Addis Ababa University

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

Telecommunication Engineering Graduate Program

Game Theoretic Frame Work Based Energy Efficient RAN Infrastructure Sharing in Multi-Operator Mobile Networks

By: Tewodros Misgan.

Advisor: Dr.–Eng. Yihenew Wondie (PhD)

A Thesis Submitted to School of Electrical and Computer Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Science in Telecommunication Engineering

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APPROVED BY BOARD OF EXAMINERS

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Chairman Department of Graduate Committee	Signature	Date
Dr.-Eng.Yihenew Wondie (PhD)	____________	_______
Advisor	Signature	Date
____________________	____________	_______
Internal Examiner	Signature	Date
____________________	_______	_______
External Examiner	Signature	Date

Declaration

I, the undersigned, certify that the work contained in this thesis is entirely original, has not previously been submitted for credit at this or any other university, and has been fully acknowledged.

Tewodros Misgan Belay ________________
Name Signature

This thesis work has been submitted for examination with my approval as a university advisor.

Dr.–Eng. Yihenew Wondie (PhD) ________________
Advisor Signature

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Abstract

Recently, cellular network base station (BS) switching-off and infrastructure sharing techniques have been introduced as capable solutions for energy and cost reduction. The rising number of base stations results in redundant energy usage, particularly during low traffic durations when the base station's capacity is underutilized. In this thesis, we have studied roaming-based infrastructure sharing problems among three MNOs (mobile network operators). These operators switch-off their BSs and roam their traffic to active neighboring BSs operated by other MNOs in a specified geographical area during low-traffic periods. Our goal is to save energy and increase the system capacity of the MNOs while maintaining QOS.

We have proposed mathematical models all over this thesis based on novel non-cooperative game theoretic strategies to model and evaluate competitive interactions among MNOs. This strategy is modelled as an integrated cost-based objective function by applying different scenarios to determine which base stations should remain active. In this method, operators share infrastructure and dynamically roam their traffic to maximize throughput. We have implemented the Tit-for-Tat (TFT) algorithm to share a portion of their network and optimized it with three MNOs operating in the same area with varying traffic loads and distance (D) between UEs and BSs. We also implemented the TFT algorithm's hyper parameters. A MATLAB simulation tool was employed to evaluate the performance of proposed scheme. We demonstrate simulation results in different scenarios to quantify the financial benefits due to energy savings from our proposed scheme, which provides up to 50% BS switching of probability to MNOs and throughput gains up to 100 Mbps with roaming-based traffic load variations compared to the baseline approach.

Key terms: Infrastructure Sharing, Roaming, Game Theory, BSs Switching-Off, Nash Equilibrium, Multi-operator

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List of Acronyms

BS	Base stations
BBU	Baseband unit
BW	Band width
C-RAN	Cloud-based radio access network
CGT	Cooperative game theory
DNE	Dominance Nash equilbrum
EB	Exabyte
EPC	Evolved packet core
GTY	Game theory
HLR	Home location registry
IPD	Iterated Prisoner's Dilemma
ITU	International telecom union
LTE	Long Term Evolution
MME	Mobility Management Entity
MNOs	Mobile network operators
MOCN	Multi operator core network

MVNOs	Mobile Virtual Network Operators
OPEX	Operating expenditure
PGW	Packet Data Network Gateway
QOS	Quality of Service
RAN	Radio Access network
RRC	Radio network controller
SGW	Serving Gateway
SINR	Signal to Interference and Noise ratio
3GPP	Third Generation Partnership Project
TFT	Tit-for-Tat
WSIS	World summit on the information society
UE	User Equipment

Notations and Symbols

C_{inc}	Cost for increasing central BS power
C_{tr}	Cost for serving traffic
C_{const}	Fixed cost for BS operation
C_{roam}	Roaming traffic to another operator in the same cell
U_i	Utility function of operators
A_i	Action of operators
N	Number of operators
s_i	Strategies of operators
s_i^*	Best response strategies/probabilities
E[$C_{\ i,j}$]	Expected cost of operators
μ	Mean load of operators
ρ_1^{NE}	Probability of operator one with NE
ρ_2^{NE}	Probability of operator two with NE
OP1, Op2	Mobile network operator 1&2
Bu$_i$	Best response functional strategies
ΔM	Resources sharing factor
$c^{(i)}$	Cooperation degree of each operators [States]

CHAPTER ONE

1. Introduction

Globally, mobile data traffic has been growing exponentially in recent years, and the number of cellular network subscribers has been increasing at an exponential rate. According to [1] at the end of 2021, there will be around 8.2 billion mobile subscriptions. This number will increase to around 9.1 billion by the end of 2027. According to a forecast by Ericsson mobility, global mobile data traffic would increase by a factor of 5 from 58 Exabyte (EB) per month at the end of 2020 to 300 EB per month in 2026 [2]. The forecast also reveals that end of 2026, 5G will lead traffic growth with 53% of the total mobile data traffic.

The most difficult task for any mobile network operator, including Ethiotelecom, is to efficiently manage an increasing number of subscribers' satisfaction. The common trend among network operators is to continually implement infrastructure expansion mechanisms, but energy and operating expenditure (OPEX) costs are a great challenge for cellular network infrastructure enhancement. In [3] [4] mobile data consumption is expected to grow at a faster rate, and capacity challenges will continue to exist in Ethiopia for the foreseeable future. The total mobile data demand in Addis Ababa reached 20.27 petabytes (PB) per month in 2021, which is 38.7 times the traffic usage in 2016, as shown in Figure 1.2. This number presents real challenges to the operator in addressing the much-needed capacity. Thus, in order to address possible capacity issues, it is essential to explore new technologies that will provide capacity enhancements for mobile communications in the future. Figure 1.1 shows mobile data traffic trends in Addis Ababa from 2016 to 2021[3].

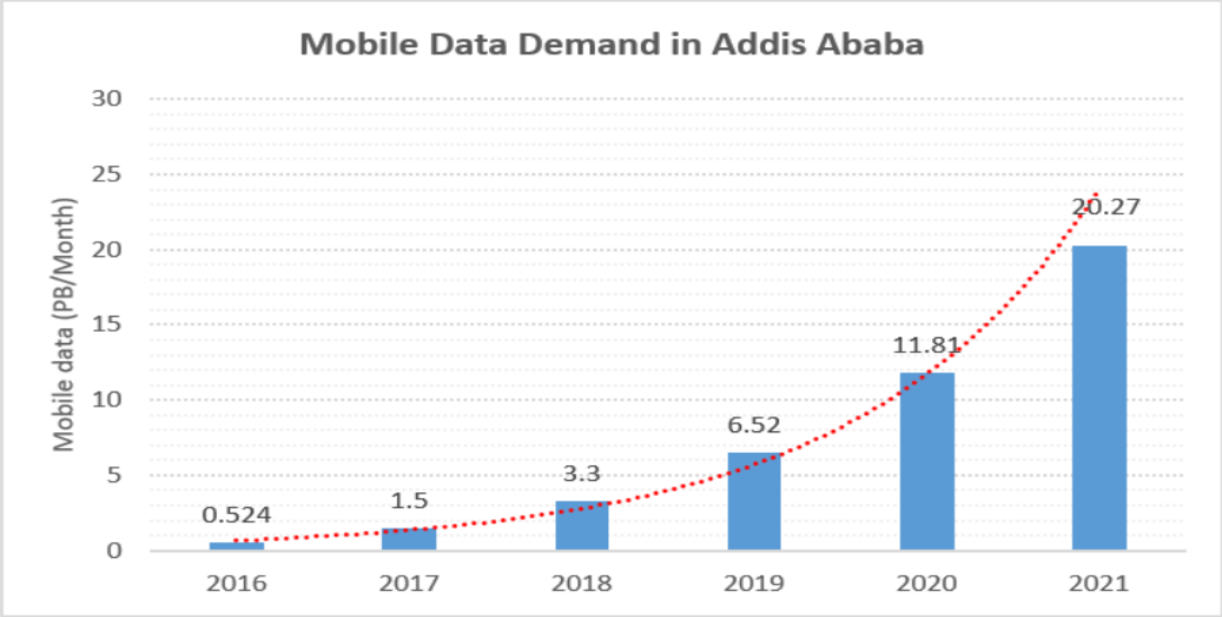

Figure 1. 1: Mobile Data Demand Trend in Addis Ababa from 2016 – 2021 [3]

Nowadays, telecommunications, mobile services, and many wireless applications dominate the world of information and communication technology (ICT). But, 2-3% of energy consumption is for ICT in global aspects, which results in around 3% of the total CO2 emissions [5]. Cellular network energy dissipation is distributed among different network elements/nodes such as data centers, core networks, and base stations. Many of the literature concludes that base stations (BSs) are the main energy-consuming components that take up to 60% of the power dissipation of cellular networks [6]. Thus, we should re-consider and develop green communication research solutions to reduce greenhouse gas emissions and cellular network energy consumption. The main driver for MNOs to share their network infrastructure is cost reduction. Infrastructure sharing in mobile networks is shared use of existing or jointly deployed network infrastructure among multiple operators (MNOs) [5].

Intra-cell roaming-based infrastructure sharing essentially extends the traditional roaming-based sharing in two ways: 1) it takes place in the same region where the MNOs offer their mobile services, and 2) it is dynamic (and not on a permanent basis), especially during low traffic times. According to a forecast by Ericsson Mobility, the amount of mobile data traffic worldwide will increase by a factor of 5, from 58 Exabyte (EB) per month at the end of 2020 to 300 EB per month in 2026. Additionally, a variety of network topologies are required because to the engagement of numerous stakeholders (such as MNOs, reliable parties, regulatory bodies, etc.) in future cellular environments [7].

The characteristics of certain current and potential multi-operator network topologies, as well as potential stakeholder roles, are given in this thesis. We review the current state of the art for BS switching off techniques in single-operator networks and highlight the novel difficulties that appear in multi-operator contexts. Finally, we present a game-theoretic framework that enables the operators to choose how to individually switch off their own BSs. In addition to the anticipated gains in energy efficiency, the suggested method enables the MNOs to drastically cut their financial costs without being reliant on the tactics of the other MNOs that coexist, giving them the essential incentives to play the game.

1.1. Research Motivations

The concept of network infrastructure sharing has been researched in recent years to address two main different types of issues. The underutilization of dedicated RAN resources auctioned out to MNOs has created a roadblock for the industry's future growth due to the rising demand for mobile services [8]. In other words, in places or times where demand may be low, like in rural areas or developing nations, during the night, the high cost of network infrastructure forces the operators to charge higher prices from their customers, making mobile services unaffordable for many people, further decreasing demand[1], [9].

MNOs must raise their capital expenditures (CAPEX) and operational expenses (OPEX) in line with the anticipated rise in capacity demand. Allowing the MNOs to share their infrastructure is one viable paradigm to overcome these problems. In order to reduce operational costs while also maximizing the usage of current network resources [10], [11].

In [12], the Third Generation Partnership Project (3GPP) has defined standards for network sharing. As a result, by sharing infrastructure among MNOs, network services such as infrastructure sharing, which can be passive or active, can be deployed more quickly. The term "passive sharing" describes the sharing of real estate, such as structures, locations, masts, and power sources. Antennas, backhaul, base stations, and other active network components, as well as core network components, are shared during active sharing. Therefore, active sharing like this permits mobile roaming. It enables an MNO to use a different network in an area where its own infrastructure is not covered. Over 65% of European MNOs have implemented infrastructure sharing, utilizing both active and passive radio access, according to a market study [13].

