c^{\text{LEO}}}\right), \tag{3.9d}$$

$$d^{\text{LEO}}_{k,m,T}(t) = d^{\text{LEO}}_{k,m,q}(t) + d^{\text{LEO}}_{k,m,tr}(t) + d^{\text{LEO}}_{k,m,\rho}(t) + d^{\text{LEO}}_{k,m,c}(t), \tag{3.9e}$$

where $d^{\text{LEO}}_{k,m,q}(t)$ is the queue delay, $d^{\text{LEO}}_{k,m,tr}(t)$ is the transmission delay, $d^{\text{LEO}}_{k,m,\rho}(t)$ is the propagation delay, $d^{\text{LEO}}_{k,m,c}(t)$ is the computing delay, and $d^{\text{LEO}}_{k,m,T}(t)$ is the total delay occur while completing the tasks of the IoT device $k(t) \in \mathbb{K}(t)$. The η is the number of CPU cycles required to compute the data at LEO-cloudlet and Ω_c^{LEO} is computing ability of the LEO-cloudlet in cycles/second. The $s_{k,m}(t)$ is the distance between IoT device $k(t) \in \mathbb{K}(t)$ and LEO-cloudlet $m(t) \in \mathbb{M}(t)$. The τ is the length of a time window, N is the total time windows.

2. **GEO-cloudlet mode:** GEO-cloud is contacted if the request by IoT device $k(t) \in \mathbb{K}(t)$ to store and compute the data files is not entertained by the LEO-cloudlet $m(t) \in \mathbb{M}(t)$. LEO-cloudlet $m(t) \in \mathbb{M}(t)$ sends the request to store and compute the data files to GEO-cloud. As the distance involved between LEO-cloudlet and GEO-cloud is very much high, so propagation delay involved will add too much latency to fulfill the request of IoT device $k(t) \in \mathbb{K}(t)$. In this case, the propagation delay [37] involved in storing and computing the requested

data files is given below:

$$d_{k,m,\rho}^{\text{GEO}}(t) = \frac{s_m^{\text{GEO}}(t)}{v}, \tag{3.10a}$$

$$d_{k,m,c}^{\text{GEO}}(t) = \eta \left(\frac{f_{k,m}^{\text{c}}(t)}{\Omega_c^{\text{GEO}}} \right), \tag{3.10b}$$

$$d_{k,m,T}^{\text{GEO}}(t) = d_{k,m,\rho}^{\text{GEO}}(t) + d_{k,m,c}^{\text{GEO}}(t). \tag{3.10c}$$

The propagation delay $d_{k,m,\rho}^{\text{GEO}}(t)$ is distance dependent where $s_m^{\text{GEO}}(t)$ is the distance between LEO-cloudlet $m(t) \in \mathbb{M}(t)$ and GEO-cloud, and Ω_c^{GEO} is computing ability of the GEO-cloud in cycles/second. Using Eq. (3.9) and (3.10), the maximum latency experienced in this communication environment is given below:

$$d_{k,m}(t) = \gamma_{k,m}(t) d_{k,m,T}^{\text{LEO}}(t) + (1 - \gamma_{k,m}(t))\, d_{k,m,T}^{\text{GEO}}(t), \tag{3.11}$$

where $d_{k,m}(t)$ is the maximum delay which can be caused to a IoT device while completing its tasks.

3.4 Problem Formulation

In this sub-section, we formulate the joint admission control, IoT device association, and power allocation problem for the network shown in Fig. **??**. This problem also considers fairness in distribution/ association of $K(t)$ IoT devices with $M(t)$ LEO-cloudlets. Fairness is also maintained while spectrum resource blocks are allocated to the IoT devices in the network. First, lets introduce the objective function along with the constraints. The mathematical model of the problem is formulated in the later part. The objective function and constraints are given below:

- **Objective function:** Using (2) and (3.7), the objective of this work is to maximize the throughput of the network and is given below:

$$\mathbb{U}\left(\beta_{k,m}(t), p_{k,m}(t)\right) = \sum_{m(t)\in\mathbb{M}(t)} \sum_{k(t)\in\mathbb{K}(t)} \beta_{k,m}(t)\psi_{k,m}(t). \tag{3.12}$$

- **IoT device association:** Using (2), the constraints that ensures association of IoT device $k(t) \in \mathbb{K}(t)$ with just one LEO-cloudlet $m(t) \in \mathbb{M}(t)$ is given below:

$$\sum_{m(t)\in\mathbb{M}(t)} \beta_{k,m}(t) \leq 1 \, \forall \, k(t) \in \mathbb{K}(t). \tag{3.13}$$

- **Power allocation:** The power $p_{k,m}(t)$ is allocated by the IoT device $k(t) \in \mathbb{K}(t)$ if its admitted in the network. Using (1), and (3.5), the constraint to ensure power allocation to admitted IoT device is given below:

$$0 \leq \alpha_k(t) p_{k,m}(t) \leq P_k, \, \forall \, k(t) \in \mathbb{K}(t), \, m(t) \in \mathbb{M}(t), \tag{3.14}$$

- **Achieved data rate versus QoS data rate:** Another QoS requirement is the minimum data rate required to complete the offloading tasks if IoT device $k \in \mathbb{K}$ is admitted in the network . Using (1), (3.5), (3.6), and (3.7), the constraint to ensure QoS minimum data rate is given below:

$$\psi_{k,m}(t) \geq \alpha_k(t) \Psi_{k,m}, \, \forall \, k(t) \in \mathbb{K}(t), \, m(t) \in \mathbb{M}(t), \tag{3.15}$$

- **Achieved data rate versus QoS latency:** Another QoS requirement for the admitted IoT device is that achieved data rate should be such that maximum latency threshold is not compromised. Using (1), (3.5), (3.6), and (3.7), the constraint to ensure QoS minimum data rate is given below:

$$\psi_{k,m}(t) \geq \alpha_k(t) \left(\frac{f^{\mathrm{s}}_{k,m}(t) + f^{\mathrm{c}}_{k,m}(t)}{D_{k,m}(t)} \right), \, \forall \, k(t) \in \mathbb{K}(t), \, m(t) \in \mathbb{M}(t), \tag{3.16}$$

- **Latency:** One of the quality of service (QoS) requirement is the minimum latency in accomplishment of task offloading to the LEO-cloudlet. Using (3), (3.9), (3.10), and (3.11), the constraint to ensure QoS minimum latency is given below:

$$d_{k,m}(t) \leq \alpha_k(t) D_{k,m}, \, \forall \, k(t) \in \mathbb{K}(t), \, m(t) \in \mathbb{M}(t), \tag{3.17}$$

- **LEO-cloudlet storage:** The constraints that ensures sum of data size of files to be store at LEO-cloudlet $m(t) \in \mathbb{M}(t)$ is with in its storage capacity is given below:

$$\sum_{k(t)\in\mathbb{K}(t)} \gamma_{k,m}(t) f^{\mathrm{s}}_{k,m}(t) \leq \Omega^{\mathrm{LEO}}_{s} \, \forall \, k(t) \in \mathbb{K}(t). \tag{3.18}$$

- **Fairness in IoT device association:** The distribution of $K(t)$ IoT devices traffic load in terms of association with $M(t)$ LEO-cloudlets should follow fairness to avoid over loading of a LEO-cloudlet. Using (3.4), the constraint to ensure fairness in distribution IoT devices traffic is given below:

$$\delta_{k,m}(t) \geq \alpha_k Q_{\mathrm{UFI}}, \, \forall \, k(t) \in \mathbb{K}(t), \, m(t) \in \mathbb{M}(t). \tag{3.19}$$

- **Fairness in RBs allocation:** The distribution of $K(t)$ IoT devices traffic load should follow fairness to avoid overloading and underloading of $M(t)$ LEO-cloudlets. Using (3.8), the constraint to ensure fairness in distribution RBs is given below:

$$\varphi_{k,m}(t) \geq \alpha_k Q_{\mathrm{RFI}}, \, \forall \, k(t) \in \mathbb{K}(t), \, m(t) \in \mathbb{M}(t). \tag{3.20}$$

The objective function and constraints defined in (3.12) - (3.20) helps in formulating a mathematical model to achieve latency aware resource allocation, i.e., fairness in IoT device association and resource blocks allocation etc and task offloading in GEO-LEO Satellite Networks. The symbols and notations used in problem formulation are summarized in Table **??**. To achieve throughput maximization in GEO-LEO satellite networks, the mathematically problem with objective function $\mathbb{U}$ is given below:

$$\max \mathbb{U}\left(\beta_{k,m}(t), p_{k,m}(t)\right) \tag{3.21a}$$

$$\text{s.t.} \sum_{m(t)\in\mathbb{M}(t)} \beta_{k,m}(t) \leq 1 \, \forall\, k(t) \in \mathbb{K}(t), \tag{3.21b}$$

$$0 \leq \alpha_k(t) p_{k,m}(t) \leq P_k, \, \forall\, k(t) \in \mathbb{K}(t), \, m(t) \in \mathbb{M}(t), \tag{3.21c}$$

$$\psi_{k,m}(t) \geq \alpha_k(t) \Psi_{k,m}, \, \forall\, k(t) \in \mathbb{K}(t), \, m(t) \in \mathbb{M}(t), \tag{3.21d}$$

$$\psi_{k,m}(t) \geq \alpha_k(t) \left(\frac{f^{\mathrm{s}}_{k,m}(t) + f^{\mathrm{c}}_{k,m}(t)}{D_{k,m}(t)} \right), \, \forall\, k(t) \in \mathbb{K}(t), \, m(t) \in \mathbb{M}(t), \tag{3.21e}$$

$$d_{k,m}(t) \leq \alpha_k(t) D_{k,m}, \, \forall\, k(t) \in \mathbb{K}(t), \, m(t) \in \mathbb{M}(t), \tag{3.21f}$$

$$\sum_{k(t)\in\mathbb{K}(t)} \gamma_{k,m}(t) f^{\mathrm{s}}_{k,m}(t) \leq \Omega^{\mathrm{LEO}}_{s} \, \forall\, m(t) \in \mathbb{M}(t), \tag{3.21g}$$

$$\delta_{k,m}(t) \geq \alpha_k Q_{\mathrm{UFI}}, \, \forall\, k(t) \in \mathbb{K}(t), \, m(t) \in \mathbb{M}(t), \tag{3.21h}$$

$$\varphi_{k,m}(t) \geq \alpha_k Q_{\mathrm{RFI}}, \, \forall\, k(t) \in \mathbb{K}(t), \, m(t) \in \mathbb{M}(t). \tag{3.21i}$$

