ENERGY EFFICIENT RESOURCE ALLOCATION IN SATELLITE-TERRESTRIAL INTEGRATED NETWORK

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

SEPTEMBER 2022

THESIS ACCEPTANCE CERTIFICATE

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AUTHOR's DECLARATION

I, **Maj Umair Fakhar** declare that this thesis titled **Energy Efficient Resource Allocation in Satellite-Terrestrial Integrated Networks** and the work presented in it are my own and has been generated by me as a result of my own original research.

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- I have acknowledged all main sources of help.
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Maj Umair Fakhar,
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DEDICATION

This thesis is dedicated to

MY BELOVED PARENTS,

MY WIFE, SISTER AND BROTHERS,

HONORABLE TEACHERS AND FRIENDS

for their love, endless support and encouragement

ACKNOWLEDGEMENTS

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.

The achievement of this thesis is accomplished with the participation and co-operation of all guidance committee. With affection and deep appreciation I acknowledge my indebtedness to honorable thesis supervisor Dr. Humayun Zubair Khan, who not only supported me with every possible guidance but also encouraged my spirits at critical junctures that lead to the successful completion of this thesis.

Words cannot encapsulate feelings, I am deeply thankful to guidance and evaluation committee members Dr. Muhammad Imran and Dr. Mudassar Ali who provided me with every possible assistance that channeled towards the completion of this thesis. What I am and what I shall be is the gift and efforts of my teachers and the university management. I consider it a great honor to be a part of one of the best universities of our country.

The loving support from my family and friends has been invaluable, whose courage and helps enable me to complete my MS Degree in Electrical (Telecommunication) Engineering. I am very grateful for the guidance of faculty members of Electrical Engineering Department and especially the Head of Electrical Engineering Department for their everlasting encouragement that has fuelled my sense of continued determination over the years.

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NOTATIONS

Notation	**Definition**
$\mathbb{U}$	Set of users
$\mathbb{B}$	Set of BSs
m_u	User u admission in STIN
$n_{u,b}$	User u association with BS b
P_b	Maximum transmit power of BS b
$p_{u,b}$	Allocated power to user u by BS b
$p_{u',b}$	Allocated power to user $u^{'}$ by BS b
P_c	Total circuit power
$g_{u,b}$	Channel gain between user u and BS b
$g_{u',b}$	Channel gain between user $u^{'}$ and BS b
$\bar{g}$	Rayleigh random variable
A_o	Antenna gain
ξ	Zero mean Gaussian random variable
$d_{u,b}$	Distance between a user u and a BS b
d_o	Far field distance of antenna
γ	Path loss exponent
σ^2	Gaussian white noise variance
N_{rb}	Number of RBs in C-band / Sub-6GHz band
Q_u	QoS rate requirement of user u
T_{RB}	Total RBs available
$f_{u,b}$	Bandwidth allocated to user u by BS b
$r_{u,b}$	Number of RBs required to meet QoS requirement
$c_{u,b}$	Achievable rate by user u
Υ_{b-h}	Constraint b to constraint h
D_b	Maximum radius of BS b
$Ç_{ESA}$	ESA's computational complexity
$Ç_{OAA}$	OAA's computational complexity

ACRONYMS

Acronym	**Definition**
$STIN$	Satellite Terrestrial Integrated Network
EE	Energy Efficiency
UA	User Association
UF	User Fairness
RBs	Resource Blocks
QoS	Quality of Service
QoE	Quality of Experience
3G	3^{rd} generation
4G	4^{th} generation
5G	5^{th} generation
LTE	Long Term Evolution
RAN	Radio Access Network
$HetNets$	Heterogeneous Networks
GEO	Geosynchronous Earth Orbit
GBB	GEO Satellite based BS
BSL	Large Base Stations
BSS	Small Base Stations
$D2D$	Device to Device
BS	Base Station
$MINLP$	Mixed Integer Nonlinear Programming
NLP	Non-linear Programming
$MILP$	Mixed-Integer Linear Programming
$NP - Hard$	Non-deterministic Polynomial-time Hard
CCT	Charnes-Cooper Transformation
CFP	Concave Fractional Programming
OAA	Outer Approximation Algorithm
ESA	Exhaustive Search Algorithm
$BONMIN$	Basic Open-source Nonlinear Mixed Integer Programming
$Flop$	Floating-point Operation
DL	Downlink
UL	Uplink
UE	User Equipment
$STGS$	Satellite-Terrestrial Gateway Station
ICT	Information Communication Technology
IoT	Internet of Things
TTC	Tracking, Telemetry, and Command
$EIRP$	Effective Isotropic Radiated Power
ES	Earth Station
ISL	Inter Satellite Links

ABSTRACT

Satellite-Terrestrial Integrated Networks (STIN), where a satellite access network liaising with terrestrial networks, is useful not only in proffering seamless coverage but also in improving the backhaul capacity for heavy traffic / dense network scenarios. Therefore, an energy-efficient STIN is envisioned to be a valued gap filler both in public safety networks and in the provision of high-speed data services with ubiquitous coverage in remote areas. STIN necessitate admission control, user association, optimal power distribution and spectrum resource allocation to attain the desired quality-of-service standards. This thesis investigates joint admission control, user association and power distribution for ensuring fairness while associating users in STIN and fairness in the allocation of spectrum resources to associated users in STIN with an overall objective to maximize the energy efficiency of STIN. The reviewed problem is a concave fractional programming problem which by utilizing Charnes-Cooper transformation is converted into a concave optimization problem. Subsequently, the concave optimization problem is resolved via the proposed outer approximation algorithm. The performance of the ϵ-optimum solution is extensively evaluated via the execution of different system parameters including number of users, user association, user fairness and resource block fairness.

Chapter 1

INTRODUCTION

This chapter begins with an overview of the satellite terrestrial integrated networks (STIN), highlighting its necessity. Later on, STIN along with the challenge in relation to energy efficient resource allocation is discussed. Moreover, the thesis motivation, objectives and contributions are elaborated along with thesis organization.

1.1 Significance of STIN

Natural calamity or unanticipated circumstances make terrestrial networks encumbered and incapacitated which is triggered by a large number of users calling for assistance concurrently. Consequently, unblocked networks are of utmost importance for meeting users' requirements, which are expected to be deployed speedily, sustainably, and dynamically [1]. Apart from this, it is difficult to completely cover sparsely populated areas with wireless networks owing to the high cost of deploying terrestrial infrastructures and its low usage [2]. An ideal solution which can fulfil these requirements is satellite-terrestrial integrated networks (STIN).

Satellite communication systems can provide great flexibility as they can be deployed without geographical constraints not only in remote or natural calamity hit areas but also in areas already having communication infrastructure to decongest terrestrial wireless networks. The STIN architecture is envisioned as a valuable gap filler in both public safety networks and in the provision of high-speed multimedia and broadband services in remote areas [3], [4].

Earlier due to extravagant cost of satellites, only a limited number of researches considered utilizing satellites for assisting terrestrial networks. Fortunately, due to the rapid evolution of satellites including its maintenance procedures, it can attain high bandwidth and low latency, making it cost-effective for industrial execution [5]. Therefore, keeping in view its efficient transmission, satellite communication is expected to become ubiquitous in the future wireless networks. In this regard, increasingly researches have been taking satellite integrated with terrestrial networks for the design and execution of a high-performance and energy-efficient STIN. STIN architecture contains a satellite and terrestrial components which offers wide coverage and high throughput. Figure 1.1 illustrates architecture of STIN.

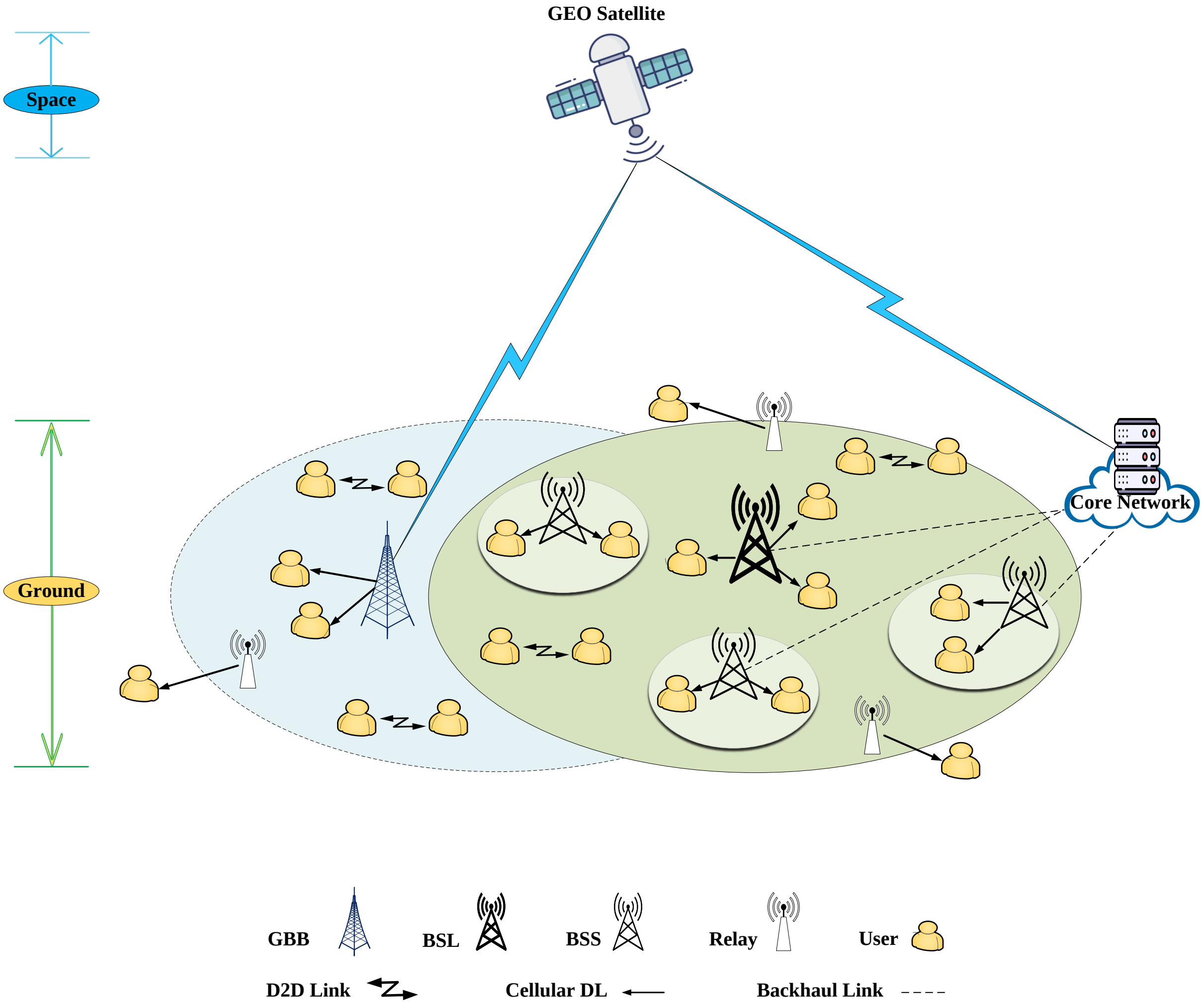


Figure 1.1: **STIN Architecture**

1.2 Advantages of STIN

By combining the advantages of both satellite and terrestrial networks, the STIN promises to provide seamless energy efficient mobile communication access for all types of users and the same has drawn considerable attention of both the academia and industry. Some advantages of STIN are stated as follows:

- Satellite link can be treated as a backup connection for critical cell sites.
- Provision of wide coverage, high flexibility and seamless communication services.
- Provision of high-speed multimedia and broadband services in remote or calamity hit areas.
- Decongestion of terrestrial wireless network / infrastructure.

1.3 Applications of STIN

There are quite a lot of applications of STIN for which it can be employed. It includes the following:

- Global telephone backbones.
- Connections for remote or developing areas.
- Global mobile communication.
- Disaster Management.
- Internet access

1.4 Energy Consumption and STIN

There is a rapid upsurge in global energy consumption due to the mobile networks [6], [7]. Information communication technology (ICT), which includes mobile networks, consumes up to ten percent of the world's total energy consumption and more than two percent of total carbon dioxide emissions [8], [9]. Both energy consumption and carbon dioxide emissions are directly associated with each other and are one of the sources of the greenhouse effect. Energy efficiency (EE) is a design parameter for assessing STIN performance [10]. Therefore, to enhance the EE of STIN and to reduce the energy consumption and carbon dioxide emissions, there is a requirement for exploring energy-efficient user association (UA) and spectrum allocation algorithms for STIN which not only reduces the energy consumption but simultaneously also maintains the desired quality of service (QoS) standards.

1.5 Energy Efficiency

EE is defined as the ratio of amount of bits transmitted from a node to the energy consumed in watts during a particular time period.

$$EE = \frac{R_B}{P_T} \tag{1.1}$$

where R_B denotes the data rate in bits per second and P_T denotes the total consumed power in watts. Therefore, unit of EE is bits/sec/watt or bits/joule.

1.6 Energy Efficient Resource Allocation in STIN

EE of STIN can be enhanced via placement of power efficient base stations (BS) in the access network and by utilizing network deployment approaches like heterogeneous networks (HetNets) [11]. HetNets are regarded as a viable option for increasing the EE of a terrestrial network. HetNets are made up of large base stations (BSL) that are superimposed with small base stations (BSS) and other BSS technologies such as relays and device-to-device (D2D) communication [12]. BSS use less transmit power than BSL due to the existence of a relatively shorter distance between transmitter and receiver. Consequently, as a result of the little transmit power, the battery of the user equipment (UE) is also saved. Furthermore, BSS circuitry is simple, requiring minimal power and no supplementary energy requirement for cooling. As a result, HetNets may be thought of as a way to enhance EE of terrestrial networks [11]. On the other hand, by improving the EE, the service time of the satellites can be effectively extended and their size can also be reduced [13].

STIN offers an effective backhauling solution. It helps in breaking the communication bottleneck triggered due to dense traffic between the user and the core network. The satellite's orbital movement leads to the dynamic change of backhaul links and interrupted link connectivity [14], [15]. Moreover, spectrum allocation may be confronted with severe co-channel interferences produced by overlapping coverage of multiple access points [16]. UA has a significant part in the enhancement of EE, load balancing and spectrum efficiency, hence it can be used as a method to coordinate backhauling [17]. Therefore, STIN demands an energy-efficient UA and spectrum allocation, where a geosynchronous earth orbit (GEO) satellite access network alongside a terrestrial network including a HetNet, which is useful in not only proffering seamless coverage but also in improving the backhaul capacity for dense network scenario [16].

1.7 Related Work

Past work in [18, 19, 20, 21, 22] investigates satellite networks and work in [23, 24, 25, 26, 27, 28, 29, 30] investigates terrestrial networks. Table 2.1 summarises previous work on various EE techniques in satellite and terrestrial networks.

Authors in [18] propose a two-step quadratic transformation method converting the original EE maximization problem to an equivalent convex one and subsequently solving it by an alternating optimization algorithm. Authors in [19] formulate an energy-efficient data offloading mechanism for multi-cell STIN where EE is increased by integrating resource allocation for satellite-terrestrial terminal downlink and power distribution for satellite backhauling. Authors in [20] explore knee-point driven EE and spectral efficiency joint optimization problems. Authors in [21] investigate power allocation strategy for effective EE maximization of satellite communication beneath the interference constraints inflicted by terrestrial communication. Authors in [22] consider a secure beamforming strategy for Rate splitting multiple access-based cognitive STIN in the attendance of numerous eavesdroppers where secrecy EE of the earth station under imperfect wiretap channel state information is maximized.

Authors in [23] propose an integrated cache-enabled low earth orbit (LEO) satellite and terrestrial cooperative transmission scheme for enabling EE in radio access networks. Authors in [24] explore optimized global EE in a multi-beam LEO satellite communication network and develop the problem of joint optimization of beam assignment and power allocation for its maximization.

Authors in [25] introduce relay selection and power distribution for EE maximization and load balancing for random linear network coding (RLNC)-assisted cooperative unicast D2D. Authors in [26] introduce hierarchical resource allocation concept for minimizing energy consumption whereas warranting high spectrum utilization.

Table 1.1: **Related Work and Novelty**

Parameters	[18] **2022**	[19] **2020**	[20] **2021**	[21] **2019**	[22] **2020**	[23] **2020**	[24] **2021**	[25] **2022**	[26] **2021**	[27] **2021**	[28] **2020**	[29] **2021**	[30] **2022**	This Work
Admission control											✓	✓		✓
User association										✓	✓	✓	✓	✓
Power distribution		✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓
Communication in DL		✓					✓							✓
GBB	✓	✓	✓	✓	✓									✓
BSL					✓			✓		✓	✓		✓	✓
BSS								✓	✓	✓	✓		✓	✓
Relay								✓		✓	✓		✓	✓
D2D								✓		✓	✓		✓	✓
Balanced traffic load								✓						✓
Balanced RBs distribution									✓					✓
EE maximization	✓	✓		✓	✓	✓	✓	✓	✓		✓	✓		✓

Authors in [27] formulate mathematical models to guarantee energy-efficient UA, traffic offloading and power distribution using uplink (UL) downlink (DL) decoupled access and UL-DL coupled access schemes in HetNets. Authors in [28] devise an optimization problem for EE for conducting performance analysis of UL-DL coupled access and UL-DL decoupled access strategies in HetNet. Authors in [29] consider EE maximization via DL hybrid nonorthogonal multiple access along with UE clustering in HetNets. Authors in [30] devise a joint EE maximization and cell association with large and small cells supported by D2D and relay. These papers focus on UA and resource allocation strategies for EE maximization in HetNets.