1.2. Statement of the problem

Telecom operators, including Ethiotelecom, deploy their networks considering peak traffic volume to undertake QOS in high traffic scenarios, but in low traffic scenarios, the minimum amount of BSs is enough to solve the traffic. Existing BSs are underutilized and redundant, especially with low traffic on the network. And the major challenges are energy consumption, waste of RAN resources, CAPEX, and OPEX costs of cellular networks [7]. The base station (BS) consumes 60-80% of cellular network power, especially at high traffic loads, and energy consumption increases proportionally with traffic load [14]. Energy consumption increases proportionally with traffic load, as shown in Figure 1.2.

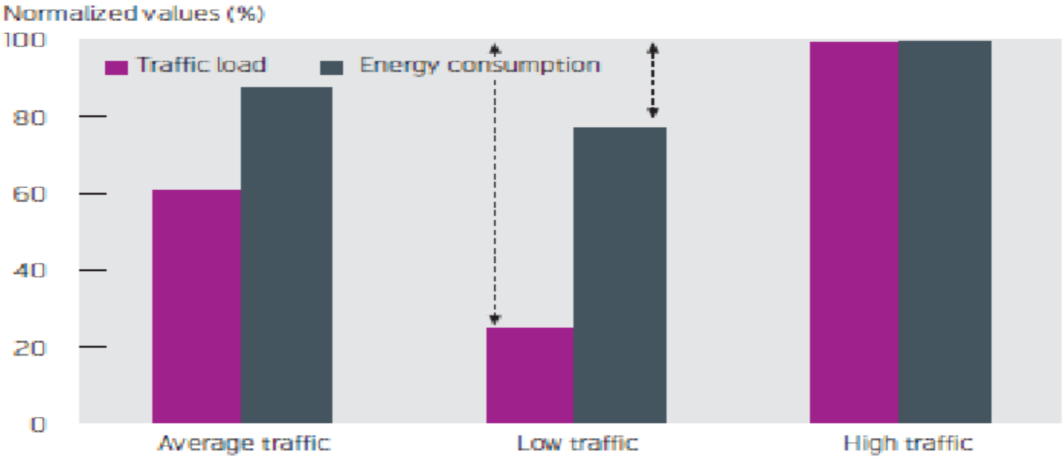

Figure 1. 2: Base station power consumption vs traffic load [14]

This research, motivated by the aforementioned problems and taking into account that Ethiopia is going to have more than one network operators in the coming years, including Safaricom Ethiopia.

To overcome the above problems, we have proposed multi-operator infrastructure sharing techniques among operators that operate in the same geographical area. In this thesis, we have proposed i) BSs switching off framework work between multi-operators and serving a certain geographical area jointly during low traffic periods (night zone), when the base station capacity is underutilized, to reduce operational costs and energy efficient. Means that operators switch off their bastion and roam their traffic to active neighboring operators during low traffic cases. ii) Roaming-based infrastructure sharing between operators during RAN resources is underutilized when the load conditions of neighboring operators are subjected to temporal traffic variations. In this scenario, a high-load operator could transfer its traffic to a low-load operator by using the dynamic infrastructure sharing (roaming) technique to increase system capacity and QOS between operators. The interaction among operators can be modelled and analyzed using game theory.

1.3. Objective

1.3.1. General Objective

The main objective of this thesis is to model the problem of infrastructure sharing schemes between multi-operators with a game-theoretic framework to address operational cost reduction and system capacity problems.

1.3.2. Specific Objective

The Specific Objectives of this thesis include:-

- To identify factors which are necessary for infrastructure sharing
- Develop a mathematical model as a strategic non-cooperative game to investigate infrastructure sharing problems.
- Develop a multi-agent framework based on environmental parameters, the number of MNOs, and dynamic user loads.
- Validate the performance of the proposed scheme with experimental analysis (game-theoretic TFT algorithm).
- Analysis the mathematical and simulation framework to compare the performance of conventional and proposed techniques (BS switching and roaming)
- Finally, to recommend future works based on our findings

1.4. Scope and limitation

1.4.1. Scope of the Research

This research covers the technical opportunities and aspects of infrastructure sharing with three mobile network operators operating in the same geographical area. The general problem addressed by this thesis is how to increase the gains of MNOs in terms of incentive costs due to bastion switching off, roaming based infrastructure sharing, and throughput maximization of the system in selective regions during limited user traffic (Night zone) scenarios. We model and analyze the interaction among competitive operators by using game theory.

1.4.2. Limitations of the research

- Due to the unavailability of realistic data regarding different MNOs in our country, we have used hypothetical environmental-generated data mathematically and used those parameters for system-level simulation.
- The scope of this thesis is restricted and addresses the advantages of infrastructure sharing among three operators in a specific geographical area.

1.4.3. Contributions of the Research

- New methods of multi-operator collaboration and dynamic user association are researched in order to serve roaming traffic between the operators while reducing overall power consumption.
- Reduce duplication of infrastructure, encourage active infrastructure sharing among operators, and promote more environmentally friendly networks.
- Game theory gives insights into the most important theoretic bases for modelling RAN sharing, and game theory is used to inspire practical designs for operators as it is mainly used as an engineering approach in wireless communication.
- Operators are reducing their overall power consumption. When considering the relative BS positions between MNOs and their UEs' coverage areas.
- Improve the flexibility of mobile networks and services to boost the performance of telecommunication services

1.5. Literature Review

Numerous studies have been done on the issue of collaboration and infrastructure sharing among multi-operators in the same geographic area. In this section, we examine different studies on infrastructure sharing between operators that operate in the same region under different conditions. Studies were conducted on passive and active network infrastructure sharing among operators. In other words, many studies offer policies to improving energy effectiveness and spectrum utilization by means of cognitive radio or cooperative spectrum sharing. In this paper, we review studies related to infrastructure sharing among network operators in the same geographical area to accommodate operational cost reduction and system throughput maximization in cellular networks.

In [3], conducted on the concept of energy-efficient cellular networks with multi-operators on base stations, they follow the approaches of proper allocation of RAN resources and radio resource management using sleep mode algorithms implementation and around 45-50% cut down on operational costs by reducing electricity bills and maintenance costs. But, the main drawback was they focused on energy minimization only without considering QOS and coverage issues.

In [10], this study concluded that multi-operator connectivity can be an efficient way to achieve reliable communication. Multi-operator connectivity as a form of redundancy to support the design of reliable networks and implement super quantiles as a measure of reliability, the benefits are particularly evident when there are connectivity issues because several connections can better fulfil overall demand and prevent service interruptions. However, redundant connections come at a cost to operators in terms of lower spectral efficiency. This is especially destructive in high-demand networks, where the use of redundant resources introduced by sharing can lead to increasing demand for spectrum (or any other scarce network resource), potentially decreasing the capacity operators can offer to their subscribers.

In [7], [15] Mobile network operators cost and energy consumption are both dramatically rising as a consequence of the cellular networks' rapid expansion. Network underutilization during low traffic has motivated the idea of a new framework: infrastructure sharing within the same geographical region. The main option for MNOs, however, is whether to allow other MNOs to handle their traffic or to be able to disable parts of their network. For multi-operator situations, they suggest a novel game-theoretic framework infrastructure sharing algorithm that allows the deactivation of unused base stations (BSs) during times of low traffic. They have presented this framework, allows that MNOs to independently estimate the switching-off probabilities that reduce their conflicting interests. This approach motivated by the MNOs' competing interests.

The game-theoretic methodology introduced by Bousia et al [15], Enables the MNOs to independently estimate the switching off probability that lower their expected financial cost. Regarding the switch-off pattern, choose the one that balances the switch-off time periods, roaming expenses, energy savings, and quantity of energy saved to the greatest extent possibly up to 35% in their proposed pattern.

Marsan and Meo have proposed two interesting BS sleeping schemes for multi-operator situations in their work [16]: roaming-to-one and roaming-balanced. In the first work, only one BS operates in each cell during periods of low traffic, serving users of all operators, whereas in the roaming-balanced scheme, the MNOs in a given cell alternately switch-off their BSs for varying extents of time to balance the anticipated financial costs related to the roaming process. Despite the fact that both strategies significantly reduce energy consumption, they both ignore the possibility of turning off all BSs in a particular cell and moving traffic to an active cell.

Introduce an innovative strategy based on coalitional game theory in [17] to identify possible areas for collaboration between multiple operators providing service to the same region. The suggested scheme unifies the rules for successful cooperation and outlines the fundamental formation requirements (i.e., pricing) for several scenarios with different market and spectrum shares among three operators. The findings demonstrate that (i) cooperation amongst MNO sub-coalitions is consistently advantageous, resulting in more revenues and better services quality(QOS) for end users, and (ii) given customer price in various scenarios, the cooperation of all operators (grand coalition) is worth better. More analyses over the past few years in literature have taken a multi-operator spectrum sharing scenario into account [18]. These papers have been looked into, and the most of them are based on the ideas of DSA and spectrum reframing, which allow multiple generations of cellular networks to share the same radio spectrum. Both the economic and network performance facets of the spectrum sharing issue in a cellular radio network are acknowledged. It was suggested that round robin scheduling be used to spread call loads among base stations and promote spectrum sharing, boosting their usefulness.

[19] Introduces a new flexible framework built on the Open AI Gym toolkit that makes it probable to build customizable settings for sharing radio resource environments. The systematic creation and evaluation of agents (such as reinforcement- and learning-based agents) is made possible by this method. Focus on game theory components instead since multiplayer games developed in these settings can be viewed as a series of social dilemmas. It demonstrates that, in such iterated games, mutual cooperation delivers superior outcomes even while none of the agents are motivated to do so at each phase (i.e., Nash equilibrium is not the best situation).

The potential energy savings associated with sharing network method, whereby various network operators can share all or a sizable portion of the network infrastructure already in place in a country, were examined in [20] study of network infrastructure sharing among European Mobile Operators. The straightforward analytical models suggested that between 35% and 60% less energy would be needed to run mobile networks in the majority of European nations. In their analysis, they calculated the energy savings that MNOs providing service in the biggest European nations may accomplish the effect of the approach to network sharing being widely used. Additionally, their findings suggested that by skillfully utilizing existing technologies, operators may avoid nearly half of the energy expenditures they currently incur.

Network operators are able to compete and dynamically choose the quality target to give to their clients while also aiming to maximize their revenues according to the techno-economic model in [21]. Nash equilibrium (NE), which emerged in a non-cooperative game, demonstrates the ideal point at which operators may satisfy customers' needs. Most of the research that has been looked at is focused on engineering principles that satisfy end users' QOS requirements as well as economic ones that aim to maximize the revenues of all involved operators.

In this thesis, we have proposed infrastructure sharing with three operators operating in the same geographical area. The main concept is to increase effective RAN resource utilization during low traffic durations, mostly in the night zone. To overcome these problems, MNOs want to collaborate with each other to benefit from their resources, resulting in a closer or lower load. We consider clusters of three operator cells. While each cell includes BSs of different MNOs. Modelling their interaction in a non-cooperative tit-for-tat strategy game from the pool with equal access rights in different geographical setting scenarios.

Please - see appendix C for summary of Literature review

1.6. Methodology

In this thesis, the general methodology followed during the study of optimal infrastructure sharing among MNOs to accommodate operational cost reduction and system throughput maximization with a non-cooperative game theoretic approach and following methods is considered.

Literature review: Regarding the concept and research done on infrastructure sharing and game theory, books, journals, and internet sources are relevant.

Data collection: Most of the mathematical models considered all over this thesis based on game theoretic approach and contain global data like input power, operating bands and the necessary parameters. The parameters for this work is also literature aided from ITU and 3GPP releases documents. Collecting necessary reports from Ethiotelecom optimization engineering section.

Mathematical modeling and problem formulation with gametheortic scheme:

- Formulate a cost model with a utility function.
- Formulate a data-rate model.