Each IoT device $k(t) \in \mathbb{K}(t)$ is not allowed to associate with more than one LEO-cloud $m(t) \in \mathbb{M}(t)$ is ensured by constraint (3.21b). The power allocated to an admitted IoT device $k(t) \in \mathbb{K}(t)$ in the UL transmission should be within maximum power available is ensured by constraint (3.21c). The achieved data rate of an IoT device should be more than minimum QoS data rate requirement is ensured by constraint (3.21d). Similarly, the achieved data rate of an IoT device should be such that data transmitted take time less than QoS latency is ensured by constraint (3.21e). QoS maximum threshold for latency is ensured by constraint (3.21f). Sum of the data files to be stored at a LEO-cloudlet should be within the storage capacity of a LEO-cloudlet is ensured by constraint (3.21g). The fairness in the IoT devices traffic offloading is ensured by constraint (3.21h). The fairness in allocation of resource blocks among IoT devices is ensured by constraint (3.21i).

Chapter 4

PROPOSED ALGORITHM

The problem in (3.21) is a typical combinatorial optimization case with a mix of discrete, continuous, and non-linear variables. The problem at hand is complex, challenging, and non-deterministic polynomial-time hard (NP-hard) [38]. In (3.21), the maxima of the objective function with discrete domain can be searched using brute force algorithm. In brute force algorithm, all possible search spaces are touched/solved to reach the optimal solution. However, the brute force algorithm implies exponential increase in the search space with the increase in the number of IoT devices, i.e., the solution of $2^{|X|}$ optimization problems is required in the simulations. Therefore, we involve OAA to solve combinatorial optimization problem in (3.21).

After relaxation, the OAA divides the problem in (3.21) into two below sub-problems:

- Non-linear problem (NPL)
- Mixed integer linear problem (MILP)

4.0.1 Description of Outer Approximation

Lets $\mathbb{O}$ and $\Delta_{3.21b-3.21i}$ are the objective and constraints in (3.21), $\mathbb{W} = \{x_n^{\mathrm{d}}, x_n^{\mathrm{u}}, p_{n,f}^{\mathrm{d}}, p_{n,f}^{\mathrm{u}}\}$ and $\mathbb{Z} = x \cup \mathbb{W}$. Following prepositions should be satisfied:

1. $\mathbb{W}$ is compact, non-empty, and convex. Fixing $\mathbb{W}$ with $\mathbb{Z}$ changes the objective $\mathbb{O}$ and constraint $\Delta_{3.21b-3.21i}$ to a convex function in $\mathbb{W}$.
2. $\mathbb{O}$ and $\Delta_{3.21b-3.21i}$ can be differentiated.
3. Fixing $\mathbb{Z}$, problem in (3.21) changes to a NLP problem and constraints $\Delta_{3.21b-3.21i}$ are satisfied fully.
4. Fixing $\mathbb{Z}$, NLP problem gives the $\epsilon = 10^{-3}$ optimal solution (upper bound).

Algorithm 1 : **Outer approximation algorithm**

$i \leftarrow 1$

Initialize $\mathbb{Z}$

$\epsilon \leftarrow 10^{-3}$

$Convergence \leftarrow FALSE$

while $Convergence == FALSE$ **do**

$$\mathbb{W}^i \leftarrow \begin{cases} \underset{\mathbb{W}}{\text{arg min}} & -\mathbb{O}\left(\mathbb{Z}, \mathbb{W}\right) \\ \text{subject to} & \Delta_{3.21b-3.21i}\left(\mathbb{Z}, \mathbb{W}\right) \leq 0; \end{cases}$$

Upper Bound $\leftarrow \mathbb{O}\left(\mathbb{Z}^i, \mathbb{W}^*\right)$

$$\left(\mathbb{Z}^*, \mathbb{W}^*, \kappa^*\right) \leftarrow \begin{cases} \underset{\mathbb{Z},\mathbb{W},\kappa}{\text{arg min}} \quad \kappa \\ \text{subject to} \\ \kappa \geq -\mathbb{O}\left(\mathbb{Z}^i, \mathbb{W}^i\right) \\ -\nabla\mathbb{O}\left(\mathbb{Z}^i, \mathbb{W}^i\right)\binom{\mathbb{W}-\mathbb{W}^i}{0} \\ \Delta_{3.21b-3.21i}\left(\mathbb{Z}^i, \mathbb{W}^i\right) \\ -\nabla\Delta_{3.21b-3.21i}\left(\mathbb{Z}^i, \mathbb{W}^i\right)\binom{\mathbb{W}-\mathbb{W}^i}{0} \leq 0 \end{cases}$$

Lower Bound $\leftarrow \kappa$

if Upper Bound $-$ Lower Bound $\leq \epsilon$ **then**

$Convergence \leftarrow TRUE$

else

$i \leftarrow i + 1$

$\mathbb{Z}^i \leftarrow \mathbb{Z}^*$

end if

end while

4.0.2 NLP-Stage

In this stage, $\mathbb{Z}$ is fixed to change the problem in (3.21) to NLP problem and its solution gives the upper bound of the ϵ optimal solution. At i^{th} cycle, $\mathbb{Z}^i$ is the value of binary indicators that gives optimal solution (upper bound). The solution of NLP-Stage drives the MILP problem in MILP-Stage. NLP problem is given below:

$$\begin{aligned} &\min_{\mathbb{W}} \ -\mathbb{O}(\mathbb{Z}^i, \mathbb{W}) \\ \text{subject to:} \\ &\Delta_{3.21b-3.21i}(\mathbb{Z}^i, \mathbb{W}) \leq 0 \end{aligned} \tag{4.1}$$

The optimal solution (upper bound) including binary indicators $\mathbb{Z}^i$ are obtained after solving the NLP problem in (4.1). The formulated problem in (3.21) can be reframed as under:

$$\begin{aligned} &\min_{\mathbb{Z}} \min_{\mathbb{W}} \ -\mathbb{O}(\mathbb{Z}^i, \mathbb{W}) \\ \text{subject to} \\ &\Delta_{3.21b-3.21i}(\mathbb{Z}^i, \mathbb{W}) \leq 0 \end{aligned} \tag{4.2}$$

The (4.2) can be rewritten as:

$$\min_{\mathbb{Z}} \ -\Phi(\mathbb{Z}) \tag{4.3}$$

such that

$$\begin{aligned} &\Phi(\mathbb{Z}) = \min_{\mathbb{W}} \ -\mathbb{O}(\mathbb{Z}^i, \mathbb{W}) \\ \text{subject to:} \\ &\Delta_{3.21b-3.21i}(\mathbb{Z}^i, \mathbb{W}) \leq 0 \end{aligned} \tag{4.4}$$

The problem in (4.3) is projection of (3.21) on $\mathbb{Z}$ space. As all constraints $\Delta_{3.21b-3.21i}$ hold true for the NLP problem in (4.1) for all $\mathbb{Z}^i$, so solution of the new projection problem can be given as under:

$$\min_{\Delta} \min_{\mathbb{W}} \; -\mathbb{O}(\mathbb{Z}^i, \mathbb{W}^i) - \nabla\mathbb{O}(\mathbb{Z}^i - \mathbb{W}^i)\begin{pmatrix} \mathbb{W} - \mathbb{W}^i \\ \mathbb{Z} - \mathbb{Z}^i \end{pmatrix}$$

$$\text{subject to:} \tag{4.5}$$

$$\Delta_{3.21b-3.21i}(\mathbb{Z}^i, \mathbb{W}^i) - \nabla\Delta_{3.21b-3.21i}(\mathbb{Z}^i, \mathbb{W}^i)\begin{pmatrix} \mathbb{W} - \mathbb{W}^i \\ \mathbb{Z} - \mathbb{Z}^i \end{pmatrix} \leq 0$$

Another variable κ is introduced to minimize the problem as under;

$$\begin{aligned}
&\min_{\Delta,\mathbb{W},\kappa} \; \kappa \\
&\text{subject to:} \\
&\kappa \geq -\mathbb{O}(\mathbb{Z}^i, \mathbb{W}^i) - \nabla\mathbb{O}(\mathbb{Z}^i - \mathbb{W}^i)\begin{pmatrix} \mathbb{W} - \mathbb{W}^i \\ \mathbb{Z} - \mathbb{Z}^i \end{pmatrix} \\
&\Delta_{3.21b-3.21i}(\mathbb{Z}^i, \mathbb{W}^i) - \nabla\Delta_{3.21b-3.21i}(\mathbb{Z}^i, \mathbb{W}^i)\begin{pmatrix} \mathbb{W} - \mathbb{W}^i \\ \mathbb{Z} - \mathbb{Z}^i \end{pmatrix} \leq 0
\end{aligned} \tag{4.6}$$

4.0.3 MILP-Stage

The binary indicators $\mathbb{Z}^i$ obtained in NLP-Stage are used in MILP-Stage. Another optimal solution (lower bound) is obtained after solving the MILP problem in (4.6). ϵ - optimization algorithm linearizes the objective $\mathbb{O}$ and constraints $\Delta_{3.21b-3.21i}$ in (4.1) and drives the problem in MILP-Stage using optimal solution (upper bound) including binary indicators $\mathbb{Z}^i$ at i^{th} cycle [39, 40]. After each cycle, optimal solution (upper bound) and optimal solution (lower bound) are compared and algorithm ends if the difference of both solution is less then $\varepsilon = 10^{-3}$. Otherwise, algorithm moves to next cycle to get new binary indicators $\mathbb{Z}^{i+1}$ at $(i+1)^{th}$ cycle. The algorithm ends when reaches the optimal solution when optimal solution (upper bound) and optimal solution (lower bound) difference is below ϵ.