1.8 Motivations

After examining Table 2.1 and reviewing the previous work on STIN [18] - [30] to the best of the authors comprehension, research gap considering the previous work on STIN identified is that joint admission control, UA and power allocation to ensure fairness while associating users in STIN and fairness in allocation of spectrum resources to associated users in STIN with an objective to maximize EE has not been investigated in the past. The direction of the research remained focused in the following areas:

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

1.9 Objectives

Motivated by the gaps found in past research work, this research work targets the following objectives to optimally allocate resources for energy efficiency maximization in STIN:

- Creating an energy efficient STIN model incorporating GEO satellite liaised with HetNets encompassing LBS, SBS, Relay and D2D.
- Defining objective function for energy efficiency maximization.
- Defining constraints, i.e., user admission, user association, fairness while associating users, power, resource block allocation, fairness in allocation of resource blocks etc.
- Defining a optimization problem from objective function.
- Developing an algorithm/ technique based on defined optimization problem.
- Using developed algorithm/ technique, performance analysis via extensive simulations using Matlab.

1.10 Contributions

Considering fairness-based admission control, UA, spectrum resource allocation and power distribution we formulate an EE maximization problem. This problem is a mixed integer nonlinear programming (MINLP) problem which is complex and is a non-deterministic polynomial-time hard (NP-hard). Subsequently it is solved via ϵ-optimal algorithm. The foremost contributions of this work are as follows:

- This work explores fairness in UA and spectrum resource allocation with an objective to maximize EE in STIN. This is achieved via joint admission control, UA and power distribution to ensure, fairness while associating users in STIN and fairness in allocation of spectrum resources to associated users in STIN.
- A two stage ϵ-optimal algorithm is employed which is established on branch and bound algorithm for solving MINLP problem. In the first stage we solve the non-linear programming (NLP) problem after fixing binary variables and obtain optimal solution's upper bound whereas in the second stage we solve the mixed-integer linear programming (MILP) problem and obtain optimal solution's lower bound.

- The performance of the energy efficient STIN model using developed algorithm is verified via extensive simulations and results in the later part of the thesis.

1.11 Thesis Organization

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

Chapter: 2 Heterogeneous Networks and Satellites - 5G This chapter emphasises on fairness in UA and spectrum allocation for EE maximization in a heterogenous networks augmented with GEO satellite for ensuring any time anywhere global access to the users in the network. 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 users in STIN with an objective to maximize EE is elaborated to reach optimal solutions for performance improvement in terms of EE in STIN.

Chapter: 3 System Model and Problem Formulation This chapter focuses on communication model for STIN that certifies users in the network with global access at any time and from any location. This model comprises communication links including GBB, BSL, BSS, relays and D2D. A mathematical model for STIN considering fairnes based admission control, UA, power distribution and EE maximization in DL is formulated. The goal of proposed optimization model is to maximize the EE of STIN.

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

Chapter: 5 Simulations and Results In this chapter simulation results exhibit advantage of the proposed algorithm as mentioned in **chapter:4** for attaining fairness-based admission control, UA, power distribution and EE maximization. These results also provide considerable understanding of the proposed algorithm's convergence.

Chapter: 6 Conclusion The contributions of the thesis are summarized here. The organization of dissertation is shown in Figure 1.2.

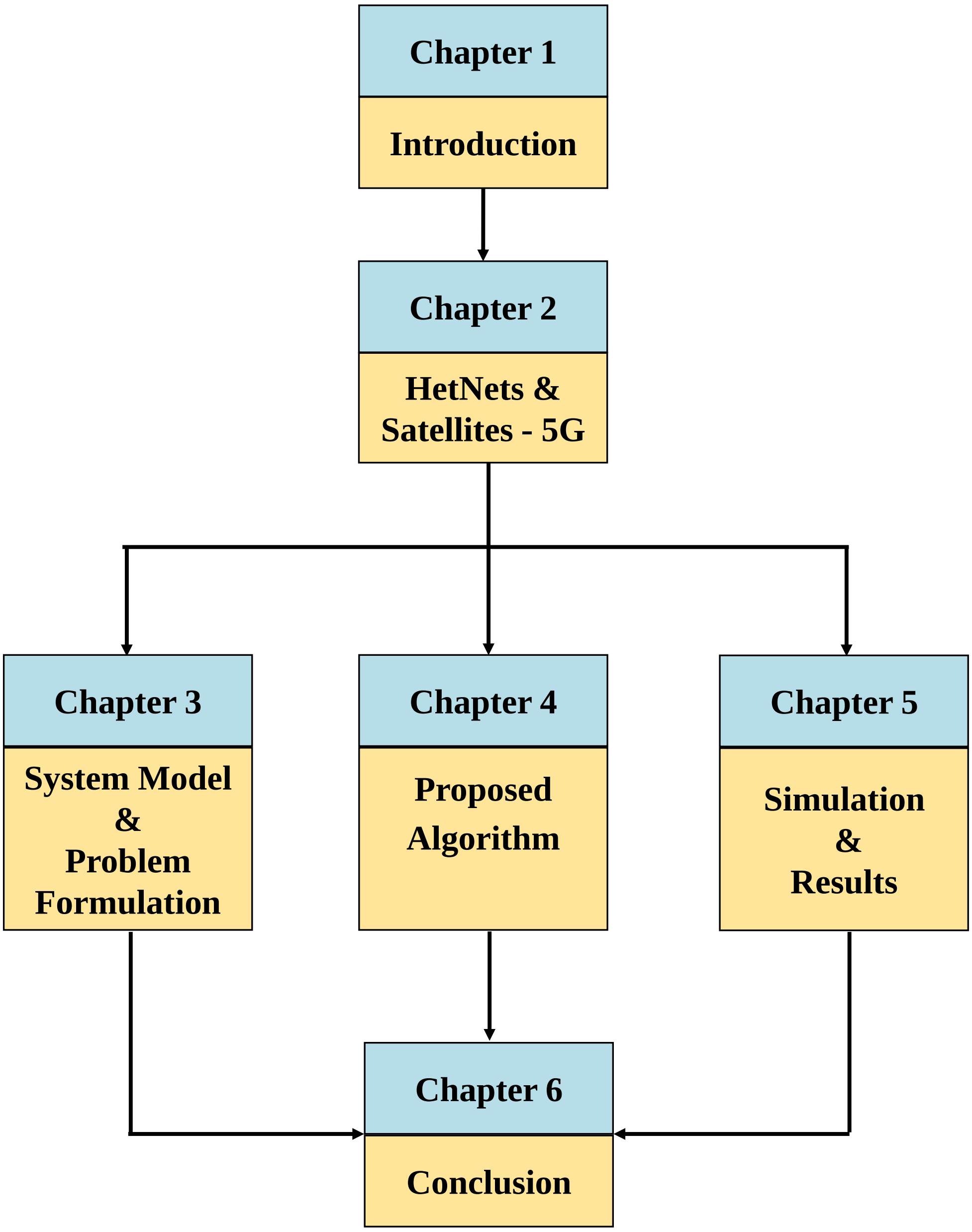


Figure 1.2: **Thesis Organization**

Chapter 2

HETEROGENEOUS NETWORKS AND SATELLITES - 5G

2.1 HetNets

Various standards and technologies have been developed to meet the demand for enhanced services with a higher data rate in cellular networks. Future cellular networks will feature increased indoor/outdoor coverage and a greater capacity. By placing receivers and transmitters closer together, capacity and coverage of cellular networks can be increased. This approach has been adopted in HetNets where large, powerful, and costly large base stations (BSL) is surrounded by small, low-power, and cost-effective small base stations (BSS), Relays, and device-to-device connections (D2D). The HetNets scenario is depicted in Figure 2.1, and a comparison of HetNets nodes is provided in Table 2.2.

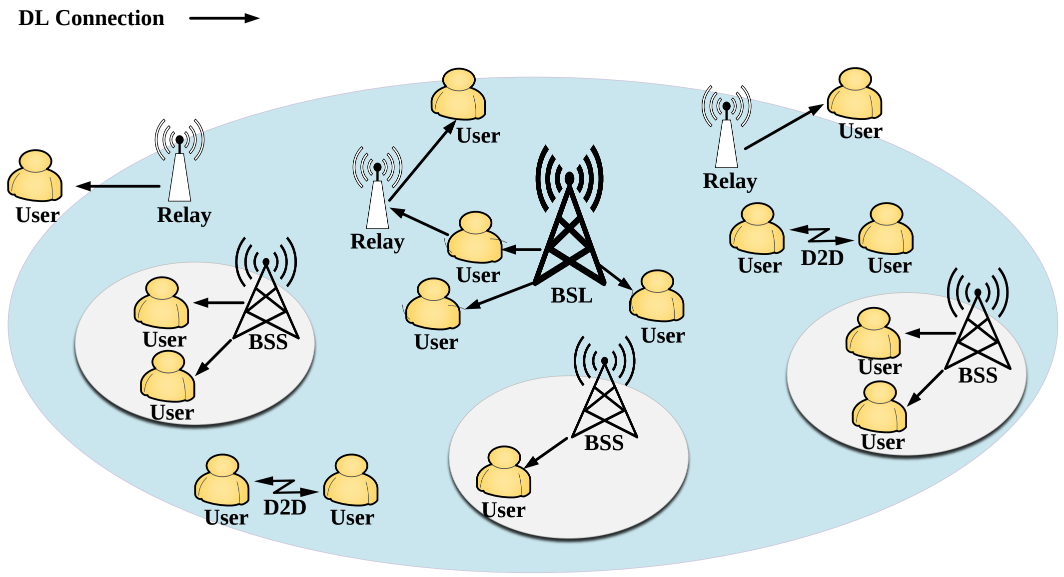


Figure 2.1: **A communication scenario in HetNet**

Table 2.1: **Comparison of HetNets Nodes**

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

2.1.1 BSL

BSL is the fundamental serving component of 3G and 4G cellular networks. It is towered (40-60m), has a long range (300-2000m), is highly powered (30-40watt), and is expensive ($60,000 per year) when deployed outdoors for maximum cellular network user coverage.

2.1.2 BSS

BSS, such as femtocells and picocells, assist in offloading additional traffic of mobile data from BSL and extending coverage in cell edge areas, homes, and workplaces. BSS is connected to the cellular core network via optical fiber/wireless backhaul. In addition, BSS improves EE and spectral efficiency in HetNets. Another advantage of BSS in HetNets is a reduction in capital and operational expenditures (CAPEX, OPEX) [31]. BSS features in HetNets include the following:

- **Picocells**: Cellular operator employs Picocell, an indoor/outdoor system with BSL-like characteristics. It is a small, short-range (40-100m), low-powered (200-2000mW), and cost-effective ($10,000 per year) outdoor device for boosting cellular network coverage in cell edge regions [32]. Picocells are connected to the cellular core network by optical fibre and wireless backhaul. Picocell runs without air conditioning and has low OPEX relative to BSL [33].

- **Femtocells**: Femtocells, a home BS, is outdoor solution and is installed by subscriber. It is small size, short range (10-40m), low powered (10-100mW) and cost effective ($100 per year) solution deployed in indoor (home or offices) by subscriber [32].

2.1.3 Relay

In HetNets, BSL coverage is extended to blind areas utilising relays that are installed/operated outdoors by the operator to transport data from user to BSL and vice versa [32]. It is a medium-sized (5-10 m), medium-range (500-2000 m), low-power (0.1-1 watts), and cost-effective ($10,000 per year) outdoor solution for extending BSL coverage in blind cell edge locations. Optical fiber/wireless backhaul is being used to connect relays to the cellular core network [33].

2.1.4 D2D

EE and spectrum efficiency can be guaranteed by permitting direct communication link amongst users in D2D mode in HetNets. BSL regulates D2D communication in HetNets [34]. In D2D mode, user in close proximity can share images, videos, and engage in video gaming and social networking. D2D mode requires single hop communication and consumes power in milliwatts.

2.2 Traffic offloading in HetNets

In HetNets, traffic is offloaded utilising complementary networks to assure QoS and QoE whenever and wherever practicable. By routing traffic to users through alternative channels, BSL will be relieved of the burden of managing user traffic across the cell coverage region. In HetNets, however, the deployment of complementary networks must ensure interference mitigation, enhanced EE, and maximum throughput. BSS, Wi-Fi, and opportunistic communication which are the primary traffic dumping technologies are described as folows [35]:

2.2.1 Traffic offloading via BSS

BSS is a developing cellular technology for providing quality cellular services in blind and cell edge locations [36]. The majority of data traffic are originated from offices and households, as per previous research [37, 38]. However, BSL coverage in offices and residences is limited. In HetNets, the optimum solution for coverage, capacity, and higher throughput for indoor users is a BSS placed inside homes and offices. A wired backhaul connects the BSS to the cellular operator's main network. Thus, mobile data traffic is offloaded from the BSL and easily provided to indoor users via BSS with improved QoS and QoE while incurring fewer capital and operational expenses.

2.2.2 Traffic offloading via Wi-Fi

Wi-Fi offers increased data rates, but with restricted mobility and coverage. Wi-Fi is the most prevalent way for users to access wireless services, as all mobile devices have Wi-Fi technology built in. Wi-Fi is an effective way for service providers can shift mobile data traffic from the BSL's expensive licensed spectrum to the free spectrum resources [39]. Following are the ways in which Wi-Fi provides offloading:

- **On the spot offloading**: When an access point is inside the service region, mobile data traffic is transmitted over Wi-Fi; otherwise, traffic is redirected to the BSL or BSS.
- **Delayed offloading**: Mobile data traffic is delayed until Wi-Fi connectivity is restored if the service is unavailable.

2.2.3 Opportunistic communication for traffic offloading

Efficient offloading of mobile data traffic is also possible via opportunistic communication [40]. Mobile data traffic, such as weather forecasts, sports news, and movie trailers, can be delivered to targeted users who can then distribute the content via Wi-Fi, Bluetooth, or D2D communication link [41].

2.3 HetNets and UA

Future 5G cellular networks will emphasise cellular networks with densified HetNets [42]. Cellular network performance is significantly impacted by UA. In 4G HetNets, user affiliation with HetNets nodes, i.e. BSL, BSS, Relay, and D2D etc., is determined by the DL with the strongest SINR. This is a bad approach since transmit power imbalance across HetNets nodes will result in the majority of users associating with the BSL and the minority of users associating with BSS, relays, and D2D [43]. This results in inefficient deployment of BSSs in HetNets, which prevents 5G HetNets from maximising the benefits of offloading.

3GPP release 10 recommended biased UA to address this issue, which occurs when the received power from BSS is artificially enhanced by adding a bias to maximise user association/offloading to BSS. UA to BSS by biasing also produces in an increase in interference to BSS from the BSL [44]; hence, interference nullifies the benefits of user offloading from BSL to BSS. To maximise network utility, the value of biassing must be chosen with care to achieve the optimal trade-off between offloading and network throughput [45]. User performance metrics are described as follows:

2.3.1 Outage/coverage probability optimization and UA

In wireless networks, the performance of a specific user is defined by the outage/coverage probability utilising stochastic geometry. Authors in [46] and [47] evaluated performance of UA based on the maximum SINR in the DL in k-tier HetNets using stochastic geometry. For k-tier HetNets, results based on coverage probability with interference and cell load were provided. In addition, the authors demonstrated that coexisting HetNets nodes had varying cell loads, with a small number of idle nodes adding nothing to the aggregate interference in HetNets. Consequently, the authors of [47] enhanced the SINR model presented in [46] by taking the activity factor of coexisting nodes in HetNets into account. Adding picocells and femtocells with light loads to HetNets increased the chance of coverage, according to additional research. However, random deployment of BSSs in the coverage region of BSL may result in an overloaded BSL and an under utilised BSS in HetNets [47].

2.3.2 Spectrum efficiency optimization and UA

Spectrum efficiency is one of the performance metrics used to evaluate cellular network performance. The authors of [48] suggested a dynamic UA for throughput maximization for DL in HetNets. The authors derived the upper bound for the throughput in the DL using convex optimization and developed a less complex heuristic technique for UA to reach the upper bound of throughput in HetNets. In terms of average throughput in HetNets, the UA based on the heuristic algorithm in [48] beat the UA based on maximal SINR and biased value. Using game theory, the authors of [49] optimised spectrum efficiency for UA by creating a utility-based bargaining issue for throughput maximisation where many BSs compete for the highest number of users in the DL in HetNets.

2.3.3 EE optimization and UA

The ever-increasing volume of mobile data traffic and the anticipated growth of wireless networks will result in a significant increase in energy consumption. This will lead to a rise in carbon emissions within the surrounding echo system. As a result, mobile stakeholder are developing energy-efficient technology for future ”green” mobile networks. There are numerous works on UA based on EE in HetNets. The authors in [50] proposed UA with maximum transmit power and minimum required rate constraints for UL in HetNets for EE. The authors of [51] optimized the UA for the DL in HetNets to increase the data rate to energy consumption ratio. The authors of [52] examined the EE of UA by minimizing the overall amount of power utilized in HetNets.

2.3.4 Backhaul bottleneck and UA

Conventional 3G cellular networks with well-planned traditional BSL had a flawless backhaul; however, this is not the case with HetNets, in which BSS, relays, and D2D entities are distributed arbitrarily. The authors of [42] recognised the benefits of super dense HetNets that may be used when HetNets are supported by a dedicated backhaul. In HetNets, one cannot therefore overlook the significance of backhaul restrictions. The authors of [53] analysed UA and utility for throughput of all users with backhaul constraint, whereas the authors in [54] designed a UA waterfilling algorithm for all users weighted throughput with backhaul constraints for BSSs. The authors of [55] researched heuristic approaches to increase network capacity while taking into account the backhaul constraint. Using game theory, the authors in [56] devised UA that is cache-aware while taking the backhaul constraint in HetNets into consideration.

2.3.5 Mobility support and UA

Densified HetNets pose a significant challenge for mobility support in UA. In HetNets, BSS with lower transmit power will have restricted coverage footprints. Therefore, a UA algorithm that does not account for a user's moderate or high mobility will result in much more handovers in HetNets than in a standard 3G cellular network with BSL alone.