System-level simulations: We use a novel framework to create some fully adaptable MATLAB and gametheortic algorithm (TFT) environmental settings for simulating cooperation among multi-providers.

Analysis and interpretation of simulation results: summarizing in detail the techniques, the opportunities, the challenges and performances of deployment green cellular network multi-operator infrastructure sharing design mechanisms.

Finally, recommendations and future work.

1.7. Thesis Layout

The thesis' remaining sections are structured as follows:

Chapter 2 provides the theoretical background of the thesis, introduces the fundamental concepts of cellular networks, infrastructure sharing among multi-operator mobile networks, and its types and mechanisms, An overview of mobile networks and the evolution of base station architecture in the cellular network In addition, it provides background on RAN, explaining its fundamentals, the main components of its architecture, its advantages, and the technical challenges it faces.

Chapter 3 provides a brief outline to the basic principles of game theory and methods to model and analyze infrastructure sharing in multi-operators and share strategies.

Chapter 4 states that the proposed bastion switching of algorithms and roaming based RAN sharing strategies based on repeated non-cooperative strategic games are explained, the system model and problem formulation as cost functions. Throughputs calculation with non-cooperative repeated game RAN Sharing among multi-operators is stated here.

Chapter 5 focuses on the simulation scenario, simulation parameters, UE distributions, and cost and energy consumption models are stated. Simulation results are discussed and interpreted. Chapter 6 concludes the thesis and recommendation and future directions.

CHAPTER TWO

2. Theoretical Background of Optimal Infrastructure Sharing in Multi-Operator Mobile Networks

This chapter mainly focuses on the fundamentals and background overview of infrastructure sharing among multi-operator mobile networks. Mobile network infrastructure developments and the evolution of traditional Base Station (BS) architecture are discussed. The types of different RAN architecture based on the function of the baseband processing split between the remote radio unit and baseband unit pool are described in detail. The components of the RAN, including the RRU, BBU Pool, and optical fiber front haul transport network, are explained in detail. Moreover, the advantages, benefits, and challenges of the RAN architecture are also explained. In addition, related technologies that are relevant to RAN are outlined in this chapter.

2.1. Overview of Mobile Infrastructure Sharing Globally

When operators collaborate to share components of their network infrastructure for service provisioning, this is known as mobile infrastructure sharing. The main goals are to maximize resources utilization, maximize financial returns on investments, and create business models that are centered on providing accessible and inexpensive ICT services. In Europe, the USA, and India, there is a greater prevalence of sharing at high levels of mobile communication infrastructure. With more than 760 MVNOs operating globally, mobile network virtual operators (MVNOs) are expanding in Europe, Australia, and North America. But one of the major problems to development in Africa, particularly in the sub-Saharan region, is the absence of infrastructure [21] [20] [22].

In the previous ten years, mobile telecommunications services have grown significantly, opening up cellular services to a portion of the population who previously had no access to them. To enhance mobile service penetration and boost competition in the mobile industry, particularly in rural parts of emerging nations, however, significant advancements are needed. Mobile network deployment involves significant upfront costs that must be recovered by imposing substantial fees on users who utilize mobile services. This frequently drives up the cost of mobile services and may deter operators from adopting new technologies in developing regions.

Sharing mobile infrastructure can encourage the adoption of new technologies and the rollout of mobile broadband, opening up access to broadband services to a broader segment of the global population. In the end, mobile network sharing can contribute significantly to increasing access to information and communication technologies (ICTs), fostering economic growth, enhancing quality of life, and assisting developing and developed nations in achieving the millennium development goals and WSIS goals [22].

2.2. Evolution of Mobile Networks and Infrastructure Sharing

As a broad definition, infrastructure sharing is the shared use (of existing or jointly deployed) network infrastructure among multiple MNOs. Expectedly, the common driver across the several infrastructure sharing instances accompanying the recent technology migrations is energy consumption and cost reduction, especially at roll-out. However, the degree to which infrastructure sharing contributes to lowering capital and operational costs depends significantly on the type of network sharing agreement (which network elements are shared, the geographical footprint, whether spectrum is shared).

Nevertheless, the degree of sharing is also subject to national and international regulation [23]. Infrastructure sharing has become instrumental since the roll-out of 3G networks, while an even larger number of sharing agreements have been recorded so far for 4G [24]. Moreover, Infrastructure sharing is a significant enabler for 5G, given its performance targets and, in particular, the very dense network deployments that will require at least site sharing due to limited site availability. Furthermore, there is innate support for infrastructure sharing in the envisioned 5G architecture [25]; two important terms related to infrastructure sharing in 5G are multi-tenancy and network slicing. Multiple tenants (mobile broadband providers, industry verticals, etc.) with very different service requirements will coexist in the same network under multi-tenancy [26]. Network slicing, in turn, is a method of supporting multi-tenancy, that is, a method of creating end-to-end logically independent networks from a common pool of network resources that can accommodate the specific needs of each tenant.

2.2.1. Multi-Operator Network sharing Architectures

Mobile operators have recently given a lot of thought to radio access network (RAN) sharing, which enables investment as well as operational expense to be minimized and the network development period to be shortened, as a result of the enormous costs associated with 4G and beyond telecommunications infrastructure. A particularly efficient method for RAN sharing and actually for spectrum sharing is the multi operator core network (MOCN).In this topic, we present some of the possible scenarios (described in Fig.2. 1) [27] and we briefly discuss the challenges and the traits of each particular scenario.

In Fig.2. 1(a) a single operator (MNOA) deploys and owns the spectrum and the network infrastructure in a specific area. As none of the other operators in the same region are physical (MVNOs), they must rent spectrum and network infrastructure from MNOA in order to provide services to their customers. Because to its ease of use and inherent benefits, this approach, also known as national roaming, has already been implemented successfully in a number of nations.

MVNOs might be advantageous for end users as it encourages market competition, while at the same time allowing the local basic MNO to profit from the installed infrastructure.

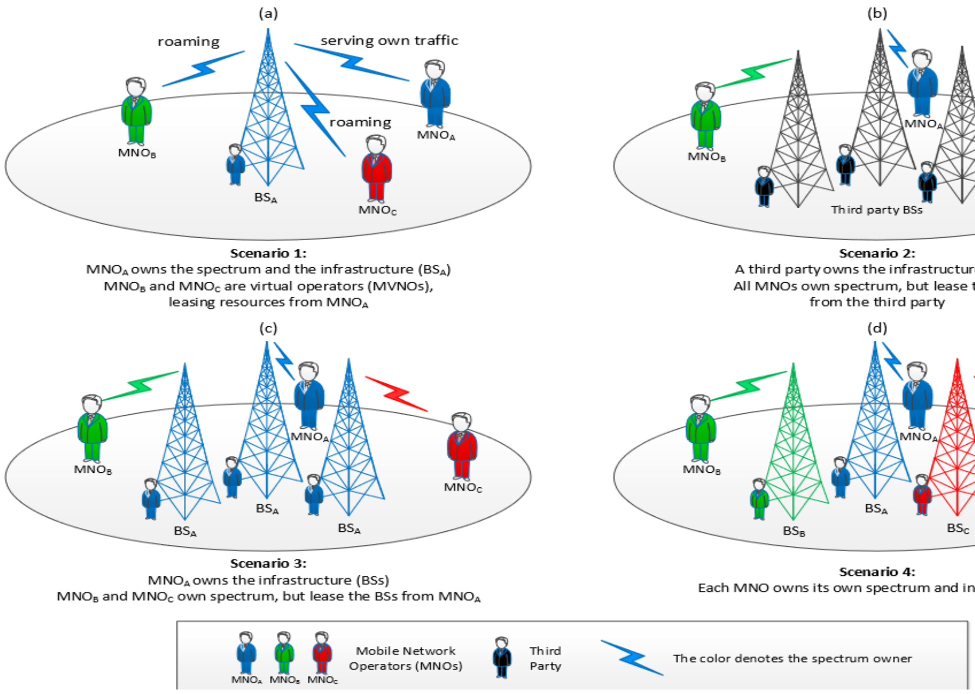

Figure 2. 1: Multi-Operator Cellular Network sharing Architectures [27]

The MNOs with a spectrum license may enter into agreements for the employment of the access and core networks because the entire infrastructure in a given area has been installed and is held by an impartial, trustworthy third party (Fig. 2.1(b)).

The main advantage of this model, which is gaining popularity in many nations (including Spain), is the significantly lower CAPEX for the MNOs, who are no longer responsible for maintaining the hardware infrastructure and are also able to offer their services on demand in a specific geographic area. Yet, the network lease implies higher OPEX, which over time might not be economical for the Mobil operators.

In Fig. 2.1(c), there is one operator that has deployed the whole network infrastructure and leases part of it to other interested MNOs. This scenario is fueled by the fact that the same locations (e.g., rooftops) are usually suitable for all MNOs, and as a result, an operator who has built out its network is able to capitalize on the potential interest of other MNOs in the specific location. The two main differences between this architecture and the two aforementioned schemes are that (I) the interested MNOs are not virtual because they have their own spectrum license, and (II) the infrastructure owner is an operator rather than an independent entity. This architecture can also be seen as a hybrid model that combines some of the fundamental characteristics of the two aforementioned schemes. (Fig. 1(d)).In the same area, numerous MNOs have set up and maintained their own networks. Since it carries the lowest possible risk for the operators, this model now rules cellular networks. In addition, given the operators' rationale and the telecommunications industry's inherent competitiveness, it is also extremely likely to show up in future architectural designs, particularly in populated locations with heavy traffic.

In this case, MNOs have total command over their networks, giving them the ability to predict expenditures. For the installation and operation of the network.

2.3. Models and Technical Approaches of Infrastructure Sharing

There are various ways to share a network, from sharing radio access networks (RANs) and other active components like network roaming and the core network sharing that passively shared cell sites and masts [28].The network sharing mechanism can be defined as active, which requires the sharing of electronic infrastructure, or as passive, which refers to sharing of non-electronic infrastructure such as space or physical supportive infrastructure

2.3.1. Active and Passive Infrastructure Sharing among conventional MNOs

The three infrastructure sharing types are passive sharing of sites, masts, and building premises, active sharing of active network components such as radio access network (e.g. antenna, radio network controller (RNC), switches, and backhaul equipment, and roaming-based sharing, in which MNOs share cell coverage for a pre-determined duration[4].

Passive sharing includes building premises, sites, and masts. When two or more networks share physical space, it is referred to as passive sharing. Passive sharing is a type of network sharing where two or more networks share physical space. Operators can trade elements of a mobile device’s active layer, such as antennas, radio nodes, node controllers, backhaul and backbone transmission. Table 2.1 shows Network infrastructure sharing types and its cross ponding incentives

Table 2.1: Commercial incentives of telecom infrastructure sharing [14]

Types of network sharing	Commercial incentives of infrastructure sharing
Site (co-location)	• Minimize site acquisition periods for new candidates • Access to key important places, especially where there is small room for new installations, • concerns about the environment and alleged health
Mast (Tower)	• Reduced environmental and optical influence • Minimized CAPEX (site build)
RAN	• Less sites and masts are required to provide the same coverage. • CAPEX and OPEX reduction (via shared physical backhaul)
Core Network	• Savings on CAPEX and OPEX if there is available capacity • Lower maintenance and operating costs
Roaming	• decreased or postponed infrastructure investment • Interoperability across the operator's own distinct 3G and 2G networks without any issues

2.3.2. Roaming-Based Infrastructure Sharing

Roaming-based sharing, as used in the context of network sharing, refers to a situation in which one operator is wholly dependent on another operator's coverage in a certain, predetermined area. Operators operating in new regions are continuously looking for low-cost methods to boost capacity and coverage. Additionally, it will be more open to passive sharing techniques. You might find cost savings and cutting-edge technical options in established areas thanks to operators' active sharing. There are opportunities to optimize access transmission using leased lines and microwave links, even while operators in emerging areas seek out cost-cutting strategies and cutting-edge technology solutions. Dedicated chances for active sharing, microwave links, and leased lines that aim to maximize access transmission [4]

2.4. Drivers Technical Enablers of Infrastructure Sharing

According to market maturity levels and country differences, infrastructure sharing agreements' business motivations and structure are likely to vary. There are several significant, broad strategic and economic drivers [20]

- Network expansion into underserved areas that would otherwise be unprofitable or have a payback period greater than the business target.
- Cost reduction
- CAPEX /OPEX
- Facilitation of market entry
- To overcome the service outage

2.4.1. Barriers (Challenges) of Infrastructure Sharing

Infrastructure sharing could seem like a good strategy to bring mobile services to underserved, distant, and sparsely populated places, but it has its own difficulties or limitations that must be overcome. Depending on whether sharing is passive or active, there are several technological limitations that need to be taken into account or resolved prior to the actual implementation. As the degree of sharing rises, it necessitates coordination and cooperation between or among operators who are engaged in infrastructure sharing [20].