4.0.4 Convergence and Optimality of Outer Approximation

According to [41, 42], OAA converges linearly. For a given value of $\mathbb{Z}$, OAA provides the best answer to the MINLP problem with a function with objectives and convex limitations. For all constant values of $\mathbb{Z}$, OAA uses the branch and bound approach to find the best possible solution, which it finds to be within a factor of $\varepsilon = 10^{-3}$. After reaching an optimal solution with $\varepsilon = 10^{-3}$ [41], OAA stops in the finite cycles if four prepositions hold for all values of $\mathbb{Z}$. To be $\mathbb{W}$ optimal in (4.6), a point must satisfy the condition that κ ¿ $\mathbb{O}(\mathbb{Z}^i, \mathbb{W}^i)$. It is impossible to find a workable solution to the MILP issue for any values of $\mathbb{Z}$ if κ is less than $\mathbb{O}(\mathbb{Z}^i, \mathbb{W}^i)$. Values of $\mathbb{Z}^i$in (4.6) for which no possible solutions will be omitted from future MILP problems. It leads to the convergence of OAA.

4.0.5 Complexity of Outer Approximation

The difficulty of OAA is discussed here. The number of F flops quantifies the complexity. Real floating-point arithmetic is performed using a flop. One flop is added when operating, such as addition, division, or multiplication. On each complicated addition and multiplication, two and four flops are added. Multiplying a matrix with dimensions $m \times n$ by a matrix with dimensions $n \times o$ uses 2mno flops. Each flop is increased by one when an element is added to or removed from a set. Flop [43] is increased by one for each logical and assignment operator.

OAA is initialized by including 5 flops by these guidelines. To solve the NLP issue and find the upper bound of the most effective approach, we add $2XY$ and $4XY\Delta$ flops correspondingly. The MILP issue can be solved with an additional $4XY\Delta$ flip, and a lower bound on the optimal solution can be obtained with an additional $2XY\Delta$ flop. When comparing lower and higher bounds, 2 flips are added. Creating and setting up new binary variables costs an additional 4 flops. As a result, the following is the whole flop count F_{OAA} for OAA:

$$
\begin{aligned}
F_{OAA} &= 5 + 2XY + 4XY\Delta + 4XY\Delta + 2XY\Delta + 4 \\
F_{OAA} &= 9 + 2XY + 10XY\Delta \\
F_{OAA} &\approx 2XY + 10XY\Delta
\end{aligned}
\tag{4.7}
$$

In 4.7, the OAA's intricacy is described. It is also possible to express the complexity of the OAA in terms of Big O, with the formula $O(X \times Y) + O(X \times Y \times \Delta)$ when total LEO-cloudlets Y, unlimited Internet of Things X, and total constraints Δ are entered.

Chapter 5

SIMULATION AND RESULTS

Eq. (21), representing the MINLP problem, is effectively solved using the Outer Approximation Algorithm (OAA). The advantages and benefits of the proposed algorithm are demonstrated through comprehensive simulation results in this section. To implement the OAA, we utilize the widely recognized open-source software Basic Open-source Nonlinear Mixed Integer Programming (BONMIN) [44]. By leveraging the OAA, we are able to efficiently tackle the complexities inherent in the MINLP problem formulation.

The key performance parameters to show the advantages of the proposed strategy are as follows:

- Number of IoT associated.
- Fairness in IoT association.
- RB allocation.
- Fairness in RB allocation.
- Average throughput achieved.

5.1 Simulation Setup

The simulation incorporates specific system parameters, as detailed in Table III. The maximum power levels for various components are set throughout the simulations: The LEOs P_l at a maximum power of 43 dBm and the GEO P_g at 46 dBm. Furthermore, the maximum radius values are assigned as 1000 km for LEOs, and 4200 km for GEO. The height at which LEO satellites H_l are from the IoT devices is 1000 km, and GEO satellite H_g is 37786 km. Minimum data rates of 0.2, 0.4, 0.6, 0.8, and 1.0 Mbps are mandated to ensure optimal performance. The system permits a minimum of 5 IoTs, while the maximum allowed is 40, with an increment of 5 IoTs. The total number of available Resource Blocks T_{RB} for user allocation is 160. Additional system characteristics include a zero mean Gaussian random variable denoted as with a 10 dB value, and the maximum allowable latency was set to 5 ms. These specific system parameters govern the simulation, contributing to its uniqueness and ensuring its originality.

Table 5.1: **System Parameters**

Parameters	**Value**
P_l	43 dBm
P_g	46 dBm
H_l	1000 km
H_g	37786 km
T_{RB}	160
R_m^{d}	{0.2,0.4,0.6,1.0} Mbps
$b_{k,m}$	0.1 Mbps
R_m^{u}	{0.2,0.4,0.6,1.0} Mbps
G	50
$\zeta_{x,y}(t)$	10 dB
f_l^{c}	10^9 c/s
f_g^{c}	5×10^9
f_l^{s}	2 Gbps
f_g^{s}	50 Gbps
$l_{k,m}(t)$	5 ms
Min IoTs	5
Max IoTs	40
Increment	5

5.2 Results and Discussions

In this section, simulation results exhibit advantage of the proposed algorithm for attaining fairness-based admission control, UA, power distribution and Throughput maximization.

5.2.1 IoT Association

Fairness and non-fairness-based [45], [46] IoT association scenarios are discussed in Fig 2, which depicts the total number of IoT devices and IoT devices associated with a hybrid GEO-LEO satellite network. The plot illustrates how the two parameters are related, with IoT devices ranging from 5 to 40 IoTs with an increment of 5. The results indicate that in both scenarios (fairness and no fairness-based IoT association), many IoT devices are effectively associated with the LEO and GEO satellites due to the proposed algorithm. In both scenarios, the plot reveals a slight difference in the association of IoT devices. The plot reveals that less no. of IoT devices are associated with the fairness-based association scenario compared to the non-fairness-based IoT association scenario. Figure 3 portrays a positive association between the number of IoTs in the hybrid GEO-LEO satellite network. It's important to note that our proposed algorithm is highly effective in scenarios where user acquisition is based on fairness and scenarios where it's not.

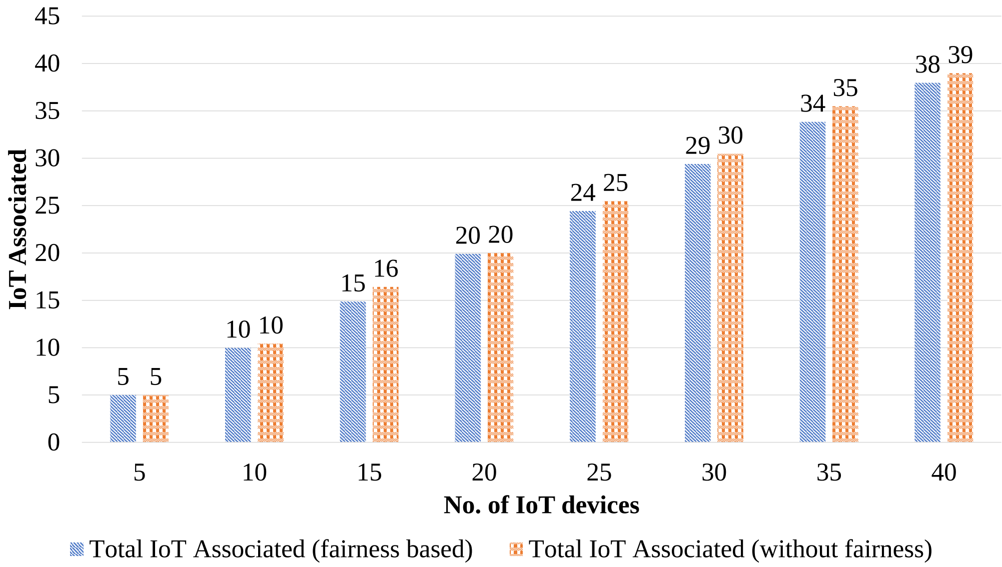

Figure 5.1: **No. of IoT Devices vs IoT Devices Associated in a hybrid GEO-LEO Satellite Network.**

Observe Figure 3, which clearly illustrates the correlation between the number of IoT devices connected to each satellite in the hybrid network and the desired quality of service (QoS) rate. The graph includes multiple satellites (LEOs and GEO) with different orbital velocities and QoS rates ranging from 0.2 to 1 Mbps. The findings unequivocally indicate that GEO has significantly fewer IoT connected to it when compared to other LEO satellites. The possible cause for this issue may be the long propagation, processing, and transmission delay from the IoT device to the GEO, and the other reason can be the task offloading when LEO cannot entertain the request. GEO will be requested to process it; hence, GEO has fewer associations than LEOs. Additionally, the graph indicates that LEO1, LEO2, and LEO3 have a similar number of IoT devices associated with them, regardless of the required QoS rate. The evidence indicates that LEO has a fair distribution of more IoT devices, and GEO has fewer IoT devices. Additionally, according to Figure 3, the association of the IoT devices to the satellites declines (24 to 22 IoTs) when there is an increment in the required QoS rate. It is logical as higher QoS rates demand more resources from the satellites, resulting in fewer IoT devices being associated with them.

The graph in Figure 4 illustrates the QoS rate requirements versus UA (no fairness) for each satellite (LEO1, LEO2, LEO3, and GEO) about varying quality of service rate requirements. The plot reveals an IoT association load imbalance among different satellites in a system where fairness is not considered. It is crucial to ensure fairness to achieve optimal resource utilization and efficient IoT offloading in hybrid GEO LEO satellite networks; it is crucial to ensure fairness.