The authors of [57] analyzed user speed for UA with biased rule and calculated DL coverage probability using stochastic geometry tools. The findings of [57] demonstrated that the network's performance and likelihood of coverage were significantly enhanced by the mobility-dependent bias factor. To maximize network performance, the authors in [58] utilised a markov modulated Poisson process [59] to jointly describe the UA and mobility problem.

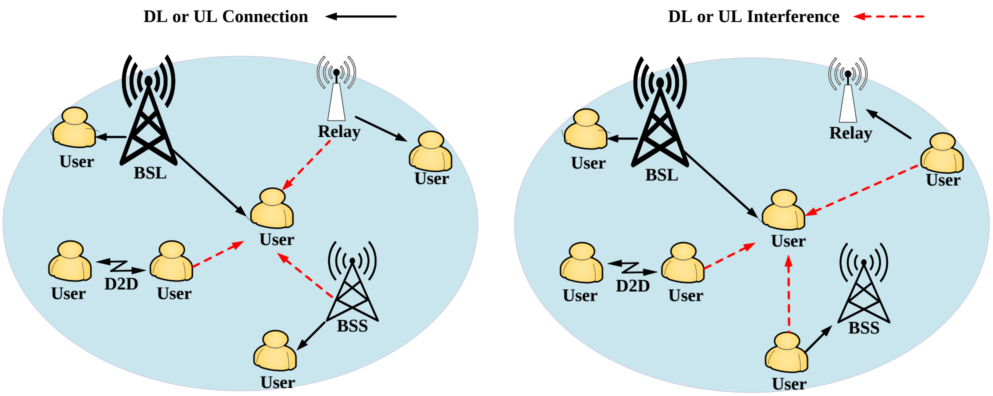
2.4 Interference in HetNets

In HetNets, the increase in heterogeneity caused by the scheduled deployment of BSLs and the unscheduled deployment of BSS, relays, and D2D causes severe inter-tier and cross-tier interference. Inter-tier and cross-tier interference in HetNets can be classified as DL and UL interference, which is expounded on in the next section.

2.4.1 Interference to Users

A user encounters two types of interference when it associates with and receives data from the BS in the DL of HetNets:

- **DL to DL interference:** When the user associates/ receives data from the associated BS in the DL, reception by the user from all un-associated BSs transmitting to other users in the DL is called DL to DL interference as shown in Figure 2.2(a).
- **UL to DL interference:** When the user associates/receives data from the associated BS in the DL, reception by the user from all other users transmitting to un-associated BS in UL is called UL to the DL interference as shown in Figure 2.2(b).



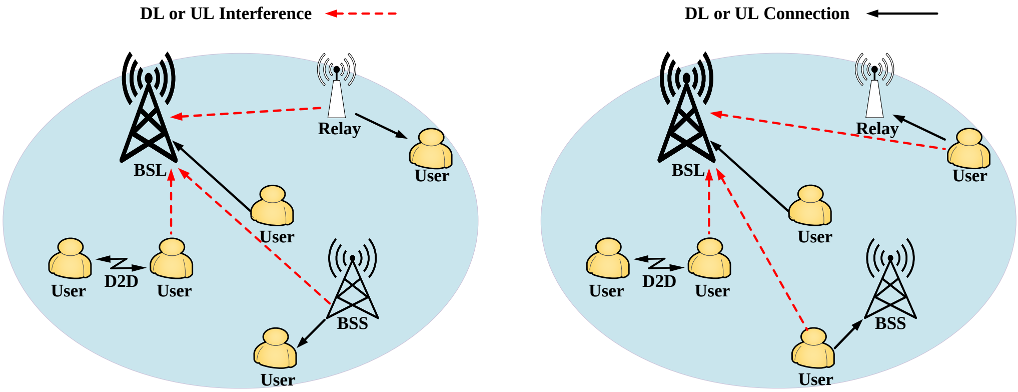
(a) DL to DL Interference (b) UL to DL Interference

Figure 2.2: **Interference in DL**

2.4.2 Interference to BS

A BS experiences two types of interference when it associates and receives data from related user in the UL of HetNets:

- **DL to UL interference:** When the user transmits to the associated BS in the UL, reception by associated the BS from all other BSs transmitting to other users in the DL is called DL to UL interference as shown in Figure 2.3(a).
- **UL to UL interference:** When the user transmits to the associated BS in UL, reception by associated BS from all other users transmitting in the UL is called UL to UL interference as shown in Figure 2.3(b).



(a) DL to UL Interference (b) UL to UL Interference

Figure 2.3: **Interference in UL**

2.5 Optimization theory

The UA problem is modeled employing a utility. The decision wether a particular service is provided to a user is quantified by utility [60]. The UA problem may constitutes utility like throughput, QoS, EE or spectrum efficiency etc, depending on adopted metric. These attributes are modeled as sigmoidal [61], logarithmic [62] and exponential [63] utility functions in recent studies. One of the popular optimization tool used for solving the UA problem is combinatorial optimization discussed below.

2.5.1 Combinatorial Optimization

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

$$\begin{aligned} \max_{N} \mathcal{U}(n,\mu) = & \quad \sum_{u=1}^{U}\sum_{b=1}^{B} n_{u,b}\mu_{u,b} \\ s.t. & \\ & f_i(n) \le c_i, \; i = 1....,p. \end{aligned} \tag{2.1}$$

where $n_{u,b}$ represents the UA and is given below:

$$n_{u,b} = \begin{cases} 1, & \text{if user } u \text{ is associated to BS } b \\ 0, & \text{otherwise.} \end{cases}$$

Network utility is represented by $\mathcal{U}$. Utility for user u associated to BS b is represented by $\mu_{u,b}$. Resource constraints like power, spectrum and QoS requirements are represented by $f_i(x) \le c_i$. Since, a user u can associates to single BS b at a time, therefore, $n_{u,b} = \{0, 1\}$. 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 [64] or Lagrangian dual analysis [65] are invoked to find near optimal solution of formulated problem in Eq. (2.1).

2.6 Satellites

Satellites are designed specifically for use in communications. They are utilized for mobile applications including communication with ships, automobiles, planes, handheld terminals, TV and radio transmission. They are liable for delivering these services to a certain location (region) on the earth. The bandwidth and power of these satellites are determined by the footprint size desired, the complexities of the traffic control protocol methods, and the cost of the ground stations.

The signals of a satellite are most effective when they are focused on a specific location. When the region is concentrated, the emissions are confined to the specific area, limiting disturbance to adjacent systems. This results in increased spectrum efficiency. Importantly, satellite antenna patterns must be constructed to optimally cover the chosen geographical area. Satellites should be constructed with consideration for their short and long-term utility during their lifetime. If the satellite drifts from its orbit due to external influences, the earth station (ES) should be able to control it [66]. Table 2.2 compares the characteristics of satellite-based and terrestrial wireless networks [67].

Table 2.2: **Comparison of satellite and terrestrial wireless networks**

Characteristics	**Terrestrial Wireless**	**Satellite**
BS Coverage	1km	BS coverage for LEO exceeds 500km and for GEO provides even worldwide coverage
Cell Radius	0.1-1.0km	LEO's cell radius is 50km and GEO's cell radius is 400km
Network Deployment	Various BSs before use	The entire system must be configured to deliver services, with a protracted lead time
Network Extension	Cell-splitting to increase capacity, neccesitates system re-engineering; equipment upgrades are easy	Capacity increased only by deploying additional satellites; Hardware upgrades can only be substituted by satellite
Requirement of Transmission Power	High	Middle to High
Propagation Delay	Low	High

2.7 Configuration of a Satellite Communication System

Figure 2.4 depicts a satellite communication system's interface with terrestrial entities. The satellite system consists of three segments: the space segment, the control segment, and the ground section [66]. Details are as follows:

- **Space Segment**. The space segment consists of one or more operational and reserve satellites arranged in a constellation.
- **Control Segment**. The control segment comprises of all ground infrastructure for the monitoring and controlling of satellites, often known as tracking, telemetry, and command (TTC) stations, and for the management of satellite traffic and associated resources for communication networks.
- **Ground Segment**. The ground segment includes all traffic ES. These stations can range in size from a few centimeters to tens of meters, depending on the sort of service being considered.

2.8 Communication Links

The link between transmitting and receiving devices comprises of either a radio or optical modulated carrier. The efficiency of the transmitting equipment is determined by its effective isotropic radiated power (EIRP), which is the power provided to the antenna multiplied by the antenna's gain in the direction under consideration. $\frac{G}{T}$, the proportion of the antenna receive gain, G, in the considered direction to the system noise temperature, T, measures the performance of receiving equipment; $\frac{G}{T}$ is known as the receiver's figure of merit [66]. Figure 2.4 depicts the following types of links:

- UL from 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-

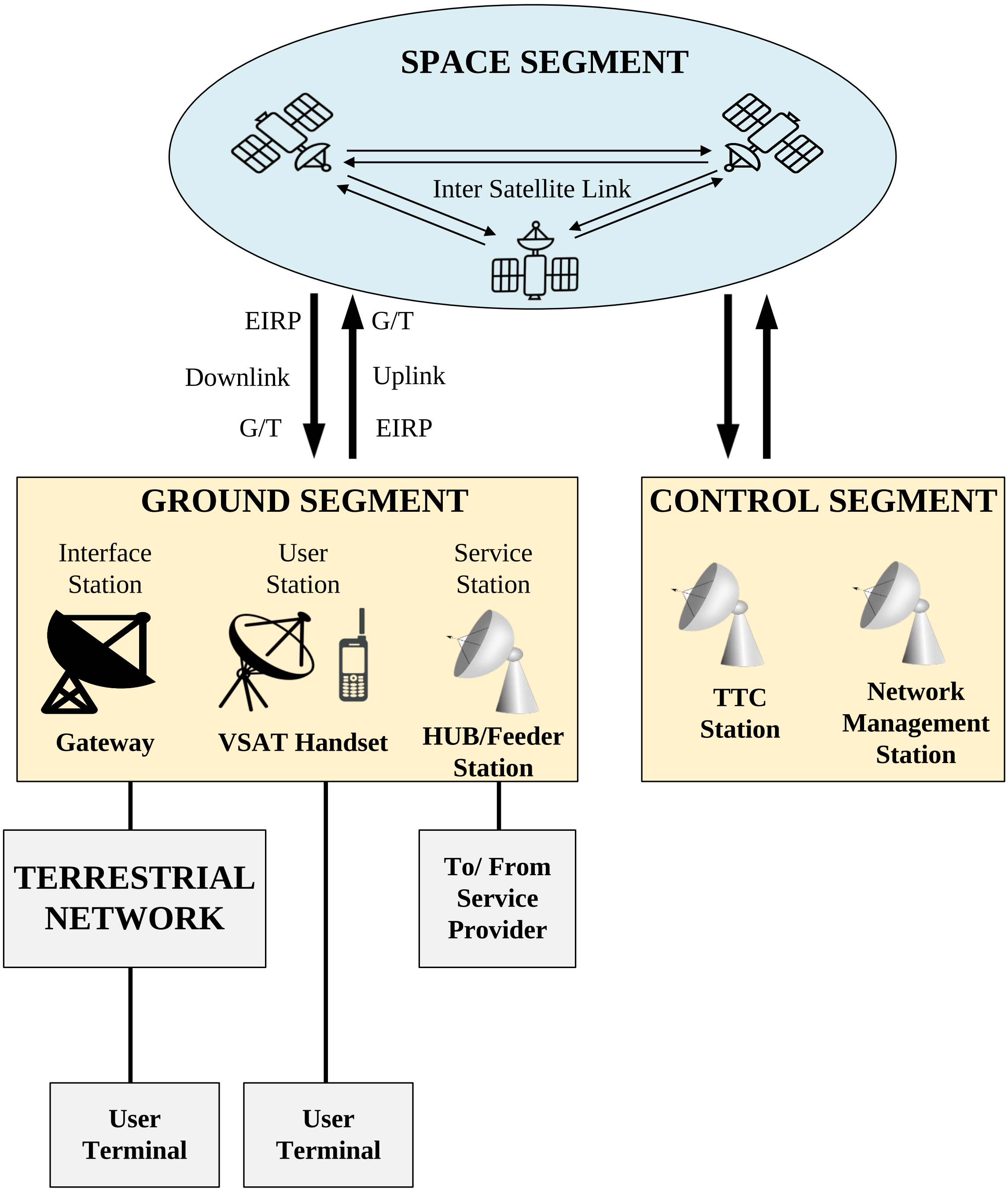


Figure 2.4: **Interface of satellite communication system with terrestrial entities**

relay satellites communicate with their base stations through optical links. Baseband signals providing information for communication purposes modulate carriers.

2.9 Role of Satellites in 5G Networks

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

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

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

- Growing traffic as well as the amount of connections outside of densely populated urban hubs in more remote/ rural extents as a result of the emergence of Internet of Things (IoT).
- Offering coverage for mobile devices.
- Computining and data caching moving closer to the networks' edge and beyond areas having abundant fiber accessibility.

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

In order to encounter these challenges, satellites require to offer a variety of functions, including the last mile problem, on the move connectivity, backup for important services in emergency, edge-networking, and IoT congested traffic locations outside densely networked city areas.

Briefly, satellites will be essential in shaping the collective 5G destiny. The terrestrial and satellite components will decide the type and level of connection that 5G networks can offer. In fact, as opposed to what they could have enabled in principle.

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

It is not just hypothetical that terrestrial and space-based telecommunications networks will converge for 5G. Together, these three factors— changing business models, expanding bandwidth demand, and developing satellite system technology—make it plausible, however not unavoidable, for satellites to play an important part in telecommunications networks in broad-spectrum and 5G networks in specific [68].

2.10 Potential Functions of Satellites in 5G Networks

To deliver on the full promise of 5G networks (near-universal, instantaneous coverage for a large number of connected devices), satellites will also need to play a far more central role in future telecommunications networks, with both terrestrial and space-based components performing a greater variety of tasks. For the first time, the expansion of satellite sector both in terms business models and technology is now achievable [68].

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

2.10.1 Backhaul

Traditionally, backhaul was conducted mostly by point-to-point wireless or fiber. To meet the fast growing requirements for their 4G/ LTE network expansions, mobile network operators throughout the globe are examining new backhaul technologies due to the increasing requirements of telecommunications systems. As 5G installations progress, the need for a greater choice of backhaul options will only expand. As the number of small cells inside the radio access network (RAN) rises, so does the need for backhaul between the RAN and the main network. 5G networks have a viable alternative for real-time data backhaul now that LEO swarms are approaching. Given the needs of 5G networks and the expansion of satellite systems, it is feasible for satellites to supplement current backhaul mechanisms in order to satisfy the increasing requirements.

2.10.2 Redundancy

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

2.10.3 Remote and Rural Connectivity

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

Chapter 3

SYSTEM MODEL AND PROBLEM FORMULATION

3.1 System Model

This article explores energy-efficient UA and energy-efficient spectrum allocation in STIN. This communication model certifies users in the network with global access at any time and from any location. As illustrated in Fig. 3.1, this model comprises communication links including GEO satellite-based BS (GBB), BSL, BSS, relays and D2D. GBB and BSL dispense seamless coverage in the same zone, BSS is the coverage gap filler in dead zones, relay extends BSL coverage, and D2D mode allows two users in close proximity to communicate. We presume that satellite and terrestrial networks are integrated to authorize users with seamless access to both services within the network.

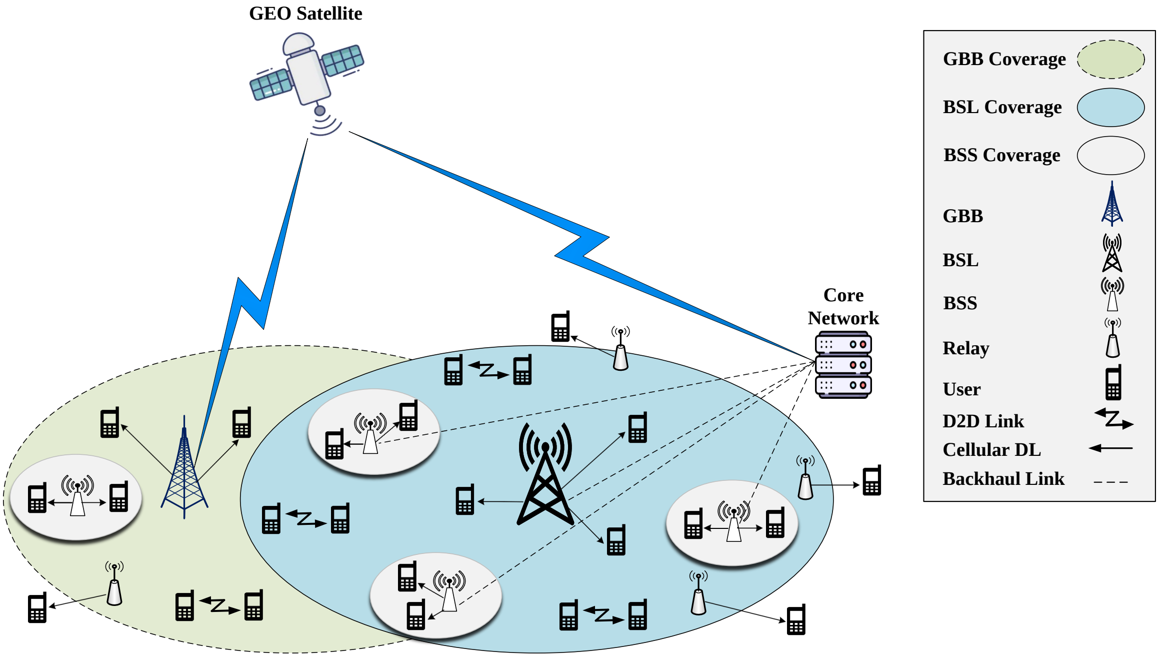


Figure 3.1: **Satellite-Terrestrial Integrated Network Model.**

The satellite-terrestrial gateway station (STGS) is connected to the core network. GEO satellite is connected to STGS and GBB via C-band backhaul. The HetNets nodes, i.e., BSL, BSS, relays etc. are connected to STGS via optical fiber backhaul. GBB receives data from the GEO satellite over C-band and subsequently the same is transmitted to users over C-band. Likewise, BSL, BSS, relays, and D2D are operating in the sub-6GHz band. To evade co-channel interference from BSL to BSS and D2D, it is assumed that the BSL's spectrum differs from that of the BSS and D2D in each cell. Omnidirectional antennas are used to cover the users by the BSS, relay, and D2D. Within the GBB and BSL coverage area, the location of BSS and relays follows a Poisson point process. The location of users follows the uniform distribution in the serving BS's coverage area.