- Complexity involved in the sharing process,
- Unwillingness to share due to a lack of capacity or limited space on existing infrastructure,
- Lack of a regulatory and policy framework for infrastructure sharing
- incompatibility of different technologies,
- High contractual exit costs arising from breach of contract,
- high charges by infrastructure owners,
- High contractual exit costs arising from breach of contract,
- Dominant operators fear market share losses and
- Competition due to reduced control and interdependence.

2.5. Geographical Dimension of Network Sharing

All approaches defined in this thesis can be applied by three operators undertaking business in the same geographical area, initially operators serve their users but in the scenarios of infrastructure sharing one operator users' traffic served by other MNOs. . For the sake of simplicity, we limit our illustrations to a two-operator case. Besides, various possibilities for structure are available in the following section:

2.5.1. Standalone Case

As shown in Fig. 2.2, in a standalone case, each operator affords full service coverage for the whole area by operating its own cellular network services.

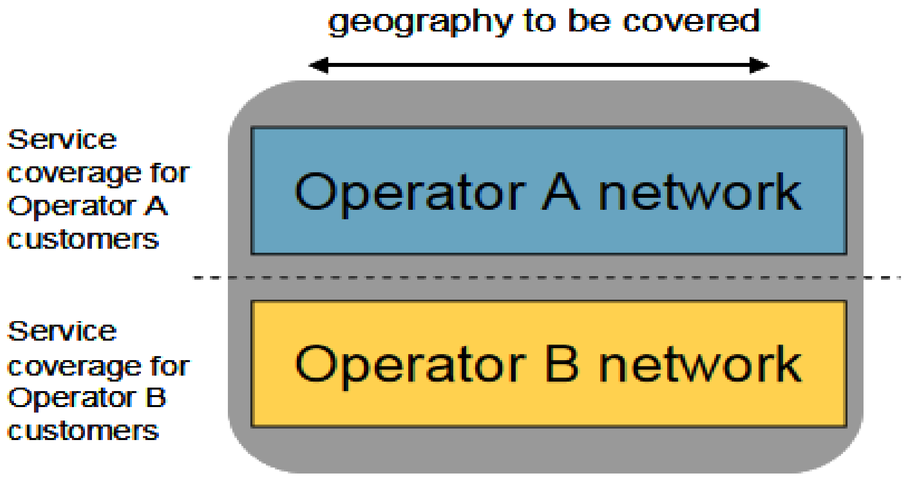

Figure 2. 2: Non-sharing case between operators [22]

2.5.2. Full Split

In this case, MNOs serve disjoint, complementary areas. This line of attitude is interesting for operators with an analogous strength of mutual service (roaming) agreements. In this scenario, which promotes extended coverage or an overview of new technology at the lowest mutual cost, a consolidation scenario requires an optional phase-out synchronized between operators but no relocation of equipment.

2.5.3. Unilateral Shared Region

The unilateral sharing model specifically used to pool the roll-out requirements of incumbents and new entrants because it releases the Greenfield operator from the burden of investing in its own full-coverage infrastructure, which may be insufficient compared to its small subscriber number. Again, roaming would be the corresponding technical solution.

2.5.4. Common Shared Region

Depending on the technical solution, operators can merge all of their sites, their radio networks, or even their core networks. In the worst scenario, they only keep a small piece of the core network separate, particularly the parts related to subscriber ownership like the billing system, home location registry (HLR), and authentication. Naturally, a full implementation of geographic sharing is always more effective than a partial execution of the same technical technique. The only distinction between a full split and full sharing for a roaming-based solution is the regional selection criterion for the former (i.e., one operator rolls out or concentrates in one area), whereas the latter denotes a case-by-case determination of the roll-out or phase-out without regard to regional selection criteria. When growth is present.

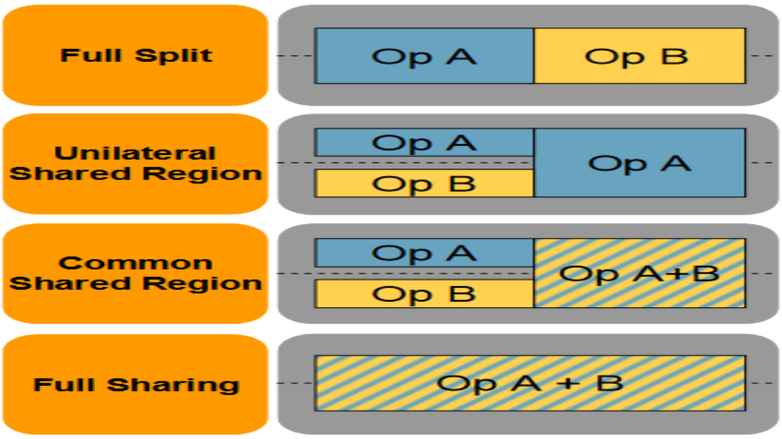

Figure 2. 3: Geographic sharing options between operators [22]

2.6. Background of Radio Access Networks

Mobile networks have evolved from telephony-based systems to all-digital communication. Systems. Every architectural breakthrough has been made possible by new mobile requirements. Services that were not possible with legacy systems due to flaws in their outdated architecture in order to understand the RAN architecture for the next generation of mobile systems (such as 5G), it is important to look back at previous and current RAN developments. This section will briefly describe the architectural evolution of RAN.

2.6.1. Traditional RAN

The baseband and radio units' functions are combined into one base station under the conventional RAN architecture. Because to the substantial losses incurred by the coaxial cables used to connect the radio modules, as depicted in Figure 2.2, the antenna is often located close to the radio modules. The 1G and 2G era of mobile network deployments employing architecture [29]

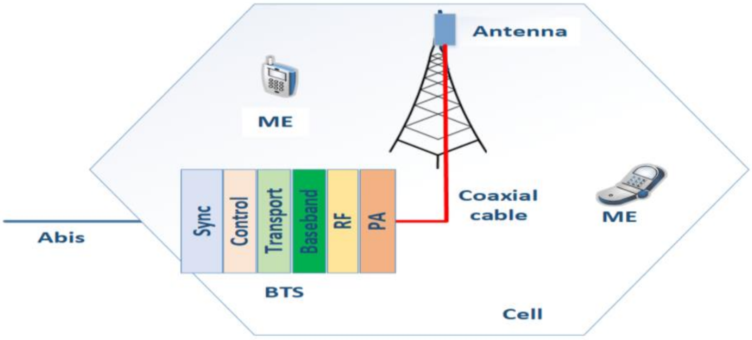

Figure 2. 4: Traditional Macro Base station [29]

2.6.2. Cloud-based Radio Access Network (C-RAN)

Base station density will significantly increase as we move from 4G to 5G, increasing the cost of site acquisition and network building. Furthermore, the user experience is harmed by strong co-channel interference at cell margins caused by intensive base station deployment. The creation of the cloud-based radio access network overcame these issues (C-RAN).The deployment of BBUs centrally makes site acquisition easier and minimizes the amount of equipment needed at each location, which lowers the cost of rentals, energy, and equipment rooms. Cooperation among BBUs greatly enhances performance at cell edges. The shortcomings of the conventional RAN are best addressed by C-RAN, which thanks to its features is the RAN design of the future. Figure 2.3 depicts the primary concept of C-RAN, which is to consolidate all BBUs into a centralized pool of cloud computing-based, shared, and virtualized BBUs. Each RRU is linked to its respective BBU pool through a low-latency, high-bandwidth optical link called the front haul link [2].

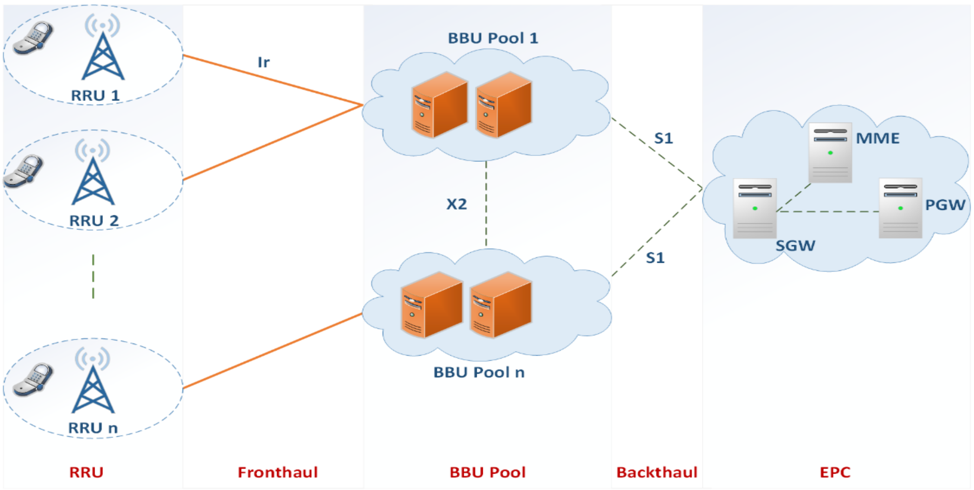

Figure 2. 5 : The general architecture of Cloud RAN [2]

2.6.3. Main components of C-RAN

A Baseband Unit (BBU) Pool, Remote Radio Unit (RRU) networks, and a front-haul transport network are the three main parts of the Cloud RAN architecture. The essential elements listed below are summarized in the C-RAN architecture [29].

BBU pool: A BBU pool is situated at a centralized location, such as a data center or the cloud. It consists of several highly capable computing and storage BBU nodes. These BBUs are in charge of processing resources and dynamically distributing them to RRUs in accordance with the demands of the network at the time.

RRU network: Similar to access points or towers in conventional cellular networks, an RRU network links wireless devices.

Front haul: also known as the transport network, is the layer of connectivity between a BBU and a group of RRUs that offers high-bandwidth links to accommodate the needs of several RRUs. Different technologies, such as optical fiber communication, cellular communication, or millimeter-wave communication, can be used to implement front-haul communications. Since optical fiber communication offers the largest bandwidth requirement, it is regarded as optimal in C-RAN. However, it has expensive implementation and strict costs. Cellular communication, also known as millimeter wave communication.

CHAPTER THREE

3. Game Theory Approach in Multi-Operator Resources Sharing

3.1. Game Definition

Game theory (GT) is a branch of mathematics that facilitates the modelling and study of the interactions between numerous decision-makers (known as players) who may have competing or unavoidable goals. In a game, each player's benefit or cost from an interactive situation is influenced by both its own choices and those made by the other players as well.

