RESOURCE ALLOCATION FOR THROUGHPUT MAXIMIZATION IN SATELLITE-TERRESTRIAL INTEGRATED NETWORKS

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THESIS ACCEPTANCE CERTIFICATE

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Maj Zarrar Tariq,
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DEDICATION

This thesis is dedicated to

MY BELOVED PARENTS,

MY WIFE, DAUGHTER AND SON,

HONORABLE TEACHERS AND FRIENDS

for their love, endless support and encouragement

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I am grateful to Allah Almighty who has bestowed me the strength and the passion to accomplish this thesis and I am thankful to Him for His mercy and benevolence, without whose consent I could not have indulged myself in this task.

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NOTATIONS

Notation	Definition
$\mathbb{I}$	Set of UEs
$\mathbb{J}$	Set of BSs
u_i	UE i admission in STIN
$v_{i,j}$	UE i association with BS j
P_j	BS j maximum transmit power
$P_{i,j}$	Power allocated by BS j to UE i
$P_{i',j}$	Power allocated by BS j to UE $i^{'}$
$h_{i,j}$	Channel gain between UE i and BS j
$h_{i',j}$	Channel gain between UE $i^{'}$ and BS j
G_o	Antenna gain
$\bar{h}$	Rayleigh random variable
ζ	Zero mean Gaussian random variable
$d_{i,j}$	The distance between a UE i and a BS j
d_o	Antenna far field distance
α	Path loss exponent
σ^2	Gaussian white noise variance
$Q_{i,j}$	QoS rate requirement of UE i
$b_{i,j}$	Bandwidth allocated to UE i by BS j
$r_{i,j}$	Number of RBs required to meet QoS requirement
$c_{i,j}$	Achieve able rate by UE i
T_{RB}	Total available Resource Blocks
C_{b-i}	Constraint b to constraint i

ACRONYMS

Acronym	Definition
$1G$	1^{st} Generation
$2G$	2^{nd} Generation
$3G$	3^{rd} Generation
$4G$	4^{th} Generation
$5G$	5^{th} Generation
UE	User Equipment
UA	User Association
BS	Base Station
RB	Resource Block
DL	Down Link
UF	User Fairness
QoS	Quality of Service
QoE	Quality of Experience
$STIN$	Satellite-Terrestrial Integrated Network
$HetNets$	Heterogeneous Networks
$SatCom$	Satellite Communication
$AOCS$	Attitude and Orbit Control System
$TTC\&M$	Telemetry, Tracking, Command, and Monitoring
GEO	Geosynchronous Earth Orbit
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
HEO	Highly Elliptical Earth Orbit
MBS	Macro Base Station
GEB	GEO Satellite based BS
LSB	Large Size Base Station
SSB	Small Size Base Station
$D2D$	Device-to-Device
ES	Earth Station
STG	Satellite Terrestrial Gateway
$SINR$	Signal to Interference Plus Noise Ratio
$MINLP$	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

ABSTRACT

To meet the futuristic communications needs, a satellite-terrestrial integrated network (STIN) has been proposed and is a strong contender amongst emerging architectures. Different approaches have been researched and mainly two models are being considered for STIN implementation. In our STIN model, we have considered a satellite-based base station, dovetailed with a terrestrial N-tier heterogeneous network (HetNet). Joint admission control, user association (UA), and power allocation while ensuring fairness while associating user equipment (UE) in STIN and fairness in the allocation of spectrum resources to associated UEs in STIN with an objective to maximize throughput has not been investigated in the past. Classically, a macro base station (MBS) has the maximum resources as compared to small base stations and in HetNets a UE associates with a single BS depending upon the received signal strength. Consequently, most UEs are expected to be associated with a dominant transmit power MBS which is not an optimal approach as various new challenges arise such as unfair traffic load and interference resulting in overall reduced throughput. In the proposed approach, we have made an endeavor to meet these challenges and formulated a throughput maximization problem considering joint admission control, fair UA, power, and fair spectrum resource allocation. The formulated problem is a mixed integer non-linear programming (MINLP) problem that is non-deterministic polynomial-time hard (NP-hard) and to achieve an optimal solution it requires exhaustive search. But, the computational load of exhaustive search increases exponentially as the number of UEs increases. Therefore, to obtain a near-optimal solution having low computational load an outer approximation algorithm (OAA) is proposed. To evaluate the proposed algorithm, extensive simulation work has been performed. The effectiveness of the proposed approach is verified by the results in terms of fairness in UA, fairness in resource block (RB) allocation, and throughput in the downlink (DL).

Chapter 1

INTRODUCTION

The evolution of wireless communications followed by an overview of the STIN is discussed in this chapter. Moreover, related work, the thesis motivation, objectives, and contributions are elaborated along with the thesis organization.

1.1 Evolution of wireless communications

The path to modern-day wireless communications was unlocked by an Italian scientist, G. Marconi, by transmitting the character 'S' using morse code by electromagnetic waves. After this milestone event in mankind's history, present-day society cannot even contemplate living without wireless communications. The transformation of wireless communication from radio and television to modern smart cellular phones has made it possible for people to live more comfortable lives. The wireless communications evolution with regard to mobility, coverage, data rate, and spectral efficiency are depicted in Figure. 1.1 [1]. In particular, the advancements in wireless technologies are discussed as follows:

1.1.1 1G

1^{st} generation (1G) was unveiled in the 1980s which supported data rate up to 2.4 kbps. 1G prominent technologies were the nordic mobile telephone (NMT), total access communication system (TACS), and advanced mobile phone system (AMPS). Low capacity, poor voice, and no security features were the disadvantages of 1G wireless communication [2].

1.1.2 2G

2^{nd} generation (2G) with digital technology came in the 1990s. 1st 2G technology was the global system for mobile communications (GSM) followed by code division multiple access (CDMA) and IS-95. These technologies offered voice communication, short message service (SMS), and e-mail with data rate up to 64 kbps. 2G cellular

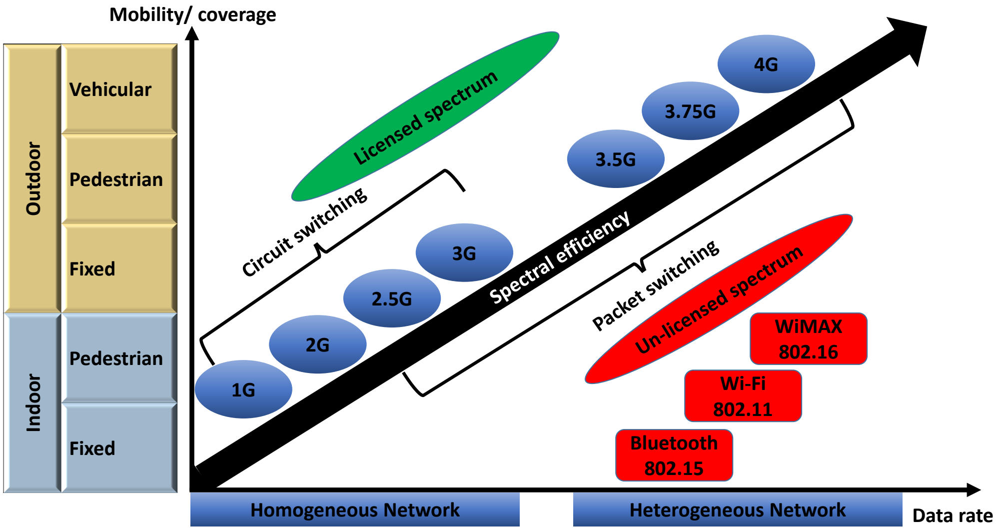

Figure 1.1: **Evolution of wireless communication**

phone used low-power radio signal thus enhancing the battery life of mobile phones [2, 3].

1.1.3 2.5G

General packet radio services (GPRS) merged with 2G wireless systems and known as 2.5G. Circuit switching combined with packet switching using 2G system framework supported data rates up to 144 kbps. Code Division Multiple Access (CDMA) 2000, a North American standard, Enhanced Data Rate for GSM Evolution (EDGE) along with GPRS are the main technologies of 2.5G wireless systems [2, 3].

1.1.4 3G

3^{rd} Generation (3G) emerged in latter part of 2000 with data rate up to 2 Mbps. 3G achieved remarkable milestones like better voice quality and roaming service along with high-speed access to internet protocol-based services in wireless networks. 3G has inherent disadvantages like more power consuming mobile hand sets along with expensive network planning [2, 3]. 3G technologies include universal mobile telecommunications systems (UMTS), wideband code division multiple access (WCDMA) and code division multiple access (CDMA) 2000 [3].

1.1.5 3.5G

Evolution data optimized (EVDO) and high speed uplink/downlink packet access (HSUPA/HSDPA) merged with 3G system and known as 3.5G. It supports data rate up to 30 Mbps [3].

1.1.6 3.75G

3G merged with worldwide interoperability for microwave access (WIMAX) and long term evolution technology (LTE) to be known as 3.75G. WIMAX and LTE has complemented network capacity, and can extend data hungry services like video on demand, online gaming and peer-to-peer file sharing to a large number of users in wireless network [3, 4].

1.1.7 4G

2G and 3G successor is 4^{th} Generation (4G) supporting data rate up to 1 Gbps. IP-based solutions for voice, data and multimedia services are imparted from previous generation enable anywhere and anytime quality of service (QoS) and quality of experience (QoE). Digital Video Broadcasting (DVB), Multimedia Messaging Service (MMS), High Definition TV and video chat are multimedia based applications being run on the 4G wireless network [5, 6].

1.1.8 5G

5^{th} Generation (5G) is currently being rolled out (2022). 5G is about delivering high data rate services, whose requirement is based on the result of the exponential growth in high end devices with infotainment applications, i.e., laptops, smartphones, wearable devices, tablets, machine-to-machine communication devices, etc. It is widely accepted among the research community that improvements done in 4G cellular networks cannot cater the predicted mobile data traffic's exponential growth in the near future. 5G cellular networks demand a paradigm shift to meet future 5G cellular network demands like ultra-high data rates, coverage, low latency, capacity, QoS and QoE.

1.2 Overview of STIN

Globally, the average speed of mobile network connection in 2018 was 13.2 Mbps and will increase by 43.9 Mbps which is more than three times, by 2023 according to Cisco [7]. Moreover, by 2025 the number of connected IoT devices will be around 30.9 billion making services possible such as smart cities, digital health care, and mission-critical assistance according to an IoT strategies report [8]. The rapid development in communication networks is having a huge impact on the routine lives of people and they are discontent with merely delivering messages but desire to use the network to interact with everything [9]. Consequently and owing to an outburst in the use of mobile and wireless devices, existing terrestrial networks will eventually face adversities in fulfilling the huge data requirements of users. Additionally, it is nearly impossible to make terrestrial infrastructure ubiquitous for the provision of telecommunication services. To address the aforementioned problems, the integration of satellite stations with the current terrestrial network seems promising [10].

Lately, the STIN has picked up steam as a linchpin in the attainment of seamless connectivity, universal multi-access, and wide-area coverage [11, 12, 13, 14]. To incite the base stations (BSs) diversity with regard to backhaul capacity, coverage area, and backhaul delay, the satellites are employed for backhauling the terrestrial BSs in STIN [15, 16]. This diversity increases the difficulty for UEs with different requirements to discover suitable service BSs, which has an adverse effect on improving resource utilization of the network. UA is the UE's association with the best serving BS for network performance improvement with regard to network capacity, balancing load, and power [17, 18]. Different approaches have been researched and mainly there are 2 models which are being considered for STIN implementation. Broadly in the first approach, UEs are directly associated with the satellite instead of any terrestrial BSs. In the second model, satellites are employed to provide backhaul connectivity to BSs. In our STIN model, we have considered the second approach in which we have taken a satellite-based BS, dovetailed with a terrestrial N-tier heterogeneous network (HetNet). STIN can be realized by incorporating geosynchronous earth orbit (GEO) or low earth orbit (LEO) satellites. However, GEO satellites have a large footprint and less mobility as compared to LEO satellites hence making resource management less challenging [19, 20]. Furthermore, comparatively GEO satellites have more onboard communication and computational resources. Aforesaid, we have incorporated GEO satellites in our STIN model. Figure 1.2 illustrates the architecture of STIN.

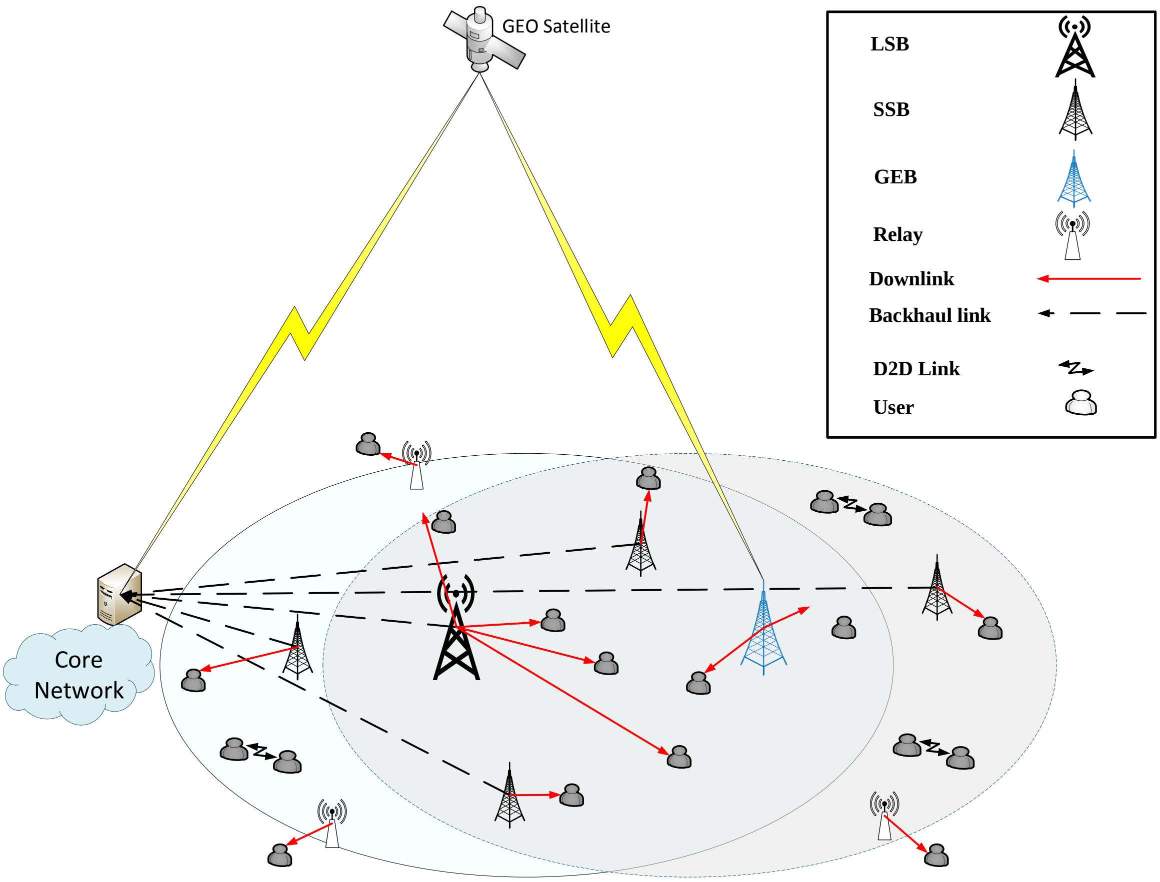

Figure 1.2: **STIN Architecture**

1.3 Heterogeneous networks

In past, HetNets encompassing large size base station (LSB) in addition to small size base stations (SSB), relays, and device-to-device (D2D) communication have played an important role in increasing throughput, serving more UEs, and providing seamless coverage [21]. In a cellular network, BS power consumption is near 80% of the network consumption. This is because LSB has high transmit power to have coverage in large cell area (urban LSB inter cite distance is 500 m and suburban LSB inter cite distance is 1732 m in long term evolution) [22]. LSB, with less capital cost, is suitable for low user density in larger area at a cost of larger energy consumption. Energy consumption can be reduced by reducing LSB transmit power with reduced cell size. However, this combination will require more LSBs to give full coverage in subject area and will increase capital cost. A flexible solution to offer an economical solution in terms of capital and energy cost with full coverage in a particular area is offered by heterogeneous network (HetNet). In HetNet, SSBs in addition to relays and D2D are deployed with existing LSB and operate on same frequency or use a different orthogonal frequency. SSBs, relays, and D2D deployed in coverage area of LSB, take traffic load from heavily loaded LSB and augment coverage and capacity [23, 24]. HetNets are a new trend in the following areas [25, 26, 27]:

- to increase network capacity
- to enhance network coverage
- to achieve energy efficiency
- to offload traffic from LSB

In HetNets fair UA is an important challenge. UEs in the overlaying region of two neighboring BSs can overburden one while the other serves fewer UEs. To assess wireless network resource management many indices such as Jain, min–max, and Gini have been proposed. The Jain's fairness index has been utilized in this work to clinch load balancing amid different nodes of STIN [28].

1.4 Fairness

Another crucial challenge in the distribution of radio resources in wireless networks is facilitating fairness among UEs. Each UE should be given equal radio resources, which is the traditional fairness challenge in packet scheduling among UEs. [29].The fairness issue in HetNets occurs not only during scheduling within a cell but also during the UA decision between cells at various tiers. In particular, an allocation is max-min fair if radio resources are distributed so that UE lowest possible rates are maximized [30, 31]. Simply put, UEs having poor channel quality will get more radio resources, while those having a good channel quality will get less of them. The Jain's fairness index [32] has been widely utilized for fairness evaluation, [33, 34], which is given as:

$$\mathbb{J}(r_1, ..., r_n, ..., r_N) = \frac{\left(\sum_{n=1}^{N} r_n\right)^2}{N\sum_{n=1}^{N}(r_n)^2}, \tag{1.1}$$

Jain's fairness index rates the fairness of a set of values where N is the number of UEs and r_n is the throughput of the n^{th} UE.

1.5 Related Work

Table 2.1 summarises previous work on various techniques in satellite and terrestrial networks whereas details are elaborated in the succeeding paragraphs.