Let set of users $\mathbb{U} = \{1, 2, 3, ..., U\}$ is served by set of BSs $\mathbb{B} = \{g, l, s, r, d\}$. Here, $g =$ GBB, $l =$ BSL, $s =$ BSS, $r =$ relay and $d =$ D2D.

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

$$m_u = \begin{cases} 1, & \text{User } u \text{ is admitted} \quad (3.1a) \\ 0, & \text{Otherwise} \quad (3.1b) \end{cases}$$

Definition-2: Let binary variable for user association is given below:

$$n_{u,b} = \begin{cases} 1, & \text{User } u \text{ is associated with BS } b \quad (3.2a) \\ 0, & \text{Otherwise} \quad (3.2b) \end{cases}$$

At any given time, a BS can serve multiple users, however, a user u can associate itself with only one BS b at a given time. Users and BSs should be associated in such a way that their traffic load is distributed fairly amongst several mobile stations in the network. The following is a mathematical representation of user u admission, association, and fairness in user traffic offloading:

$$\sum_{b \in \mathbb{B}} n_{u,b} = m_u, \, \forall \, u \in \mathbb{U}, \tag{3.3a}$$

$$\sum_{b \in \mathbb{B}} n_{u,b} \leq 1, \, \forall \, u \in \mathbb{U}, \tag{3.3b}$$

$$\digamma_{u,b} = \frac{\left(\sum\limits_{b \in B} n_{u,b}\right)^2}{B \sum\limits_{b \in B} (n_{u,b})^2}, \, \forall \, u \in \mathbb{U}, \tag{3.3c}$$

where $\digamma_{u,b}$ in (3.3c) is Jain's fairness index [69] where $0 \leq \digamma_{u,b} \leq 1$. The value of $\digamma_{u,b} = 1$ when 100% fairness is achieved in association of users in STIN.

Every BS b has a maximum power P_b and the same power is assigned to different users associated with BS b. $p_{u,b}$ represents the power that BS b has assigned to user u. The mathematical relation for power distribution is as follows:

$$\sum_{b \in \mathbb{B}} p_{u,b} \leq P_b \, \forall \, u \in \mathbb{U}, \tag{3.4a}$$

$$0 \leq p_{u,b} \leq P_b, \, \forall \, b \in \mathbb{B}, \, u \in \mathbb{U}. \tag{3.4b}$$

The channel gain [70] amongst a user u that is associated with a BS b is as follows:

$$g_{u,b} = \bar{g} \xi A_o \left(\frac{d_o}{d_{u,b}}\right)^{\gamma}, \, \forall \, b \in \mathbb{B}, \, u \in \mathbb{U}. \tag{3.5}$$

where $\bar{g}$ denotes Rayleigh random variable, ξ represents the zero mean Gaussian random variable with σ as standard deviation [71], A_o symbolizes the antenna gain, d_o symbolizes the far field distance of antenna, $d_{u,b}$ symbolizes the distance amongst a user u and a BS b and γ symbolizes the path loss exponent.

Using the UA in (3.2a), power allocated in (3.4b) and channel gain in (3.5), the signal to interference plus noise ratio (SINR) of a user u which is associated with a BS b is as follows:

$$\mathrm{SINR}_{u,b} = \frac{n_{u,b}p_{u,b}g_{u,b}}{\sum\limits_{u \neq u'} n_{u',b}p_{u',b}g_{u',b} + \sigma^2}, \ b \in \mathbb{B} \ \& \ u \in \mathbb{U}. \tag{3.6}$$

where σ^2 represents Gaussian white noise variance.

The following Shannon capacity formula [72] determines the achievable rate $c_{u,b}$ of user u which is associated with BS b in the DL is given below:

$$c_{u,b} = f_{u,b} log_2 \left(1 + SINR_{u,b}\right), \forall \, b \in \mathbb{B}, \, u \in \mathbb{U}. \tag{3.7}$$

where SINR is given in (3.6) and $f_{u,b}$ is bandwidth allocated to user u associated with BS b. The number of resource blocks (RBs) allocated to user u by BS b is determined by the user's QoS rate requirement Q_u. RBs allocated by BS b to the user u to meet the QoS rate requirement are calculated below:

$$r_{u,b} = \left\lceil \frac{Q_u}{f_{u,b}c_{u,b}} \right\rceil, \forall \, b \in \mathbb{B}, \, u \in \mathbb{U} \tag{3.8a}$$

$$x_{u,b} = \frac{r_{u,b}}{\sum\limits_{b \in B} n_{u,b}}, \forall \, b \in \mathbb{B}, \, u \in \mathbb{U} \tag{3.8b}$$

$$y_{u,b} = \frac{\left(\sum\limits_{b \in B} x_{u,b}\right)^2}{B \sum\limits_{b \in B} \left(x_{u,b}\right)^2}, \forall \, u \in \mathbb{U}, \tag{3.8c}$$

where $\lceil \cdot \rceil$ denotes ceiling function and $r_{u,b}$ represents RBs allocated to the user u by BS b for a particular QoS rate requirements. $x_{u,b}$ in (3.8b) symbolizes the ratio of RBs allocated to a user u assocoated with BS b to meet QoS Q_u and total users associated with BS b in STIN. $y_{u,b}$ in (3.8c) is Jain's fairness index [69] for fair distribution of RBs among U users where $0 \leq y_{u,b} \leq 1$. The value of $\Upsilon_{u,b} = 1$ when 100% fairness is achieved in allocation of RBs in STIN.

3.2 Model for Energy Consumption - Uplink

The energy consumption model for each user in the downlink power optimization technique is divided into two main categories: circuit energy and transmission energy. The circuit energy is concerned with circuit components like processing units, convertors and amplifiers while the transmission energy, on the other hand, is the energy consumed by the transmitter in transmitting the data. In this set-up, P_c symbolizes circuit energy while $p_{u,b}$ symbolizes consumption of the transmission energy for user u associated with BS b [73]. Hence the total energy consumed by any user u can be expressed as follows:

$$P_{total} = P_c + p_{u,b}. \tag{3.9}$$

EE is defined as the ratio of total bits transmitted to the energy consumed in watts.

$$EE = \frac{c_{u,b}}{P_{total}} \tag{3.10}$$

where $c_{u,b}$ denotes the data rate in bits per second and P_{total} denotes the total consumed power in watts. Therefore, unit of EE is bits/sec/watt.

3.3 Problem Formulation

A mathematical model for STIN considering fairnes based admission control, UA, power distribution and EE maximization in DL is formulated.

3.3.1 Objective Function

The objective of this work is to maximize EE in STIN. EE is defined as the ratio of total bits transmitted by $\mathbb{B}$ BSs in the downlink in STIN to the energy consumed during transmission in watts.

$$EE = \frac{\sum\limits_{b\in\mathbb{B}}\sum\limits_{u\in\mathbb{U}} n_{u,b}c_{u,b}}{P_c + \sum\limits_{b\in\mathbb{B}}\sum\limits_{u\in\mathbb{U}} p_{u,b}}. \tag{3.11}$$

3.3.2 Constraints

The goal of proposed optimization model is to maximize the EE of STIN under following constraints:

- **Admission control constraint:** It ensures admission of a user u in STIN.

$$\sum_{b \in \mathbb{B}} n_{u,b} = m_u,\ \forall\, u \in \mathbb{U}, \tag{3.12}$$

where m_u represents binary variable for user admission.

- **User association constraint:** At any given time, a user u will be associated at maximum with only one BS b (BSL, GBB, BSS, relay or D2D).

$$\sum_{b \in \mathbb{B}} n_{u,b} \leq 1,\ \forall\, u \in \mathbb{U}, \tag{3.13}$$

where $n_{u,b}$ represents binary variable for user association.

- **User fairness constraint:** Fairness in the association of users with BS b (BSL, GBB, BSS, relay or D2D). The value for user fairness ≤ 1. The value of user fairness = 1 when user traffic is distributed equally among all BSs in STIN.

$$\left(\sum_{b \in B} n_{u,b}\right)^2 \leq B \sum_{b \in B} (n_{u,b})^2,\ \forall\, u \in \mathbb{U}, \tag{3.14}$$

- **Power constraint:** Every BS b (BSL, GBB, BSS, relay or D2D) has a maximum power P_b and the same power is distributed amongst different users associated with BS b. $p_{u,b}$ represents the power that BS b has assigned to user u and this is always less than or equal to the maximum power P_b of respective BS b.

$$0 \leq p_{u,b} \leq P_b,\ \forall\, b \in \mathbb{B},\ u \in \mathbb{U} \tag{3.15}$$

- **QoS of a user constraint:** Achievable rate of user u associated with BS b (BSL, GBB, BSS, relay or D2D) must be greater than the QoS rate requirement of user u.

$$c_{u,b} \geq m_u Q_u,\ \forall\, b \in \mathbb{B},\ u \in \mathbb{U}, \tag{3.16}$$

- **RB allocation constraint:** RBs required to meet QoS requirements are allocated by BS b (BSL, GBB, BSS, relay or D2D) to the user u. These allocated RBs must be less than or equal to the total RBs available.

$$\sum_{b\in\mathbb{B}} r_{u,b} \leq m_u T_{RB},\, \forall\, b \in \mathbb{B},\, u \in \mathbb{U}, \tag{3.17}$$

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

$$\left(\sum_{b\in B} x_{u,b}\right)^2 - B\sum_{b\in B} \left(x_{u,b}\right)^2 \leq 0,\, \forall\, u \in \mathbb{U} \tag{3.18}$$

3.3.3 Objective

Basing on constraints, the objective of this work is EE maximization while ensuring fairnes based admission control, UA, power distribution in STIN. Summary of the EE optimization problem is mathematically formulated as follows:

$$\max_{\mathbf{n}\,\mathbf{p}} \quad \frac{\sum\limits_{b\in\mathbb{B}}\sum\limits_{u\in\mathbb{U}} n_{u,b}c_{u,b}}{P_c + \sum\limits_{b\in\mathbb{B}}\sum\limits_{u\in\mathbb{U}} p_{u,b}}, \tag{3.19a}$$

$$\textbf{s.t.} \quad \sum_{b\in\mathbb{B}} n_{u,b} = m_u,\, \forall\, u \in \mathbb{U}, \tag{3.19b}$$

$$\sum_{b\in\mathbb{B}} n_{u,b} \leq 1,\, \forall\, u \in \mathbb{U}, \tag{3.19c}$$

$$\left(\sum_{b\in B} n_{u,b}\right)^2 \leq B\sum_{b\in B} (n_{u,b})^2,\, \forall\, u \in \mathbb{U}, \tag{3.19d}$$

$$0 \leq p_{u,b} \leq P_b,\, \forall\, b \in \mathbb{B},\, u \in \mathbb{U}, \tag{3.19e}$$

$$c_{u,b} \geq m_u Q_u,\, \forall\, b \in \mathbb{B},\, u \in \mathbb{U}, \tag{3.19f}$$

$$\sum_{b\in\mathbb{B}} r_{u,b} \leq m_u T_{RB},\, \forall\, b \in \mathbb{B},\, u \in \mathbb{U}, \tag{3.19g}$$

$$\left(\sum_{b\in B} x_{u,b}\right)^2 \leq B\sum_{b\in B} \left(x_{u,b}\right)^2,\, \forall\, u \in \mathbb{U}. \tag{3.19h}$$

Objective function in Eq. (3.19) achieves EE maximization in STIN while satisfying constraints $3.19b$ to $3.19h$. Constraint $3.19b$ ensures user admission in the STIN. Constraint $3.19c$ ensures the association of a user with a maximum of one BS. Constraint $3.19d$ ensures fairness among users while associating with BSs. Constraint 3.19e gives the range of the power that can be allocated to a user. Constraint $3.19f$ ensures QoS for a user. Constraint $3.19g$ ensures allocation of RBs to a user. Constraint $3.19h$ ensures fairness while allocating RBs among users by BS.

3.3.4 Alternate Technique

In the formulated problem as mentioned in Eq. (3.19), the denominator denotes a convex function whereas the numerator denotes a concave function. This is a Concave Fractional Programming (CFP) problem with $c_{u,b}$, and $p_{u,b}$ as real valued functions defined on the subset of R^k. Charnes Cooper Transformation (CCT) [74] is employed via substituting $p_{u,b} = \left(\frac{i_{u,b}}{j}\right)$ and subsequently CFP problem is converted into a concave optimization problem. The equivalent concave optimization problem after transformation is as follows:

$$\max_{\mathbf{n}\,\mathbf{i}} \quad j \sum_{b\in\mathbb{B}} \sum_{u\in\mathbb{U}} n_{u,b} f_{u,b} log_2 \left(1+\frac{i_{u,b} g_{i,j}}{j\sigma^2}\right), \tag{3.20a}$$

$$\textbf{s.t.} \quad \sum_{b\in\mathbb{B}} n_{u,b} = m_u, \; \forall\, u \in \mathbb{U}, \tag{3.20b}$$

$$\sum_{b\in\mathbb{B}} n_{u,b} \leq 1, \; \forall\, u \in \mathbb{U}, \tag{3.20c}$$

$$\left(\sum_{b\in B} n_{u,b}\right)^2 - B\sum_{b\in B} (n_{u,b})^2 \leq 0, \; \forall\, u \in \mathbb{U},, \tag{3.20d}$$

$$0 \leq i_{u,b} \leq jP_b, \; \forall\, b \in \mathbb{B}, \; u \in \mathbb{U}, \tag{3.20e}$$

$$f_{u,b} log_2 \left(1+\frac{i_{u,b} g_{u,b}}{j\sigma^2}\right) \geq m_u Q_u, \; \forall\, b \in \mathbb{B}, \; u \in \mathbb{U}, \tag{3.20f}$$

$$r_{u,b} \leq m_u T_{RB}, \; \forall\, b \in \mathbb{B}, \; u \in \mathbb{U}, \tag{3.20g}$$

$$\left(\sum_{b\in B} x_{u,b}\right)^2 - B\sum_{b\in B} (x_{u,b})^2 \leq 0, \; \forall\, u \in \mathbb{U} \tag{3.20h}$$

$$P_c j + \sum_{u\in\mathbb{U}} \sum_{b\in\mathbb{B}} i_{u,b} = 1. \tag{3.20i}$$

The transformed problem mentioned in Eq. (3.20) is a MINLP problem. This is a complex and NP-hard UA and power distribution problem [75]. Eq. (3.19) represents an optimization problem that exhibits combinatorial nature. To find a global optimum solution to this problem, an exhaustive search over all feasible schedules in P(U) is required to be performed which is impracticable for any network of feasible size since $|P(U) = 2^{|U|}|$. Therefore, keeping in view its less complex outer approximation algorithm (OAA) is implemented for solving the formulated problem and subsequently to obtain $\epsilon = 10^{-3}$ optimal solution.

Chapter 4

PROPOSED ALGORITHM

The problem in (3.20) consists of a blend of non-linear and binary variables. This is a typical specimen of a MINLP problem. During simulations, the search space for formulated problems rises exponentially as the number of users grows, i.e. $2^{|U|}$ optimization problems are expected to be resolved in every iteration. Accordingly, given the presence of binary variables, the computational complexity of the articulated problems is infeasible even in a smaller network. Thus, these sorts of problems including UA and power distribution are complicated and NP-hard [75]. So, we employ the ϵ-optimal algorithm to address the articulated problems. The ϵ-optimal algorithm applies the decomposition principle which bifurcates the problem into the undermentioned subproblems:

- NLP problem.
- MILP problem.

Since NLP and MILP problems aren't overly complicated, therefore ϵ-optimal algorithm congregates in a specific number of iterations and offers optimum solution [64, 76].

4.1 Description of ϵ-Optimal Algorithm

Suppose Ω and $\Upsilon_{\text{b-h}}$ symbolize objective function and constraints of problems in (3.19). $\mathbb{T}$ symbolize binary variables $\mathbb{T} = \{m_u, n_{u,b}\}$, $\mathbb{Y} = \{i_{u,b}\}$ and $\mathbb{Z} = \mathbb{T} \cup \mathbb{Y}$. Four prepositions which hold correct for said Problems in (3.19) are as follows:

1. $\mathbb{Y}$ is convex, compact and not empty.
2. For a fixed $\mathbb{Z}$, Ω and $\Upsilon_{\text{b-h}}$ are convex in $\mathbb{Y}$.
3. For a fixed $\mathbb{Z}$, Ω and $\Upsilon_{\text{b-h}}$ are differentiable.