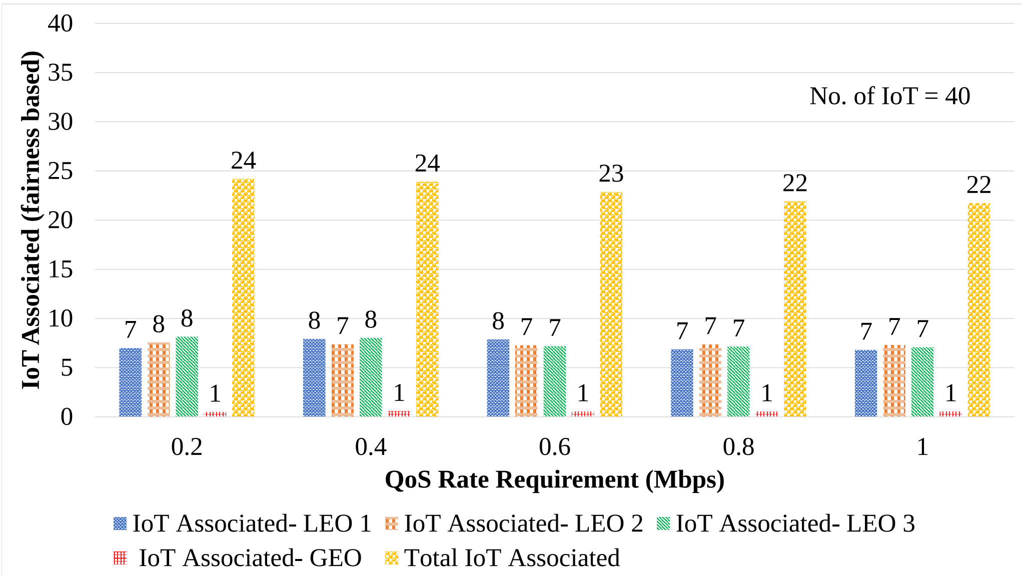

Figure 5.2: **QoS Rate Requirement vs IoT Devices Associated (fairness based).**

5.2.2 IoT Fairness

Figure 5 illustrates the correlation between the suggested algorithm governing the fairness of IoT Association and IoT devices and the overall total of the IoT devices. Fairness increases from its initial value of 0.84705 when the no. of IoT devices and the association of IoTs increase to their maximum value of 0.98676. It occurs because

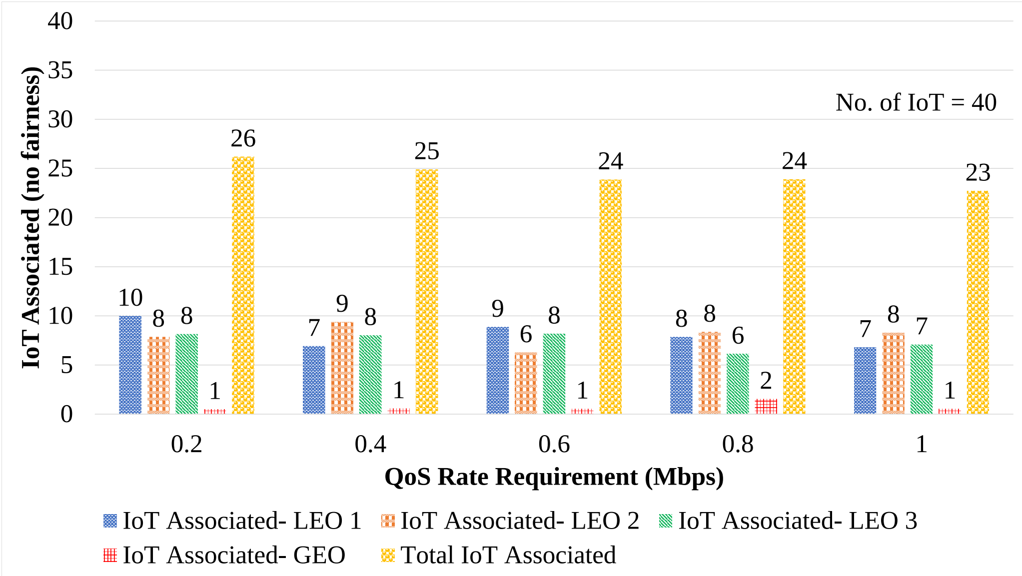

Figure 5.3: **QoS Rate Requirement vs IoT Devices Associated (Without fairness).**

fewer opportunities exist for fair IoT association across different satellites when there are fewer IoT devices. We can overcome this problem by increasing the no. of IoT devices. The graph demonstrates a significant boost in fairness when IoT devices increase from 5-20, i.e. (0.84705 to 0.96694). The prospects for fair IoT distribution can be achieved when there is an increase in the number of IoT devices other than it is more challenging to accomplish justice with fewer IoT devices. Furthermore, when there is an increment in no. of IoT devices from 20-40, the fairness index exhibits a moderate rise (0.96694 to 0.98676), indicating that as the network's IoT devices increase, the fairness index value gradually approaches 1, ensuring 100% IoTs association fairness. In essence, the findings presented in Figure 5 affirm the effectiveness of the proposed algorithm in ensuring fairness in IoT distribution, even when the network comprises a vast number of IoT devices. The algorithm achieves optimal resource utilization and efficient task offloading, thus improving the hybrid network's overall performance.

In figure 5.4, Uneven distribution of devices can result in congestion in certain areas or on specific satellite beams, leading to performance degradation and potential service disruptions. Unfair distribution of IoT devices may result in some devices receiving a disproportionately higher share of network resources, such as bandwidth or processing capabilities. This can lead to congestion, increased latency, and degraded performance for devices that receive inadequate resources. Consequently, the overall network effi-

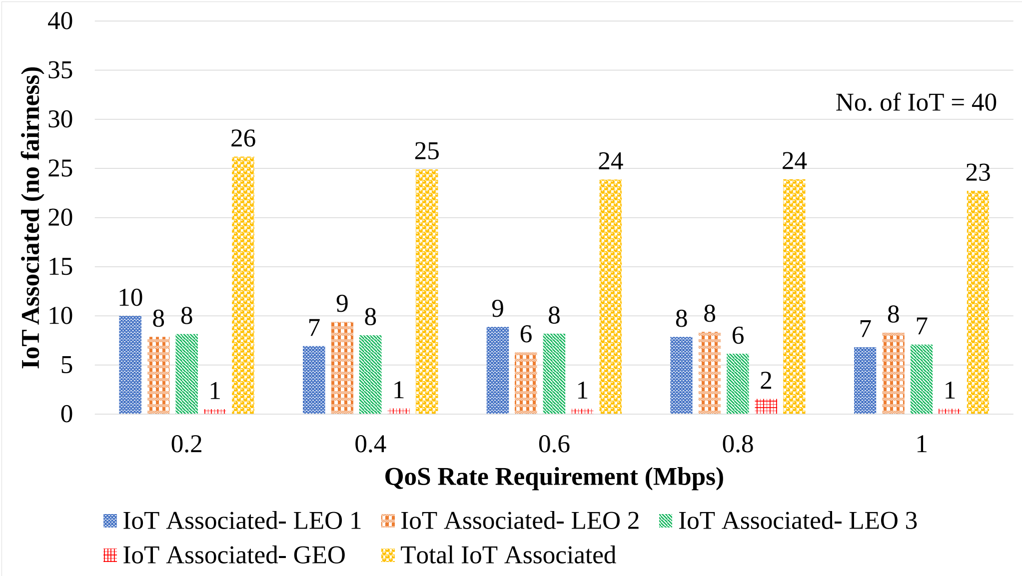

Figure 5.4: **QoS Rate Requirement vs IoT Devices Associated (Without fairness).**

ciency and user experience may suffer.

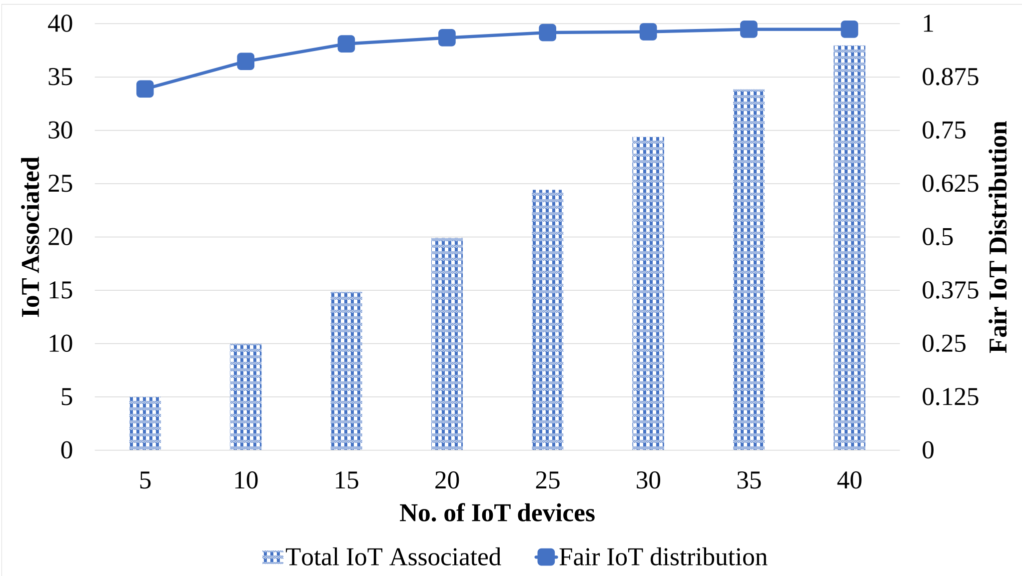

Figure 5.5: **IoT Devices vs IoT Devices Fairness.**

The graph in Figure 6 illustrates the relationship between the aggregate amount of IoTs and the fair distribution of IoT devices and IoT associated with the different quality of service (QoS) rates (0.2- 1.0 Mbps). The graph demonstrates that as more IoTs access the network, there is an improvement in the fairness of IoT association. These results are consistent with the findings of Figs. 2 and 5. According to the results of Figs. 3 and 4 show that QoS is raised from 0.2 Mbps to 1.0 Mbps the association of IoT devices reduces as the For instance, IoT devices requesting 0.2, 0.4, 0.6, 0.8 Mbps in the presence of 40 IoT devices, all have comparable fairness values for associations were 0.968, 0.985, 0.968 and 0.986. The results speak for themselves, demonstrating that our proposed approach is highly effective in improving association of IoT device's fairness, even when higher QoS rates are involved.