The authors in [35] probed satellite and cellular network integration with the aim of satellite-based backhauling and proposed guidelines for satellite-based backhaul for next-generation cellular networks. In [36] the authors considered a network model comprising a GEO-based base station, LSB, and SSB and proposed a distributed UA with a grouping mechanism in which a greedy-based UA algorithm with user grouping maximizes the sum rate and achieved load balance by matching algorithm with the grouping of UEs.

In [37] considering a STIN the authors presented a dynamic UA (DUA) approach to address the UA problem caused by backhauling. In DUA, algorithms of dynamic extension of cell range and greedy-based user-centric UA considering task classification were used for load balancing and ensuring the task processing demands. The authors in [38] analyzed the performance of resource allocation and UA in a STIN incorporated with the cache. For collective optimization of UA and resource allocation of terrestrial and satellite networks, two algorithms were proposed that improved the DL throughput and also ensured the number of accessed ground users.

The authors in [39] considered multicast beamforming for joint user access selection and resource association for the terrestrial-satellite cooperation network to maximize the network's capacity under scheduling and power constraints. The authors in [40] probed the cooperative UA and resource allocation for task offloading in hybrid GEO-

LEO satellite networks and presented a cooperative UA and resource allocation, and used Deep reinforcement learning for dynamic UA and convex optimization is utilized to optimally achieve resource allocation with fixed UA matrix.

The authors in [41] presented the benefits of using Ku-band on the UE site and the composite of C and Ku bands on the gateway site for maximizing the throughput of the GEO satellites. In [42] the authors proposed a predator-prey model which is Lotka-Volterra based for resource allocation in satellite-terrestrial networks for achieving load balancing.

In [43] the authors considered a hybrid HetNet with both millimeter Wave (mmWave) and sub-6 GHz communications. A UA strategy that is mobility-aware is presented to ensure robust and reliable mmWave transmissions, in which mmWave channel state estimation is done with the help of Markov chain method. The authors in [44] presented the relay selection along with power allocation for energy efficiency maximization and balancing the load for random linear network coding aided cooperative unicast D2D (RLNC D2D) communications underlaying HetNets.

In [45] the authors discussed a practical near-optimal solution for UA, power allocation, admission control, and throughput maximization problems in HetNets using OAA. The authors in [46] proposed an algorithm for UA, power allocation, admission control, and maximizing throughput by employing coupled and decoupled UA schemes in HetNets. In [47] the authors presented a two-stage ϵ-optimal algorithm for UA, capacity, and spectrum efficiency in beyond 5G HetNets. The authors in [48] investigated joint secure UA, power, and resource allocation to maximize the secrecy rate in an N-tier HetNet.

Table 1.1: **Related work and novelty**

Parameters	[35] **2019**	[36] **2021**	[37] **2020**	[38] **2021**	[39] **2018**	[40] **2021**	[41] **2021**	[42] **2021**	[43] **2018**	[44] **2022**	[45] **2020**	[46] **2021**	[47] **2021**	[48] **2022**	This paper
Admission Control											✓	✓	✓	✓	✓
UA		✓	✓	✓	✓	✓			✓		✓	✓	✓	✓	✓
Power allocation		✓	✓	✓	✓					✓	✓	✓	✓	✓	✓
Transmission in DL	✓	✓		✓	✓	✓	✓		✓						✓
GEB	✓	✓			✓										✓
LSB		✓	✓		✓				✓		✓	✓	✓	✓	✓
SSB		✓	✓	✓				✓	✓	✓	✓	✓	✓	✓	✓
Relay								✓		✓	✓	✓	✓	✓	✓
D2D										✓	✓	✓	✓	✓	✓
Fair traffic load		✓	✓	✓		✓		✓		✓					✓
Fair RBs distribution						✓			✓	✓					✓
Throughput maximization	✓	✓		✓	✓		✓				✓	✓	✓	✓	✓

1.6 Motivations

After a comprehensive review of the literature on the subject, [35] - [48] and concluding from Table 1.1 to the best of the author's knowledge joint admission control, UA with fairness, power allocation, and fairness in the allocation of spectrum resources to associated UEs in STIN with an objective to maximize throughput has not been investigated in the past. The direction of the research remained focused on the following areas:

- The major part of research work on STIN so far has been on throughput maximization, power allocation, and UA.
- Existing techniques do not incorporate Satellite with Terrestrial HetNet elements, i.e., LSB, SSB, Relay and D2D in STIN
- Existing techniques do not incorporate joint admission control, UA, and power allocation while ensuring the following:
  - Fairness while associating UEs in STIN.
  - Fairness in the allocation of spectrum resources to associated UEs in STIN.
- Existing techniques haven't investigated throughput maximization as an objective keeping in view above stated considerations.

1.7 Objectives

Motivated by the gaps found in past research work, this research work aims the following objectives to optimally allocate resources with fairness for throughput maximization in STIN:

- Creating a system model of STIN with elements, i.e., GEB, LSB, SSB, Relay, and D2D. STIN feasibility will be investigated in Downlink (DL)
- Defining objective function for maximization of UEs data rate and Spectral Efficiency

- Defining constraints, i.e., UE Admission and cell association, Power, minimum QoS rate requirement, fairness in UEs association and Resource block allocation etc.
- Defining an optimization problem from the objective function.
- Developing an algorithm/ technique based on the defined optimization problem.
- Using developed algorithm/ technique, extensive simulation work on Matlab.

1.8 Contributions

Considering admission control, power allocation, fair UA, and spectrum resource allocation we formulate a throughput maximization problem. This problem is a MINLP problem that is complex and is NP-hard. Subsequently, it is solved via ϵ-optimal algorithm. Major contributions of this research work are enlisted as follows:

- Joint admission control, fair UA, and allocation of power along with spectrum resources with fairness in STIN have been investigated. Formulation of a throughput maximization optimization problem in STIN. The formulated problem is a MINLP problem and the objective function along with some constraints are non-linear.
- For solving the MINLP problem we use the branch and bound technique based two-stage ϵ-optimal algorithm. By fixing binary variables, the MINLP problem is transformed into non-linear programming (NLP) problem and dealt with in stage 1. NLP problem's solution is the upper bound of the optimal solution. In stage 2, the results of stage 1 are used to change the MINLP problem to mixed-integer linear programming (MILP) problem. MILP problem's solution yields the optimal solution's lower bound.
- The performance of the proposed STIN model is verified by the results in terms of addressing UE traffic load imbalances with fairness, allocation of spectrum resources with fairness, and throughput maximization.

1.9 Thesis Organization

Thesis is structured into six chapters as shown in Fig. 1.3. Chapter wise details are as follows:

Chapter: 2 Satellite Communication and HetNets - 5G This chapter discusses Satellite Communication and HetNets with a purview of STIN. Subsequently fairness in UA and spectrum allocation for throughput maximization in a HetNet augmented with a GEO satellite-based BS for ensuring any time anywhere global access to the UEs in STIN is discussed. These challenges form the basis for the proposed solutions in the later part of the thesis. A detailed review of joint admission control, UA and power allocation in relation to ensure fairness while associating users in STIN and fairness in allocation of spectrum resources to associated UEs in STIN with an objective to maximize throughput is elaborated to reach optimal solutions for improving the performance with regard to throughput maximization in STIN.

Chapter: 3 System Model and Problem Formulation This chapter focus on the system model ensuring joint admission control, fair UA, power allocation, fair RB distribution, and throughput maximization in STIN. The proposed communication model ensures any time anywhere global access to the UEs. Our STIN model comprises GEB, LSB, SSB, and relays along with D2D communication links. A mathematical model for STIN considering joint admission control, power distribution, fairness-based UA and spectrum resource allocation, and throughput maximization in DL is formulated. The aim of the proposed optimization model is to maximize the throughput of STIN.

Chapter: 4 Proposed Algorithm In this chapter ϵ-optimal algorithm is employed to address the formulated problems for ensuring fairness in UA and spectrum allocation with an objective to maximize throughput in STIN. The execution of ϵ-optimum solution attained via OAA is exhibited for different system parameters including UA, UF, RB fairness, and throughput maximization.

Chapter: 5 Simulations and Results In this chapter simulation results exhibit the advantages of the proposed algorithm as mentioned in the last chapter for attaining joint admission control, fair UA, power allocation, fair RB distribution, and throughput maximization in STIN. These results also provide considerable understanding regarding the proposed algorithm's convergence.

Chapter: 6 Conclusion and Future Work This work's contributions along with suggestions for future research are summarized here. The organization of this thesis is depicted in Figure 1.3.

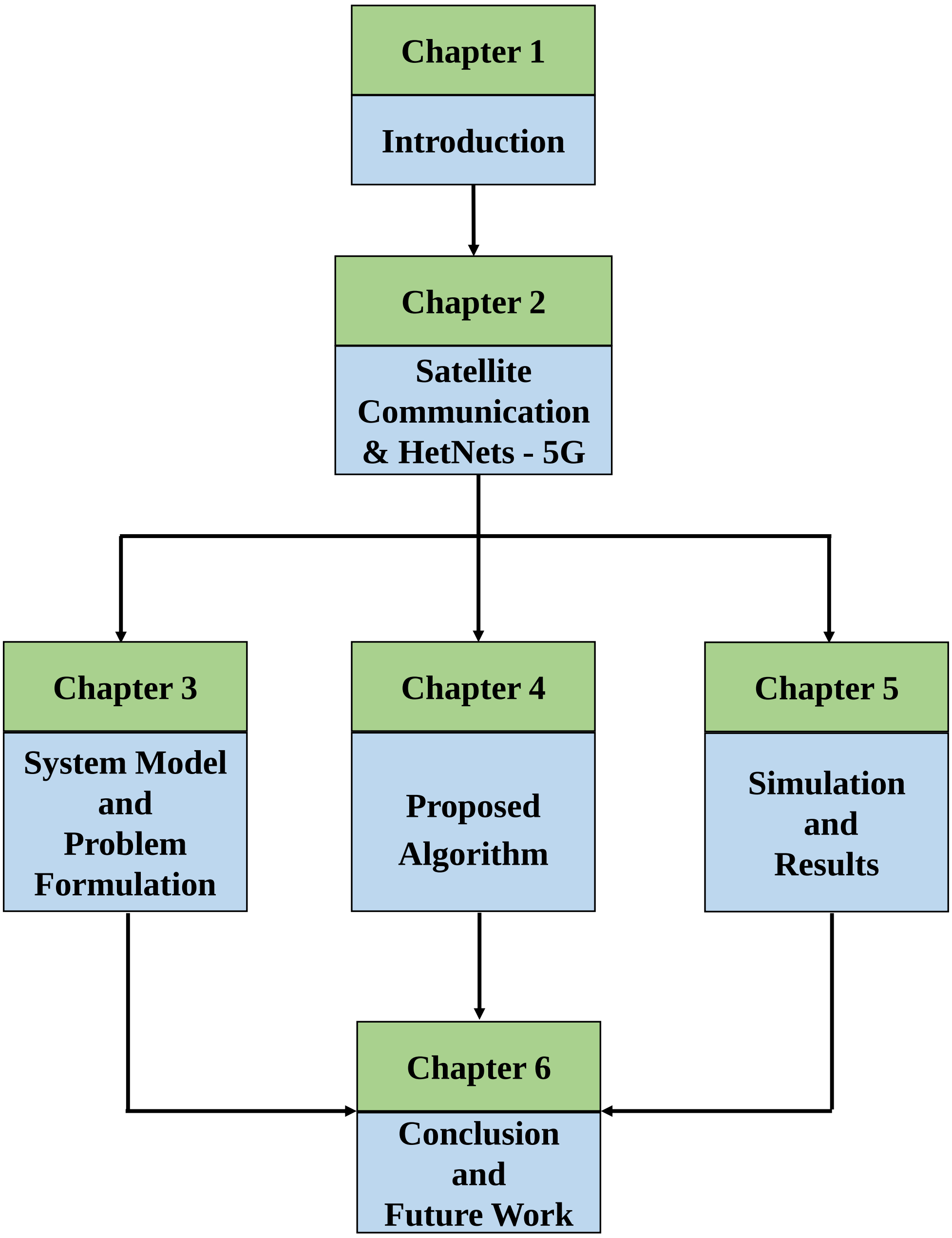

Figure 1.3: **Thesis organization**

Chapter 2

SATELLITE COMMUNICATION AND HETEROGENEOUS NETWORKS - 5G

2.1 Satellite Communication

In order to provide voice, video, data, internet, and navigation services to billions of people, satellite communication (SatCom) has become a crucial component of the global telecommunications infrastructure. There has been a huge transition in satellite applications from simple voice communication to video, data delivery, and direct television broadcasting to the home along with many futuristic services. Regardless of the rise of fiber optic links, having a lot more capacity and less cost per bit as compared to SatCom, the market for SatCom is still thriving and being invested in [49].

2.2 Brief History of SatCom

The development of SatCom is the result of research into space technologies and communications with the objectives to increase ranges and capacities while reducing the cost. The development of microwaves and missiles, two very different technologies, was sparked by the Second World War. The ability to integrate these two systems successfully eventually ushered in the era of satellite communications.

The first artificial satellite was launched in 1957, marking the beginning of the space age (Sputnik). The following experiments took place in the following years: President Eisenhower's Christmas greetings broadcasted by SCORE in 1958; the reflecting satellite ECHO in 1960; the store-and-forward transmission by the COURIER satellite in 1960; powered relay satellites (TELSTAR and RELAY in 1962); and the first geosynchronous satellite SYNCOM in (1963). The first Soviet communications satellite of the MOLNYA series was launched in 1965, the same year that the first commercial geosynchronous satellite INTELSAT I (or Early Bird) launched [50].

2.3 Satellite Orbits

When a satellite is placed in the desired orbital location, SatCom can commence. There are numerous different orbital types, each ideal for a particular application. Only a few kinds of orbits, though, are optimal for communication which are shown in Fig. 2.1. The features of satellite orbits that are frequently used for a variety of SatCom services and applications are discussed subsequently [51].

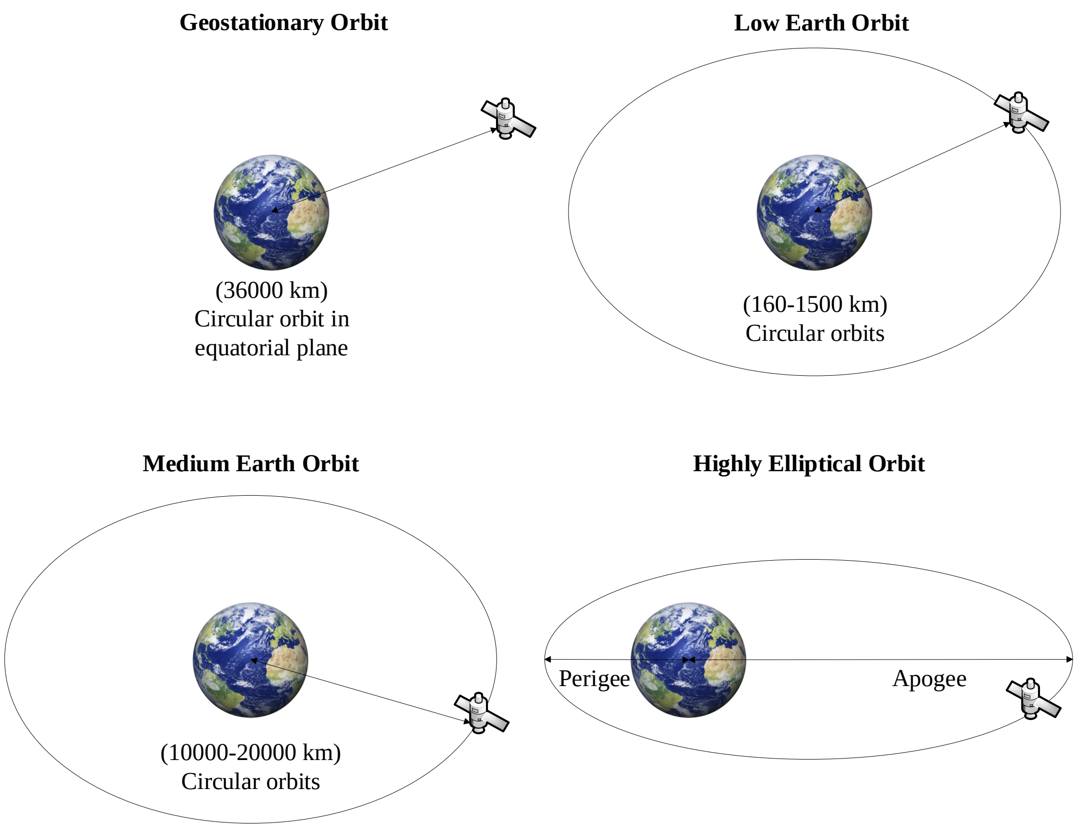

Figure 2.1: **Satellite Orbits**

2.3.1 Geosynchronous Orbit (GEO)

For SatCom, the GEO is the most popular. A GEO satellite is situated at a stable point in the equatorial plane, in a circular orbit, at an altitude of 36,000 km, which keeps the satellite in a fixed position in the sky. As a result, the satellite does not require tracking by terrestrial antennas, which is a huge benefit for SatCom. The pointing direction also remains stationary in orbit. The majority of modern communications satellites are in a GEO, due to the reason that it is excellent for transmission of data via a relay, having a relative fixed location in space, between two or more sites on the earth. It requires minimal to no ground tracking because the GEO satellite location offers an almost fixed path between the earth and satellite. Three GEO satellites spaced 120^o apart on the equatorial plane may cover the entire planet, with the exception of the pole regions. The GEO satellite's period of revolution is 23 hours and 56 minutes.

Despite being the most widely used orbit, the GEO has certain drawbacks. The radio wave signal traveling to and from the satellite experiences substantial latency (time delay) and a large path loss as a result of the long path length. A mid-latitude positioned ground station will have a two-way delay of about 260 ms. Problems could result from this, especially for voice communications or for specific protocols that can't handle a lot of latency.