Different applications of game theoretic methods can be found in cellular networks. The interaction between players is modelled by game theory (GT), where each player attempts to maximize their utility or profit [20]. These participants can have competing interests, the idea of non-cooperative game theory systems from this. Finding an equilibrium, such as a Nash equilibrium, where players have no incentive to unilaterally depart from their chosen strategy, is of interest. The game's solution will be an equilibrium. The difficulty in creating a game is ensuring that the equilibrium is effective and close to the ideal answer, given the possibility of alternative equilibria. On the other case, some players might come to the realization that working together will enhance their utility. In this situation, members no incentive to leave their coalitions [30] [20].

In general, non-cooperative games and cooperative (coalitional) games are the two types of situations that game theory deals with. The triplet comprising a set of players, a set of strategies, and a utility function naturally forms the formal definition of a game. An individual player's assessment of gains and losses in a game is represented by the utility function.

3.1.1. Mathematical Notations of the Game

Players are the term for the decision-makers in game theory. Their strategy refers to how they decide the course of action to take. The interaction nature of game theory is what particular player's utility (or benefit) depends not only on his own actions but also on those of other players. Game theory's fundamental principle is that, given the knowledge at hand, rational players will seek out strategies that will maximize their payoff. Each strategies of a player makes to maximize his utility is influenced by the decisions made by the other players as a result of interactions.

Players, their strategy, and the formulation of the rules are used to build up the game [4]. The mathematical representation of the game G is as follows:

(i) Set of N players

(ii) Set of Ai of actions accessible to each player i ϵ N

(iii) For each player i ϵ N a utility function: A limited number of N players make up an N-player normal-form game:

$$G = \{N, (A_i)_{i \epsilon N}, (U_i)_{i \epsilon N}\} \qquad 3.1$$

Strategy spaces { s_1, s_2, s_3 and s_N } are the players' strategy spaces

Payoff/reward functions for this players. $U_i: s_1 \text{ X } s_2 \ldots\ldots x\, s_N \rightarrow \text{R}$

For a two-player prisoner's dilemma game, N = 2,

N = 2 players have the following available strategy spaces: $s_1 = s_2$ = (Cooperate, Defect) or $s_1 = s_2$ = (1, 2).

The payout functions are u1(s) = A_S and u2 (s) =B_S, mapping an element of s $\in s_1 X s_2$ = (1, 1), (1, 2), (2, 1), (2, 2) is real number.

3.2. Basic Models of the Game

Cooperative games and non-cooperative games are the two main branches of game theory. Operators in this game formulation behave logically in accordance with their strategies, with the main goal of maximizing their outcome. However, the rules imposed by the game's situation have a significant impact on how operators' strategies are supposed to work. A cooperative game compromises analytical methods for examining cooperative behavior of rational players.

3.2.1. Cooperative games

Cooperative game theory (CGT) provides analytical tools for studying the behavior of rational when they cooperate. CGT's main focus defines the formation of cooperating groups of players that can reinforce the positions of the players in a game. In a cooperative game, it is very beneficial for the players or users to work as team in order to receive the greatest total payoff or utility. A cooperative (coalitional) game in game theory is one in which groups of cooperative players (coalitions) can impose cooperative behavior. Consequently, instead of individual players, groups of individuals competing in a coalition game make up the players in a cooperative game. Due to significant overhead signaling and trust difficulties, cooperative games in wireless networks are practically unappealing, but they offer a special Pareto optimal solution for problem modelling [20]. In this thesis, non-cooperative games are used to model infrastructure sharing among MNOs.

3.2.2. Non-Cooperative games

In game theory, a non-cooperative game is one in which the decision-makers (players) act independently. Players in a non-cooperative game may have interests that are completely different with one another or partially. Low communication overhead and no presumption of knowledge of a players [31]. It depicts a competitive scenario where each player must make a choice independently of the other players given the potential choices of the other players and their impact on the player's objectives or utilities. Non-cooperative does not always imply that the players do not cooperate, without centralized control, but it means that any cooperation that might arise must be self-enforcing with no communication or coordination of strategic choices among the players. In non-cooperative game repeated game appears when the players have to interact with each other more than one time, and every interaction between the players is called a stage which has utility, and the total utility of the game will be the summation of the utility for each stage in the period of the game for each individual players.

Generally, a non-cooperative game can be characterized as a zero-sum game or a non-zero-sum game. The Nash equilibrium is the most well-known type of solution for a non-cooperative game with two or more participants [14]. The Nash equilibrium represents any combination of strategies in which each player’s strategy is his best choice, given the other players’ choices. Each player can therefore get information about the other players' equilibrium strategies. The Nash equilibrium in Table 3.1 is described below:

First, we'll invented that Player A is in control and that Player B has chosen a specific course of action. Due to our opponent's move, we therefore underline and highlight with a red backdrop the best reward. Second, we assume that Player A (the opponent) has chosen a specific action and that we are Player B. Due to our opponent's move, we therefore underline and highlight with a yellow background the best reward.

Table 3. 1: Nash equilibrium solution [14]

Player A\ Player B	Action b1	Action b2	Action b3
Action a1	1, 2	3, 4	5, 5
Action a2	0, 10	2, 8	3, 6
Action a3	6, 3	5, 2	4, 4

As we can notice this game presents a unique Nash equilibrium at (5, 5).

3.3. Game Modelling Strategies

The players can employ a variety of game Strategies to achieve different game resolutions. Optimal/Suboptimal Solution, Best Response, Nash Equilibrium, Max-Min Strategy, Mixed Strategy, Dominant Strategy, Pure Strategy, and Pure Strategy. In order to quantify infra-structure sharing between operators, the best response strategy and Nash equilibrium are used throughout this paper.

3.3.1. Strategy

A strategy is one of a player's potential moves in game theory. A strategy in an extended game is an entire set of options, one for each choice the player must undertake. In game theory, players or users typically aim to make the best feasible movements or sequence of actions known as strategies in order to maximize the best payout or utility [32]. A player's strategy will determine their action at any given time during the game and for any possible history of play up to that point.

3.3.2. Nash Equilibrium

A Nash Equilibrium (NE) is defined as a profile of strategies such that each player's strategy is an optimal response to the other players' strategies. The concept of a NE is derived from imposing an additional constraint that beliefs must be consistently aligned across players. A NE, also known as a strategic equilibrium, is an alternative list of strategies, one for each participant that has the quality that no player can change his approach and obtain a better outcome individually. Therefore, no player will alter their approach and receive a greater payout as long as the other player's plan stays the same [33].

Game G, with strategy outline (s_i s_j), where s_i is the strategies of player i and the strategy of all other remaining players represented as s_j

Thus: the function of best utility (Nash equilibrium) expressed as in equation 3.2 below

$$Bu_i(s_i^*, s_j) \geq Bu_i(s_i, s_j) \qquad 3.2$$

The above equation is accurate when all strategy $s_i \in s_i$ and all player i ∈ N. And strategy be able to Nash equilibrium for any player if there is no strategy of s_i^* that satisfies an improved utility, given that all other players' strategies are other than s_j

3.3.3. Best Response

Game theory's concept of the "best response" is typically used in situations where a player must choose the best strategy or tactics that will lead to the most favorable outcome for that player while taking into account the strategies of other players [33], [34]. Each player can select a set of policies or adjustments that will maximize their current utility or reward by making the assumption that they will work, knowing the game's payoff structure and what applies to their own payoff. The Nash equilibrium depends on the idea of a best action or optimal course of action. Mathematical expression of the best response strategies among a set of strategies of rational players. A strategy $s_i^* \in s_i$ is best response for player i to $\boldsymbol{s_j} \in \boldsymbol{s_j}$ and $\forall\, s_i \in s_i$ equation 3.3 represents best response from the list of all strategies of each rational players

$$\mathrm{B}u_i(s_i^*, s_j) \geq Bu_i(s_i, s_j) \qquad 3.3$$

Where, $\mathrm{B}u_i$ =Best response functional strategies

s_i^* =best response strategies/probabilities

3.4. Prisoner’s dilemma

The common example used to explain a game theory is prisoner’s dilemma. The story tells about two suspects for committing a crime and put into a jail before trial. It is a game where two supposed prisoners are separated and given an opportunity to confess or deny committing a crime. Thus, the prisoners have same two strategies: confess and refuse (C, R) [35]. The prisoners are in different cells, means no any ways to communicate each of them has to make their decision individually. However, the decision made by one prisoner affects the other prisoner stay in prison. The foremost policy is defecting, but acting in self-interest leads to sub-optimal collective outcomes. The Nash equilibrium, where one player confesses whereas the other denies, results in both prisoners pursuing individual logic and betraying each other, resulting in a suboptimal collective outcome. Players like to maximize their payoff, which is to have a minimum stay in prison. However, one opponent does not have a control on the other one’s decision, which in turn affects its payoff. Consider the two operators (OP1 and OP2) communicating under wireless network sleep mode communication to maximize their utility dilemma matrix game in the below table. The actions of the operators remain active, and sleep mode is represented with blue and red colors, respectively. The player's payoffs and strategy in matrix form represented by:

Table 3. 2: Two operator’s BS active and sleep mode dilemma game under matrix form

		OP2	
		Active mode	Sleep mode
Op1	Active mode	$1-e, 1-e$	$-e, 1$
	Sleep mode	$1, -e$	$0, 0$

In this context, the two operators can independently and simultaneously decide whether to share a cellular network. Depending on both decisions, each operator gets utility in the form of energy efficacy, known as the payoff matrix, in which $0 \leq e \leq 1$.

The communication problem corresponding to the above matrix form can be modelled as a strategic-form game where the set of participants is N = {OP1, Op2} and the action (strategy) sets are $\boldsymbol{s_k}$= {sleep mode, active mode} for k∈ {1, 2}. The utility function for OP1 (the one for OP2 follows by symmetry) is given by:

$$\text{u1}\ (s_1, s_2) = \begin{cases} -e \quad if\,(s_1, s_2) = (active\ mode, sleep\ mode) \\ 0 \quad if\ (s_1, s_2) = (sleep\ mode, sleep\ mode) \\ 1 - e \quad if\ (s_1, s_2) = (active\ mode, active\ mode) \\ 1 \quad if\,(s_1, s_2) = (sleep\ mode, active\ mode) \end{cases} \qquad 3.4$$

The above mentioned game is expected to be a static (equivalently, one-shot) game subsequently each operator takings a single action once and for all. Its finite game, it has at least one mixed NE. To find these equilibria, let us denote by ρ_1 (resp.,ρ_2) the probability that OP1 (resp., OP2) allocates to the action active mode. The mixed NE of the considered game can be found by computing the expected utilities.

For operator OPK with k ∈ {1, 2}, it writes as $\tilde{u}_k(\rho_1, \rho_2) = -e\rho_{\mathrm{k}} + \rho_{-\mathrm{k}}$ the best-response of player k is given by: $\forall\rho_{-\mathrm{k}} \in [0, 1]$, $\widetilde{BR}_k\ (\rho_{-\mathrm{k}}) = 0$. Subsequently, Nash equilibria are connection points of the best-responses, the unique mixed NE is $(\rho_1^{NE}, \rho_2^{NE}) = (0, 0)$, which is a pure NE consisting of the action profile (sleep mode, sleep mode).

CHAPTER FOUR

4. System Modeling, Assumptions and Problem Formulation

This section presents the system model, multi-operator framework, the system capacity, the objective function, the energy consumption model, the cost model, the deployment scenarios, and the appropriate mathematical formulations and tools. The processes needed to complete the key activities are oversimplified in figure 4.1, which is depicted below.