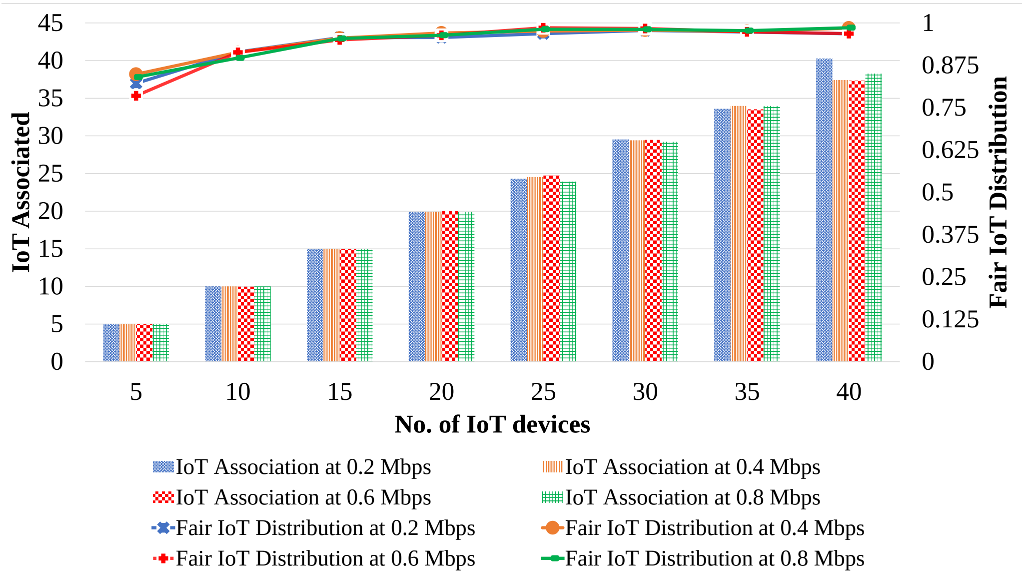

Figure 5.6: **IoT Devices Associated vs IoT Devices at different QoS rate requirements**

Figure 7 shows how the fairness index is affected by the number of IoT devices, IoT associations, and allocated RBs. The suggested method improves Fairness in allocating RBs, as shown by the rising pattern (0.5955 to 0.9380) as the number of IoT devices and IoT associations increases from 5 to 40 and subsequently from 5 to 30. Reduced opportunities for fair RB distribution exist when the total IoT devices decrease. However, with more randomly placed IoT devices in the network, the fairness index improves due to the increased opportunity for fair RBs distribution. From 5 to 26 IoT devices, a clear and substantial increase in fair value (from 0.5955 to 0.8908) exists. As the number of IoT devices increases from 26 to 40, the fairness index gradually rises until it reaches 0.9380 for all but the smallest of these increases. As the number of IoT devices increases, the fairness index of the RBs is approaching 1, which suggests the fair distribution of Resource Blocks (RBs).

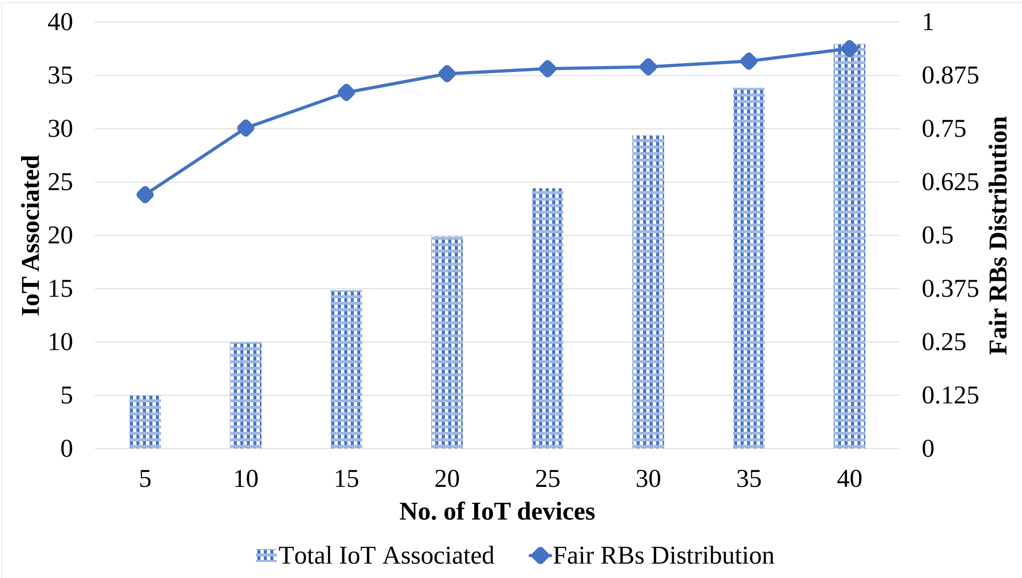

Figure 5.7: **IoT Devices vs IoT Devices Associated and RB (Fairness Distribution)**

5.2.3 RB Fairness

Using the different QoS requirements (0.2, 0.4, 0.6, 0.8, and 1.0 Mbps), Fig. 8 plots the total number of IoT devices against IoTs associated and RB fairness distribution. Figure 8 demonstrates how the association of IoT and RB improves their ability to meet the minimal QoS requirements of each user as the total IoT devices increase. As previously mentioned, the required rate for Quality of Service lowers from 0.2 Mbps to 1.0 Mbps, and the decrement in the total number of IoT devices is associated accordingly. Values 0.873, 0.902, 0.921, 0.9401, and 0.953 for the fairness of RBs allocation when there are 40 IoT devices and QoS requirements of 0.2, 0.4, 0.6, 0.8, and 1.0 Mbps, respectively, are calculated. By demonstrating that the RB allocation process becomes fairer with rising QoS rate requirements, our results provide credence to the usefulness of the suggested algorithm.

5.2.4 RB Allocation

The total no. of IoT devices versus IoT devices associated and the Total RBs allocated is depicted in Figure 9. A direct correlation exists between increased IoT association and the total RBs allocated. The distribution of RBs increases with the increase in the association of IoT devices. The system allows 14 RBs to service 5 IoT devices, which rises to 138 when the total no. of associated IoT devices increases to 40. Distinct Quality-of-Service rating criteria (0.2, 0.4, 0.6, 0.8, and 1.0 Mbps) association of IoTs

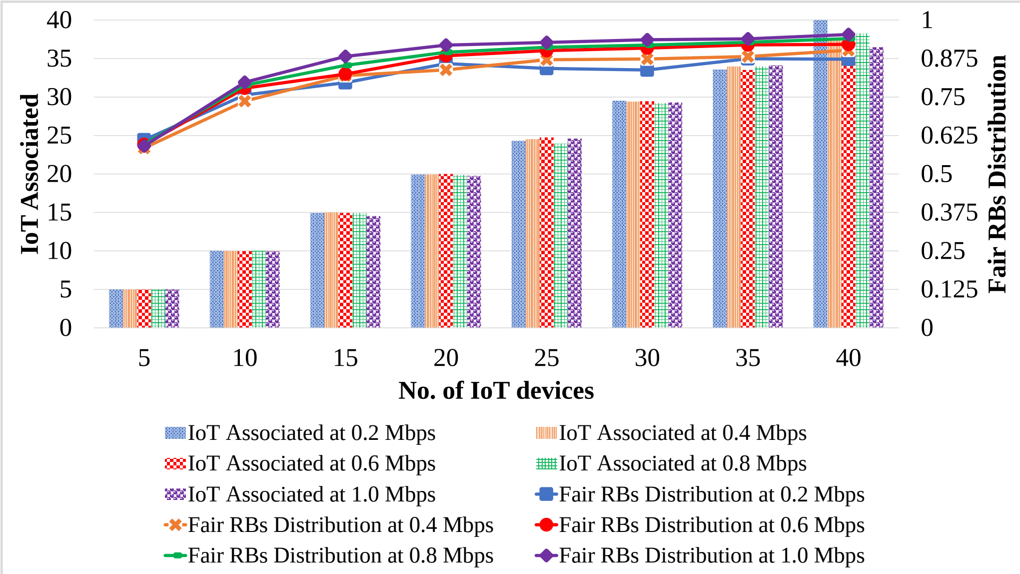

Figure 5.8: **IoT Devices vs IoT Devices Associated and RB at different QoS rate requirements.**

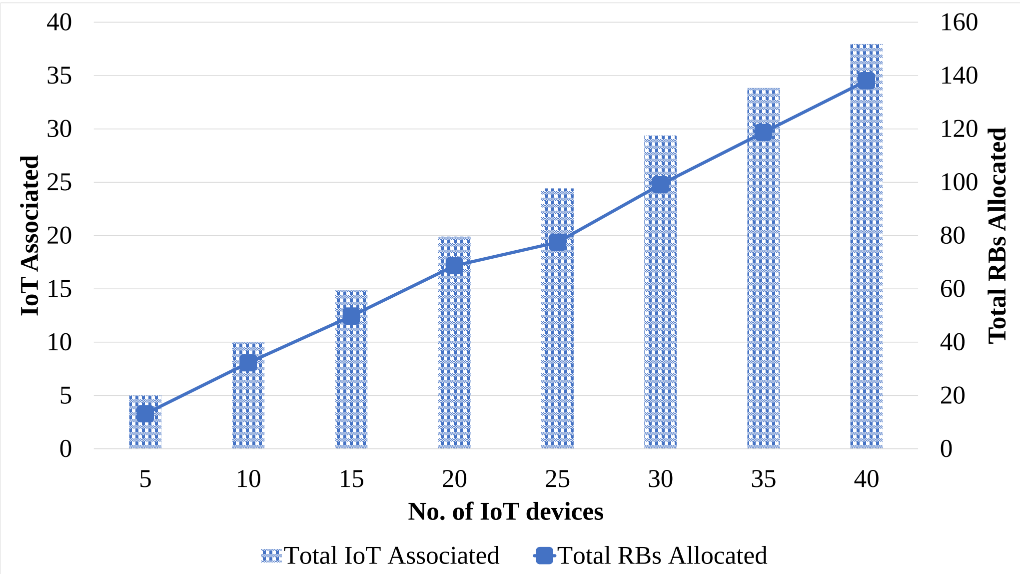

Figure 5.9: **IoT Devices vs IoT Devices Associated and Allocated RBs.**

and RB allocation can be proportional to the number of IoT devices in Figure 10. As shown in Figure 5, the trend for the IoT association depends on the rate. It can be proven that the number of RBs allocated to a given number of IoT devices will vary according to their individual QoS rate requirements. 40 IoT devices will require 61, 87, 106, 123, and 132 RBs depending on whether the necessary Quality of Service (QoS) rate is 0.2, 0.4, 0.6, 0.8, or 1.0 Mbps. The algorithm efficiently allocates an adequate number of resource blocks to ensure the desired level of service quality requested by the IoT devices.