The locations having high latitude cannot receive coverage from the GEO satellite. Operation at higher inclination angles can boost coverage significantly, but this causes additional issues, like the requirement for more ground antenna tracking, hence increasing the costs and complicating the system.

Owing to the restrictions of one equatorial plane availability and inter-satellite distance to prevent interference from one another, the number of satellites that may operate in GEO is restricted. International treaties, administered by the International Telecommunications Union closely coordinates the distribution of frequency band and service allocations with the distribution of geosynchronous orbital locations or slots. There are now only 72 to 180 slots available, which depends on the frequency band and the service being offered, with satellites spaced between two and five degrees apart.

2.3.2 Low Earth Orbit (LEO)

LEO satellites are satellites operating far below the GEO altitude, often at altitudes between 160 and 2500 km, and in nearly circular orbits. There are a number of features of the LEO satellite that can be useful for communications applications. The earth-satellite links are significantly shorter, which leads in lower path losses and smaller, low power antenna systems. Shorter path distances also result in less propagation delay. With the right inclinations, LEO satellites can extend coverage to high latitude areas, including polar regions, that are inaccessible to GEO satellites.

LEO satellite has a limited operational window due to its continuous motion and it is only available for about 8 to 10 minutes to a fixed location on earth. It is necessary to have a constellation of several LEO satellites with communication links between them to enable point-to-point communication if continuous global or vast area coverage is sought. To provide the needed coverage, some modern LEO satellite networks use 12, 24, and 66 satellites.

Due to the earth terminals' advantages of low power and small size, the LEO orbit has received substantial consideration for mobile applications. The size of LEO satellites is significantly smaller and requires considerably less energy to deploy into orbit as compared to GEO satellites, hence having lower total life cycle costs. However, more LEO satellites are needed for the provision of communications services similar to the GEO scenario.

2.3.3 Medium Earth Orbit (MEO)

MEO, or medium altitude orbit, refers to satellites that orbit between LEO and GEO, often at altitudes of 10,000 and 20,000 km. The repeated ground traces for recurring ground coverage, the adjustable number of revolutions per day, and sufficient relative satellite-earth motion to permit precise and accurate position measurements are among the desirable qualities of the MEO. An earth terminal at a fixed place would receive one to two hours of observation time from a standard MEO. Applications in meteorology, remote sensing, navigation, and position determination have identified MEO satellites to have properties that are helpful. For instance, the Global Positioning System (GPS) makes use of a constellation of up to 24 satellites that are in orbits that last 12 hours and are located at a height of 20,184 km.

2.3.4 Highly Elliptical Orbit (HEO)

High elliptical (high eccentricity) orbiting satellites, or HEOs, have maximum altitudes (apogee) comparable to GEOs and minimum latitudes (perigee) comparable to LEOs. High-latitude areas that are inaccessible to GEO and require longer contact periods than achievable with LEO satellites are covered by HEO. When a satellite is farthest to the earth but is traveling slowly through space, at its apogee, it can provide extended dwell time.

The Molniya orbit, named after the satellite system that served the (former) Soviet Union is the most popular HEO orbit for communications satellites. The orbit is intended to give extended coverage in high northern latitudes, which make up the majority of the land mass of the former Soviet Union and where GEO satellites cannot. The perigee and apogee altitudes of a typical Molnyia orbit are nearly 10000 km and 40,000 km respectively. The orbit repeats the same ground trace twice daily because its nominal period is 12 hours. Due to its high eccentricity, the satellite spends barely two hours per rotation in the southern hemisphere and roughly ten hours per rotation in the northern hemisphere. When appropriately phased, two satellites on HEO Molniya orbits can offer practically seamless high-latitude sites, coverage in the northern hemisphere.

2.4 Architecture of SatCom System

An operational communications satellite system is made up of a number of components or segments, ranging from ground-based and network components to space components in an orbital configuration. The individual system components will depend on the satellite system intended application, such as fixed satellite service, mobile service, or broadcast service. Fig. 2.2 can be used to represent a generic satellite system that can be used for most satellite applications.

A satellite (or satellites) in orbit that relays information between UEs via ground terminals makes up the basic structure of the system. Voice, data, video, or any combination of the three may be used to relay information. To connect with the ground terminal, the UE data might need to be transmitted via terrestrial means. The satellite is managed from the ground by a satellite control facility, frequently referred to as the master control centre (MCC), which performs tracking, telemetry, command, and system monitoring tasks.

- **Space Segment**. The orbiting satellite (or satellites) and the ground satellite control infrastructure required to keep the satellites operational make up the satellite system's space segment.

- **Ground Segment**. The Ground Segment consists of the transmit and receive earth stations and the associated equipment to interface with the UE network.

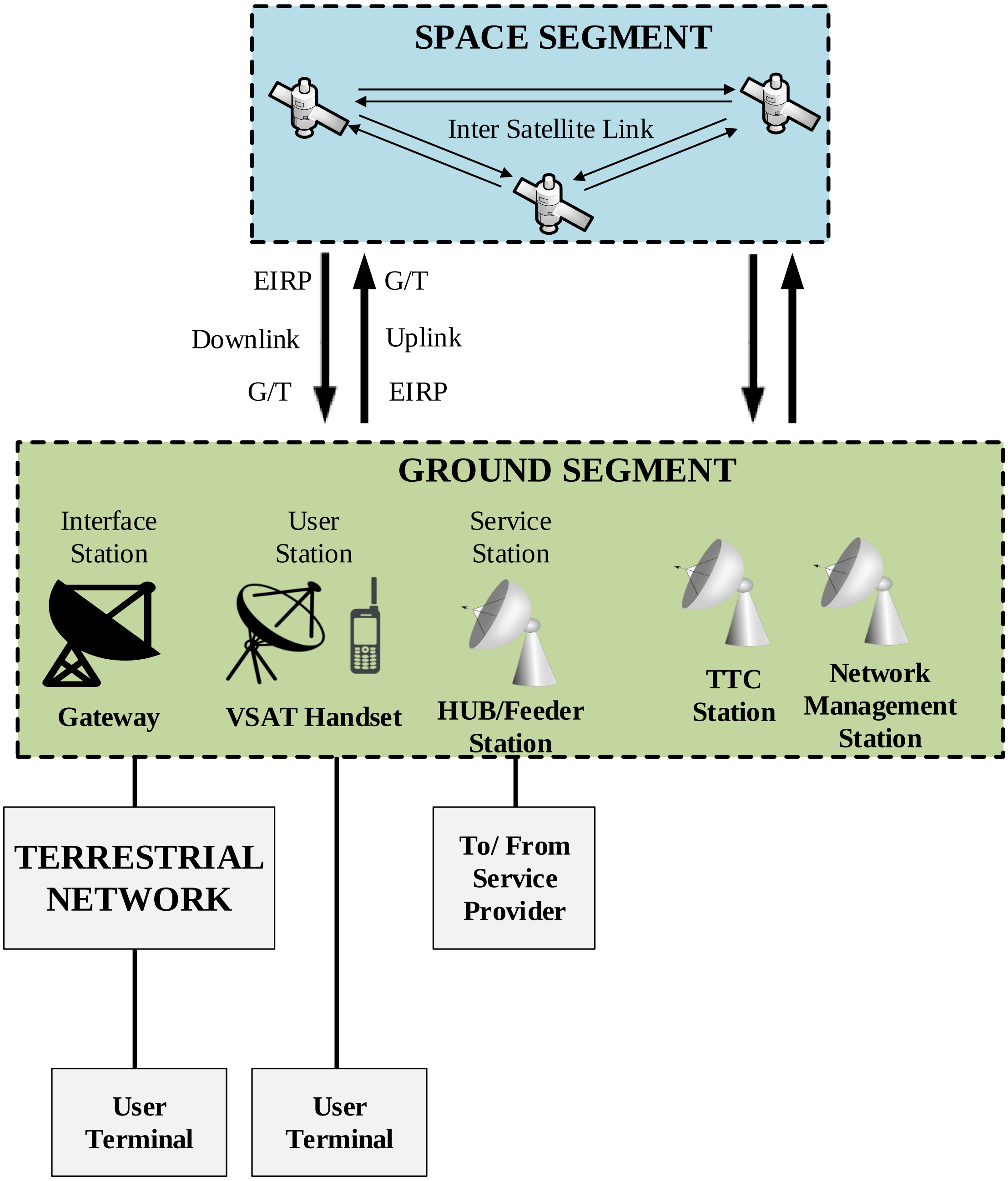

Figure 2.2: **Architecture of SatCom System**

2.5 Space Segment

The bus and the payload are two functional categories into which the space segment equipment carried by the satellite can be divided and can be described as follows:

- **Bus**. The term ”bus” describes both the fundamental satellite structure and the satellite supporting subsystems. The physical structure, the power subsystem, the attitude and orbital control subsystem, the thermal control subsystem, and the command and telemetry subsystem make up the bus subsystems.

- **Payload**. A satellite's payload is the hardware that delivers the services that the satellite is designed to deliver. The payload of a communications satellite is the communication equipment. The transponder and antenna subsystems are further divisions of the communications payload.

2.6 Satellite subsystems

The details of the major satellite subsystems are as follows [49]:

2.6.1 Attitude and Orbit Control System (AOCS)

AOCS subsystem comprises inertial devices or gas jets that regulate the attitude of the satellite and rocket motors along with electric propulsion systems that are used for course correction of the satellite to the proper orbit when external factors cause it to drift off station.

2.6.2 Telemetry, Tracking, Command, and Monitoring (TTC&M)

Both the satellite and the controlling earth station house these systems. The telemetry system sends information to the controlling earth station, using a telemetry link, gathered from numerous onboard sensors that monitor the health of the satellite. The tracking system, which gives data on the range, elevation, and azimuth angles of the satellite, is located at earth station. The orbital elements may be computed through repeated measurements of these three parameters, and changes in the satellite's orbit can then be identified. The control system is used to adjust the satellite's position and attitude based on telemetry data obtained from the satellite and orbital information obtained from the tracking system. Additionally, it is used to control switches on the satellite and to aim the antenna and configure the communication system to meet the needs of the current traffic.

2.6.3 Power System

Solar cells provide the electrical energy for all communication satellites. The communication system, specifically its transmitters, along with all other satellite's electrical systems, need power. Due to the fact that these subsystems support the communications system, the latter application is known as housekeeping. For a 1U cubesat, power systems can produce as low as 1W of DC power, and for a large GEO platform, up to 20 kW of power.

2.6.4 Communications Subsystems

A communications satellite's essential component is the communications subsystem, and everything else on the satellite exists only to support it. The communications equipment frequently only makes up a minor portion of the satellite's total weight and volume. It typically consists of two or more antennas that operate at microwave frequencies for communication over wide bandwidths, as well as a group of receivers and transmitters that are used for amplification and retransmission of the received signals. These receiver-transmitter devices are referred to as transponders. On satellites, there are generally two different types of transponders. The baseband processing transponder, which is only used with digital signals and the received signal converted to baseband, processed, and then retransmitted. The aforementioned strategy is generally referred to as onboard processing (OBP). The other type is a linear or bent pipe transponder, in which received signal is amplified and retransmitted at a different frequency.

2.6.5 Satellite Antennas

Satellite antennas can be viewed independently of the transponders despite being a component of the communication system. The antenna systems on large GEO satellites are extremely sophisticated and create either multiple spot beams that are pointed at specific locations on earth or beams that have forms that are specifically matched to the sections of the earth's surface that the satellite serves. Generally, satellite have antennas that operate in a single frequency band, like the C-band, Ku-band, or Ka-band, however there are some satellite antennas designed to work in two bands. Mostly, a satellite operating in various frequency bands has four or more antennas. Spot beam antennas can boost a satellite's communication capacity. The satellite may have one or more antennas that use various frequency bands and two orthogonal polarizations to produce numerous distinct beams within its footprint. Complex phased array antennas on LEO satellites for internet connectivity are capable of producing numerous electronically steered beams. As the satellite follows its orbit, each beam is angled toward a gateway station or a user terminal.

2.6.6 Thermal Control

Large temperature changes will be experienced by orbiting satellites, due to outer space harsh environment. One side of the satellite will be heated by solar thermal radiation, while the side that faces space will be subjected to freezing temperatures. Heat must be managed because a lot of the satellite's own equipment will produce it. Thermal radiations that are reflected from the earth have the potential to impact low-orbiting satellites. The satellite thermal control system's goal is to keep the satellite's temperature as stable as possible by reducing or shifting the heat that causes the huge thermal gradients that are formed inside the satellite. Thermal control in a satellite is provided using a variety of methods which mainly include thermal blankets and shields, radiation mirrors, heat pumps, and thermal heaters, etc.

2.7 Communication Links

The link between transmitting and receiving devices comprises of either a radio or optical modulated carrier. The efficiency of the transmitter 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 [50]. Figure 2.2 depicts the following types of links:

- UL from Earth Station (ES) to satellites.
- DL from satellites to ES.

- Inter-satellite links amongst satellites.

ULs and DLs are comprised of modulated radio frequency carriers, whereas inter-satellite links (ISLs) may be radio frequency or optical. Several large-capacity data-relay satellites communicate with their base stations through optical links. Baseband signals providing information for communication purposes modulate carriers.

2.8 SatCom & 5G

SatCom have a wide range of applications since its inception. With the development of Internet-based applications, satellite communications systems are currently through a transformation phase that is centering the system design on data services, specifically broadband SatCom. The primary drivers behind this are the swift embracing of media streaming over linear media broadcasting and provision of broadband service to underserved areas (such as emerging nations, the aviation and maritime industries, and rural areas). The dovetailing of several wired and wireless technologies is another significant 5G milestone. Aforesaid, SatCom can ensure seamless integration aimed at specific use cases that can benefit from their special qualities. Simultaneously, a variety of manufacturing and launching possibilities that were previously exclusively available to governments and a few major international enterprises have been developed by private ventures. The New Space initiative has made it possible to realize futuristic broadband and earth observation missions that are dependent on the SatCom systems advancements [52].

2.8.1 New Space

While the term ”New Space” alludes to a new attitude toward space, it does not specifically relate to any new technology. It evolved from three primary factors: Privatization of space, shrinking of satellite size, and space data-based novel services. In contrast to the conventional institutional method, privatization implies the production and, in particular, the launch of satellites by private enterprises like Rocket Lab and SpaceX. Concurrently, satellite and component miniaturization made it possible to multiplex several very small sized (cube, micro, and nano) satellites in one launcher. By enabling quick and cost-effective access to space, the first two factors together have led to the latter. Aforesaid, a large number of data-gathering constellations have been sent into space, providing a variety of services such as earth observation, asset tracking, and sensor data collection etc.

New Space has sparked new possibilities for data collection from ground sensors directly via satellites, which is termed as the Satellite Internet of Things. Several private companies are currently developing prototypes and striving to deliver a workable commercial service. Most of these endeavors depend on LEO, which creates new communication challenges which have been discussed earlier. All of these endeavors would typically need a vast network of ground stations for high availability. Nevertheless, networks of ground stations that can be shared among the different constellations have been developed by cloud-based services (like Amazon Web Services), which provide easy access to state-of-the-art computing for processing the data.

2.8.2 Satellite On-board capabilities

Advanced SatCom strategies have traditionally been constrained by the OBP capabilities. First off, since most satellites function as relays that frequency convert, amplify, and forward signals, therefore, onboard processing is generally waveform-independent. Second, signals undergo a significant path loss which must be addressed but the power available is also limited which is directly related to the mass and launch cost of the satellite. Thirdly, as the possibility of repair or replacement after the satellite is in space is limited, the used onboard technologies and components must be extremely reliable and durable. Nonetheless, recent improvements in power generation, digital processing components and radio frequency energy efficiency have enhanced the OBP capabilities, owing to which cutting-edge communication technologies like free-space optics, beam forming, and flexible routing/channelization can be realized. Additionally, software defined radios which are space-hardened can enable on-board waveform-specific processing, that are upgradeable during the satellite's lifespan. Last but not least, reduced launch costs and conveyor-belt production enable more innovative strategies to meet the most recent advancements in communication technology.

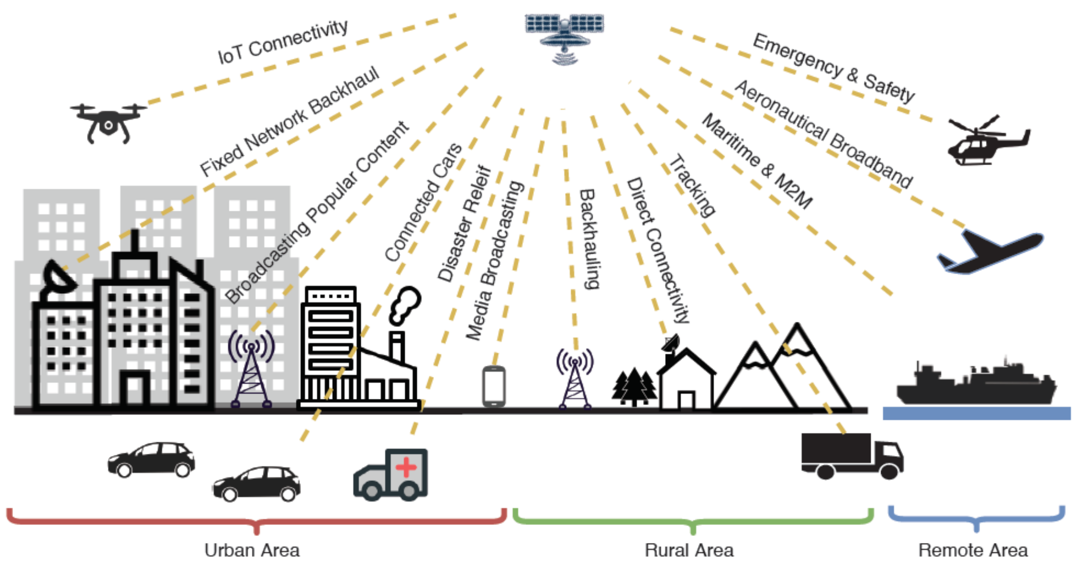

Figure 2.3: **Role of Satellites in 5G Eco-System**

2.8.3 Role of Satellites in 5G Eco-System

In order to meet the requirements of future significant business areas like the transportation and automotive industries, entertainment and media, e-Health, Industry 4.0, etc., 5G will be more than merely an evolution of the prior standards. ITU-R for International Mobile Telecommunications (IMT) for 2020 and beyond (IMT-2020) [53] defines three main categories of 5G use cases: enhanced mobile broadband (eMBB), massive machine type communication (mMTC), and ultra-reliable and low latency communications (uRLLC). The importance of SatCom in the 5G ecosystem is widely recognized. It is commonly acknowledged that satellites can play an important role in the 5G eco-system. In order to research the function of satellites in 5G, the 3rd Generation Partnership Project (3GPP) started new activities in 2017 [54, 55]. The 3GPP identified three main groups of use cases for Non Terrestrial Networks (NTN) 5G systems [56]. Firstly, by assuring service continuity when it cannot be provided by a single or combination of terrestrial networks, NTN can greatly increase the ”5G network reliability”. This is particularly true for mission-critical communications and moving platforms (cars, trains, and aircraft). Secondly, NTN can ensure ”5G service ubiquity” in un-served (deserts, oceans, forests, etc.) or under-served areas where a terrestrial network does not exist or is too impractical or expensive. At last, NTN is able to provide ”5G service scalability” owing to the satellite’s effectiveness at multicasting or broadcasting over a vast geographic area. An illustration of satellite use cases in 5G eco-system can be shown in Fig. 2.3.