4.1. Game Theoretic Base Stations Switching-Off Strategies in Multi-Operator Environments

This chapter takes into account a region covered by three operators. Each operator's BSs completely cover the area, and the network is sized to accommodate peak traffic volumes. Therefore, BSs can occasionally be redundant, especially when the network's traffic load is very low. We suggest an energy-efficient mechanism in which the three operators work together to switch off/on number of BSs and pool their resources to serve the area together during times of low traffic[7], [36].The behavior of users, which varies greatly during the day, has a direct impact on the traffic load of cellular network. As a result, a typical cellular network's traffic load drastically changes during a day. The real network traffic load will vary dramatically over the course of a single day, with the highest traffic load occurring from 10:00 AM to 18:00 PM and the lowest traffic load being from 2:00 AM to 6:00 AM at midnight according to figure 4. 1. A portion of the BSs will be idle when traffic load is very low because operators currently deploy their BSs in accordance with peak traffic demand to give comprehensive coverage of an entire area regardless of variable traffic loads [36].The main contribution lies on the following:-

(i) We propose a game-theoretic algorithm used in real, multi-operator centralized networks.

(ii) To help operators decide if infrastructure sharing will be viable, we outline the cost analysis clearly accounting for operational, roaming, and overhead costs.

(iii) To assess the network performance, we present an analytical probabilistic model. This model shows how our technique improves network energy efficiency without QOS degradation

4.2. System Modelling and Assumption

According to the distributed gaming model, taking into account the deployment scenario involving three Operators (Operator A, B, and C), These operators cover a certain geographical area, as shown in Figure 4.2, and the following descriptions of the roaming-based RAN sharing and BS switching off strategies because they have their own interests and emotions, the operators are reluctant to reveal data that is unique to them, such as CSI, channel utilization, or traffic load. The telecommunications organizations are prohibited from deploying their antennas on the same structure due to legislative restrictions. As a result, each cell is serviced by three BSs, each of which is under the control of a different operator. This indicates that the service regions of the three operators largely overlap. However, resource underutilization exists since BSs are sized for peak traffic needs and collocated in the same environment.

Fig. 4.2 describes three possible cases for cell operation in multi-operator environments where each MNO controls and operates its own bastion. In a simple scenario, all the BSs are active (Cell A), and each operator is responsible for serving the traffic of its users. In the case that all BSs have been switched off (Cell B), the active BSs of neighboring cells (Cell A) of each MNO can extend their range in order to avoid service outages. Finally, in the case that only a subset of the BSs has been switched off (Cell C), their respective traffic can be roamed to the active BSs of the same cell.

The overall Steps involved in proposed model evaluations are described in Fig. 4.1 below.

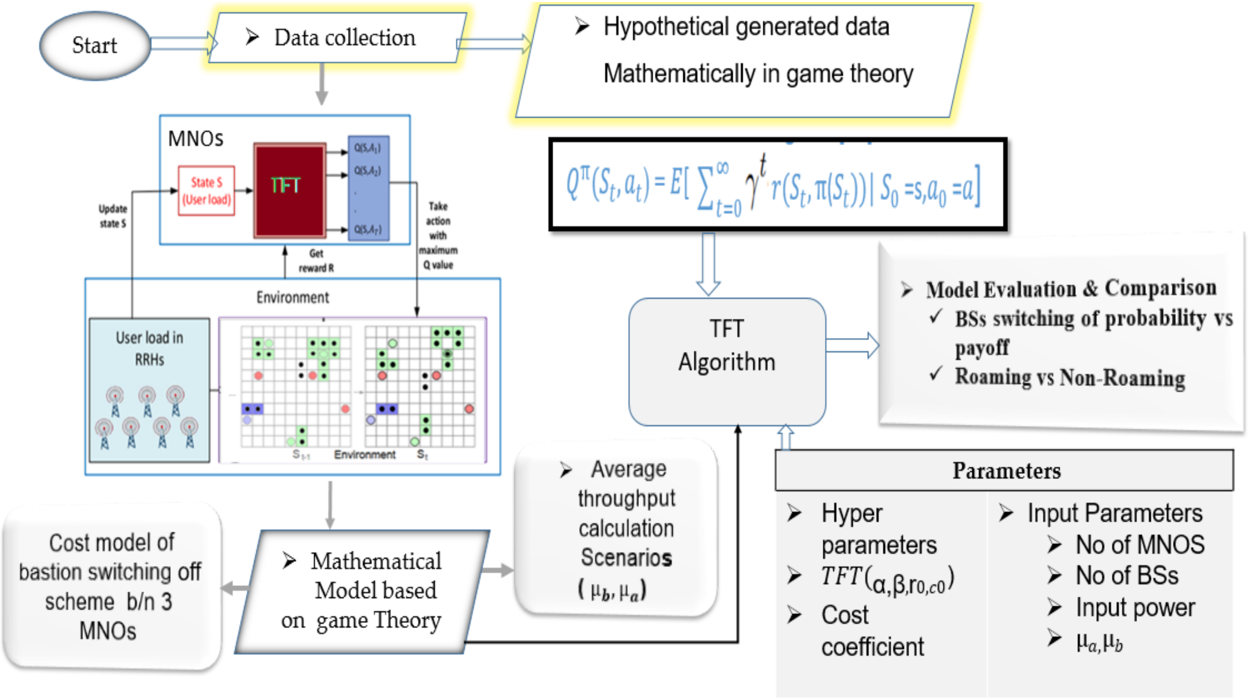

Figure 4. 1: System modeling (Steps involved in proposed model evaluations)

4.2.1. Bastion Switch off Algorithm

Today, one of the most promising methods for improving cellular networks' energy optimization is the use of switch-off mode. In periods of high traffic, all of a cellular network's BSs are typically required to deliver the desired QOS to end users; however, in periods of low traffic, only a portion of BSs are necessary to deliver the same services, and some BSs that are idle can enter low-power switch-off mode[15].

When there are underutilized BSs, the idea behind the sleep mode technique is to dynamically adjust the network's capacity to the immediate traffic demands. Switching off some BSs implies that the coverage and service provisioning are undertaken by the BSs that remain active which increase their radiated power so that to serve satisfactorily the whole area and guarantee the required quality of service (QOS).

In this thesis we have considered the 7-cell cluster among three mobile network operators which depicted in Fig. 4.3. The central BS is always on to ensure QOS, whereas the six surrounding cells (j) are subject to the switching off algorithm. The three essential steps in the switch-off scheme:-

Step1: - Each BS of the three operators calculates the anticipated operational costs, explicitly accounting for the unique roaming and overhead expenses. We also assume that the BSs can use the X2 interface to retrieve the traffic load data of other BSs in the same cell [7]

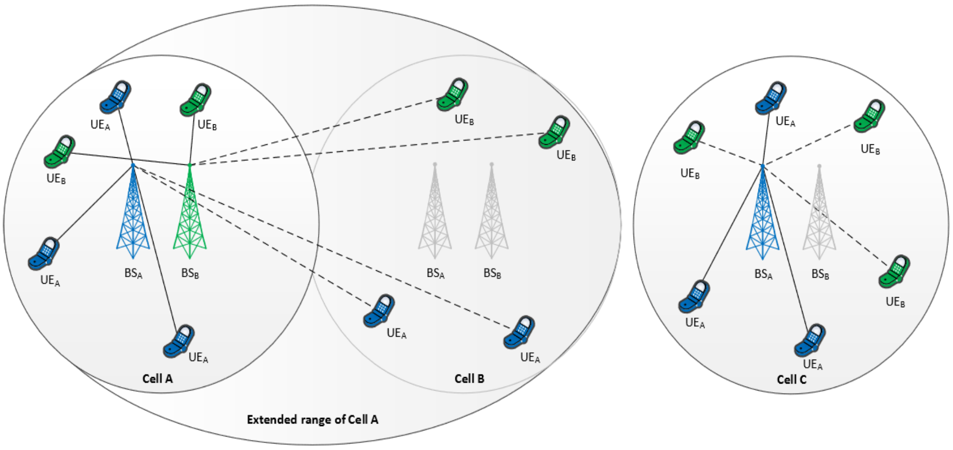

Figure 4. 2: Roaming based Radio Access Network (RAN) sharing among Operators [7]

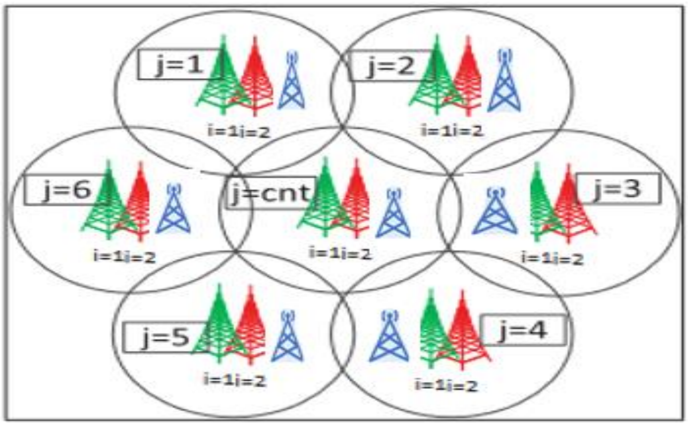

Figure 4. 3: Seven - cell cluster of three MNOs [15]

A fundamental temporal pattern that is strongly related to sleep cycles in humans is revealed by the aggregated mobile traffic . Additionally, aggregated network traffic over an X-Y grid shows a statistical relationship between nearby cells, whereas traffic patterns at distant cells offer some insight into how traffic consumption would change at a "target" cell . Similar to this, research from Addis Abeba, Ethiopia, demonstrates that mobile data traffic of mobile network has a consistent pattern of consumption every day of the week, peaking at around 10:00 p.m. and declining to its lowest value at around 4:00 a.m[37].

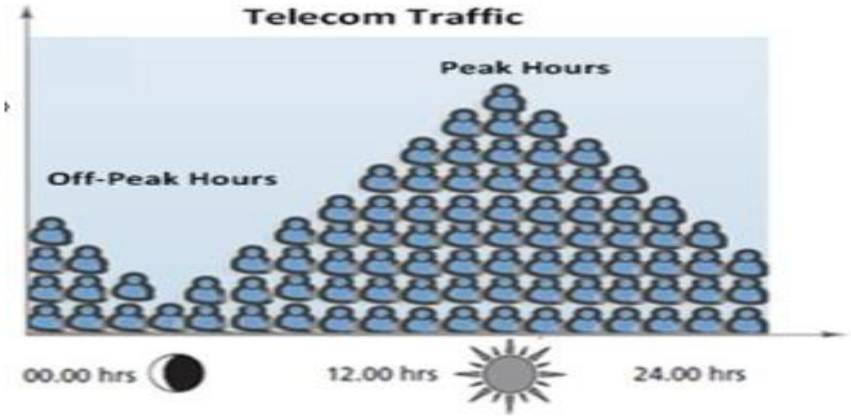

Figure 4. 4: Daily traffic load variations during 24-h [37]

Step 2: The BSs use a non-cooperative game theoretic scheme to choose whether or not to switch off their BSs based on cost functions.

Step 3: Cells with some BSs that need to be turned off are stacked on top of the other cells to create a list of the six cells. To switch cells with the same number of BSs, the ones that receive the least overall traffic are switched-off first. Following the creation of the list, the BSs at the top are turned off, and the remaining BSs handle their traffic. Optimize the objective function until maximum number of switched-off BSs is reached keeping QOS; step 3 is repeated.