4. Fixing $\mathbb{Z}$ switches a MINLP problem to an NLP problem which has a possibility of an exact solution.

4.1.1 First Stage

In the first stage, in order to transform MINLP problems as given in (3.20) to NLP problem $\mathbb{Z}$ is fixed at $\mathbb{Z}^k$. NLP problem's solution is the upper bound of the optimum solution. Following is the NLP problem:

$$\min_{\mathbb{Y}} \; -\Omega(\mathbb{Z}^k, \mathbb{Y}) \tag{4.1a}$$

$$\text{s.t. } \Upsilon_{\text{b-h}}(\mathbb{Z}^k, \mathbb{Y}) \leq 0 \tag{4.1b}$$

4.1.2 Second Stage

NLP problem as mentioned in (4.1) are solved to get the binary variables of $\mathbb{Z}$ at $\mathbb{Z}^k$. Results of the first stage are used in the second stage to modify the MINLP problems as mentioned in (3.20) to the MILP problem. Following is the MILP problem:

$$\min_{\mathbb{Z}} \min_{\mathbb{Y}} \; -\Omega(\mathbb{Z}^k, \mathbb{Y}) \tag{4.2a}$$

$$\text{s.t. } \Upsilon_{\text{b-h}}(\mathbb{Z}^k, \mathbb{Y}) \leq 0 \tag{4.2b}$$

(4.2) can also be written as:

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

such that

$$\varphi(\mathbb{Z}) \; = \min_{\mathbb{Y}} \; -\Omega(\mathbb{Z}^k, \mathbb{Y}) \tag{4.4a}$$

$$\text{s.t. } \Upsilon_{\text{b-h}}(\mathbb{Z}^k, \mathbb{Y}) \leq 0 \tag{4.4b}$$

Problem mentioned in (4.3) is the projection of (3.20) on $\mathbb{Z}$-space. Since all constraints apply for NLP problem as mentioned in (4.1) for each and every $\mathbb{Z}^k$, therefore we can write the solution for projection problem as follows:

$$\min_{\Upsilon}\min_{\mathbb{Y}} \quad -\Omega(\mathbb{Z}^k, \mathbb{Y}^k) - \nabla\Omega(\mathbb{Z}^k - \mathbb{Y}^k)\begin{pmatrix}\mathbb{Y}-\mathbb{Y}^k\\ \mathbb{Z}-\mathbb{Z}^k\end{pmatrix} \tag{4.5a}$$

$$\text{s.t. } \Upsilon_{\text{b-h}}(\mathbb{Z}^k, \mathbb{Y}^k) - \nabla\Upsilon_{\text{b-h}}(\mathbb{Z}^k, \mathbb{Y}^k)\begin{pmatrix}\mathbb{Y}-\mathbb{Y}^k\\ \mathbb{Z}-\mathbb{Z}^k\end{pmatrix} \leq 0. \tag{4.5b}$$

With the introduction of a new variable ϑ, the problem in (4.5) may be expressed as follows:

$$\min_{\Upsilon,\mathbb{Y},\vartheta} \quad \vartheta \tag{4.6a}$$

$$\text{s.t. } \vartheta \geq -\Omega(\mathbb{Z}^k, \mathbb{Y}^k) - \nabla\Omega(\mathbb{Z}^k - \mathbb{Y}^k)\begin{pmatrix}\mathbb{Y}-\mathbb{Y}^k\\ \mathbb{Z}-\mathbb{Z}^k\end{pmatrix} \tag{4.6b}$$

$$\Upsilon_{\text{b-h}}(\mathbb{Z}^k, \mathbb{Y}^k) - \nabla\Upsilon_{\text{b-h}}(\mathbb{Z}^k, \mathbb{Y}^k)\begin{pmatrix}\mathbb{Y}-\mathbb{Y}^k\\ \mathbb{Z}-\mathbb{Z}^k\end{pmatrix} \leq 0 \tag{4.6c}$$

4.1.3 Steps of ϵ-optimal algorithm's Iterative Approach

In (4.6), the MILP problem offers an optimal solution's lower bound. The branch and bound algorithm is utilized to resolve the MILP problem [77]. Once the objective function i.e. Ω and constraints function i.e. $\Upsilon_{\text{b-h}}$ are linear, the MILP problem is driven by NLP problem's solution at $\mathbb{Z}^k$ [78, 79]. Following are the steps followed by the ϵ-optimal algorithm's iterative approach:

1. As the algorithm progresses towards an ϵ optimal solution, the lower bound increases whereas the upper bound decreases.

2. If the difference between the lower and upper bound is below ϵ, it is an optimal solution.

3. If the difference exceeds ϵ, the new binary variables $\mathbb{Z}$ are set to $\mathbb{Z}^{k+1}$. Subsequently, both NLP and MILP problems are resolved again in the succeeding repetition to obtain new lower and upper bounds.

4. Once the difference between the lower and upper bound is smaller than ϵ, the optimal solution is attained.

5. Flow chart depicting ϵ-optimal algorithm is shown in Fig. 4.1.

4.2 Algorithm Convergence and Optimality

According to [64,78], the ϵ-optimal algorithm converges linearly. Once binary variables $\mathbb{Z}$ are fixed at $\mathbb{Z}^k$, objective and constraints functions i.e., Ω and $\Upsilon_{\text{b-h}}$ are convex. While all four prepositions are satisfied, the branch and cut method is utilized by ϵ-optimal algorithm [77] in order to arrive at an optimum solution in a limited number of steps, inside $\epsilon = 10^{-3}$. By implementing the ϵ-optimal algorithm, the solution is ensured inside the bound ϵ of the optimum solution for any value of $\epsilon > 0$. Lower values of ϵ provide the confirmed correct values of the solution. For specified binary variable $\mathbb{Z}$, which specifies that optimality of $\mathbb{Y}$ according to (4.6) might be:

1. If $\vartheta \geq \Omega(\mathbb{Z}^k, \mathbb{Y}^k) \rightarrow viable\ solution$
2. Otherwise $\vartheta \leq \Omega(\mathbb{Z}^k, \mathbb{Y}^k) \rightarrow not\ a\ viable\ solution$

Thus, the MILP problem mentioned in (4.6) may not comprise a $\mathbb{Z}^k$ value that doesn't have a viable solution. Therefore, this guides the ϵ-optimal algorithm to converge in a limited number of steps. The convexity of the objective and constraint functions leads to the algorithm's optimality for any fixed values of $\mathbb{Z}$. The OAA algorithm's comprehensive convergence proof is provided in [64]. A globally optimum solution may be computed using an exhaustive search algorithm (ESA) for Eq. (3.19), however, there is an exponential increase in computing effort. If we denote complexity by Ç and the number of users by u in STIN then the ESA's computational complexity will be expressed as follows:

$$Ç_{ESA} = 2^{2u} \tag{4.7}$$

However, by employing OAA an ϵ-optimal algorithm can be found via an infinite number of iterations [76]. In a simplified form, the OAA's computational complexity will be expressed as follows:

$$Ç_{OAA} = \frac{u^2 \kappa}{\omega} \tag{4.8}$$

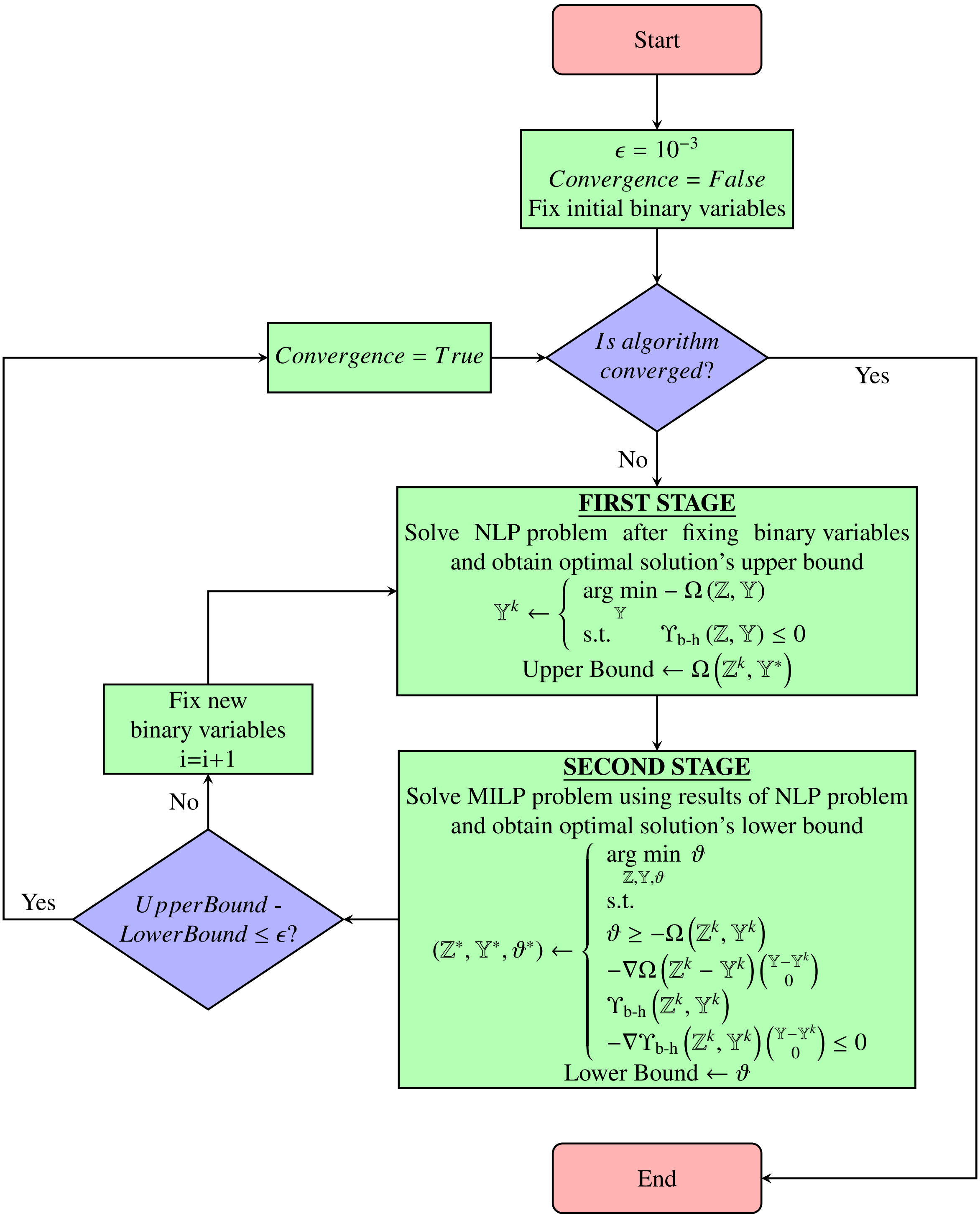


Figure 4.1: **Flow chart - ϵ-optimal algorithm.**

where κ symbolizes the number of constraints whereas ω symbolizes ϵ-optimal algorithm's error tolerance from the global optimum solution. One additional advantage which OAA has over ESA is that it guarantees the provision of an ϵ optimum solution. Fig. 4.2 illustrates the trend of OAA and ESA computational complexity.

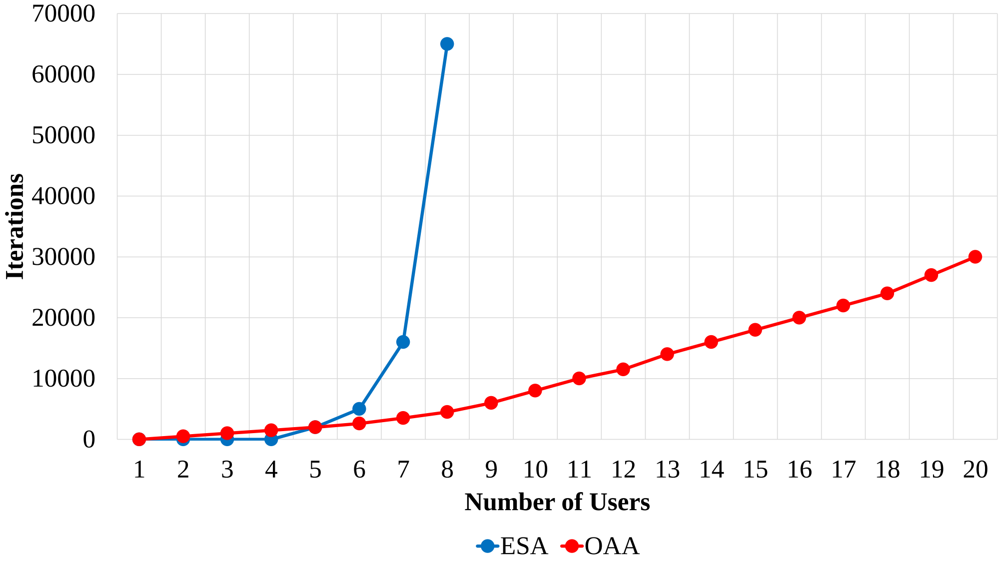


Figure 4.2: **Number of Users vs Computational Complexity - OAA and ESA**

4.3 Complexity of ϵ-Optimal Algorithm

Flops [1] are used to calculate complexity [80]. In the commencing phase of the ϵ-optimal algorithm add on five flops. NLP problem's solution adds on $4UB\Upsilon$ and $2UB$ flops. MILP problem's solution adds on $2UB\Upsilon$ and $4UB\Upsilon$ flops. While comparing NLP and MILP problems, two flops are added. Four flops are added by guessing new binary variables. On the basis of flops, the complexity of the ϵ-optimal algorithm is as follows:

$$E = 5 + 2UB + 4UB\Upsilon + 4UB\Upsilon + 2UB\Upsilon + 4, \tag{4.9a}$$

$$E = 9 + 2UB + 10UB\Upsilon, \tag{4.9b}$$

$$E \approx 2UB + 10UB\Upsilon. \tag{4.9c}$$

---

[1] A flop stands for floating-point operation and the number of flops is used to assess the complexity. Furthermore, a division or multiplication operation adds one flop. Two flops are added by complex addition, while four flops are added by complex multiplication. $2lmo$ flops are added by the multiplying $l \times m$ dimension matrix by $m \times o$ dimension matrix. The assignment operator and the logical operator both add one flop. Two flops are required for the $log_2(x)$

Likewise, depiction of ϵ-optimal algorithm's complication by Big O is $O(U \times B) + O(U \times B \times \Upsilon)$. Where U, B and Υ symbolizes users, STIN BSs and constraints respectively.

Chapter 5

SIMULATION AND RESULTS

The simulation results obtained depicts the performance of the proposed strategy for solving the fractional programming problem, as mentioned in Eq. (3.19) with regards to EE of STIN. These results also provide considerable understanding regarding the proposed algorithm's convergence. Basic open-source nonlinear mixed integer programming (BONMIN) [74] is utilised in order to execute outer approximation.

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

- Number of users associated.
- Fairness in UA.
- RB allocation.
- Fairness in RB allocation.
- Average throughput achieved.
- Average EE achieved.

5.1 Simulation Setup

System parameters utilised in simulation are mentioned in Table 5.1. For the entire simulations, maximum power for BSL P_l, GBB P_g, BSS P_s, relay P_r and D2D pair P_d are set to 43 dBm, 41.5 dBm, 40 dBm, 40 dBm and 35 dBm whereas maximum radius of BSL D_l, GBB D_g, BSS D_s, relay D_r and D2D pair D_d are set to 1000 m, 600 m, 400 m, 400 m and 100 m respectively. Minimum data rates required are 0.2, 0.4, 0.6, 0.8, 1.0 Mbps. Minimum users allowed are 5, while maximum users allowed are 40 with an increment of 5. The total number of available RBs that can be allocated to the users are 150. The far field distance of antenna d_o, is set to 10 m, zero mean gaussian random variable ξ to 10 dB and path loss exponent γ to 2. The total circuit power P_c is set to 10^{-6} Watts.

Table 5.1: **System Parameters**

Parameters	**Value**
P_l	43 dBm
P_g	41.5 dBm
P_s	40 dBm
P_r	40 dBm
P_d	35 dBm
D_l	1000 m
D_g	600 m
D_s	400 m
D_r	400 m
D_d	100 m
Q_u	$\{$0.2,0.4,0.6,0.8,1.0$\}$ Mbps
T_{RB}	150
$f_{u,b}$	0.1 Mbps
A_o	50
d_o	10 m
ξ	10 dB
γ	2
P_c	-30 dBm
$Min\, Users$	5
$Max\, Users$	40
$User\ Increment$	5

5.2 Results and Discussions

In this section, simulation results exhibit advantage of the proposed algorithm for attaining fairness-based admission control, UA, power distribution and EE maximization. In this regard, a performance comparison has also been carried out between fairness-based and without fairness-based [28, 30] implementation of UA, EE and throughput of the STIN system model.

5.2.1 User Association

Fig. 5.1 shows a graph of the number of users versus UA (both fairness-based and without fairness) i.e., the total number of available users versus the number of users which get associated with a BS (either BSL, GBB, BSS, relay or D2D). It is evident from Fig. 5.1 that with the increase in the number of users there is a proportional increase in both fairness-based and without fairness-based UA i.e. association of users with available BSs increases with the increase in the number of users in STIN. This is quite obvious that if the number of available users increases in STIN, more will be the likelihood that they will get associated with any of the available BS. It is evident from Fig. 5.1 that both fairness-based and without fairness-based UA are almost similar, only a slight difference in the overall average of the total number of associated users with any of the available BSs have been observed between both scenarios. However, the main difference lies in the fair distribution of the associated users amongst available BSs in both scenarios. In fairness-based UA, the association of the users with a particular BS is carried out keeping in view the fair distribution of load amongst available BSs whereas for the system lacking fairness-based UA, the association of the users with a particular BS is not carried out considering the criteria of fair distribution of load amongst available BSs. The same has been further elaborated in the ensuing paragraphs.