2.9 HetNets

To meet the requirement of improved services with a higher data rate in cellular networks, numerous standards and technologies have been developed. The bandwidth and indoor/outdoor coverage of cellular networks will improve over the course of time. The cellular network’s capacity and coverage can be enhanced by placing transmitters and receivers closer. This strategy has been used in HetNets, where small, low-power, and inexpensive SSBs, relays, and D2D links surround huge, powerful, and expensive LSB. Figure 2.4 shows the HetNets scenario, and Table 2.1 depicts the comparison of different HetNets nodes.

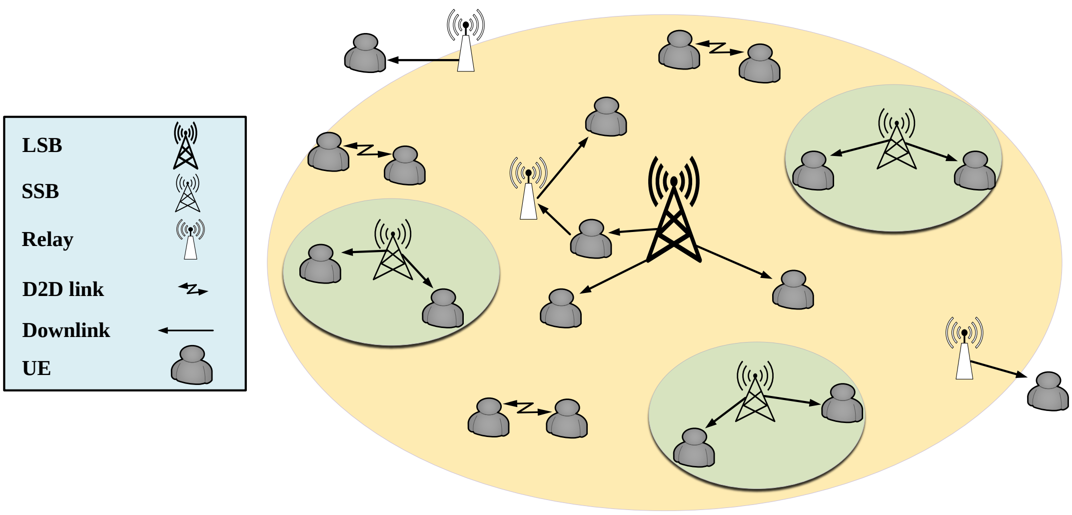

Figure 2.4: **A communication scenario in HetNet**

2.9.1 LSB

The fundamental serving component of a standard 3G or 4G wireless network is LSB. It is towered (40–60 m), long-range (300–2000 m), powerful (30–40 watt), and expensive ($60,000/year) provides maximum coverage for BSs in the cellular network.

Table 2.1: **HetNets nodes comparison**

Properties	**Macrocell**	**Picocell**	**Femtocell**	**Relay**	**D2D**
Standard	LTE Rel.8	LTE Rel.9	LTE Rel.9	LTE Rel.10	LTE-A Rel.12
Coverage	$\leq 2000m$	$\leq 100m$	$\leq 30m$	$\leq 300m$	$\leq 1000m$
Power	30-40W	200-2000mW	10-100mW	200-2000mW	$< 40W$
Backhaul	S1 interface	X2 interface	IP over internet	X2 interface	NA
Frequency band	Licensed	Licensed	Licensed	Licensed	Licensed
Access	Open	Open	Open	Open	open
Deployment	Outdoor	Outdoor	Indoor	Outdoor	Indoor/ outdoor
Installation	By operator	By operator	By user	By operator	By user
Cost	Highly expensive	Expensive	Cheap	expensive	Cheap

2.9.2 SSB

The objectives of extension of coverage area in cell edge areas, homes and offices and extra mobile data traffic offloading, are achieved by employing SSBs (femtocell and picocell). SSBs generally use optical fiber or wireless backhaul for communication with cellular core network. Additionally, employment of SSBs also result in spectral and energy efficiency enhancement in HetNets [57]. Moreover, an added advantage of SSBs in HetNets is, lower capital and operational expenditure (CAPEX, OPEX) [58]. The following are some features of SSBs in HetNets:

- **Picocells**: A cellular operator installs the Picocell, as an indoor/outdoor solution, with LSB like characteristics. For improving coverage in cell edge areas of the cellular network, it is small sized, short ranged (40-100m), low powered (200-2000mW), and cost effective ($10,000/year) outdoor solution [57]. To connect a picocell to the cellular core network, optical fiber/wireless backhaul is utilized. In comparison to LSB, picocell doesn't use air conditioning and has lower OPEX [59].

- **Femtocells**: A home BS called femtocells is an outdoor solution that the subscriber installs. It is a small sized, short ranged (10–40m), low powered

(10–100mW), and cost effective (100–150/year) solution that is used indoors (at homes or businesses) by subscribers [57].

2.9.3 Relay

Relays installed or operated outdoors by an operator are used to extend LSB coverage to blind areas and to transport data from UE to LSB and vice versa in HetNets [57]. To extend LSB coverage in blind cell edge locations, relays are medium-sized (5-10m), medium-range (500-2000m), low power (0.1-1W), and cost effective ($10,000/year) outdoor solution. Relays are connected to the cellular core network via optical fiber or wireless backhaul [59].

2.9.4 D2D

By enabling direct connection between devices in HetNets that is D2D mode, spectrum and energy efficiency can be guaranteed. In HetNets, LSB regulates D2D communication [60]. When in D2D mode, BSs nearby can exchange images, films, or engage in social networking or video gaming in HetNets. D2D mode uses a single hop for communication and requires only milliwatts of power.

2.10 Traffic offloading in HetNets

To assure QoS and QoE whenever and wherever it is practicable in HetNets, traffic offloading is done utilizing complementary networks. The burden of LSB in managing UEs traffic within the cell coverage region will be lessened if traffic to UEs is routed via other means. Nevertheless, complementary network deployment must guarantee to minimize interference, maximize throughput, and assure EE in HetNets. SSBs, Wi-Fi, and opportunistic communication are the main technologies for traffic offloading [61] described as:

2.10.1 Traffic offloading via SSB

In order to provide quality cellular services in blind and cell-edge areas, SSB is an emerging cellular technology [62]. Previous research revealed that households and workplaces accounted for the majority of data traffic [63, 64]. However, LSB has poor coverage in homes and offices. Aforesaid, SSB installed inside homes and offices is the ideal solution for indoor UEs in HetNets in terms of coverage, capacity, and increased throughput. A wired or wireless backhaul connects the SSB to the core network. Therefore, mobile data traffic is offloaded from the LSB to the SSBs, and seamlessly delivered to indoor UEs with improved QoS and QoE at lower capital and operational costs.

2.10.2 Traffic offloading via Wi-Fi

Since all mobile devices have Wi-Fi built-in, from the UEs perspective, Wi-Fi is a common way to access wireless service. Wi-Fi offers greater data rates with constrained coverage and mobility. From the perspective of the service provider, Wi-Fi is a good means for offloading mobile data traffic from the LSB with expensive licensed spectrum to free cost unlicensed spectrum [65]. Wi-Fi offers offloading in the following ways:

- **On the spot offloading**: When an access point is within the coverage area, mobile data traffic is sent over Wi-Fi else traffic is switched to the LSB or SSB.
- **Delayed offloading**: Mobile data traffic is delayed till the Wi-Fi service is available if it is not currently available.

2.10.3 Opportunistic communication for traffic offloading

Opportunistic communication is another effective method for offloading mobile data traffic. [66]. Mobile data traffic like weather forecast, movie trailers, sports news etc, can be delivered to targeted UEs which can further propagate the content using Wi-Fi, Bluetooth or device-to-device communication [67].

2.11 HetNets and UA

Cellular network with densified HetNets is a prominent theme in the 5G cellular network's [68]. UA has a major role in the cellular networks performance. In 4G HetNets, UA with HetNets nodes, i.e., LSB, SSB, Relay and D2D etc is based on the DL signal having strongest SINR. It is a suboptimal solution since transmit power disparity among HetNets nodes will result in most of the UEs associated with the LSB and the few UEs with SSB, relays and D2D [69]. This results in the inefficient deployment of

SSBs in HetNets which will not achieve the maximum dividends of offloading in 5G HetNets.

3GPP release 10 proposed biased UA to deal with this challenge where the received power from SSB is artificially increased by adding a bias for maximizing UEs offloading/ association to SSB. UA to SSB by biasing also results in increasing the interference to SSB from the LSB [70], and therefore the dividends attained by user offloading from LSB to the SSB are nullified by interference. So the value of biasing needs to be selected carefully to get the best trade-off between offloading and network throughput to maximize network utility [71]. UEs performance metrics are discussed below:

2.11.1 Outage/coverage probability optimization and UA

Performance of a particular UE is determined by outage/coverage probability using stochastic geometry in wireless network. Using stochastic geometry, authors in [72] and [73] analyzed performance of UA in N-tier HetNets depending on the maximum SINR in the DL. Results based on coverage probability with interference and load experienced by cells were presented for N-tier HetNets. Moreover, authors showed that coexisting HetNets nodes have different cell loads with few idle nodes contributing null to aggregate interference in HetNets. Therefore, authors in [73] improved the SINR model given by [72] by considering the activity factor of coexisting nodes in HetNets. It was further shown that the coverage probability was enhanced by adding picocell and femtocell with light load in HetNets. However, random deployment of SSBs in coverage area of LSB may lead to overloaded LSB and under utilized SSB in HetNets [73].

2.11.2 Spectrum efficiency optimization and UA

One important performance metric for evaluating the effectiveness of a cellular network is spectrum efficiency. The authors in [74] proposed a dynamic UA for sum-rate maximization for DL in HetNets. The authors employed convex optimization to attain the upper bound for the sum-rate in the DL and proposed a less complex heuristic algorithm for UA to get upper bound of the sum-rate in HetNets. The UA based on the heuristic algorithm in [74] outperformed UA based on maximum SINR, and biased value in terms of average sum-rate in HetNets. The authors in [33] optimized spectrum efficiency for UA employing game theory by formulating a utility based bargaining problem for data rate maximization where multiple BSs competing for the association of the maximum UEs in the DL in HetNets.

2.11.3 Backhaul bottleneck and UA

Traditional 3G cellular network with well planned classical LSB had a perfect backhaul, however, this is not true in the case of HetNets where SSBs, relays and D2D entities are deployed randomly. The authors in [68] observed the dividends of ultra dense HetNets that can be capitalized when HetNets is backed by a well planned/ dedicated backhaul. Therefore, the importance of constraints for backhaul cannot be ignored in HetNets.

The authors in [75] investigated UA and utility for sum-rate of all UEs with backhaul constraint whilst [76] devised a UA waterfilling algorithm for all UEs weighted sum-rate with backhaul constraints for SSBs. Authors in [77] investigated heuristic algorithms to enhance network capacity while considering backhaul constraint. Using game theory, authors in [78] designed UA which is cache aware while considering the backhaul constraint in HetNets.

2.11.4 Mobility support and UA

Mobility support for UA is a great challenge in densified HetNets. SSB with low transmit power will have limited coverage footprints in HetNets. Therefore, compared to a standard 3G cellular network having LSB alone, a UA algorithm that does not cater a UE's moderate or high speed mobility will cause more handovers in HetNets.

The authors in [79] considered UEs speed for UA with biased rule and derived DL coverage probability using tools of stochastic geometry. The results in [79] showed that the network performance and coverage probability were improved effectively with mobility dependent bias factor. Authors in [80] used a markov modulated Poisson process [81] to model jointly the UA and mobility problem to optimize network performance.

2.12 Interference in HetNets

The increase in heterogeneity with planned deployment of LSB and unplanned deployment of SSBs, relays and D2D in HetNets lead to severe inter-tier and cross-tier interference. Interference in HetNets (Inter-tier and cross-tier) can be categorized as DL and UL interference which is further elaborated in the following sub-section:

2.12.1 Interference to UE

There are two types of interferences that can be experienced by a UE in HetNets, when it is associated with a BS in the DL and receives data, which are as under:

- **DL to DL interference:** As the UE associates and receives data from the associated BS in the DL, reception by the UE from all un-associated BSs transmitting to other UEs in the DL is termed as DL to DL interference as depicted in Figure 2.5(a).

- **UL to DL interference:** When the UE associates/receives data from the associated BS in the DL, reception by the UE from all other UEs transmitting to un-associated BS in UL is termed as UL to DL interference as depicted in Figure 2.5(b).

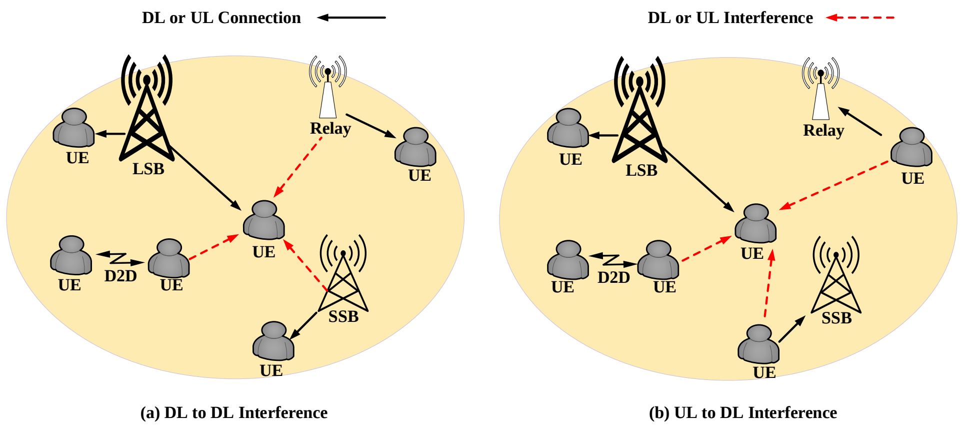

Figure 2.5: **Interference in DL**

2.12.2 Interference to BS

There are two types of interferences that can be experienced by a BS in HetNets, when it receives data from the associated UE in UL and details are as under:

- **DL to UL interference:** When the UE transmits to the associated BS in the UL, reception by associated BS from all other BSs transmitting to other UEs in the DL is termed as DL to UL interference as depicted in Figure 2.6(a).

- **UL to UL interference:** When the UE transmits to the associated BS in UL, reception by associated BS from all other UEs transmitting in the UL is termed as UL to UL interference as depicted in Figure 2.6(b).

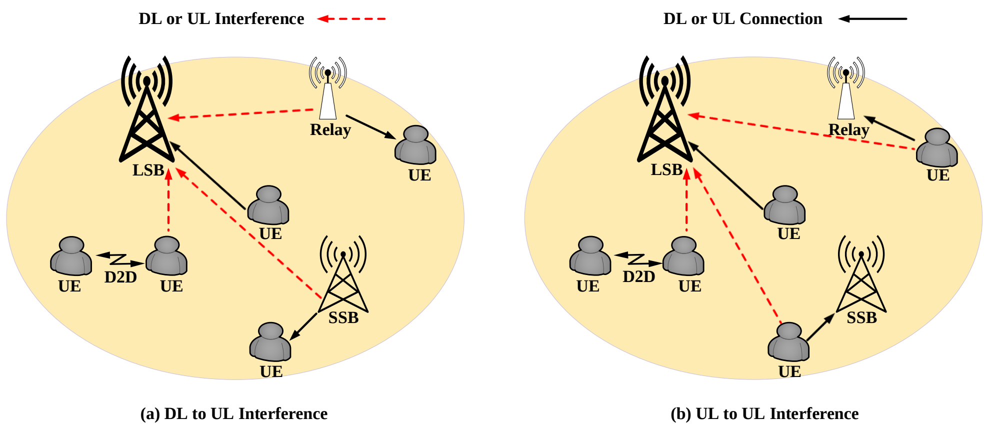

Figure 2.6: **Interference in UL**

2.13 Optimization theory

The UA problem is modeled employing a utility. The decision that a particular service is provided to a UE is quantified by the utility [82]. The UA problem may constitute utility like throughput, QoS, or spectrum efficiency etc, depending on adopted metric. These attributes are modeled as sigmoidal [83], logarithmic [84] and exponential [85] utility functions in recent studies. A popular optimization tool used for the solution of UA problem is combinatorial optimization, which is discussed below.