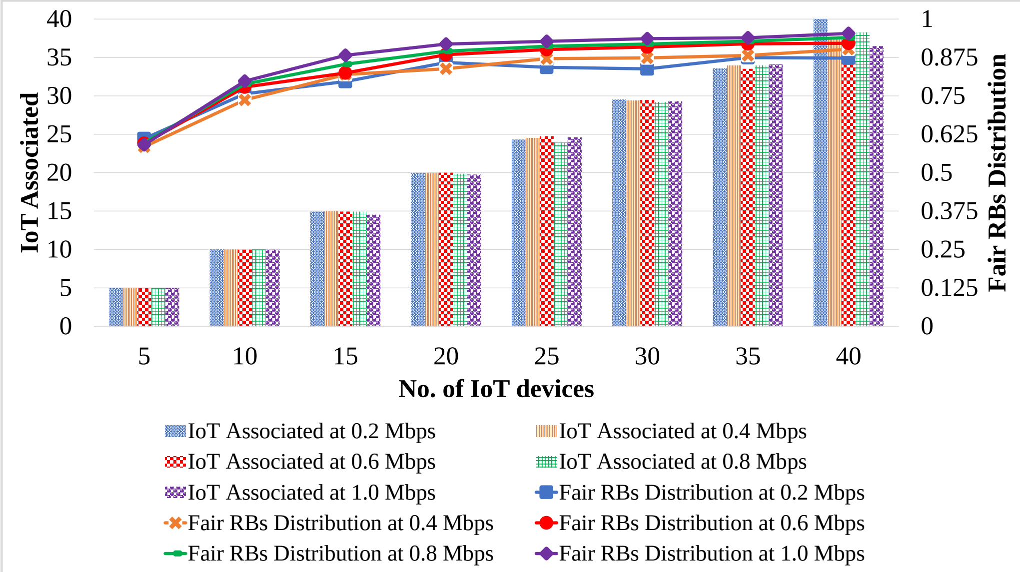

Figure 5.10: **IoT Devices vs IoT Devices Associated and RB Fairness at different QoS rate requirements.**

Figure 11 shows the needed quality of service (QoS) for IoT devices associated with allocated RBs in a hybrid GEO-LEO satellite network. According to Fig. 11, as the demand for a higher quality of service among hybrid GEO-LEO satellite IoT devices increases, the ratio of associated IoT devices to allocated RBs increases. With higher QoS rate requirements comes a lower IoT association, as it takes more power to sustain high data rates and, consequently, with high data rates, the power demand for an IoT to get associated also increases.

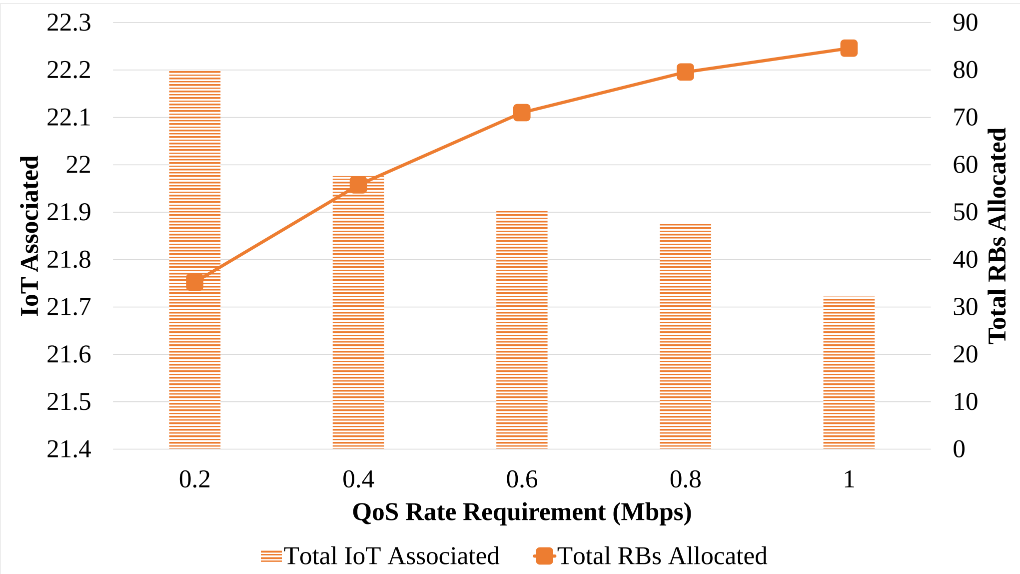

Figure 5.11: **QoS rate requirement vs IoT Devices Associated and Allocated RBs.**

5.2.5 Throughput

Throughput and IoT device association are plotted against the total no. of IoT devices in Figure 12. The throughput of an associated IoT is proportional to the total number of IoT devices in use. Consistently maximum throughput has been obtained, proving the main objective.

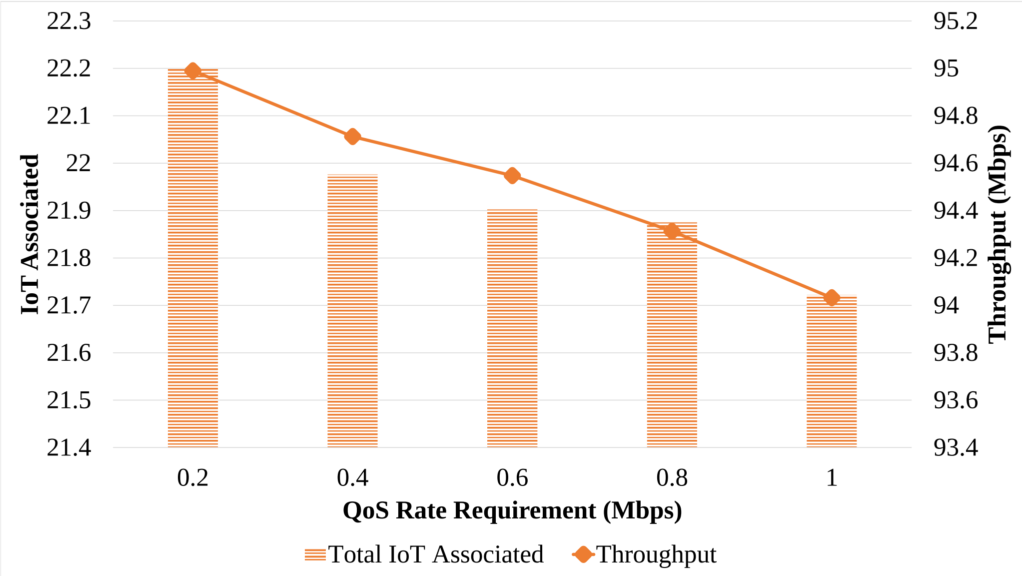

Figure 5.12: **IoT Devices vs IoT Devices Associated and Throughput.**

No. of IoT devices versus associated IoTs and throughput for varying quality of service (QoS) requirements (0.2, 0.4, 0.6, 0.8, and 1.0 Mbps) is displayed in Fig. 13. As was previously mentioned concerning Figs. 6, 8, and 10, the IoT association behavior is consistent. Maximum throughput is achieved for low QoS rate requirements, whereas it drops significantly as the rate needed for QoS increases in a hybrid GEO-LEO satellite network.

The QoS required rate vs. associated IoT and throughput is plotted in Fig. 14. At a rate of 0.2 Mbps, there are 15 IoT devices and 94.3 Mbps of throughput. When the minimal QoS rate requirement is met, throughput is at its highest; then, it decreases when the rate is progressively increased from 0.2 Mbps to 1.0 Mbps. Since higher data rates need more power, throughput naturally decreases with time.