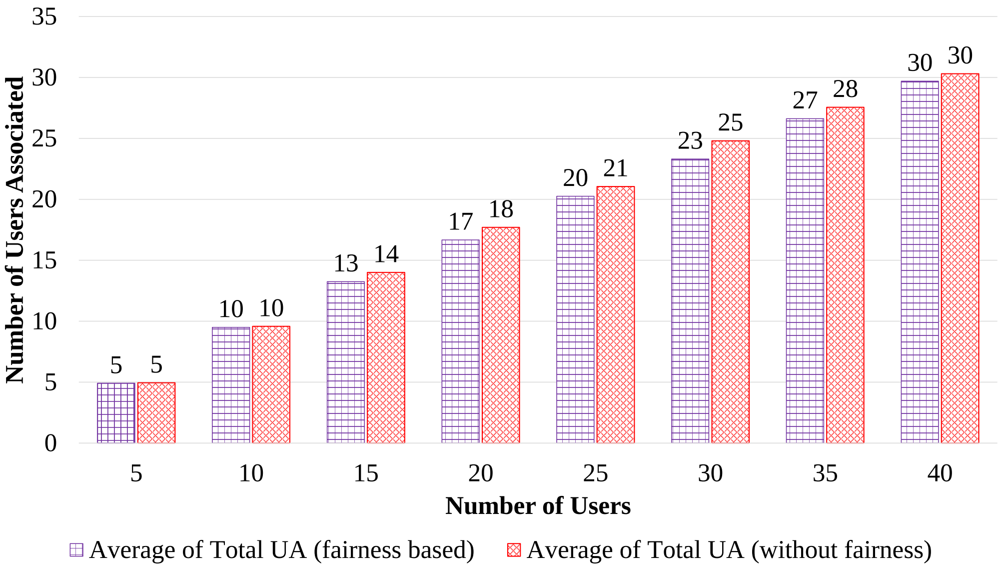


Figure 5.1: **Number of Users vs Number of UA in STIN.**

Fig. 5.2 show a plot of fairness-based UA with respective BSs (BSL, GBB, BSS, relay or D2D) against different QoS rate requirements i.e. from 0.2 to 1.0 Mbps. This plot is for 40 users. As illustrated in Fig. 5.2, for the required rate of 0.2 Mbps, the number of users associated with each BS is almost equal i.e. a fair distribution of users amongst available BSs have been observed less that of the D2D pair. Subsequently, if the required data rate is increased from 0.2 to 1.0 Mbps with a step size of 0.2 Mbps, the QoS rate requirement versus UA plot follows approximately the same behaviour as that of 0.2 Mbps data rate. D2D is again observed to be dominant in UA. This shows that D2D is dominant in UA for both low data rates and high data rates. The reason is that both the users in the D2D pair are present in close proximity and less power is required for establishing a connection between them. It is also evident from Fig. 5.2 that with a stepwise increase in QoS rate requirement from 0.2 to 1.0 Mbps, a slight drop in the total number of associated users is observed. This degradation in UA performance depicts that the system associates fewer users at high data rates as compared to that at low data rates.

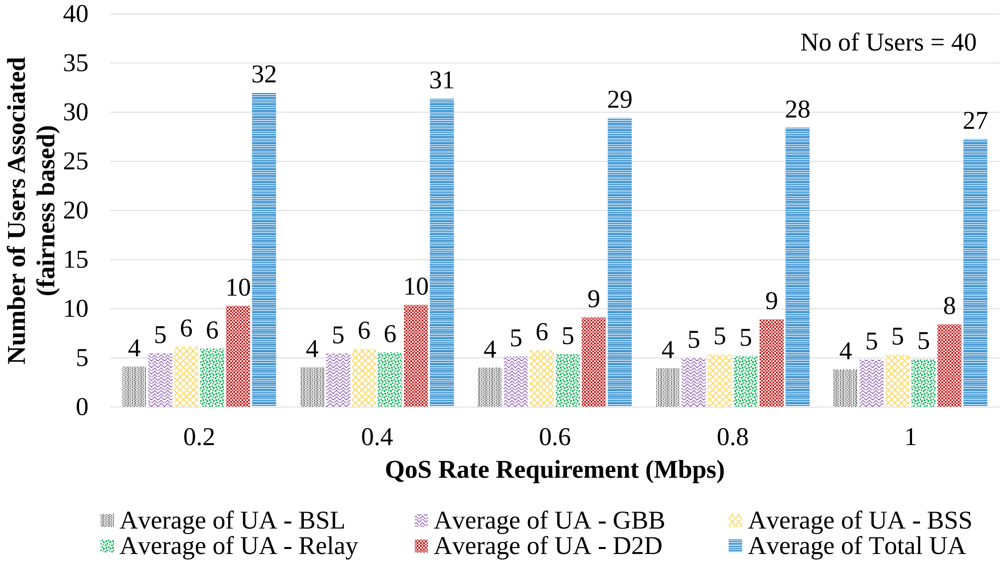


Figure 5.2: **QoS Rate Requirement vs UA (fairness based) in STIN.**

Fig. 5.3 show a plot of the system lacking fairness-based UA with respective BSs (BSL, GBB, BSS, relay or D2D) against different QoS rate requirements i.e. from 0.2 to 1.0 Mbps. Uneven distribution of the users amongst available BSs has been observed as compared to that in the fairness-based UA system as depicted in Fig. 5.2.

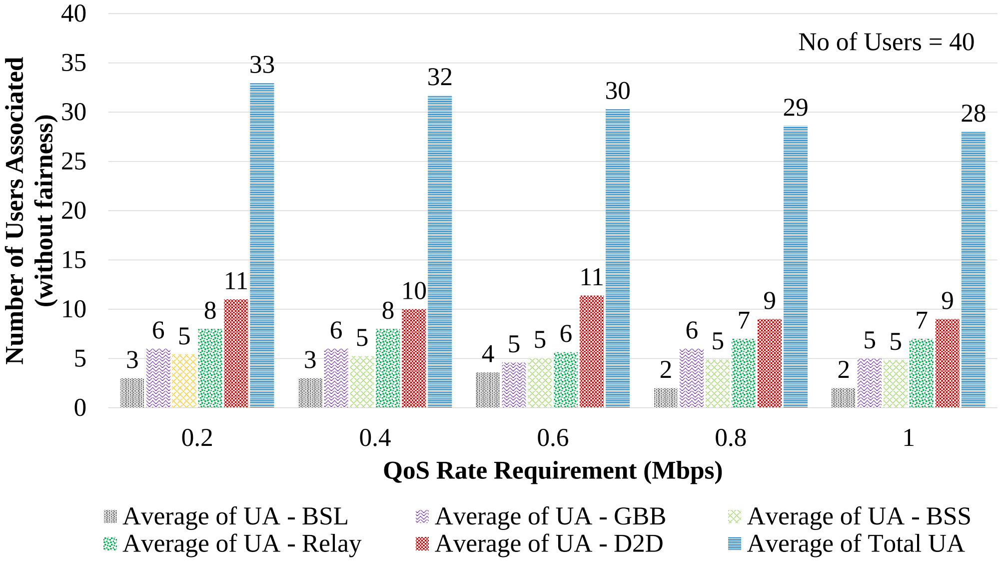


Figure 5.3: **QoS Rate Requirement vs UA (without fairness) in STIN.**

5.2.2 User Fairness

Fig. 5.4 shows graph of number of users versus UA and user fairness (UF) i.e., total number of users against number of associated users and the corresponding fairness while associating these users in STIN with available BS (BSL, GBB, BSS, relay or D2D). It is evident from Fig. 5.4 that UF increases with the relative increase in the number of associated users. If the number of users are further increased the value of UF becomes closer to 1 with almost a uniform value of UF, as depicted in Fig. 5.4. Increase in UF value is due to the fact that greater the number of available users greater will be the UA (as already seen in Fig. 5.1) and this makes it easier for the system to distribute these associated users amongst the BSs in a fair manner whereas on the other hand, once the number of users are low it becomes difficult to fairly distribute these users amongst the available BSs. This makes fairness while associating users in STIN more efficient for greater number of users as compared to that for lesser number of users.

Fig. 5.5 show plot of number of users against UA and UF index at different QoS rate requirements i.e. 0.2 Mbps, 0.6 Mbps and 1.0 Mbps. The number of users are increased from 5 to 40 users with a step size of 5 users. As illustrated in Fig. 5.5, with the increase in the number of users there is a proportional increase in UA for all QoS rate requirements however, as the QoS rate requirement is increased from 0.2 to 1.0

Mbps a gradual decrease in the total number of associated users is observed. Despite the decrease in UA with corresponding increase in QoS rate requirement, the fairness while associating these users with available BSs almost remains the same at all the three QoS rate requirements of 0.2 Mbps, 0.6 Mbps and 1.0 Mbps. These observations validates our findings in Fig. 5.2 and Fig. 5.4.

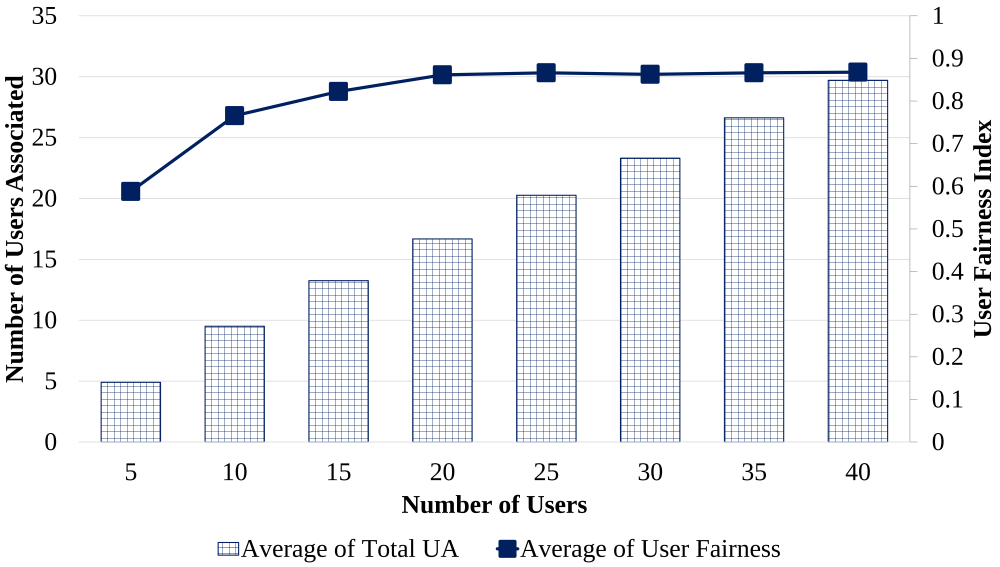


Figure 5.4: **Number of Users vs UA and User Fairness Index.**

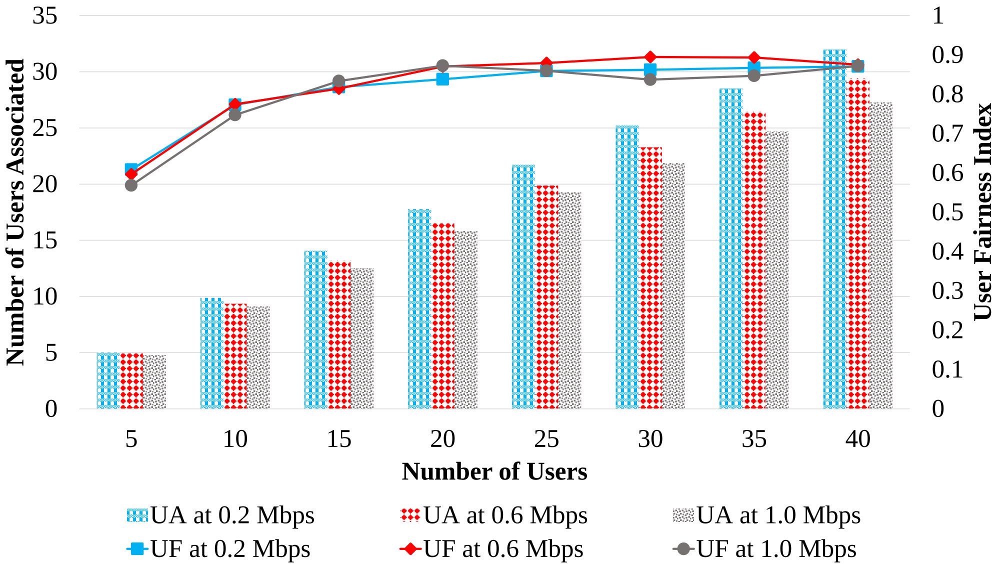


Figure 5.5: **Number of Users vs UA and User Fairness Index at different QoS rate requirements.**

5.2.3 RB Fairness

Fig. 5.6 shows graph of number of users versus UA and RB fairness i.e., total number of users against number of associated users and the corresponding fairness in allocation of RBs to these associated users in STIN. It is evident from Fig. 5.6 that RB fairness increases with the corresponding increase in the number of associated users in STIN. If the number of associated users is further increased the value of RB fairness becomes closer to 1 with almost a uniform value of RB fairness, as depicted in Fig. 5.6. Increase in RB fairness is due to the fact that greater the number of associated users with a particular BS, the more it will be easier for the system to distribute available RBs amongst them in a fair manner whereas on the other hand, once the number of associated users are low it becomes difficult to fairly distribute these RBs amongst the associated users. This makes fairness while allocating RBs to associated users in STIN more effective for greater number of users as compared to that for lesser number of users.

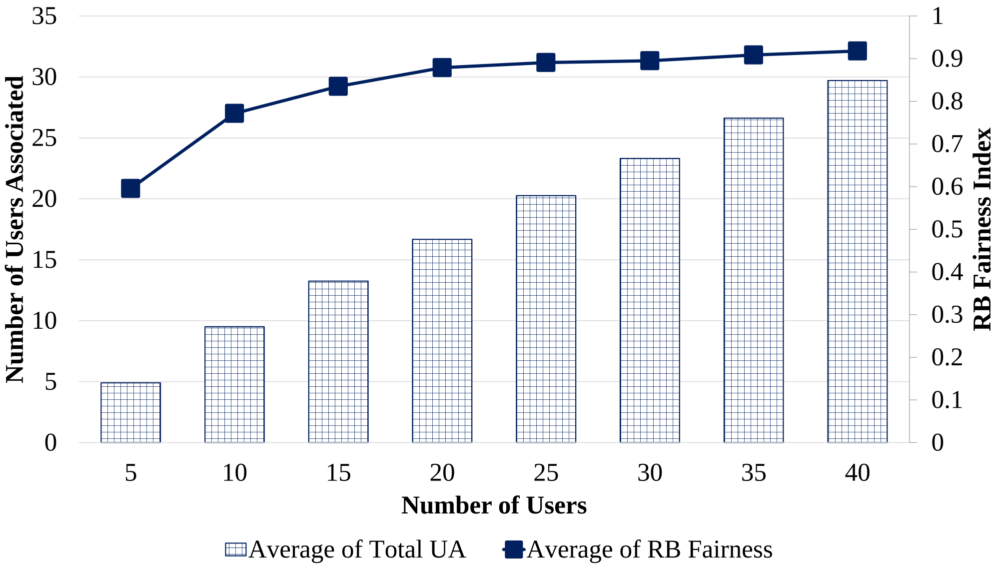


Figure 5.6: **Number of Users vs UA and RB Fairness Index.**

Fig. 5.7 show plot of number of users against UA and RB fairness index at different QoS rate requirements i.e. 0.2 Mbps, 0.6 Mbps and 1.0 Mbps. The number of users are increased from 5 to 40 users with a step size of 5 users. As illustrated in Fig. 5.7, with the increase in the number of users there is a proportional increase in UA and RB fairness for all three QoS rate requirements. This validates our findings in Fig. 5.7. However, as the QoS rate requirement is increased from 0.2 Mbps to 1.0 Mbps a gradual decrease in the total number of associated users is observed as already seen in Fig. 5.5. Other than this, the behavior of RB fairness at different QoS rate requirements is seen to be almost similar to that of UF however, a very slight difference in RB fairness values at all the three QoS rate requirements of 0.2 Mbps, 0.6 Mbps and 1.0 Mbps is noticed. The value of RB fairness at high data rate of 1.0 Mbps is observed to be slightly better as compared to that of RB fairness at low data rate values of 0.6 Mbps and 0.2 Mbps.

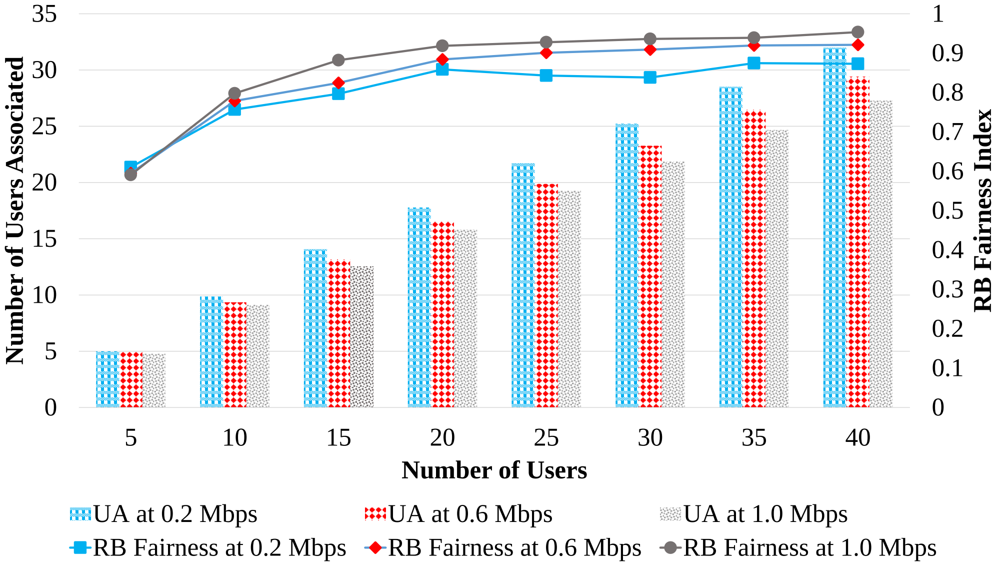


Figure 5.7: **Number of Users vs UA and RB Fairness Index at different QoS rate requirements.**

5.2.4 RB Allocation

Fig. 5.8 shows graph of number of users versus UA and RB allocation i.e., total number of users versus the number of associated users in STIN and the RBs / spectrum resources allocated to these associated users in STIN by respective BS i.e. BSL, GBB, BSS, relay or D2D. It is evident from Fig. 5.8 that the number of allocated RBs increases with the corresponding increase in the number of associated users in STIN. It is clear from the graph that with the increase in the number of users both UA and RBs allocation to the associated users in STIN increases simultaneously. This behavior validates our findings of Fig. 5.1 that greater the number of available users greater will be the UA. With the increase in the number of associated users there will be a simultaneous increase in the requirement of RBs that are required to be allocated to these associated users by the respective BSs.