2.13.1 Combinatorial optimization

A general model for the UA problem with resource constraints to maximize utility in 5G HetNets is as under:

$$\max_{X} \mathcal{U}(x,\mu) = \sum_{m=1}^{M}\sum_{n=1}^{N} x_{m,n}\mu_{m,n}$$

$$s.t. \qquad (2.1)$$

$$f_i(x) \leq c_i,\ i = 1....,p.$$

where $x_{m,n}$ represents the UA and is given below:

$$x_{m,n} = \begin{cases} 1, & \text{if UE } n \text{ is associated to BS } m \\ 0, & \text{otherwise.} \end{cases}$$

Network utility is represented by $\mathcal{U}$. Utility for UE n associated to BS m is represented by $\mu_{m,n}$. Resource constraints like power, spectrum and QoS requirements are represented by $f_i(x) \leq c_i$. Since, a UE n can associates to single BS b at a time, therefore, $x_{m,n} = \{0, 1\}$. As a result, UA problem becomes a combinatorial optimization problem, which is complex, challenging and NP-hard. Using exhaustive search, $2^{|K|}$, i.e, $2^{|K|}$ optimization problems are required to be solved. Therefore, exhaustive search for even medium size network is prohibitive due to complexities. This issue is overcome by making problem convex. Then, OAA [86] or Lagrangian dual analysis [87] are invoked to obtain a solution which is near optimal for the formulated problem in Eq. (2.1).

Chapter 3

SYSTEM MODEL AND PROBLEM FORMULATION

3.1 System Model

This portion discusses joint admission control, fair UA, power allocation, fair RB distribution, and throughput maximization in STIN. The proposed communication model ensures any time anywhere global access to the UEs. Our STIN model comprises GEB, LSB, SSB, and relays along with D2D communication links as indicated in Fig. 3.1. GEB and LSB provide seamless coverage in the same area, SSB fills the coverage gaps in dead zones, relay extends the coverage of LSB, and D2D mode offers communication to two UEs in the near vicinity. We assume that satellite and terrestrial networks are integrated to allow access of both services to UEs in a seamless manner in the network.

The satellite-terrestrial gateway station (STG) is in the core network. GEO satellite is communicating with STG and GEB over C-band backhaul. The HetNets nodes, i.e., LSB, SSB, relays, etc are connected to STG over optical fiber backhaul. The GEB receives data from the GEO satellite over C-band and transmits the received data to UEs over C-band. Similarly, LSB, SSB, relays, and D2D operate in the sub-6 GHz band. To mitigate the co-channel interference from the LSB to SSB and D2D, we go by the assumption that in each cell, LSB utilizes a different spectrum than that of SSB and D2D. Omnidirectional antennas are used by SSB, relay, and D2D for UE coverage. The location of GEB, SSB, and relays follows a Poisson point process within the coverage area of LSB. UEs location has a uniform distribution in the serving BS coverage area.

Let set of UEs $\mathbb{I} = \{1, 2, 3, ..., I\}$ is served by set of BSs $\mathbb{J} = \{g, l, s, r, d\}$. Here, $g =$ GEB, $l =$ LSB, $s =$ SSB, $r =$ relay and $d =$ D2D.

Definition-1: Let binary variable for UE admission is given below:

$$u_i = \begin{cases} 1, & \text{UE } i \text{ is admitted} \quad (3.1a) \\ 0, & \text{Otherwise} \quad (3.1b) \end{cases}$$

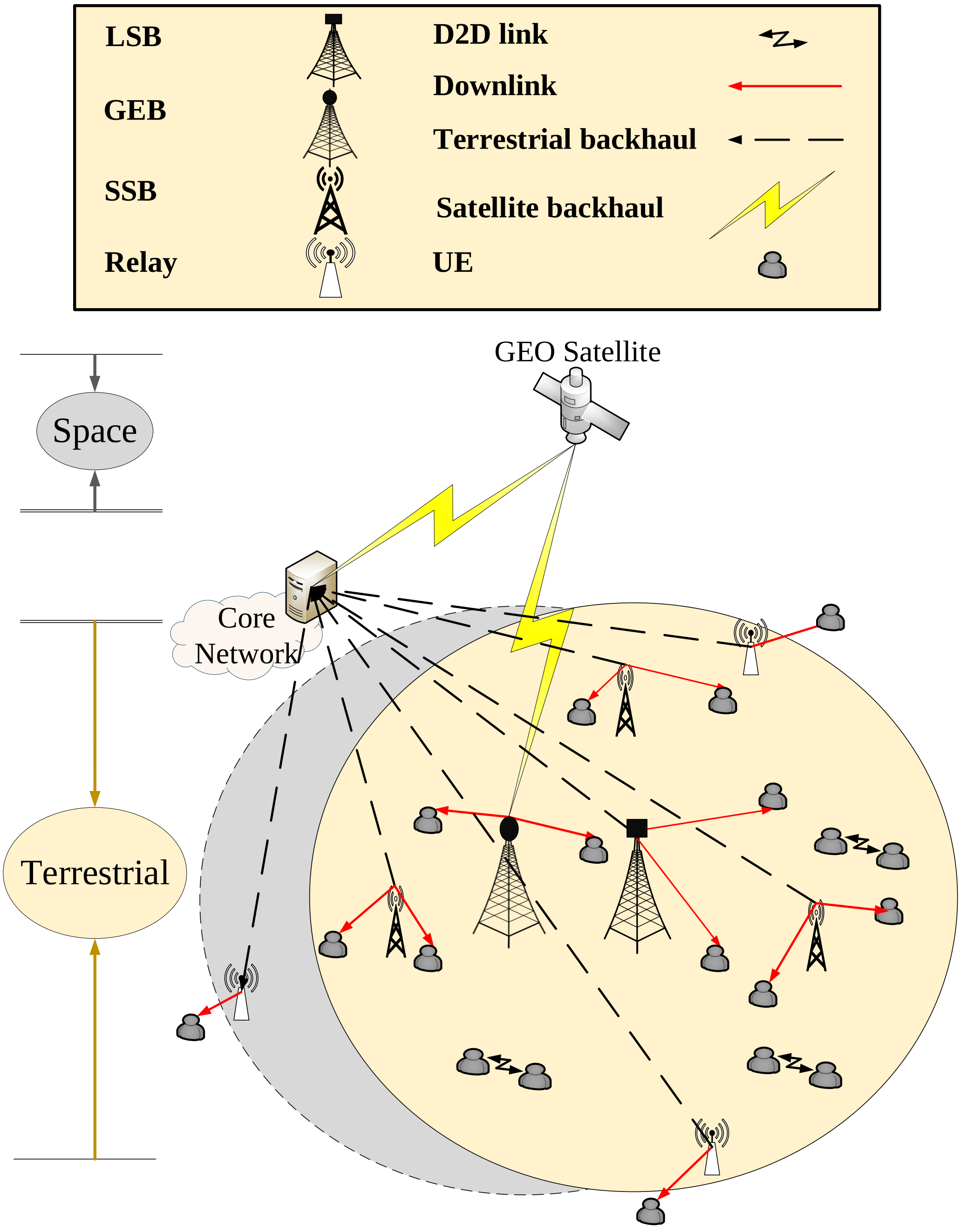

Figure 3.1: **Satellite-Terrestrial Integrated Networks**

Definition-2: Let binary variable for UA is given below:

$$v_{i,j} = \begin{cases} 1, & \text{UE } i \text{ is associated with a BS } j \quad (3.2a) \\ 0, & \text{Otherwise} \quad (3.2b) \end{cases}$$

A BS can serve more than one UE simultaneously, whereas a UE i can associate itself with a maximum of one BS j. The association of UEs with BSs should be such that UE's traffic load is shared with fairness among different BSs in the network. Mathematically, UE i admission, association, and fairness in UEs traffic offloading are given below:

$$\sum_{j \in \mathbb{J}} v_{i,j} = u_i, \; \forall \, i \in \mathbb{I}, \tag{3.3a}$$

$$\sum_{j \in \mathbb{J}} v_{i,j} \leq 1, \; \forall \, i \in \mathbb{I}, \tag{3.3b}$$

$$\phi_{i,j} = \frac{\left(\sum_{j \in J} v_{i,j} \right)^2}{J \sum_{j \in J} (v_{i,j})^2}, \; \forall \, i \in \mathbb{I}, \tag{3.3c}$$

where $\phi_{i,j}$ in (3.3c) is Jain's fairness index and $\phi_{i,j} \leq 1$. The value of $\phi_{i,j} = 1$ when UEs traffic is distributed equally among all BSs in STIN.

Every BS j has a maximum power P_j and the same power is allocated to different UEs associated with BS j. The allocated power to UE i by BS j is represented by $p_{i,j}$. Mathematically, the power allocation relation is given below:

$$\sum_{j \in \mathbb{J}} p_{i,j} \leq P_j \, \forall \, i \in \mathbb{I}, \tag{3.4a}$$

$$0 \leq p_{i,j} \leq P_j, \; \forall \, j \in \mathbb{J}, \, i \in \mathbb{I}. \tag{3.4b}$$

The channel gain [88] between a UE i associated with a BS j is given below:

$$h_{i,j} = \bar{h}\zeta G_o(\frac{d_o}{d_{i,j}})^{\alpha}, \forall j \in \mathbb{J}, i \in \mathbb{I}. \tag{3.5a}$$

where $\bar{h}$ is Rayleigh random variable, lognormal shadowing is denoted by $\zeta 10^{\frac{\zeta}{2}}$, G_o is the antenna gain, zero-mean Gaussian random variable is denoted by ζ with standard deviation σ [89], $d_{i,j}$ denotes the distance between a UE i and a BS j, antenna far field distance is d_o and α is the path loss exponent.

Using the UA in (3.2a), power allocated in (3.4b) and channel gain in (3.5a), the signal to interference plus noise ratio (SINR) of UE i associated with BS j is as under:

$$\text{SINR}_{i,j} = \frac{v_{i,j}p_{i,j}|h_{i,j}|^2}{\sum\limits_{i \neq i'} v_{i',j}p_{i',j}|h_{i',j}|^2 + \sigma^2}, \; j \in \mathbb{J} \;\&\; i \in \mathbb{I}, \tag{3.6a}$$

where σ^2 is Gaussian white noise variance.

In the DL transmission, the achievable throughput of UE i associated with BS j is given by the Shannon capacity formula [90]

$$c_{i,j} = log_2\left(1 + SINR_{i,j}\right), \forall j \in \mathbb{J}, i \in \mathbb{I} \tag{3.7a}$$

where SINR is given in (3.6a). The QoS rate requirement of a UE determines the number of RBs which are to be allocated by BS j to UE i. Mathematically, the number of RBs allocated by BS j to the UE i to fulfill the QoS rate requirement is as under:

$$r_{i,j} = \left\lceil \frac{Q_{i,j}}{b_{i,j}c_{i,j}} \right\rceil, \forall j \in \mathbb{J}, i \in \mathbb{I}, \tag{3.8a}$$

$$\eta_{i,j} = \frac{\sum\limits_{j \in J} r_{i,j}}{\sum\limits_{j \in J} v_{i,j}}, \forall i \in \mathbb{I}, \tag{3.8b}$$

$$\psi_{i,j} = \frac{\left(\sum\limits_{j \in J} \eta_{i,j}\right)^2}{J \sum\limits_{j \in J} (\eta_{i,j})^2}, \forall i \in \mathbb{I}. \tag{3.8c}$$

where $\lceil \cdot \rceil$ denotes ceiling function and $b_{i,j}$ is bandwidth allocated to UE i associated with BS j. $r_{i,j}$ is the RBs allocated by BS j to the UE i for a particular QoS rate requirements. $\eta_{i,j}$ in (3.8b) is the ratio of RBs allocated by BS j to all UEs i associated with it and the total no of UEs associated with BS j. Where $\psi_{i,j}$ in (3.8c) is Jain's fairness index for fair distribution of RBs among i UEs and $\psi_{i,j} \leq 1$. The value of $\psi_{i,j} = 1$ when RBs are distributed equally among all UEs in STIN.

3.2 Problem Formulation

This sub-section discusses a mathematical model formulation for STIN considering admission control, fairness-based UA, power allocation, fair RB allocation, and throughput maximization in DL. The aim of the proposed optimization model is throughput maximization of STIN considering the following constraints:

- **Admission control constraint**: It ensures admission of a UE i in STIN:

$$\sum_{j \in \mathbb{J}} v_{i,j} = u_i, \, \forall \, i \in \mathbb{I}, \tag{3.9}$$

  where u_i represents the binary variable for UE admission.

- **UA constraint**: At any given time, a UE i will be associated at maximum with only one BS j (LSB, GEB, SSB, relay or D2D):

$$\sum_{j \in \mathbb{J}} v_{i,j} \leq 1, \, \forall \, i \in \mathbb{I}, \tag{3.10}$$

  where $v_{i,j}$ represents binary variable for UA.

- **Fair UEs association constraint**: Fairness in the association of UEs with BS j (LSB, GEB, SSB, relay, or D2D). The value for user fairness ≤ 1. The value of user fairness = 1 when UEs are distributed equally amongst all BSs in STIN:

$$\left(\sum_{j \in J} v_{i,j} \right)^2 - J \sum_{j \in J} (v_{i,j})^2 \leq 0, \, \forall \, i \in \mathbb{I}, \tag{3.11}$$

- **Power constraints**: Every BS j (LSB, GEB, SSB, relay, or D2D) has a maximum power P_j and the same power is distributed amongst different UA with BS j. $p_{i,j}$ denotes the power that BS j has assigned to UE i and this is always less than or can be equal to the maximum power P_j of respective BS j (3.12).Eq. (3.13) gives the upper power bound of a BS j in which u_i is the UE admission variable and it's value is 1 when a UE is admitted in the network and 0 otherwise:

$$0 \leq p_{i,j} \leq P_j, \forall j \in \mathbb{J}, i \in \mathbb{I} \tag{3.12}$$

$$\sum_{j \in \mathbb{J}} p_{i,j} \leq u_i P_j \, \forall i \in \mathbb{I}, \tag{3.13}$$

- **UEs QoS rate requirement constraint**: Achievable rate of UE i associated with BS j (LSB, GEB, SSB, relay, or D2D) must be greater than the QoS rate requirement of UE i:

$$c_{i,j} \geq u_i Q_{i,j}, \forall j \in \mathbb{J}, i \in \mathbb{I}, \tag{3.14}$$

- **RBs allocation constraint**: RBs required denoted by $r_{i,j}$ to meet QoS requirement are allocated by BS j (LSB, GEB, SSB, relay, or D2D) to the UE i. These allocated RBs must be less than or equal to the total number of RBs available, which is denoted by T_{RB}:

$$\sum_{j \in \mathbb{J}} r_{i,j} \leq u_i T_{RB}, \forall j \in \mathbb{J}, i \in \mathbb{I}, \tag{3.15}$$

- **Fair RBs allocation constraint**: Fairness in the allocation of RBs / spectrum resources to associated UEs in STIN. The value of RB fairness = 1 when RBs are distributed equally amongst all UEs in STIN:

$$\left(\sum_{j \in J} (\eta_{i,j}) \right)^2 - J \sum_{j \in J} (\eta_{i,j})^2 \leq 0, \forall i \in \mathbb{I} \tag{3.16}$$

Based on the designed STIN model, the throughput maximization problem is expressed mathematically as under:

$$\max_{\mathbf{v}\,\mathbf{p}} \quad \sum_{j\in\mathbb{J}}\sum_{i\in\mathbb{I}}(v_{i,j}c_{i,j}) \tag{3.17a}$$

$$\textbf{s.t.} \quad \sum_{j\in\mathbb{J}} v_{i,j} = u_i,\ \forall\, i \in \mathbb{I}, \tag{3.17b}$$

$$\sum_{j\in\mathbb{J}} v_{i,j} \leq 1,\ \forall\, i \in \mathbb{I}, \tag{3.17c}$$

$$\left(\sum_{j\in J} v_{i,j}\right)^2 - J\sum_{j\in J}(v_{i,j})^2 \leq 0,\ \forall\, i \in \mathbb{I}, \tag{3.17d}$$

$$\sum_{j\in\mathbb{J}} p_{i,j} \leq u_i P_j\, \forall\, i \in \mathbb{I}, \tag{3.17e}$$

$$0 \leq p_{i,j} \leq P_j,\ \forall\, j \in \mathbb{J},\ i \in \mathbb{I}, \tag{3.17f}$$

$$c_{i,j} \geq u_i Q_{i,j},\ \forall\, j \in \mathbb{J},\ i \in \mathbb{I}, \tag{3.17g}$$

$$\sum_{j\in\mathbb{J}} r_{i,j} \leq u_i T_{RB},\ \forall\, j \in \mathbb{J},\ i \in \mathbb{I}, \tag{3.17h}$$

$$\left(\sum_{j\in J}(\eta_{i,j})\right)^2 - J\sum_{j\in J}(\eta_{i,j})^2 \leq 0,\ \forall\, i \in \mathbb{I}. \tag{3.17i}$$

Eq. (3.17) objective function achieves throughput maximization in STIN while satisfying the constraints $3.17b$ to $3.17i$. Constraint $3.17b$ ensures the UE admission in the STIN. Constraint $3.17c$ ensures the association of a UE with a single BS. Constraint $3.17d$ ensures fairness among UEs while associating with BSs. Constraint $3.17e$ gives the upper power bound for a BS. Constraint 3.17f gives the range of the power that can be allocated to a UE. Constraint $3.17g$ ensures QoS for a UE. Constraint $3.17h$ ensures allocation of RBs to a UE. Constraint $3.17i$ ensures fairness while allocating RBs among UEs by BS.

Chapter 4

PROPOSED ALGORITHM

Eq. (3.17) is a case of the MINLP problem owing to a combination of variables that are binary and non-linear. Formulated problem's search space increases exponentially when the number of UEs increase in the simulations, i.e., in every iteration, there are $2^{|I|}$ optimization problems that require a solution. Therefore, even for a small network, if there are binary variables, the computational load of the formulated problem is infeasible. Aforesaid, UA, and power allocation problems of this kind are complex as well as NP-hard [91]. Hence, for solution of the formulated problem we apply the ϵ-optimal algorithm. The ϵ-optimal algorithm decomposes the problem into the undermentioned sub-problems:

- NLP problem.
- MILP problem.

NLP and MILP problems have low complexity therefore, within finite iterations ϵ-optimal algorithm converges and produces the ϵ-optimal solution [86, 92].