For both the fairness-enabled and -disabled cases, shown in Figure 15, the relationship between throughput and the number of IoT devices is illustrated. Compared to the no-fairness situation, the throughput in the fairness-based scenario is higher. In a hybrid

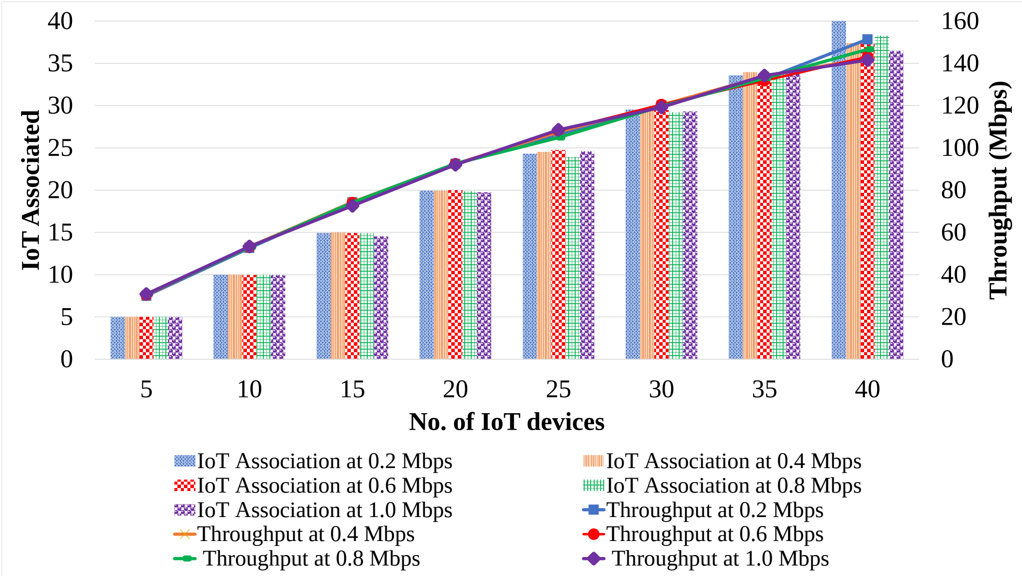

Figure 5.13: **QoS rate requirement vs IoT Devices Associated and Throughput.**

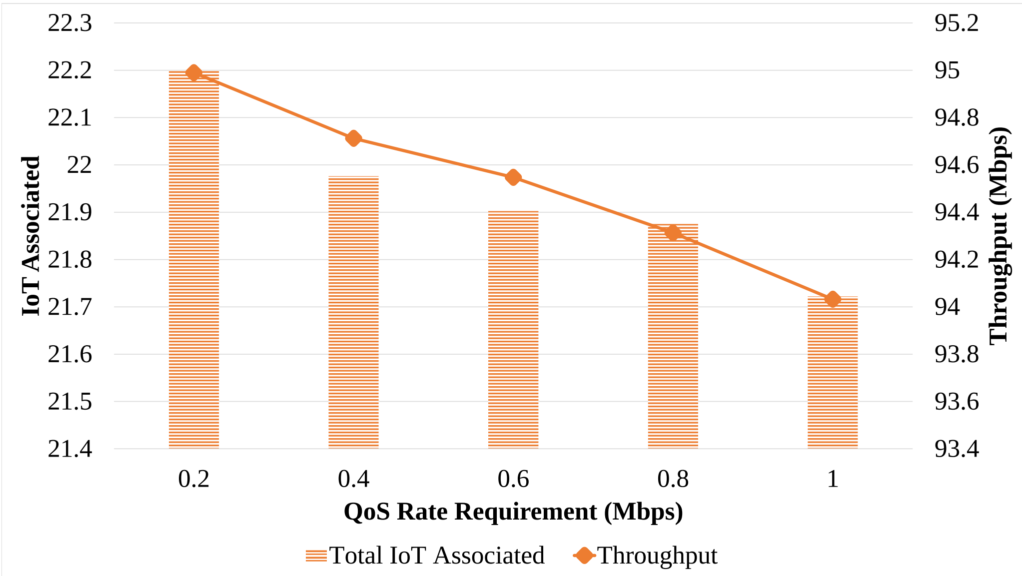

Figure 5.14: **QoS rate requirement vs IoT Devices Associated and Throughput.**

GEO-LEO satellite network, throughput increases when associated IoT is distributed relatively among satellites and where RBs are likewise allocated fairly but decreases in the scenario where associated IoTs are not distributed fairly in Fig 15. As in the fairness-based scenario it promotes better load balancing in the network. It ensures that no single IoT or group of IoTs monopolises the resources, preventing congestion. This balanced distribution of resources enhances the overall network capacity and increases the achievable throughput.

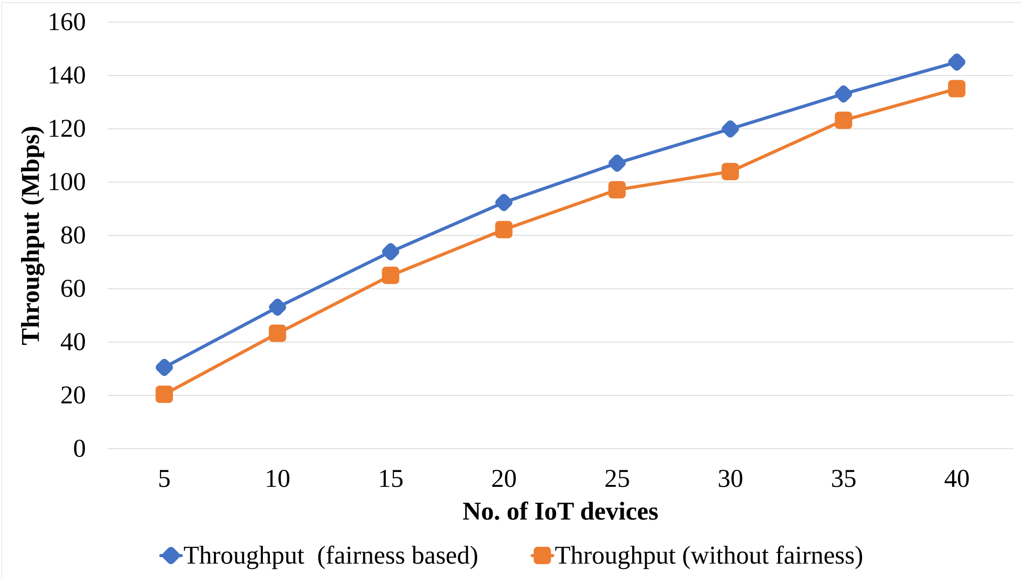

Figure 5.15: **IoT Devices vs Throughput (both fairness-based and without fairness).**

5.2.6 Effect Channel on Throughput

Fig 16 reveals that the throughput is significantly affected by the presence of rain in the channel of the hybrid GEO-LEO satellite network. In the absence of rain, the network experiences favourable conditions, increasing throughput. However, the network performance is adversely impacted when rain is considered in the channel. Raindrops introduce additional attenuation, scattering, and absorption of the transmitted signals, leading to signal loss and degradation. It causes a decrease in the overall throughput of the network. The impact of rain on the network can be further quantified by considering factors such as rain rate, frequency of operation, and path length. Higher rain rates and longer path lengths exacerbate the attenuation and signal loss, resulting in a more significant decrease in throughput.

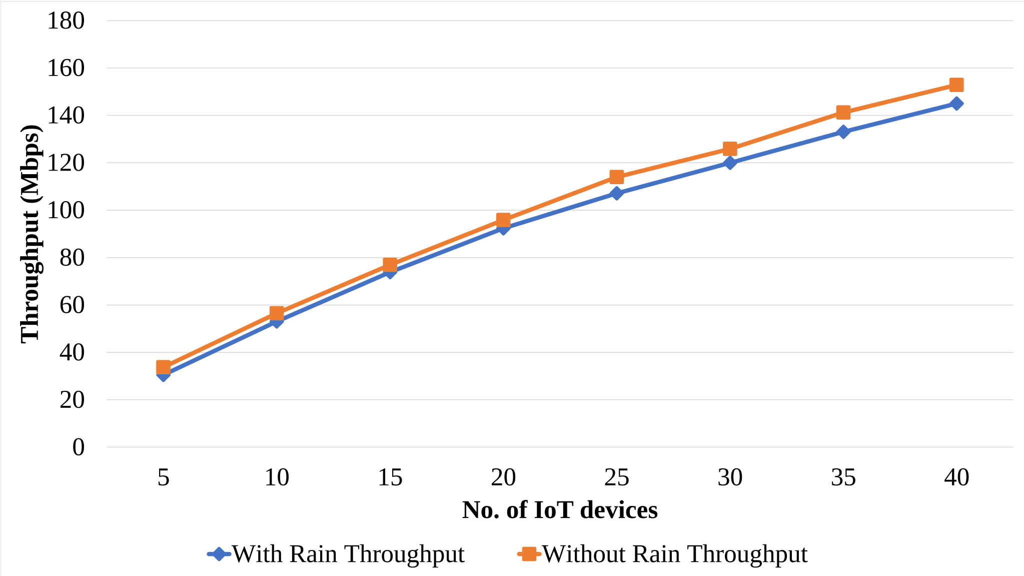

Figure 5.16: **IoT Devices vs Throughput (with rain and without rain).**

Chapter 6

CONCLUSION

In conclusion, this research paper proposes a practical solution to address various challenges in the Hybrid GEO-LEO satellite network context. The study focuses on solving admission control collaboratively, a fairness of IoT association, power control, and fairness of Resource Blocks (RBs) allocation. The proposed algorithm has been extensively tested through simulation. The outer approximation algorithm (OAA) is utilized to achieve a near-optimal solution within a specified threshold, i.e., $\epsilon = 10^{-3}$. The simulations involve the random distribution of IoTs, and the algorithm intelligently selects combinations of IoTs that satisfy all constraints. The design process involves numerous trade-offs as the constraints impose diverse restrictions to attain a feasible and optimal output. The simulation results prove the proposed model to be viable. The research contributes to the field by providing a practical solution that addresses the complexities of admission control, IoT association fairness, power control, RBs allocation fairness, and throughput maximization.

BIBLIOGRAPHY

[1] C. G. C. Index and C. Index, "Forecast and methodology, 2016–2021; white paper; cisco systems," *Inc.: San Jose, CA, USA*, 2017.

[2] H.-L. Truong and S. Dustdar, "Principles for engineering iot cloud systems," *IEEE Cloud Computing*, vol. 2, no. 2, pp. 68–76, 2015.

[3] J. Lin, W. Yu, N. Zhang, X. Yang, H. Zhang, and W. Zhao, "A survey on internet of things: Architecture, enabling technologies, security and privacy, and applications," *IEEE internet of things journal*, vol. 4, no. 5, pp. 1125–1142, 2017.

[4] H. Huang, S. Guo, W. Liang, K. Wang, and A. Y. Zomaya, "Green data-collection from geo-distributed iot networks through low-earth-orbit satellites," *IEEE Transactions on Green Communications and Networking*, vol. 3, no. 3, pp. 806–816, 2019.