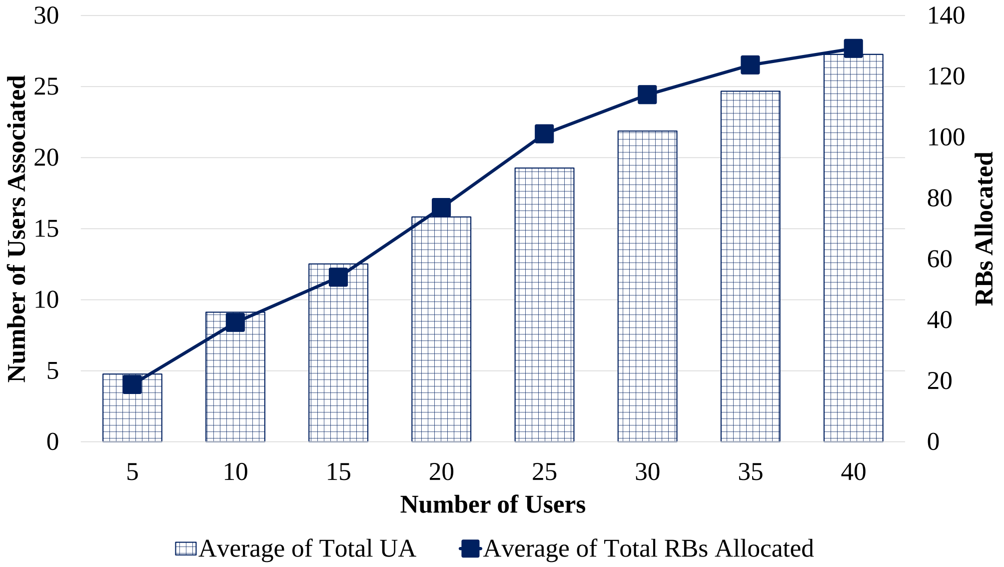


Figure 5.8: **Number of Users vs UA and Allocated RBs.**

Fig. 5.9 shows graph of QoS rate requirement versus UA and RB allocation i.e., QoS rate requirement of users versus the number of associated users and the RBs / spectrum resources allocated to these associated users in STIN. It is evident from Fig. 5.9 that the UA in STIN decreases whereas RB allocation increases with the corresponding increase in the QoS rate requirement of users in STIN. Increasing the QoS rate requirement decreases the UA, which is obvious as more power is required to maintain high data rates and subsequently at high data rates, power requirement for a user to get associated with a particular BS is also high. As a result of which UA at high data rates decreases, on the contrary RB allocation at high data rates increases as compared to that at lower data rates.

Fig. 5.10 show plot of number of users against UA and RB allocation at different QoS rate requirements i.e. 0.2 Mbps, 0.6 Mbps and 1.0 Mbps. The behavior of UA with the corresponding increase in the number of users for above mentioned QoS rate requirements is the same as already discussed in Fig. 5.5 and Fig. 5.7. Apart from this, as depicted in Fig. 5.10 it is quite evident that RB allocation to the associated users in the system varies at all the three QoS rate requirements. The RB allocation to the users associated with a particular BS is maximum at high data rate of 1.0 Mbps whereas it decreases at low data rates of 0.6 Mbps and 0.2 Mbps respectively however, irrespective of the QoS rate requirement RB allocation increases with the corresponding increase in the number of users. These observations validates our findings in Fig. 5.8 and Fig. 5.9.

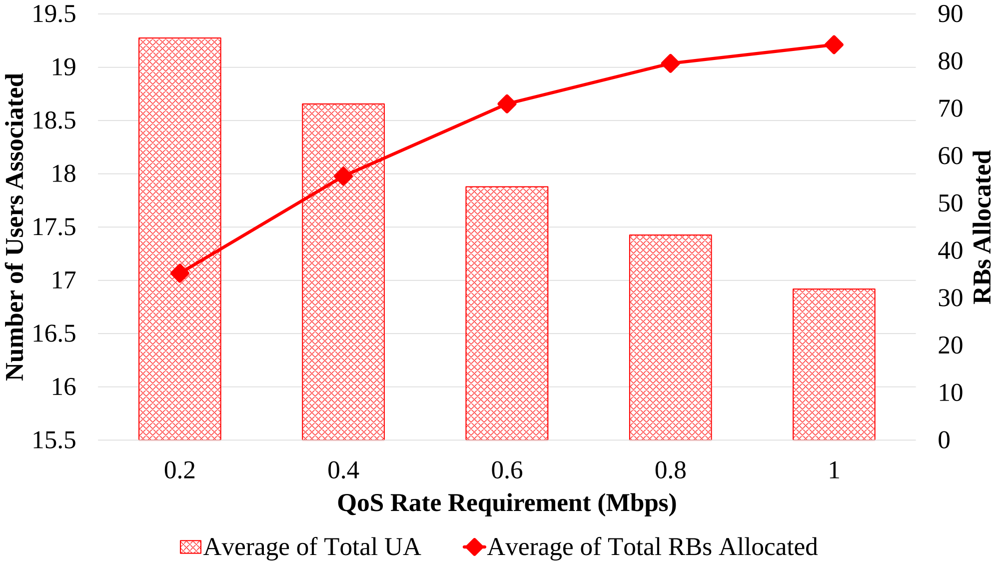


Figure 5.9: **QoS Rate Requirement vs UA and Allocated RBs.**

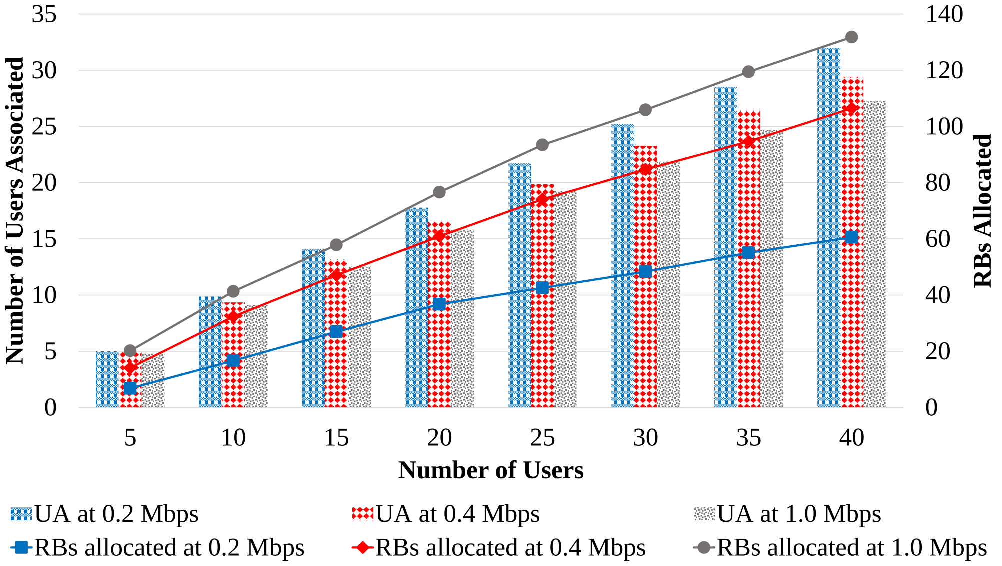


Figure 5.10: **Number of Users vs UA and RB Allovation at different QoS rate requirements.**

5.2.5 Throughput

Fig. 5.11 depicts graph of throughput and UA versus the number of users. It is evident from Fig. 5.11 that both throughput and UA increases as the number of users are increased in STIN. In the start there is an increase in the throughput with respect to increase in the number of users however later this increase has comparatively lesser effect on the throughput as the system moves towards reaching its maximum capacity.

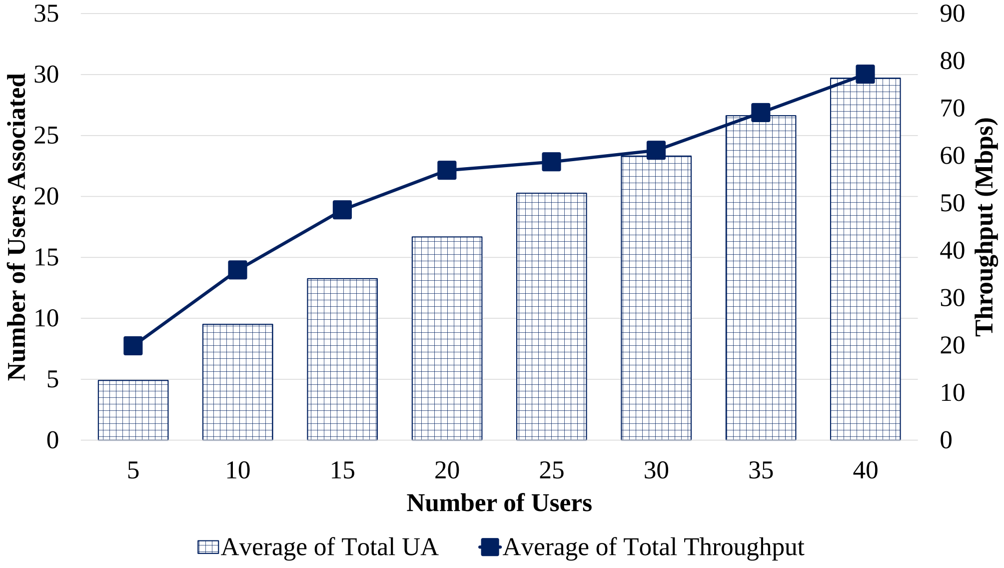


Figure 5.11: **Number of Users vs UA and Throughput.**

Fig. 5.12 depicts graph of throughput and UA versus the QoS rate requirement. It is evident from Fig. 5.12 that both UA and throughput decreases as the QoS rate requirement of users is increased from 0.2 to 1.0 Mbps with a step size of 0.2 Mbps. Decrease in the UA with corresponding increase in the QoS rate requirement validates our findings in Fig. 5.9. Throughput is maximum once the QoS rate requirement is minimum and it starts dropping once the QoS rate requirement is stepwise increased from 0.2 to 1.0 Mbps. This gradual decrease in the throughput occurs due to the fact that more power is required in order to maintain high data rates.

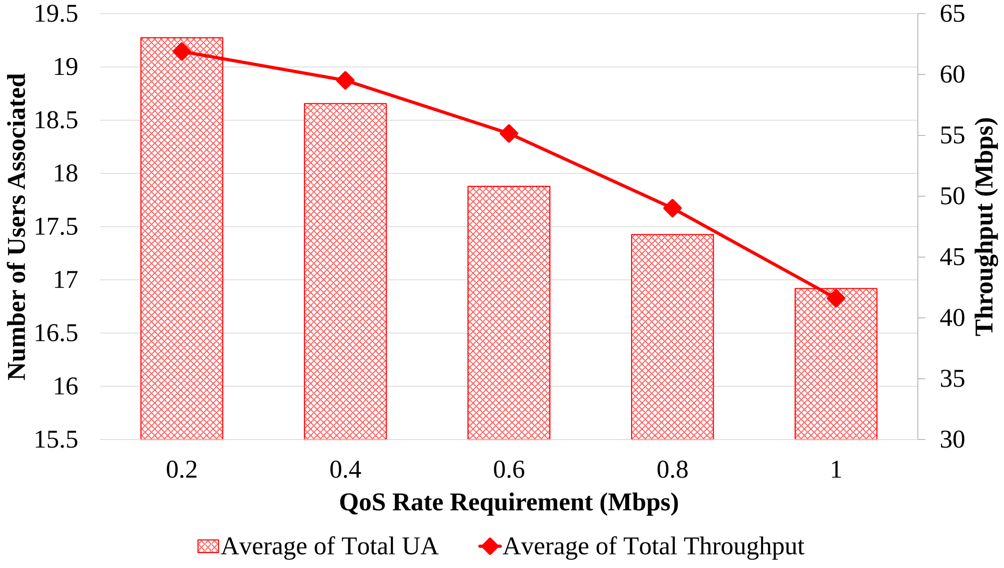


Figure 5.12: **QoS Rate Requirement vs UA and Throughput.**

Fig. 5.13 show plot of number of users against UA and throughput at different QoS rate requirements i.e. 0.2 Mbps, 0.6 Mbps and 1.0 Mbps. The behavior of UA with the corresponding increase in the number of users for above mentioned QoS rate requirements is the same as already discussed in Fig. 5.5, Fig. 5.7 and Fig. 5.10. Besides this, as illustrated in Fig. 5.13 it is evident that throughput varies at all the three QoS rate requirements. Throughput is maximum once the QoS rate requirement is minimum i.e 0.2 Mbps whereas it starts dropping once the QoS rate requirement is increased to 0.6 Mbps and 1.0 Mbps however, irrespective of the QoS rate requirement throughput increases with the corresponding increase in the number of users. These observations validates our findings in Fig. 5.11 and Fig. 5.12.

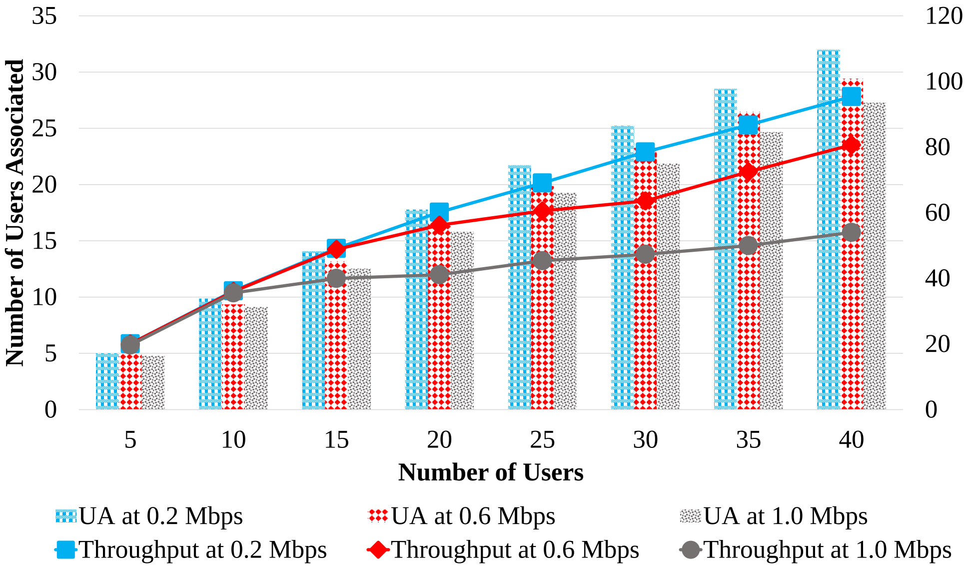


Figure 5.13: **Number of Users vs UA and Throughput at different QoS rate requirements.**

Fig. 5.14 depicts a graph of throughput (for both fairness-based UA system and system lacking fairness-based UA) versus the number of users. It is evident from Fig. 5.14 that the throughput of the fairness-based system is observed to be better than that of the system lacking fairness. Fig. 5.14 shows that if the users are fairly distributed amongst the available BSs it will simultaneously enhance the throughput of the system however in the case of the system lacking fairness-based user distribution a degradation in the throughput of the system will be observed.

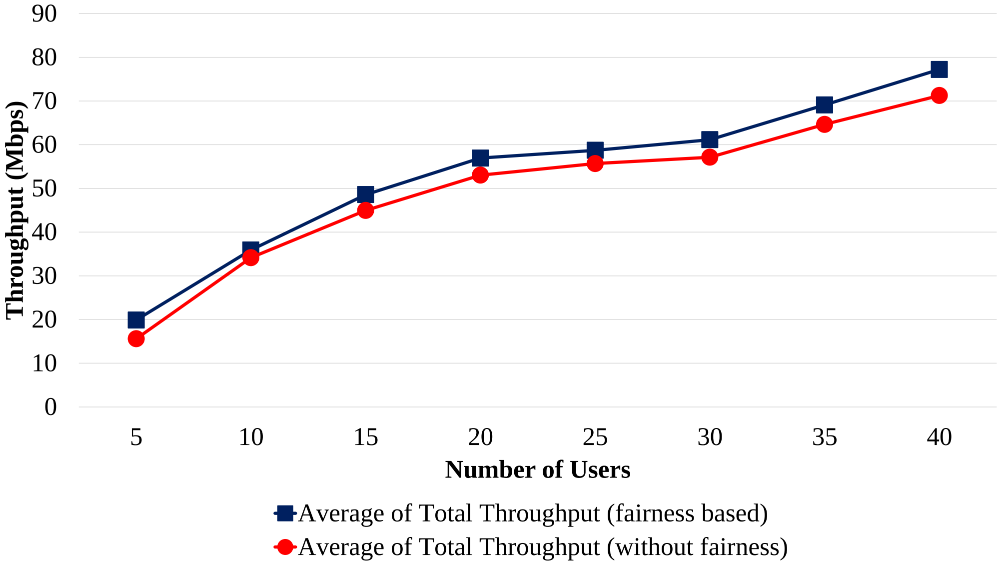


Figure 5.14: **Number of Users vs Throughput (both fairness-based and without fairness).**

5.2.6 EE

Fig. 5.15 depicts graph of EE and UA versus the number of users. It is evident from Fig. 5.15 that both EE and UA increases as the number of users are increased in STIN. This shows that with the increase in the number of users EE of STIN improves. In the start there is an increase in the EE with respect to increase in the number of users however later this increase has comparatively lesser effect on the EE as the system moves towards reaching its maximum capacity. The same behavior has also been observed previously in Fig. 5.11 regarding the throughput of the system.