4.2.2. Optimal Strategy of Base Station Switching-Off Scheme

Game theory is an appropriate instrument for studying this issue in a multi-operator context due to the presence of numerous stakeholders with competing interests and the variety of factors that may influence the choice to switch off (such as energy savings, roaming costs, traffic load, etc.). In order to do this, we present a unique game-theoretic switching-off technique for the BSs in a multi-operator environment that takes into consideration the interactions and conflicts between the various MNOs as well as the many accessible option [7]

In our case, reducing energy use is the main objective. Maintaining activity entails wasting energy. In other words, the QOS will be severely diminished if all BSs are turned off. We treat our base station switching on/off method as a static non-cooperative game with complete information where each operator i in each cell j chooses the strategy that minimizes its own cost, to evaluate this contradicting scenario.

The proposed game has three major components: G = (N, A, E [Ci, j]) [7], [38] [15]

Set of operators: There are N = three operators, analogous to the BSs of the three operators in each cell, i.e., i = 1, 2, 3. and j cells j=1, 2, 3,4,5,6 and 7

Set of actions: MNOs has two possible actions: remain on or switch off, i.e., A = (ON, OFF).

Set of cost functions: The cost function characterizes the cost of an action as a real number. Each player has an individual cost function E [Ci, j] that includes both the roaming and the operational energy consumption costs of each BS, thus focusing on the energy aspect of the problem. The strategy si, j of the BS of operator i in a cell j determines it's on/off probability. In particular, si, j = 0 denotes BS turning off, whereas si, j = 1 denotes the player staying on. The proposed game has 3 players (i.e., the MNOs in each cell), who can either stay on or turn off, and a cost function C that represents the actual costs incurred by each operator in each peripheral cell, such as the cost of operation, roaming, and increasing the power of the central BS. The symmetry of issue should also be emphasized because the players (MNOs) are all symmetric and the game's outcome is solely dependent on the strategies chosen. As a result, the proposed game is symmetric by definition, enabling us to:

i) To formulate the problem with two macro-players (player A is a givenMNO_i, while player B consists in the set of remaining (N-1) MNOs, which means operators B and C); ii) To study the problem from the player A point of view, generalizing the findings for every player.

iii) To formulate problem with two major-players, thus from the viewpoint of player A, and the other operators B and C.

In a strategic game, stable states, also known as Nash Equilibria, define players' actions. These states provide a certain payoff (response .cost) that cannot be increased or decreased if players unilaterally alter their decision. However, selecting a pure strategy in real systems is not always feasible or fair. To overcome this limitation, the study examines the mixed strategies domain, where each MNO_i selects a specific action with a certain probability. The expected cost function for player A is defined as E[C] = f ($s_{\ i}$,$S_{\ j}$, N,$Cost_{\ K}$), where $Cost_{\ K}$ represents the respective costs in each of the four different cases.

The players minimize their cost in a distributed manner, having no incentives to change strategy. The expected cost function includes four costs: fixed cost for BS operation (C_{const}), cost for serving traffic (C_{tr}), cost for increasing central BS power (C_{inc}), and cost for roaming traffic to another operator in the same cell (C_{roam}). C_{roam} Can fluctuate depending on the intentions and demands of operators [7].

The game results in four alternative states in a cell with three MNOs; these cases can be summarized in the matrix representation of the game in Table. 4.1, different cost functions.

Table 4. 1: Cost matrix of the propose game [7]

		Operator B and C	
		ON	**OFF**
Operator A	**ON**	$C_{const} + C_{tr}$	$C_{const}+ (\bar{N}_{\mathrm{roam}}+1)C_{tr}$ - $\bar{N}_{\mathrm{roam}} \cdot C_{roam}$
	OFF	$C_{roam} \;=\; \alpha * (C_{const}+ C_{tr})$	C_{inc}

Where,

ON/OFF is action of the operators during the game

C_{tr} Is normal traffic cost

C_{const} Is fixed costs of the bastion

C_{roam} Is roaming costs

$\bar{N}_{\mathrm{roam}}$ The number of roaming BSs.

α is the roaming cost factor

Total estimated cost paid by those three operators in the above cost matrix of the propose game expressed as:

Expected cost, E [$C_{(\mathrm{i,j})}$], operators (A, B and C) = {(1, 2), (2, 1)} is given by:

$$E\,[C_{(\mathrm{i,j})}] \;=\; \bar{s}_{\mathrm{A},j} \cdot \bar{s}_{\mathrm{B},j} \cdot (C_{const} + C_{tr}) + \bar{s}_{\mathrm{A},j} \cdot s_{B,\mathrm{j}} \cdot (C_{const}+ (\bar{N}_{\mathrm{roam}} + 1)\, C_{tr} - \bar{N}_{\mathrm{roam}} \cdot C_{roam}) + s_{\mathrm{A,j}} \cdot \bar{s}_{c',j} \cdot (C_{roam}) + s_{\mathrm{A},j} \cdot \bar{s}_{B',j} \cdot C_{inc} \qquad 4.1$$

In the above equation, the first term represents the average cost when all BSs are switched off, the second and third term is the average cost when one of the BSs is switched off, and the fourth term is the average cost when all BSs remain on

Where,

i and j are indexes of operators and cells respectively.

$s_{\mathrm{A},j} . \bar{s}_{\mathrm{B},c\,j}$ Strategies of the operators (ON/ON = 1, OFF/OFF = 0 ON/OFF = 0.5)

Si, j is the complementary probability equal to $\bar{s}_{i,\,j}$= 1 − si, j

E $[C_{(\mathrm{i,j})}]$ is all expected costs paid by game player operators

From table 4.1 we have generated four scenarios of base station switching on/off states

Scenario 1: Player A is ON, and Player B's operators are all ON. The fixed operational cost for the BS (Cconst) and the variable cost for serving its traffic (C_{tr}) are both included in the total cost for the MNO under investigation.

Scenario 2: Player A is ON, but a portion of Player B's operators are OFF: The switched-off BSs must move their traffic to the active ones in this situation. Typically, player A is permitted to serve N_{roam} BSs on average. As a result, player A's total cost must account for the increased operational expense of accommodating the more traffic (N_{roam} + 1) C_{tr}, as well as the associated income.

Scenario 3: Player A is OFF, but Player B has at least one operator ON. Although the operator under study has no operational expenses, it is nonetheless required to pay the active operator that handles its traffic the roaming fee (C_{roam}).

Scenario 4: Player A is not playing; Player B's operators are also not playing. In this instance, each MNO is responsible for paying the additional energy costs associated with increasing the power of the central BS (C_{inc}) to cover the region of a switched-off BS.

4.2.3. Objective Function

The objective or utility function is a performance metric whose strategy is considered a restricted access factor by which the operators try to optimize this function every game step whenever a strategy is played by another and play their own strategy later.

Operators playing non-cooperative games do not have to maintain the same utility or be aware of the utility of other operators. The utility function is occasionally defined as

$$E[C] = \mathrm{f}\,((s_i,s_j\,,N,(Cost_k) \qquad 4.2$$

Where f represents the objective or optimize function, Operators play strategies to continuously maximize their utility function. Costk, k ∈ {1, 2, 3, and 4} denote the individual cost in each of the four different cases described above. The probability that minimizes the cost function incessantly

$$\underset{k1 \dots k4}{Min} \; \hat{} \; E[C] \; s.t \; k_i \in K \qquad 4.3$$

However, the operators are interested in minimizing their throughput over time t of the repeated games rather than every time.

4.3. Four possibilities of the proposed cost matrices' assumptions and estimated cost calculations

From the above cost matrix of the proposed game, BS switching-off and the expected costs of the parameters are described as follows: Expected payoff E[C] with actions of 3 operators (A, B, and C) under different states described in table 4.2 below.

Table 4. 2: Expected cost of different states - under different MNOS action

States	Action of MNOs	Expected payoff E[C]
Scenario 1	BSs of All operators ON	$(C_{tr}) + (C_{const})$
Scenario 2	Operator A is ON and subset of operators in Player B are OFF	$C_{const} + (\overline{N}_{\mathrm{roam}}+1)C_{tr} - \overline{N}_{\mathrm{roam}} \cdot C_{roam}$
Scenario 3	Operator A is OFF at least one operator in OB or OA is ON	$(C_{roam}) = \alpha * (C_{const} + C_{tr})$
Scenario 4	All operators are OFF : expected cost/payoff	(C_{inc})

From the above table, the mathematical analysis of the proposed game

Scenario 1: In this case, all BSs in each cell are active to serve the traffic loads, so the expected cost of the clustered network is high due to all bastions are ON so it is not optimal strategies.

Scenarios 2 and 3: Are the best joint strategies BS switching off from the above the expected cost E [C] is symmetric and stable due to at least one the BSs in the cell can switch-off and save operational energy.

Scenario 4: In this case, the expected payoff E [C] is lower than in the other scenario. Due to all peripheral cells switching off their BSs, the transfer of their traffic to the central cell might compromise the offered QOS in high traffic load conditions.

From the proposed game, we can conclude that infrastructure sharing among MNOs modelling a strategic non-cooperative game is significant for reducing the operational costs of cellular networks that MNOs operating in the same geographical area.

4.3.1. Energy Consumption of the Proposed Game

The four scenarios of the energy usage are $surounding(\ N_{sur})$, the peripheral cells and central cells modeled with game-theoretical framework illustrated as [15]:

All BSs are ON:-in this case energy consumption of all surrounding cells and central cells

$$\mathbf{E}\ [E_{total}^{(ON)}] = \sum_{i=1}^{N} \sum_{j=1}^{N_{sur}} s_{(A,j)} \cdot s_{(B,C,j)} \cdot E[c] \qquad 4.4$$

$$\mathbf{E}\ [E_{C_{inc}}^{(ON)}] = \Pi_{j=0}^{N_{sur}} s_{(A,j)} \cdot s_{(B,C,j)} \sum_{i=1}^{N} \cdot E[c] \qquad 4.5$$

Where,

N_{sur} = Is six surrounding cells which includes three different BSs of 3 MNO

$i = is$ The indexes of three mobile network operators

$s_{(A,j)} \cdot s_{(B,C,j)}$ Is the strategies of operatorA and operators B&C respectively?

Expected cost $E[c]$ describes the roaming and the overhead cost, are modeled as a function of cost in the above proposed scheme in each different scenarios

All BSs are OFF:

Each BSs in the central cell, and the switched off BSs of the same operator in the peripheral cell

$$\mathbf{E}\ [E_{total}^{(OFF)}] = 0 \qquad 4.6$$

$$\mathbf{E}\ [E_{C_{inc}}^{(OFF)}] = \Pi_{j=1}^{N_{sur}} \bar{s}_{(A,j)} \cdot \bar{s}_{(B,C,\ j)} \sum_{i=1}^{N} \cdot E[c] \qquad 4.7$$

Operator A is OFF at least one operator in OB or OC is ON

$$\mathbf{E}\ [E_{total}^{(ON,OFF)}] = \sum_{j=1}^{N_{sur}} \bar{s}_{(A,j)} \cdot \bar{s}_{(B,C',\ j)} \sum_{i=1}^{N} E[c] \qquad 4.8$$

$$\mathbf{E}\,[E_{C_{inc}}^{(ON,OFF)}] = \Pi_{\mathrm{j}=1}^{N_{sur}} \bar{s}_{(\mathrm{A},j)} \cdot \bar{s}_{(\mathrm{B,C'},\,j)} \sum_{i=1}^{\mathrm{N}} E[\mathrm{c}] \qquad 4.9$$

All operators are OFF:-in this scenarios the energy consumption is only central cell of bastions.

$$\mathbf{E}\,[E_{C_{inc}}^{(OFF)}] = \Pi_{j=1}^{N_{sur}} \bar{s}_{(\mathrm{A},j)} \cdot \bar{s}_{(\mathrm{B},\,C,j)} \sum_{I=1}^{\mathrm{N}} E[\mathrm{C}] \qquad 4.10$$

4.4. Roaming-Based Multi-operator Throughput Maximization Framework

The three types of infrastructure sharing include roaming-based sharing, in which MNOs share cell coverage for a set period of time, passive sharing of sites, masts, and building premises, and active sharing of active network components like antennas, switches, and backhaul equipment. In passive infrastructure, such as building grounds, sites, and masts, passive sharing takes place. Passive sharing describes the sharing of physical space between two or more networks. Through passive sharing, they can share actual space within a network. The antennas, radio nodes, node controllers, backhaul, and backbone transmission that make up a mobile device's active layer are all exchangeable by operators. Active sharing is a more advanced form of sharing in comparison to elements of core network [4].