4.1 Description of ϵ-optimal algorithm

Let Θ denote the objective function and constraints of problems be denoted by $\Delta_{\text{b-i}}$ in (3.17). $\mathbb{E}$ denotes binary variables $\mathbb{E} = \{v_{i,j}\}$, $\mathbb{M} = \{p_{i,j}\}$ and $\mathbb{Z} = \mathbb{E} \cup \mathbb{M}$. For the problem in (3.17) following four propositions stand true :

1. $\mathbb{M}$ is non-empty, compact, and convex.
2. For fixed $\mathbb{Z}$, Θ and $\Delta_{\text{b-i}}$ are convex in $\mathbb{M}$.
3. With fixed $\mathbb{Z}$, Θ and $\Delta_{\text{b-i}}$ are differentiable.
4. An exact solution is possible by fixing $\mathbb{Z}$ which changes MINLP to NLP problem.

4.1.1 Stage-1

In stage-1, for transformation of the MINLP problem in (3.17) to NLP problem, $\mathbb{Z}$ is fixed at $\mathbb{Z}^n$. The NLP problem's solution is the optimal solution's upper bound. The NLP problem is as under:

$$\min_{\mathbb{M}} \ -\Theta(\mathbb{Z}^n, \mathbb{M}) \tag{4.1a}$$

$$\text{s.t.} \ \Delta_{\text{b-i}}(\mathbb{Z}^n, \mathbb{M}) \leq 0 \tag{4.1b}$$

4.1.2 Stage-2

Solution of the NLP problem in (4.1) yields binary variables of $\mathbb{Z}$ at $\mathbb{Z}^n$. Stage-1 results are utilized in stage-2 for transforming the MINLP problems in Eq (3.17) into MILP problem which is as under:

$$\min_{\mathbb{Z}} \min_{\mathbb{M}} \ -\Theta(\mathbb{Z}^n, \mathbb{M}) \tag{4.2a}$$

$$\text{s.t.} \ \Delta_{\text{b-i}}(\mathbb{Z}^n, \mathbb{M}) \leq 0 \tag{4.2b}$$

(4.2) can be amended as:

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

such that

$$\tau(\mathbb{Z}) \ = \min_{\mathbb{M}} \ -\Theta(\mathbb{Z}^n, \mathbb{M}) \tag{4.4a}$$

$$\text{s.t.} \ \Delta_{\text{b-i}}(\mathbb{Z}^n, \mathbb{M}) \leq 0 \tag{4.4b}$$

(4.3) is the projection of (3.17) on $\mathbb{Z}$ space. As all constraints hold for the NLP problem in (4.1) for all $\mathbb{Z}^n$, hence projection problem's solution becomes:

$$\min_{\Delta} \min_{\mathbb{M}} \quad -\Theta(\mathbb{Z}^n, \mathbb{M}^n) - \nabla\Theta(\mathbb{Z}^n - \mathbb{M}^n)\begin{pmatrix} \mathbb{M} - \mathbb{M}^n \\ \mathbb{Z} - \mathbb{Z}^n \end{pmatrix} \tag{4.5a}$$

$$\text{s.t.} \quad \Delta_{\text{b-i}}(\mathbb{Z}^n, \mathbb{M}^n) - \nabla\Delta_{\text{b-i}}(\mathbb{Z}^n, \mathbb{M}^n)\begin{pmatrix} \mathbb{M} - \mathbb{M}^n \\ \mathbb{Z} - \mathbb{Z}^n \end{pmatrix} \leq 0. \tag{4.5b}$$

Let a new variable δ be introduced therefore problem in (4.5) can be written as:

$$\min_{\Delta,\mathbb{M},\delta} \quad \delta \tag{4.6a}$$

$$\text{s.t.} \quad \delta \geq -\Theta(\mathbb{Z}^n, \mathbb{M}^n) - \nabla\Theta(\mathbb{Z}^n - \mathbb{M}^n)\begin{pmatrix} \mathbb{M} - \mathbb{M}^n \\ \mathbb{Z} - \mathbb{Z}^n \end{pmatrix} \tag{4.6b}$$

$$\Delta_{\text{b-i}}(\mathbb{Z}^n, \mathbb{M}^n) - \nabla\Delta_{\text{b-i}}(\mathbb{Z}^n, \mathbb{M}^n)\begin{pmatrix} \mathbb{M} - \mathbb{M}^n \\ \mathbb{Z} - \mathbb{Z}^n \end{pmatrix} \leq 0 \tag{4.6c}$$

4.1.3 Steps of ϵ-optimal algorithm's Iterative Approach

The MILP problem in (4.6) gives optimal solutions lower bound. The branch and bound algorithm [93] is used to solve the MILP problem. The solution to the NLP problem at $\mathbb{Z}^n$ drives the MILP problem when objective and constraints functions, i.e., Θ & $\Delta_{\text{b-i}}$, etc are linear [94, 95]. ϵ-optimal algorithms iterative approach follows the undermentioned steps:

1. With the algorithm progression to achieve ϵ optimal solution, the upper bound decreases and the lower bound increases.

2. When the difference between the lower and upper bound is less than ϵ then we get an optimal solution.

3. When the difference between the lower and upper bound is greater than ϵ, new binary variables $\mathbb{Z}$ are fixed at $\mathbb{Z}^{n+1}$. NLP and MILP problems are re-solved in the next iteration to obtain new lower and upper bounds.

4. We get an optimal solution when the difference between the upper and lower bound is less than ϵ.

5. The flow chart of the ϵ-optimal algorithm's is shown in Fig. 4.1.

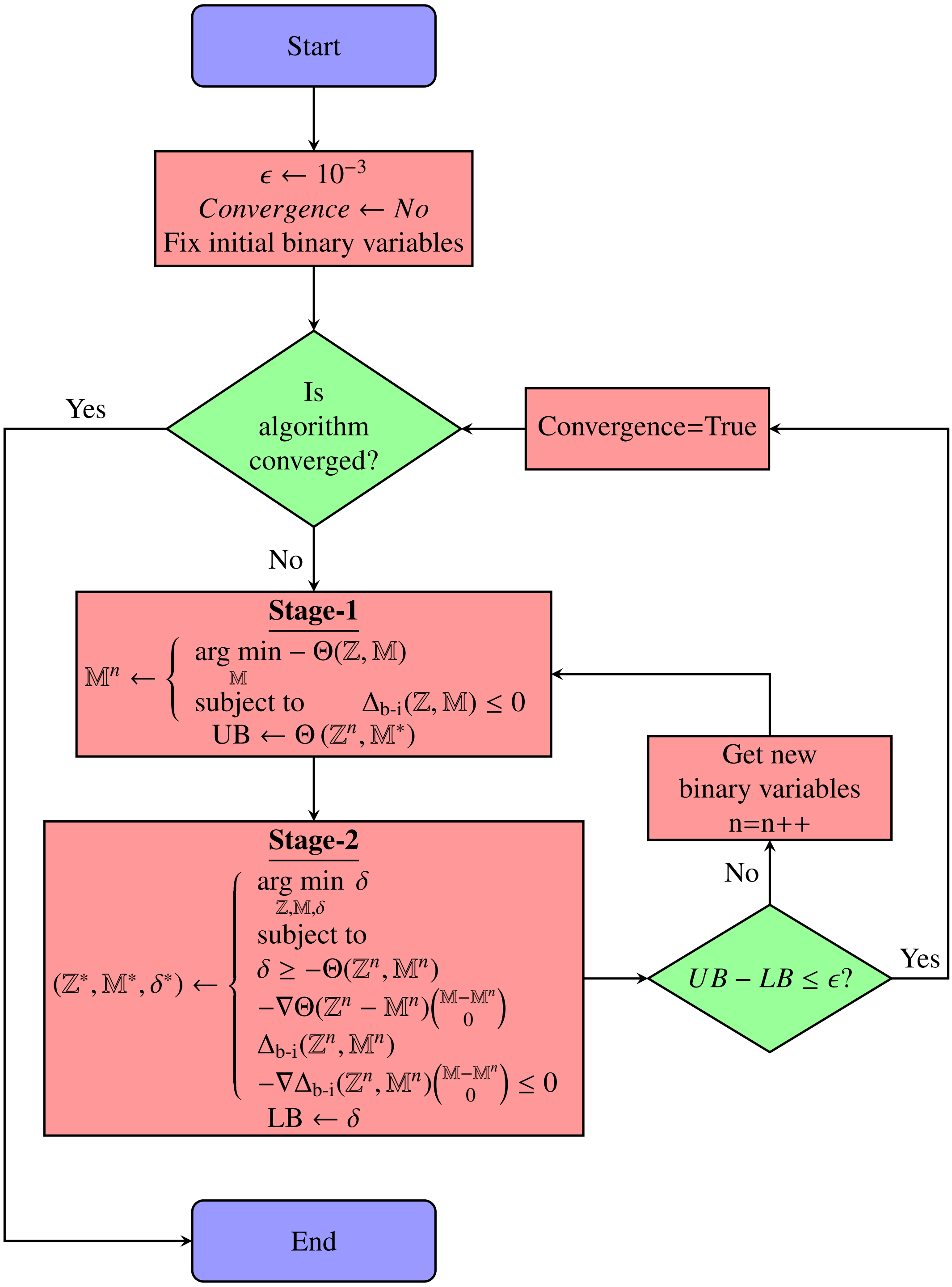

Figure 4.1: **Flow chart - ϵ-optimal algorithm**

4.2 Algorithm Convergence and Optimality

OAA converges at a linear rate and the proof is available in mixed-integer programming literature [94]. The OAA is made optimal in $\epsilon = 10^{-3}$ with branch and bound architecture. In this approach, by fixing the discrete values of $\mathbb{Z}$ any combination of UEs and BSs is never used twice. With a few discrete variables $\mathbb{Z}$ and when all the previously defined propositions are satisfied, the proposed algorithm ends in finite iterations yielding an optimal solution [92]. Using the ϵ-optimal algorithm the solution is guaranteed within ϵ of the optimal solution for any $\epsilon > 0$. The guaranteed accurate value of the solution is given by lower values of ϵ. Optimality of $\mathbb{M}$ in master problem (4.6) for a specific choice of discrete variables $\mathbb{Z}^n$, can be:

1. if $\delta \geq \Theta(\mathbb{Z}^n, \mathbb{M}) \rightarrow$ solution is feasible

2. otherwise $\delta \leq \Theta(\mathbb{Z}^n, \mathbb{M}) \rightarrow$ solution is infeasible

Those values of $\mathbb{Z}^n$ are eliminated by the algorithm which has an infeasible solution that exists for the master problem. Resultantly the algorithm converges finitely. For any fixed values of $\mathbb{Z}$, the algorithm optimality follows from the convexity of the objective and constraint function. A comprehensive proof of the OAA algorithm convergence is presented in [86]. A solution that is globally optimal can be computed for (3.17) using the exhaustive search algorithm (ESA) however, the computational complexity increases exponentially as it caters to all combinations of UEs and BSs. For I number of UEs in the network and denoting computational complexity by C_{ESA}, ESA's computational complexity is $C_{ESA} = 2^{2I}$.

However, by using OAA an ϵ-optimal solution can be found in infinite iterations [92]. Generally, the computational complexity denoted by C_{OAA}, for OAA will be $C_{OAA} = \frac{I^2 \Delta}{\tau}$, where Δ denotes the number of constraints and error tolerance of the ϵ-optimal solution from the global optimal solution is given by τ. An additional advantage of employing OAA rather than ESA is that it ensures the provision of an ϵ-optimal solution. Fig. 4.2 shows the trend of the computational complexity of ESA versus OAA.

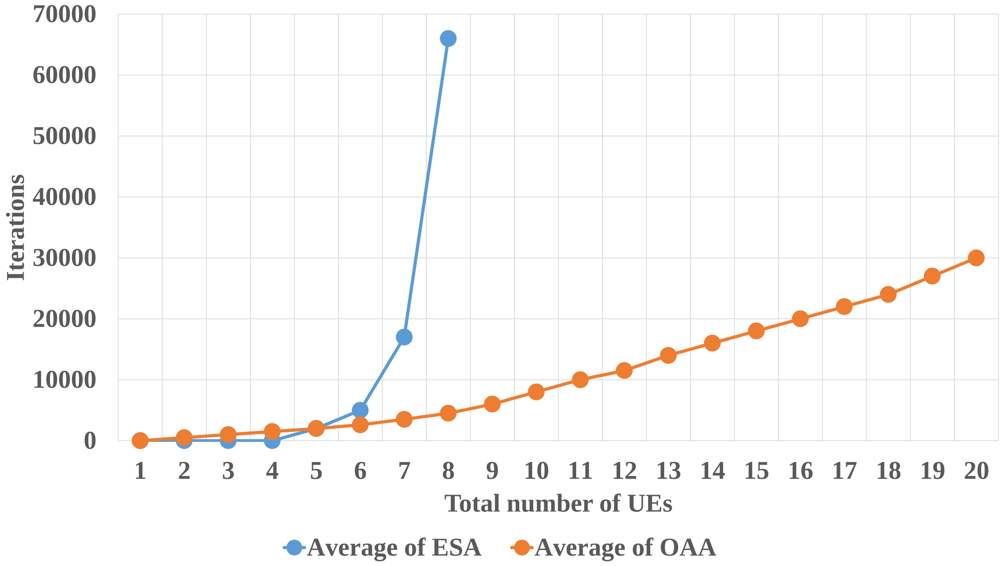

Figure 4.2: **ESA versus OAA**

4.3 Algorithm Complexity

This section discusses the ϵ-optimal algorithm's complexity. The F count of flops [1] [96] is a yardstick for assessing the computational load. 5 flops are added for the initialization stage of the ϵ-optimal algorithm. Solving the NLP problem takes $2IJ$ and $4IJ\Delta$ flops. Solving the MILP problem takes $4IJ\Delta$ and $2IJ\Delta$ flops. Comparing NLP and MILP problems takes 2 flops. 4 flops are added for guessing the new binary variables. The total flop count F_ϵ is as under:

$$F_\epsilon = 5 + 2IJ + 4IJ\Delta + 4IJ\Delta + 2IJ\Delta + 4, \tag{4.7a}$$

$$F_\epsilon = 9 + 2IJ + 10IJ\Delta, \tag{4.7b}$$

$$F_\epsilon \approx 2IJ + 10IJ\Delta. \tag{4.7c}$$

Similarly, ϵ-optimal algorithm complexity in terms of Big O notation is $O(I \times J) + O(I \times J \times \Delta)$. Where I denotes UEs, BSs are denoted by J and Δ denotes constraints.

[1] A flop is a real floating point operation and the number of flops indicate the complexity. 1 flop for each addition, multiplication and division operations. Complex addition and multiplication takes 2 and 4 flops respectively. $p \times q$ dimension matrix multiplication by $q \times r$ dimension matrix takes $2pqr$ flops. Moreover 1 flop is added for a logical operator and 1 flop for the assignment operator. The $log_2(x)$ operator takes 2 flops

Chapter 5

SIMULATIONS AND RESULTS

In this chapter, the proposed algorithm is employed for solving the MINLP problem in Eq. (3.17). The results obtained validate the advantages of the proposed algorithm. Basic open source nonlinear mixed integer programming (BONMIN) software and Matlab is used for the simulations [97].

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

- Number of UEs associated.
- Fairness in UA.
- RBs allocation.
- Fairness in RBs allocation.
- Average throughput achieved.

5.1 Simulation Setup

Simulation parameters are mentioned in Table 5.1. For the entire simulations, maximum power for LSB P_l, GEB P_g, SSB P_s, relay P_r and D2D pair P_d are set to 43 dBm, 36 dBm, 33 dBm, 33 dBm and 33 dBm whereas maximum radius of LSB D_l, GEB D_g, SSB D_s, relay D_r and D2D pair D_d are set to 1000 m, 600 m, 300 m, 100 m and 100 m respectively. Minimum data rates required are 0.2, 0.4, 0.6, 0.8, 1.0 Mbps. Minimum UEs allowed are 5, while maximum UEs allowed are 40 with an increment of 5. The total number of available RBs that can be allocated to the UEs is 150. The far field distance antenna d_o, is set to 10 m and path loss exponent α to 2.

5.2 Results and Discussions

Simulation results exhibiting the advantages of the proposed algorithm for achieving fairness-based UA, fair RBs allocation, and throughput maximization are discussed in

Table 5.1: **Simulation Parameters**

Parameters	Value
D_l	1000 m
D_g	600 m
D_s	300 m
D_r	100 m
D_d	100 m
P_l	43 dBm
P_g	36 dBm
P_s	33 dBm
P_r	33 dBm
P_d	33 dBm
d_o	10 m
G_o	50
α	2
$Q_{i,j}$	{0.2,0.4,0.6,0.8,1} Mbps
$b_{i,j}$	100 Kbps
Minimum number of UEs	5
UE increment step size	5
Maximum number of UEs	40

this section.

5.2.1 Fairness based UEs Association Analysis

Fig. 5.1 depicts the plot of the total number of UEs versus the number of UA in STIN. The total number of UEs increase with a step of 5 UEs from 5 to 40 UEs. It is evident from the plot that overall a fair number of UEs are being associated by using the proposed algorithm. Fig. 5.2 shows the plot of QoS Rate Requirement versus UA BS wise (LSB, GEB, SSB, relay or D2D) for different QoS rate requirements (0.2, 0.4, 0.6, 0.8, 1.0 Mbps). It can be observed that for different rates almost equal numbers of UEs are associated with LSB, GEB, and SSB. Similarly, almost equal number of UEs are associated to relay and D2D. It can be inferred from the plot that more UEs, irrespective of the minimum required rate to ensure QoS, are associated with low power and small coverage area relay and D2D as compared to high powered BSs i.e LSB, GEB, and

SSB. Therefore, efficient UEs offloading is occurring, which is one of the core advantages of employing HetNets. It can also be concluded from Fig. 5.2 that the number of UA decreases (32 to 27 UEs) with an increase in the QoS rate requirement (0.2 to 1.0 Mbps) which is quite intuitive.