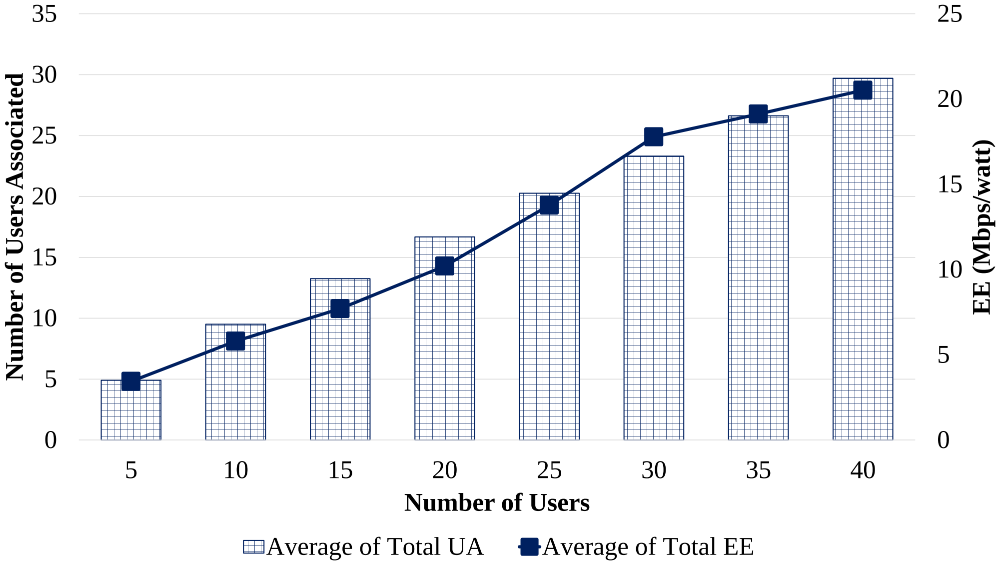


Figure 5.15: **Number of Users vs UA and EE.**

Fig. 5.16 depicts graph of QoS rate requirement versus the EE and UA. It is quite evident from Fig. 5.16 that both UA and EE decreases as the corresponding QoS rate requirement of users is increased from 0.2 to 1.0 Mbps with a step size of 0.2 Mbps. Decrease in UA with corresponding increase in the QoS rate requirement validates our findings in Fig. 5.9 and Fig. 5.12. EE is maximum once the QoS rate requirement is minimum and it starts dropping once the QoS rate requirement is stepwise increased from 0.2 to 1.0 Mbps. This shows that for low data rates EE is high whereas for high data rates EE is low. This gradual decrease in the EE occurs due to the fact that additional power is required in order to sustain high data rates. A similar behavior in case of throughput of the system has also been noticed in Fig. 5.12.

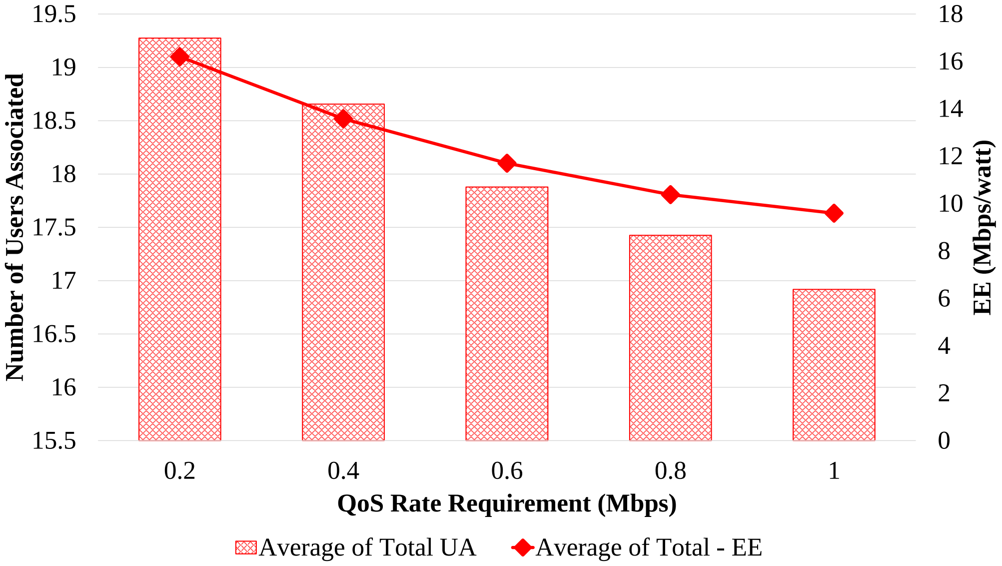


Figure 5.16: **QoS Rate Requirement vs UA and EE.**

Fig. 5.17 show plot of number of users against UA and EE at different QoS rate requirements i.e. 0.2 Mbps, 0.6 Mbps and 1.0 Mbps. The behavior of UA with the corresponding increase in the number of users for above mentioned QoS rate requirements is the same as already discussed in Fig. 5.5, Fig. 5.7, Fig. 5.10 and Fig. 5.13. Besides this, as illustrated in Fig. 5.17 it is evident that EE varies at all the three QoS rate requirements. EE is maximum once the QoS rate requirement is minimum i.e 0.2 Mbps whereas it starts dropping once the QoS rate requirement is increased to 0.6 Mbps and 1.0 Mbps however, irrespective of the QoS rate requirement EE increases with the corresponding increase in the number of users. These observations validates our findings in Fig. 5.15 and Fig. 5.16.

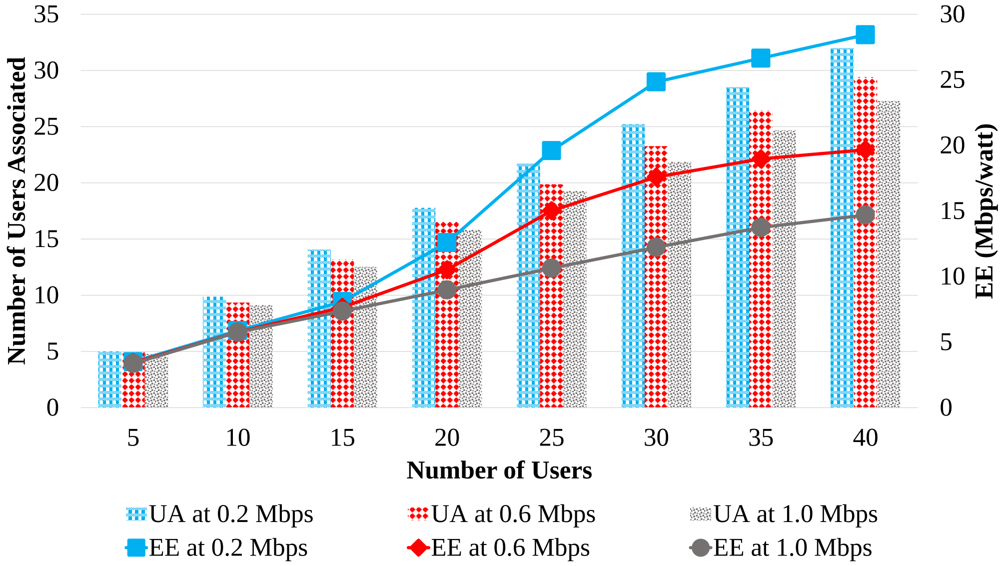


Figure 5.17: **Number of Users vs UA and EE at different QoS rate requirements.**

Fig. 5.18 depicts a graph of EE (for both fairness-based UA system and system lacking fairness-based UA) versus the number of users. It is evident from Fig. 5.18 that EE of the fairness-based system is observed to exhibit a better performance as compared to that of the system lacking fairness. Fig. 5.18 shows that if the users are fairly distributed amongst the available BSs it will simultaneously improve the EE of the system however the systems lacking fairness-based user distribution will result in degradation in the EE of the system. Similar behaviour in the case of throughput of the system has also been noticed in Fig. 5.14.

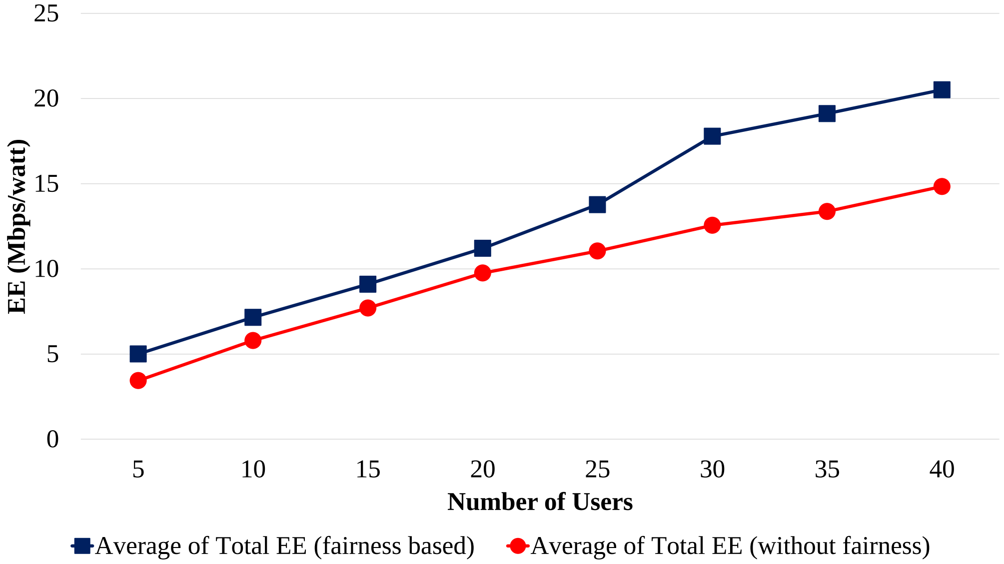


Figure 5.18: **Number of Users vs EE (both fairness-based and without fairness).**

5.2.7 EE and RB Allocation

Fig. 5.19 shows graph of number of users versus EE and RB allocation. It is clear from Fig. 5.19 that as the number of users increases both RB allocation to associated users and EE of the system increases. This illustration justifies our findings in Fig. 5.8 and Fig. 5.15 that with the increase in the number of associated users there will be a simultaneous increase in the requirement of RBs that are required to be allocated to these associated users by the respective BSs and that both EE and UA increases as the number of users are increased in STIN. This shows that with the increase in the number of users EE of STIN improves. EE maximization is mainly due to the implementation of fairness based UA and RB allocation in our STIN system model.

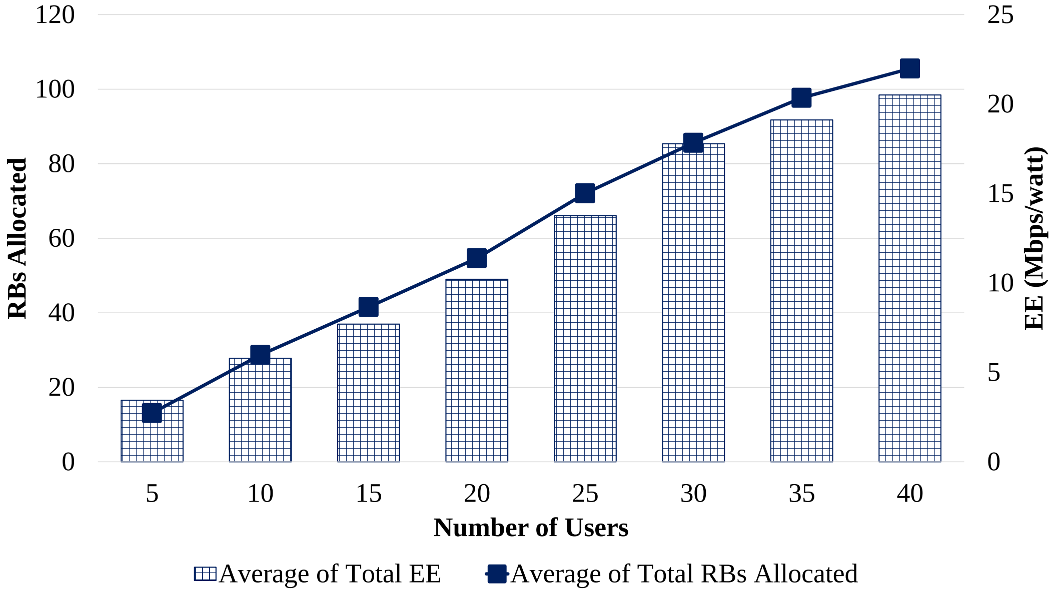


Figure 5.19: **Number of Users vs EE and RB Allocation.**

Fig. 5.20 shows graph of QoS rate requirement versus EE and RB allocation. It is observed that as the QoS rate requirement of users increases RB allocation to associated users increases however, EE in this case decreases. It is already verified in Fig. 5.16 that for low data rates EE is high whereas for high data rates EE is low. EE is maximum once the QoS rate requirement is minimum and it starts dropping once the QoS rate requirement is stepwise increased from 0.2 to 1.0 Mbps. This shows that for low data rates EE is high whereas for high data rates EE is low. This gradual decrease in the EE occurs due to the fact that additional power is required in order to sustain high data rates The fact behind this behavior is that there is a requirement of more power in order to maintain high data rates. The same has been confirmed via Fig. 5.20. On the other side RB allocation to associated users is low at low data rates and it is high for high data rates. This verifies our findings in Fig 5.9.

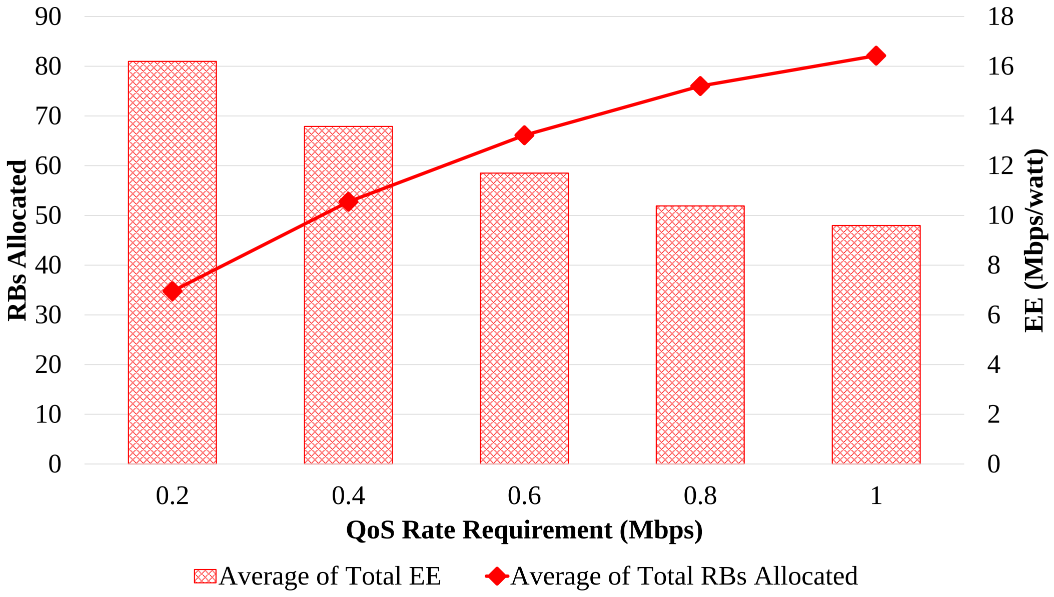


Figure 5.20: **QoS Rate Requirement vs EE and RB Allocation.**

Chapter 6

CONCLUSION

In this thesis, we explored joint admission control, user association and power distribution in order to ensure fairness while associating users in STIN and fairness in the allocation of spectrum resources to associated users in STIN with an objective to maximize EE. The reviewed problem is CFP problem which is transformed into a concave optimization problem by utilizing CCT and the same is resolved via utilising OAA in order to attain optimum results within $\epsilon = 10^{-3}$. The execution of the ϵ-optimum solution attained via OAA is exhibited for different system parameters including UA, UF, RB fairness and EE. Both UF and RB fairness increases with the relative increase in the number of users. EE also increases with the increase in the number of users whereas EE decreases with the increase in the QoS rate requirement.

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APPENDICES

APPENDIX A

Charnes-Cooper transformation for fractional programme

In a fractional programme (FP), objective function is ratio of two functions that are nonlinear in general. if $f(z), g(z)$ and $k_m(z)$ where $\mathcal{M} = \{1, 2, 3....M\}$ defined on set $S \subset R^n$, having real values, a fractional programme is defined as

$$\begin{aligned} &\max_{z \in S} \ \frac{f(z)}{g(z)} \\ &\text{subject to:} \\ &C1 : h_m(z) \leq 0 \end{aligned} \tag{1}$$

If g(z) is positive and convex, f(z) is positive and concave, assuming S is convex set, then FP is called concave fractional programme (CFP). Charnes-Cooper transformation [43] use following variable transformations to reduce a CFP to a concave programme.

$$y = \frac{z}{g(z)} \tag{2}$$

$$t = \frac{1}{g(z)} \tag{3}$$

The equivalent concave problem for Eq. (4.4) can be written as

$$\begin{aligned} &\max_{\frac{y}{t} \in S} \ t f_o \frac{y}{t} \\ &\text{subject to:} \\ &C1 : h_m(z) \leq 0 \end{aligned} \tag{4}$$