[5] F. Li, K.-Y. Lam, M. Jia, K. Zhao, X. Li, and L. Wang, "Spectrum optimization for satellite communication systems with heterogeneous user preferences," *IEEE Systems Journal*, vol. 14, no. 2, pp. 2187–2191, 2019.

[6] B. Li, Z. Fei, C. Zhou, and Y. Zhang, "Physical-layer security in space information networks: A survey," *IEEE Internet of things journal*, vol. 7, no. 1, pp. 33–52, 2019.

[7] I. Leyva-Mayorga, B. Soret, M. Röper, D. Wübben, B. Matthiesen, A. Dekorsy, and P. Popovski, "Leo small-satellite constellations for 5g and beyond-5g communications," *Ieee Access*, vol. 8, pp. 184 955–184 964, 2020.

[8] C. Jiang and X. Zhu, "Reinforcement learning based capacity management in multi-layer satellite networks," *IEEE Transactions on Wireless Communications*, vol. 19, no. 7, pp. 4685–4699, 2020.

[9] R. Wang, R. Li, P. Wang, and E. Liu, "Analysis and optimization of caching in fog radio access networks," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 8, pp. 8279–8283, 2019.

[10] G. Wu, Z. Li, and H. Jiang, "Quality of experience-driven resource allocation in vehicular cloud long-term evolution networks," *Transactions on Emerging Telecommunications Technologies*, vol. 31, no. 8, p. e4036, 2020.

[11] R. Basir, S. Qaisar, M. Ali, H. Pervaiz, M. Naeem, and M. A. Imran, "Resource allocation and throughput maximization for iot real-time applications," in *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*. IEEE, 2020, pp. 1–5.

[12] R. Basir, S. Qaisar, M. Ali, M. Aldwairi, M. I. Ashraf, A. Mahmood, and M. Gidlund, "Fog computing enabling industrial internet of things: State-of-the-art and research challenges," *Sensors*, vol. 19, no. 21, p. 4807, 2019.

[13] H. F. Atlam, R. J. Walters, and G. B. Wills, "Fog computing and the internet of things: A review," *big data and cognitive computing*, vol. 2, no. 2, p. 10, 2018.

[14] T. Leng, P. Duan, D. Hu, G. Cui, and W. Wang, "Cooperative user association and resource allocation for task offloading in hybrid geo-leo satellite networks," *International Journal of Satellite Communications and Networking*, vol. 40, no. 3, pp. 230–243, 2022.

[15] M. Grillo, A. A. Dowhuszko, M.-A. Khalighi, and J. Hämäläinen, "Resource allocation in a quantum key distribution network with leo and geo trusted-repeaters," in *2021 17th International Symposium on Wireless Communication Systems (ISWCS)*. IEEE, 2021, pp. 1–6.

[16] S. H. Chae, S.-W. Jeon, and C. Jeong, "Efficient resource allocation for iot cellular networks in the presence of inter-band interference," *IEEE Transactions on Communications*, vol. 67, no. 6, pp. 4299–4308, 2019.

[17] O. Karatalay, I. Psaromiligkos, and B. Champagne, "Energy-efficient resource allocation for d2d-assisted fog computing," *IEEE Transactions on Green Communications and Networking*, 2022.

[18] N. Moghaddas-Gholian, V. Solouk, and H. Kalbkhani, "Relay selection and power allocation for energy-load efficient network-coded cooperative unicast d2d communications," *Peer-to-Peer Networking and Applications*, pp. 1–13, 2022.

[19] M. R. Palattella, J. O'Sullivan, D. Pradas, K. McDonnell, I. Rodriguez, and G. Karagiannis, "5g smart connectivity platform for ubiquitous and automated innovative services," in *2021 IEEE 32nd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*. IEEE, 2021, pp. 1582–1588.

[20] X. Ding, Z. Ren, H. Lu, and G. Zhang, "Improving sinr via joint beam and power management for geo and leo spectrum-sharing satellite communication systems," *China Communications*, vol. 19, no. 7, pp. 25–36, 2022.

[21] R. Ge, J. Cheng, K. An, and G. Zheng, "Non-orthogonal multiple access enabled two-layer geo/leo satellite network," in *2021 29th European Signal Processing Conference (EUSIPCO)*. IEEE, 2021, pp. 890–894.

[22] S. Mao, S. He, and J. Wu, "Joint uav position optimization and resource scheduling in space-air-ground integrated networks with mixed cloud-edge computing," *IEEE Systems Journal*, vol. 15, no. 3, pp. 3992–4002, 2020.

[23] R. Basir, S. Qaisar, M. Ali, M. Naeem, and A. Anpalagan, "Energy efficient resource allocation in cache-enabled fog networks," *Transactions on Emerging Telecommunications Technologies*, vol. 32, no. 11, p. e4343, 2021.

[24] K. Wang, W. Chen, J. Li, Y. Yang, and L. Hanzo, "Joint task offloading and caching for massive mimo-aided multi-tier computing networks," *IEEE Transactions on Communications*, vol. 70, no. 3, pp. 1820–1833, 2022.

[25] R. Basir, S. Qaisar, M. Ali, and M. Naeem, "Cloudlet selection in cache-enabled fog networks for latency sensitive iot applications," *IEEE Access*, vol. 9, pp. 93 224–93 236, 2021.

[26] R. Basir, S. B. Qaisar, M. Ali, M. Naeem, K. C. Joshi, and J. Rodriguez, "Latency-aware resource allocation in green fog networks for industrial iot applications," in *2020 IEEE International Conference on Communications Workshops (ICC Workshops)*. IEEE, 2020, pp. 1–6.

[27] J. Jiang, Z. Li, Y. Tian, and N. Al-Nabhan, "A review of techniques and methods for iot applications in collaborative cloud-fog environment," *Security and Communication Networks*, vol. 2020, pp. 1–15, 2020.

[28] R. Yadav, W. Zhang, I. A. Elgendy, G. Dong, M. Shafiq, A. A. Laghari, and S. Prakash, "Smart healthcare: Rl-based task offloading scheme for edge-enable sensor networks," *IEEE Sensors Journal*, vol. 21, no. 22, pp. 24 910–24 918, 2021.

[29] V. K. Sarker, J. P. Queralta, T. N. Gia, H. Tenhunen, and T. Westerlund, "Offloading slam for indoor mobile robots with edge-fog-cloud computing," in *2019 1st international conference on advances in science, engineering and robotics technology (ICASERT)*. IEEE, 2019, pp. 1–6.

[30] G. Maral, M. Bousquet, and Z. Sun, *Satellite communications systems: systems, techniques and technology*. John Wiley & Sons, 2020.

[31] "The Role of Satellites in 5g Networks | Wilson Center," jun 23 2022, [Online; accessed 2022-07-14].

[32] R. K. Jain, D.-M. W. Chiu, W. R. Hawe *et al.*, "A quantitative measure of fairness and discrimination," *Eastern Research Laboratory, Digital Equipment Corporation, Hudson, MA*, vol. 21, 1984.

[33] B. Di, H. Zhang, L. Song, Y. Li, and G. Y. Li, "Ultra-dense leo: Integrating terrestrial-satellite networks into 5g and beyond for data offloading," *IEEE Transactions on Wireless Communications*, vol. 18, no. 1, pp. 47–62, 2018.

[34] D. Zhou, M. Sheng, R. Liu, Y. Wang, and J. Li, "Channel-aware mission scheduling in broadband data relay satellite networks," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 5, pp. 1052–1064, 2018.

[35] H. Bian and R. Liu, "Reliable and energy-efficient leo satellite communication with ir-harq via power allocation," *Sensors*, vol. 22, no. 8, p. 3035, 2022.

[36] J. F. O'Hara and D. R. Grischkowsky, "Comment on the veracity of the itu-r recommendation for atmospheric attenuation at terahertz frequencies," *IEEE Transactions on Terahertz Science and Technology*, vol. 8, no. 3, pp. 372–375, 2018.

[37] L. Tang, X. Zhang, H. Xiang, Y. Sun, and M. Peng, "Joint resource allocation and caching placement for network slicing in fog radio access networks," in *2017 IEEE 18th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*. IEEE, 2017, pp. 1–6.

[38] M. Hong and Z.-Q. Luo, "Distributed linear precoder optimization and base station selection for an uplink heterogeneous network," *IEEE transactions on signal processing*, vol. 61, no. 12, pp. 3214–3228, 2013.

[39] C. A. Floudas and P. M. Pardalos, *Encyclopedia of optimization*. Springer Science & Business Media, 2001, vol. 1.

[40] C. A. Floudas, *Nonlinear and mixed-integer optimization: fundamentals and applications*. Oxford University Press, 1995.

[41] M. A. Duran and I. E. Grossmann, "An outer-approximation algorithm for a class of mixed-integer nonlinear programs," *Mathematical Programming*, vol. 39, no. 3, pp. 337–337, 1987.

[42] R. Fletcher and S. Leyffer, "Solving mixed integer nonlinear programs by outer approximation," *Mathematical programming*, vol. 66, no. 1, pp. 327–349, 1994.

[43] C. F. Van Loan and G. H. Golub, *Matrix computations*. Johns Hopkins University Press, 1983.

[44] P. Bonami, P. Belotti, J. Forrest, L. Ladanyi, and C. Laird, "Basic open-source nonlinear mixed integer programming," *accessed on Aug*, vol. 1, 2019.

[45] F. Shahzad, M. Ali, H. Zubair Khan, M. Naeem, U. Masud, and F. Qamar, "Joint user association and energy efficiency maximization in beyond 5g heterogeneous networks," *International Journal of Communication Systems*, vol. 35, no. 8, p. e5122, 2022.

[46] H. Z. Khan, M. Ali, I. Rashid, A. Ghafoor, and M. Naeem, "Cell association for energy efficient resource allocation in decoupled 5g heterogeneous networks," in *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*. IEEE, 2020, pp. 1–5.