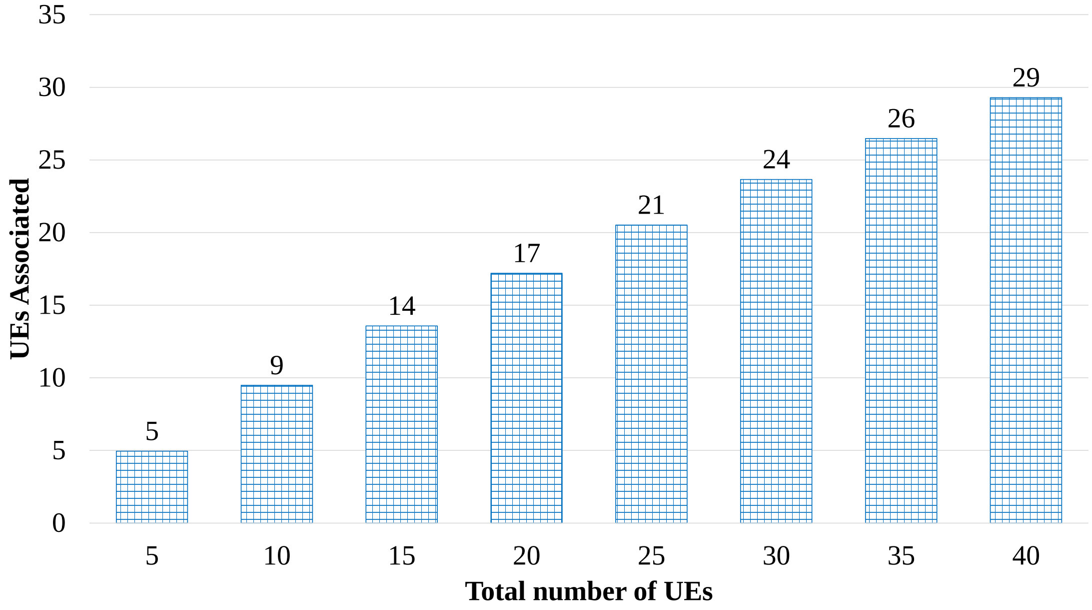

Figure 5.1: **Total number of UEs versus UA**

Fig. 5.3 shows the graph of the total number of UEs versus UA and UEs fairness. As total number of UEs increase, the number of UA increases and the proposed algorithm ensures that the fairness increase as evident from the trend (0.70 to 0.86). This is due to the reason that with less number of total UEs there are not many options available for fair UA however, as the total number of UEs increase in the network, which are geographically randomly distributed, more freedom of action for fair UA amongst different BSs is available and the value of fairness index increases. It can also be seen that initially there is a sharp increase in the fairness value (0.70 to 0.82) as the total number of UEs increase from 5 to 20. After that, there is a slight increase in the fairness index (0.82 to 0.86) for UEs increases from 20 to 40. If we further increase the total number of UEs the fairness index value will be getting closer to 1 hence achieving 100 percent UEs association fairness.

Fig. 5.4 shows the plot of the total number of UEs versus UA and UEs fairness at different QoS rate requirements i.e, 0.2 Mbps, 0.6 Mbps, and 1.0 Mbps. As the total

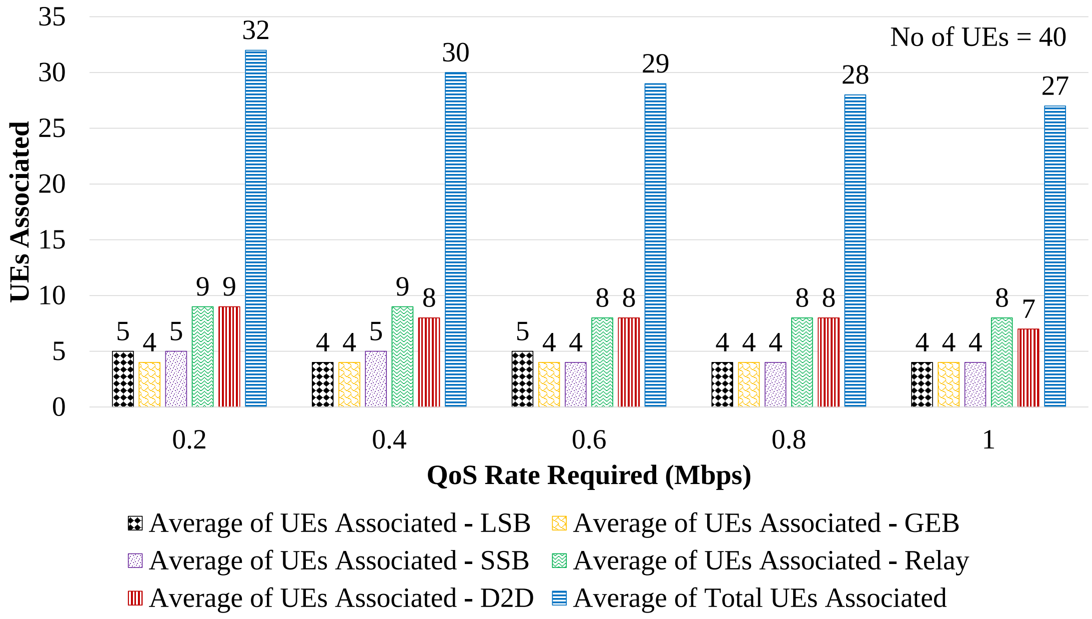

Figure 5.2: **QoS Rate Requirement versus UA BS wise**

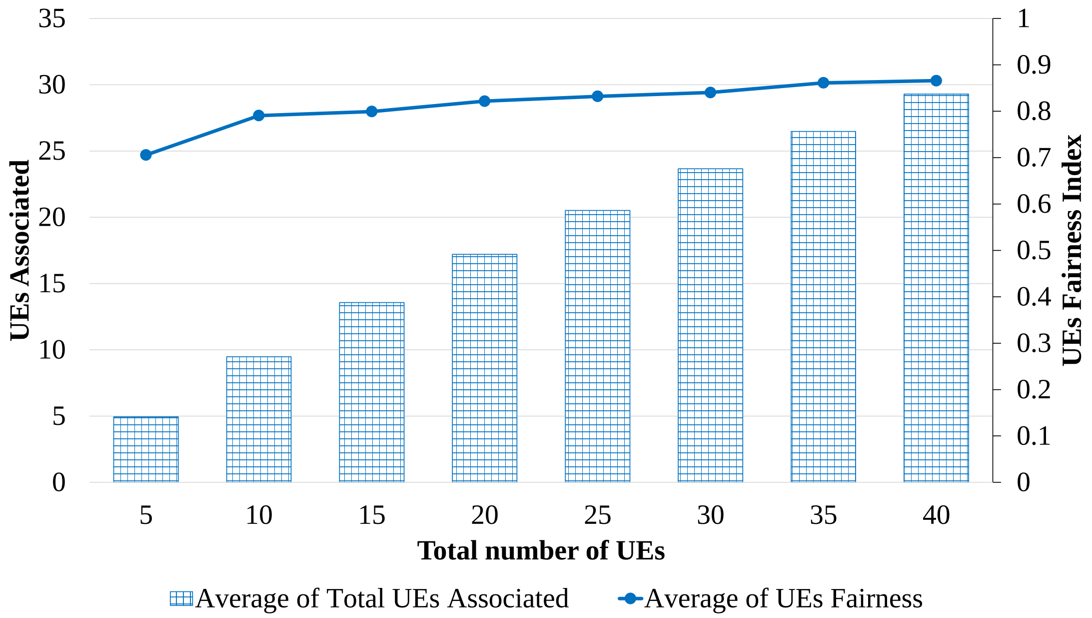

Figure 5.3: **Total number of UEs versus UA and UEs Fairness**

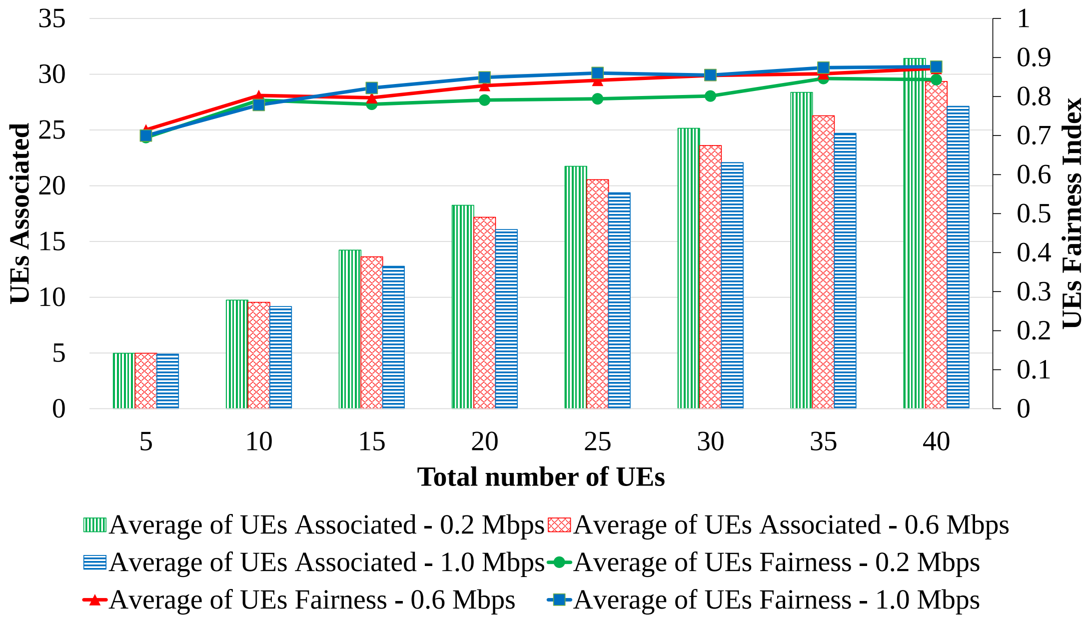

Figure 5.4: **Total number of UEs versus UA and UEs Fairness at different QoS Rate Requirements**

number of UEs increase, the number of UEs associated increase for all QoS rate requirements, and the UEs fairness also increase. This pattern validates the results of Fig. 5.1 and Fig. 5.3. However, in each step as the QoS rate requirement increase from 0.2 Mbps to 1.0 Mbps, there is a decrease in the number of UEs associated which is also in line with the findings of Fig. 5.2. When the total number of UEs is 40 and for the QoS rate requirement of 0.2 Mbps, 0.6 Mbps and 1.0 Mbps the corresponding UEs association fairness values are 0.84, 0.87 and 0.88. The effectiveness of the proposed algorithm can be validated from the aforementioned results that as the QoS rate requirement increases the UEs association fairness also increases.

5.2.2 Fairness based RBs Allocation Analysis

Fig. 5.5 depicts the plot of the total number of UEs versus UA and RBs allocated. There is a proportionate increase in the number of allocated RBs and the UA. As the number of UA is increasing more RBs are being allocated. To cater to 5 UEs the system allocates 14 RBs and when the number of associated UEs increases to 40 the number of allocated RBs increase to 102.

Fig. 5.6 shows the graph of total number of UEs versus UA and RBs allocated for different QoS rate requirements (0.2, 0.6, 1.0 Mbps). UA trend at different rates is the

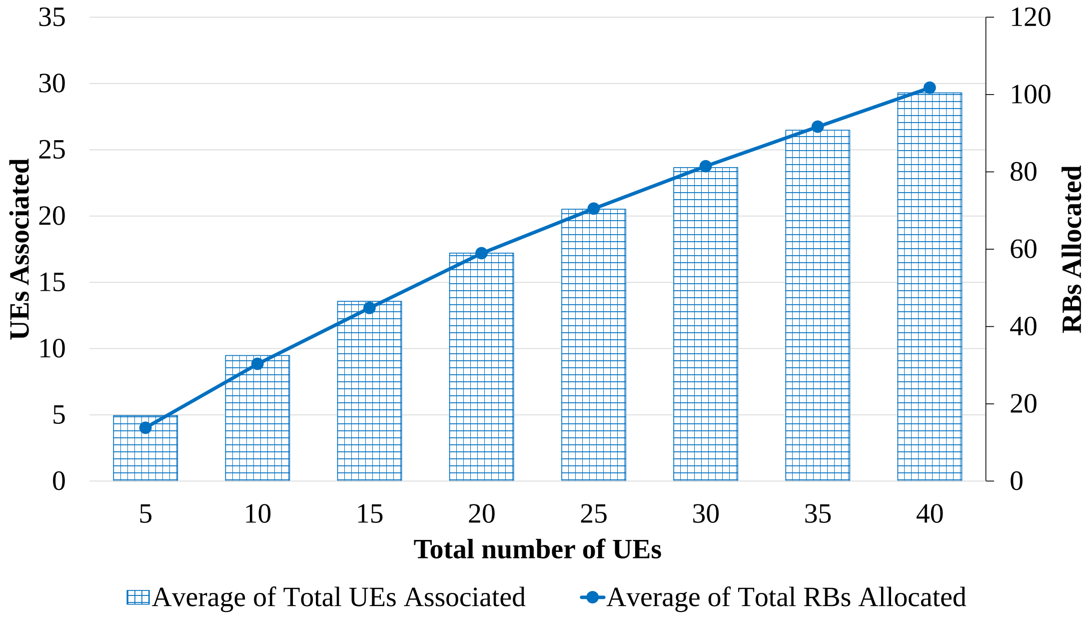

Figure 5.5: **Total number of UEs versus UA and RBs Allocated**

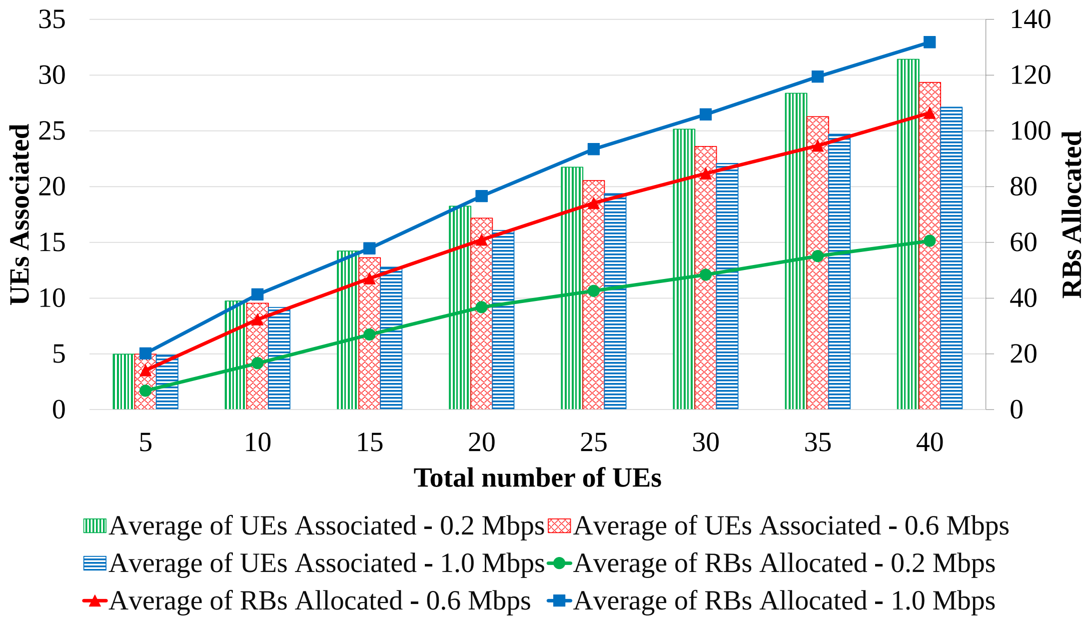

Figure 5.6: **Total number of UEs versus UA and RBs Allocated for different QoS Rate Requirements**

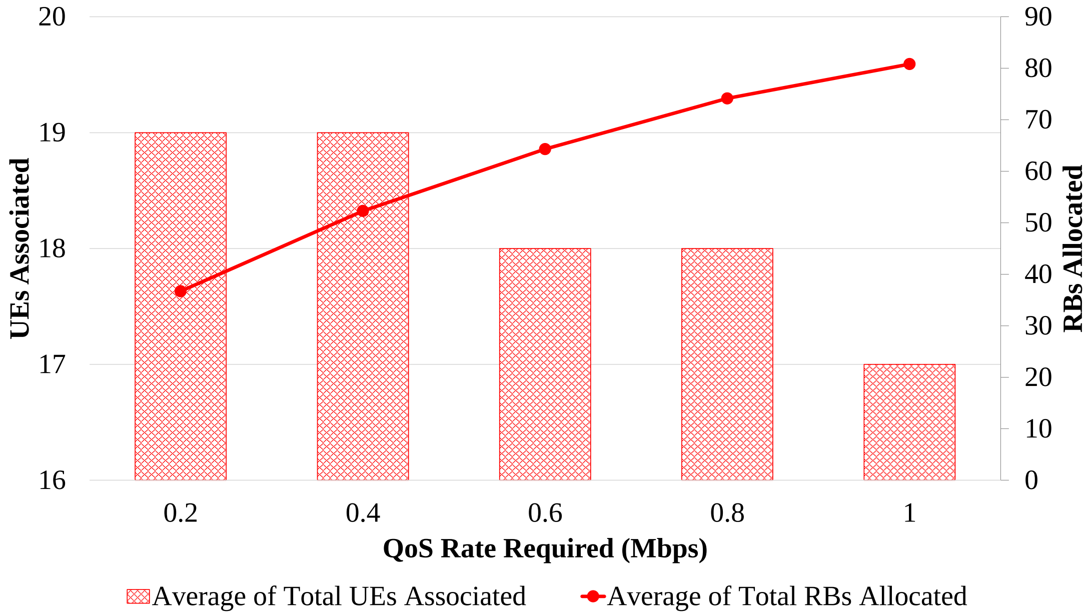

Figure 5.7: **QoS Rate Required versus UA and RBs Allocated**

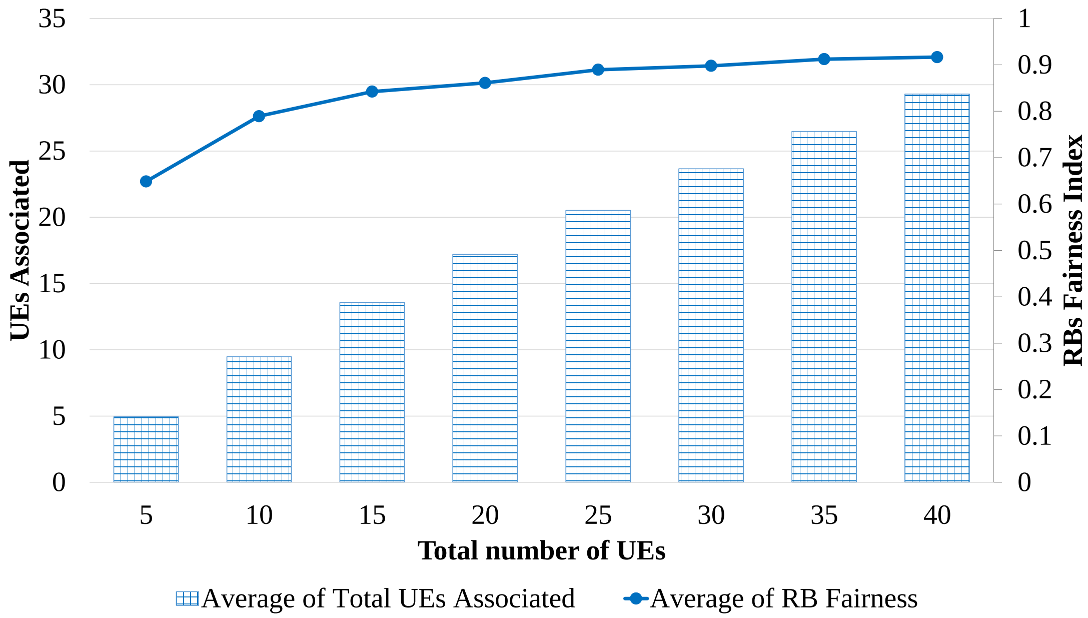

Figure 5.8: **Total number of UEs versus UA and RBs Fairness**

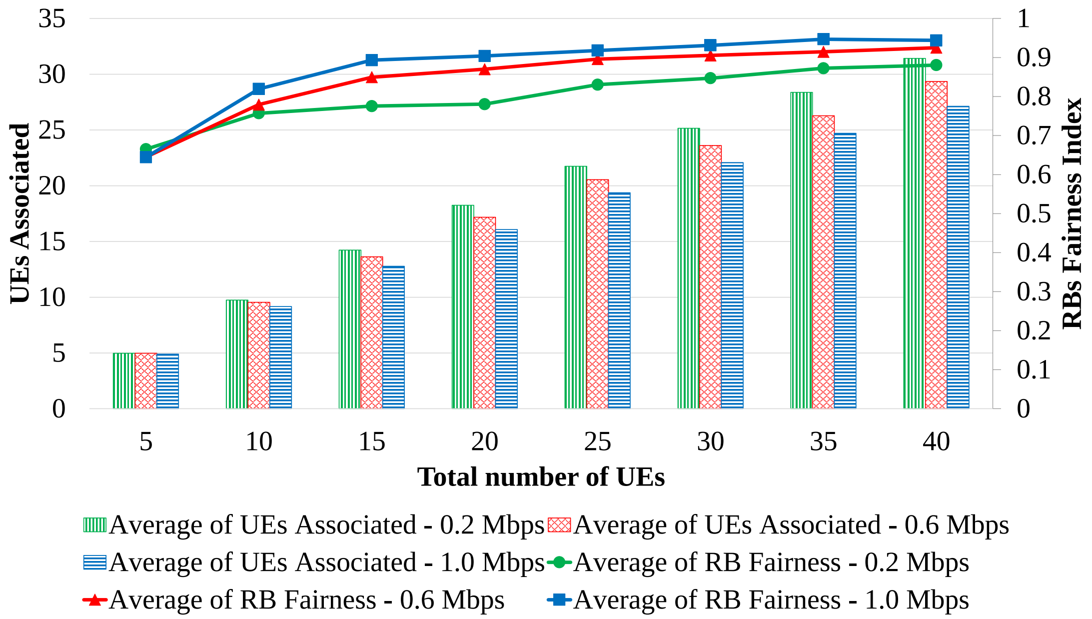

Figure 5.9: **Total number of UEs versus UA and RBs Fairness at different QoS Rate Requirements**

same as already discussed in Fig. 5.4. It can be observed that there is a variation in the no of RBs allocated for the same number of total UEs having different QoS rate requirements. When the total number of UEs is 40 and for the QoS rate requirement of 0.2 Mbps, 0.6 Mbps, and 1.0 Mbps, the corresponding number of allocated RBs are 61, 106 and 132. Thus we can conclude that to meet higher QoS rate requirements of UEs more RBs are required and are being efficiently allocated by the proposed algorithm.

Fig. 5.7 shows the plot of the QoS rate required versus UA and RBs allocated. It is pertinent to mention here that the number of UA for a particular QoS rate requirement is set to be the average of UA in all steps (where the total number of UEs is increasing from 5 to 40) in this graph. It can be observed that as the QoS rate requirement increases (0.2 Mbps to 1.0 Mbps) the number of average UA slightly decrease (19 to 17 UEs). This trend has already been observed in Fig. 5.2 and Fig. 5.4. However the number of RBs allocated increase as the QoS rate requirement increases and the reason for this behavior is that more RBs are required to fulfill the increasing QoS rate requirements of the UEs.

Fig. 5.8 shows the plot of the total number of UEs versus UA and allocated RBs fairness index. With an increase in the total number of UEs (5 to 40) and subsequently increasing UA (5 to 29), the proposed algorithm ensures that the RBs allocation fairness increase as evident from the trend (0.65 to 0.91). This is due to the reason that with less number of total UEs there are not many options available for RB allocation with fairness however as the total number of UEs increase in the network which are geographically randomly distributed, more freedom of action for fair RBs allocation amongst different UEs is available and the value of fairness index increases. It can also be seen that initially there is a sharp increase in the fairness value (0.65 to 0.86) as the total number of UEs increase from 5 to 20. After that, there is a slight increase in the fairness index (0.86 to 0.91) as UEs increase from 20 to 40. If we further increase the total number of UEs the RBs fairness index value will be getting closer to 1 hence achieving 100 percent RBs allocation fairness.

Fig. 5.9 depicts the graph of total UEs versus UA and RB fairness index for different QoS rate requirements i.e, 0.2 Mbps, 0.6 Mbps, and 1.0 Mbps. It is evident from fig. 5.9 that as the total number of UEs increases UA and RBs fairness increases for the UEs QoS rate required. In each step as the QoS rate requirement increase from 0.2 Mbps to 1.0 Mbps, there is a decrease in the number of UEs associated and this has already been discussed. When the total number of UEs is 40 and for the QoS rate requirement of 0.2 Mbps, 0.6 Mbps and 1.0 Mbps the corresponding RBs allocation fairness values are 0.88, 0.92, and 0.94. The effectiveness of the proposed algorithm can be validated from the aforementioned results that as the QoS rate requirement increases the RBs allocation fairness also increase.

5.2.3 UEs Sum-Rate Analysis

Fig. 5.10 represents the plot of the total number of UEs versus UA and throughput. It can be seen that with the increase in the total number of UEs the UA increases and the throughput also increases linearly. The results validate that the main objective of throughput maximization is being achieved. Fig. 5.11 depicts the plot of QoS rate requirement versus UA and throughput. For the 0.2 Mbps rate, the number of UA is 19 and the throughput is 52.4 Mbps. For the 1.0 Mbps rate, the number of UA is 17 with a sum-rate of 51.3 Mbps. It can be concluded that as the QoS rate requirement increases, the number of UA and throughput decreases slightly. Fig. 5.12 shows the total number of UEs versus UA and throughput at different QoS rate requirements (0.2, 0.6, 1.0 Mbps). The behavior of UA with the corresponding increase in the total number of UEs for mentioned rates is the same as already discussed in Fig. 5.4, Fig. 5.6, and Fig. 5.9. Additionally, there is a negligible variation in the throughput at different rates and for low QoS rate requirements we achieve high throughput, and when the QoS rate requirement increases the throughput slightly decreases.

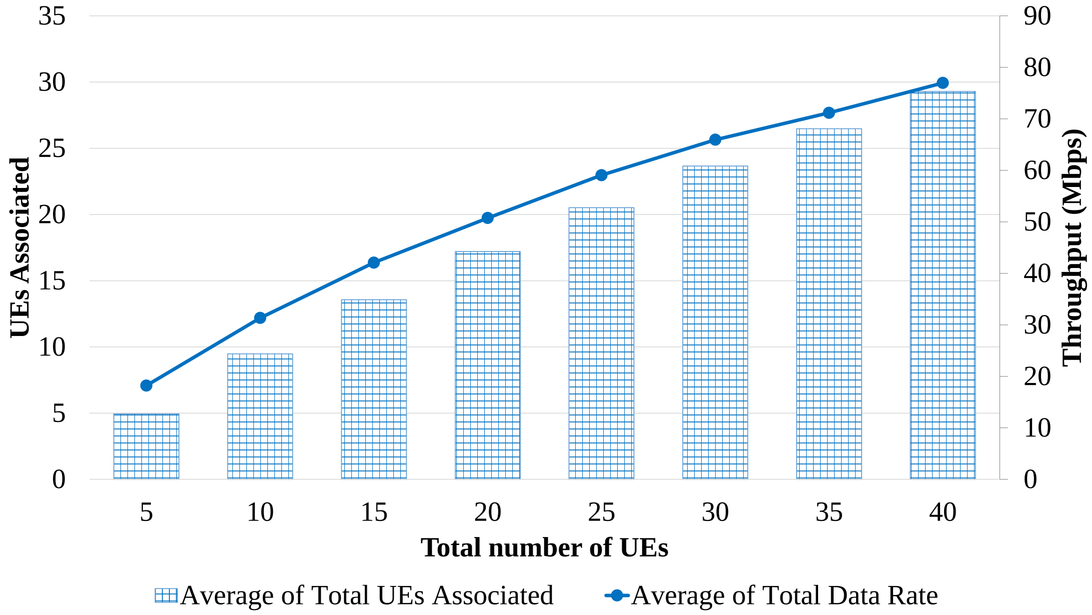

Figure 5.10: **Total number of UEs versus UA and Throughput**

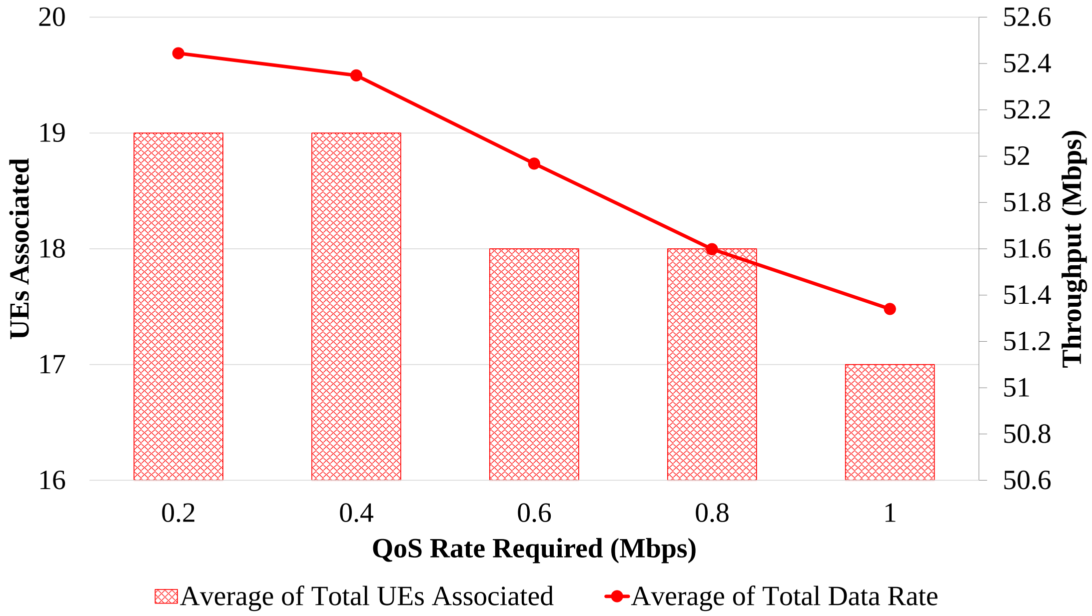

Figure 5.11: **QoS Rate Required versus UA and Throughput**

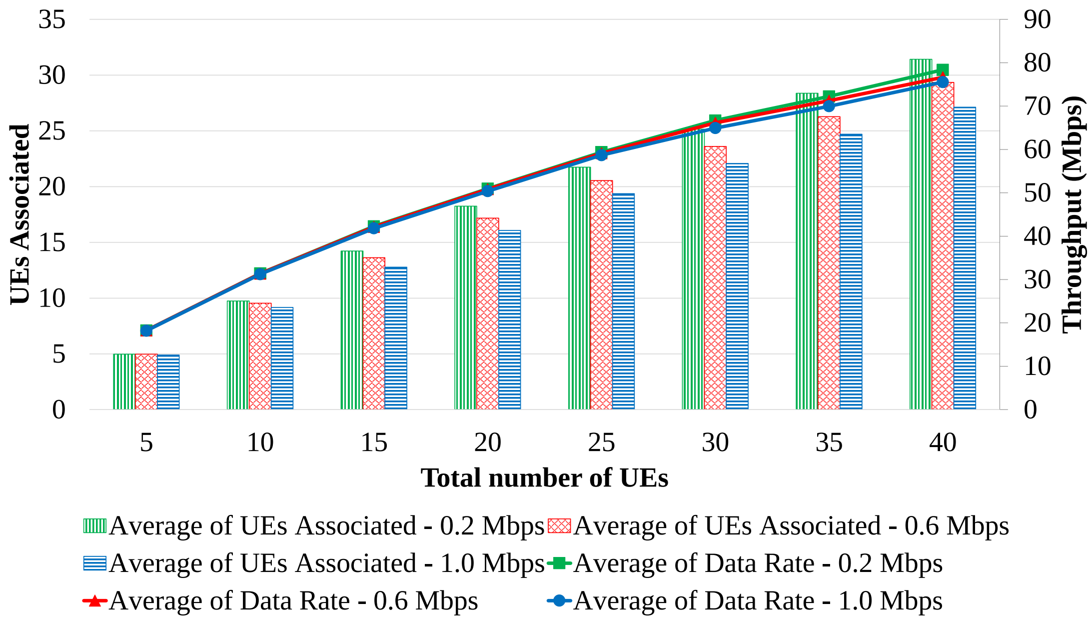

Figure 5.12: **Total number of UEs versus UA and Throughput for different QoS Rate Requirements**

Chapter 6

CONCLUSION AND FUTURE WORK

This thesis investigates a practical solution for jointly solving admission control, fair UA, power control, fair RBs allocation, and sum-rate maximization problem in STIN. Looking at formulated problem's structure, OAA is employed to reach a near-optimal solution within $\varepsilon = 10^{-3}$. Substantial simulations have been performed to evaluate the effectiveness of the proposed algorithm. UA fairness and RBs allocation fairness are of paramount importance while maximizing the main objective function which is throughput maximization of the overall system. UEs are distributed randomly in the simulations and the algorithm makes different combinations of different UEs and selects the UEs which satisfy all the constraints. Many trade-offs are being made as our constraints are imposing divergent restrictions to reach a feasible design ensuring optimal output. Results validate the effectiveness of the proposed STIN model.

6.1 Future Work

While developing this thesis, some recommendations are indicated for future work, which are listed below:

- **Resource allocation for Throughput maximization in Satellite-Aerial-Terrestrial Integrated Networks:** Incorporating an additional tier of aerial platforms like UAVs and aircrafts in STIN can greatly increase the coverage area and overall throughput however resource allocation will become more challenging.
- **Resource allocation for Throughput maximization in Satellite-Terrestrial Integrated Networks using LEO satellites:** As discussed in chapter 1 and 2 STIN can be realized by incorporating GEO or LEO satellites. If LEO satellites are considered in STIN then the communication links are significantly shorter, which leads in low path losses and smaller, low power antenna systems. Shorter

path distances also result in less propagation delay. Due to the earth terminals' advantages of low power and small size, the LEO has received substantial consideration for mobile applications. LEO satellites are much smaller and take significantly less energy to deploy into orbit than GEO satellites, hence having low total life cycle costs.

- **Resource allocation for Throughput maximization employing M-MIMO in Satellite-Terrestrial Integrated Networks:** One of the 5G goals for future wireless network is to support 1000$\times$ more single antenna devices. This ambitious goal cannot be met by conventional MIMO where we have low number of antennas on LSB. However, M-MIMO with large size antenna array is right choice of technology to support 1000$\times$ more single antenna devices in multi-tier HetNet. Therefore, one of the attractive future research directions is resource allocation to maximize sum-rate and employing M-MIMO in STIN.

- **Resource allocation for Throughput maximization employing mmWave SSB in Satellite-Terrestrial Integrated Networks:** Other 5G goal for future wireless network, i.e., 1000 $\times$ increase in bits/sec/unit area and 100 $\times$ increase in edge rate etc can be achieved by densification through multi-tier HetNet. For indoor short range transmission, mmWave communication is already operational in IEEE 802.15.3c [47] and IEEE 802.11ad [48]. However, mmWave communication has not been explored in decoupled access HetNet. Therefore, another attractive open area for future research is resource allocation to maximize sum-rate employing mmWave SSB in STIN.

- **Resource allocation for Throughput maximization in Satellite-Terrestrial Integrated Networks considering backhaul constraints:** Incorporating backhaul considerations for the resource allocation for throughput maximization in STIN will be a research field where different nodes of STIN have different backhaul capacities and limitations.

- **Resource allocation for Throughput maximization in Satellite-Terrestrial**

Integrated Networks in both UL and DL: Considering both UL and DL resource allocation for throughput maximization in STIN can be explored in the future.

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