In the background of network sharing, roaming-based sharing denotes a situation in which one operator permanently depends on another operator's coverage in a given, predetermined area. Operators working in new areas are constantly looking for inexpensive ways to increase coverage and capacity. It will also be more receptive to passive sharing strategies. While operators in developed markets look for cost savings and new technological options through active sharing opportunities aimed at optimizing access transmission using leased lines and microwave links, operators in established markets look for the same things through these same opportunities.

4.4.1. Roaming-Based Multi-operator Throughput Maximization using Repeated Non-cooperative Games

Operators do not exchange any operator-specific information in a non-cooperative game. Operators are by nature competitors, thus a legal framework or self-interest would be the justification for getting them to cooperate. Therefore, we make the assumption that operators are rational, which means they seek to maximize their system capacity through self-interest, in order to describe dynamic RAN (Roaming) sharing with a game framework strategy. The appropriate framework is the repeated games because it is believed that the operators would engage for a long time. The main idea in non-cooperative game theory is NE [12], which provides characteristics for examining how completely rational decision makers might behave, as was covered in Chapter 3. When two tactics are in Nash equilibrium, each intelligent player is aware of both of them.

4.4.2. Repeated game theoretic framework

The system consists of network topology of two operators each have its own BSs and average traffic load $(n_1 and\ n_2)\ respectivly$ in the same area. These Meta-operator controls the distribution to fulfill the strategy of the game and apply it on the operators. In every stage the resources demand for each is changing depending on the number of users in the stage [4].The operators decide to both cooperate roaming based RAN sharing depending up on symmetric/asymmetric traffic loads. The proposed frame work of roaming traffic held under less number of active users for the operators is less than the double of the large number of active users (n_1<2n_2 $and\ n_2 < 2\ n_1$).

Here is the Meta-operator distribute the pool depending on the ratio for each operator (Operator1 ratio is n_1/ (n_1+ n_2), and Operator2 ratio is n_2/ (n_1+ n_2)), to fulfill fair play, and the behavior for this stage represented as both cooperation games.

The network topology of the system comprises of two operators, each with their own BS and average traffic load $(n_1 and\ n_2)\ respectivly$ typical traffic loads in the same region. These Meta-operators manage the distribution in order to implement the game's plan for the operators. Depending on the number of users in each level, the demand for resources varies [5]. Depending on symmetric or asymmetric traffic loads, the operators choose whether to work together in roaming-based RAN sharing. The suggested framework of roaming traffic retained under a smaller number of active users is less than the twofold of the huge number of active users (n_1<2n_2 $and\ n_2 < 2\ n_1$).

Here is the Meta-operator, which divides the pool RAN resources according to each operator's ratio (Operator1 ratio is $n_1/(n_1+n_2)$, and Operator2 ratio is $n_2/(n_1+n_2)$), to fulfill fair play, and the behavior for this stage both cooperation takes which represented as (C, C). When the sum of active UEs for Opr1 (n_1) is greater or equal to the double of (n_2), then the Meta-operator decides to cooperate from shared resources (roam traffic from Op1 to OP2 and vice versa) as follows:

$$\text{Operator1 } ratio = (1 - (\frac{n_2}{2(n_1 + n_2)})) \qquad 4.11$$

$$\text{and Operator2 } ratio = (1 - (\frac{n_1}{2(n_1 + n_2)}))$$

this will satisfy the need of operator 1. This rewards for Opr1 in this stage (t) will be punishment for Opr1 in the next stage (t+1) and reward for Opr2 where the pool resources divided by the two MNOS:

$$\text{Op1 } ratio = (1 - (\frac{n_1}{2(n_1 + n_2)}))$$

$$\text{and Op2 } ratio = (1 - (\frac{n_2}{2(n_1 + n_2)})) \qquad 4.12$$

In the next stage (t+1) the two players will be punished and the pool divided by two MNOs:

$$\text{Operator1 } ratio = ((\frac{n_1}{2(n_1 + n_2)}))$$

$$\text{And Operator2 } ratio = ((\frac{n_2}{2(n_1 + n_2)})) \qquad 4.13$$

this behavior in the three steps is called team fight strategies ($Tit - for - tat$) as that is the strategy of the game played. Note that any of the condition ($n_1 \geq 2n_2 \; or \; n_2 \geq 2\,n_1$) can start $Tit - for - tat$ strategy [39]

Table 4. 3: explains the combination of the actions in the game [39]

	Op2(C)	**Op2(D)**
Op1(C)	(m_1, m_2),(C,C)	$(m_1/2)$,$(1\text{-}m_1/2)$,(C,D)
Op1(D)	$(1\text{-}m_2/2)$,$(m_2/2)$,(D,C)	$(m_1/2)$,$(m_2/2)$,(D,D)

* $m_1 = (n1/(n1 + n2)$; and $m2 = (n2/(n1 + n2)$

From the above explanation, P1 and P2 determine the punishment, but sometimes the operator is required to receive more resources depending on the total of active users in the operator.

4.5. Assumptions and problem formulation of the game

We assume that two competing and cooperative MNOs are in competition to serve a typical metropolitan area (0.5km2), shown in Figure 4.5. In this network topology, to increase system capacity and decrease service interruptions, one MNO's network traffic is served dynamically by other MNO. A MNO is taken into account when two MNOs are deployed there RAN services in the same geographic area, shown in Figure below. Operator 1 is known as the host operator, and Operator 2 is called as guest operator. To boost the overall system throughput across the whole MNO network, each operator dynamically modifies the associations of its users with the better BS. Following that, many roaming scenarios for operator 2 are understood with the system throughput model of operator 1 and 2, as a result of the system throughput enhancement.

The sharing strategies depend on the average distance between users and cells, path loss in the network, and high traffic load conditions. We model the problem as a strategic non-cooperative game with varying traffic loads for each operator. Assume all MNOs have a BS and average traffic load of ($\mu_{1,and}$ μ_2), respectively, and the same SINR for all users. MNOs try to increase their user data rate. No shadowing has been considered, but only distance-dependent path loss [21]. The total downlink transmitted power should include UEs from various operators that have roamed to the home BS, but it should not include home BS UEs that have roamed to the cooperating operator. Therefore, it is important to take into account the roaming criteria that govern roaming across cooperative providers. To determine the relationship of each UE with each BS, the roaming criterion is introduced. The average number of UEs that the home BS from various operators serves is then determined.

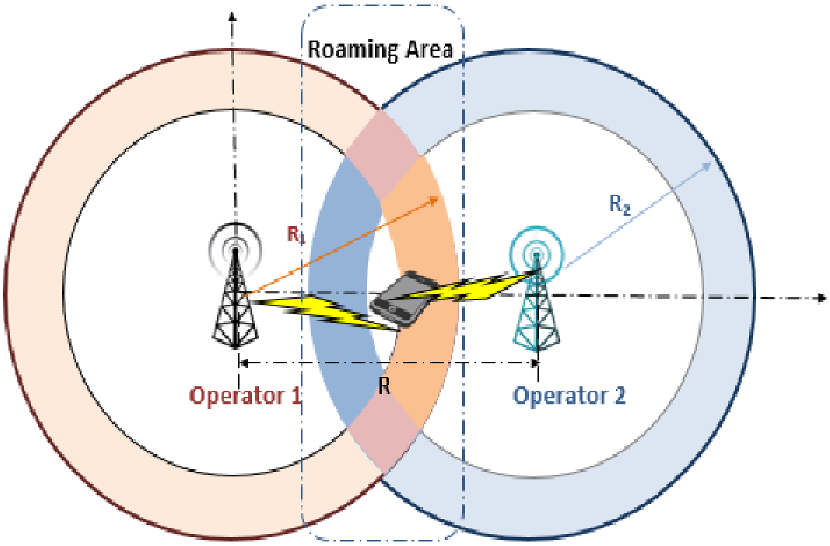

Figure 4. 5: System model of two operators [21]

4.5.1. Advantages of roaming-based infrastructure sharing scheme for multi-operator mobile networks

1. A framework for roaming-based general system throughput in multi-operator mobile systems: - Describes a closed-form expression for overall system throughput as a purpose of inter-BSs distance and cross ponding traffic loads is introduced. This statement is a component of a multi-operator mobile network's integrated roaming-based infrastructure sharing plan.

2. Innovative multi-operator collaboration and active user association to increase overall system throughput: To accommodate roaming traffic between operators and lower the MNOs' total system throughput, researchers are studying multi-operator cooperation and dynamic user association. When considering the relative BS locations amongst operators and their UEs' coverage zones, the various system throughput outlines for each operator are modelled in relation to their traffic loads [28].

3. Optimum separation among different BSs: To obtain the best throughput maximization, a novel algorithm is offered to determine the ideal separation between BSs of various operators.

4: User data rate, coverage, and capacity evaluation of the network: the effect of roaming across MNOs on overall system throughput is assessed and contrasted with a non-roaming situation, plus the power savings is illustrated in several situations. This finding shows that, in comparison to the conventional case, roaming between carriers offers more flexibility in achieving green performance. The findings also show that both carriers' UE density and cell coverage are improving as a result of roaming [21].

4.5.2. Roaming criterion

In [30] and earlier explanations, the following roaming criteria are expected in MNO networks in order to maximize system throughput: Assume it belongs to operator 1. It roamed to operator 2 based on the following criteria:

I. If (and only if) n1 is located in both the cell core area of operator 2 and the cell edge area of operator 1, it is considered to be roaming.

II. The scenarios of n_1 are not roamed if:

- It is situated in the cell central zone of operator 1.
- It is positioned at the cell edge range of MNO 1, however it is not placed on the cell central region of MNO 2. Three groups of UEs are then spread across the cell in various locations. These clusters are taken into account while calculating the downlink transmission power for each BS for both operators:
  - The core cell of UEs
  - The cell edge UEs of MNO1 who are not located in the cell core region of MNO 2

4.6. Mathematical description of the game

This section deals with the mathematical analysis of the cooperative game between two mobile network operators, and its network topology and collaboration, which is shown in Figure 4.5 with roaming-based RAN sharing based on user, BS, and traffic load factor distances. In order to understand how the algorithm behaves, we create the following hypotheses for the sake of simplicity:

- Each of the two operators, OPA and OPB, has its own BS and traffic load.
- The SINR/SNR is the same for each user inside the BS's access region.

- Shadowing has not been taken into account; only distance-dependent loss affects user rates.

The system sum rate in terms of traffic load, SINR, and sharing factor, as well as the anticipated throughput of both operators.

4.6.1. Non-roaming approach: expected throughput calculation in operators

Initially, operators try to answer users' requirements using continuous infrastructure deployment, especially BSs, in a conventional approach, but the major challenges are: increased energy demand for cellular networks; increased CAPEX and OPEX costs; and network capacity and coverage problems. The non-roaming manner, i.e., throughput calculation of operators A and B, in terms of traffic load (μ_a and μ_b) SINR (γ)and sharing factor [40] is described in Eqn. (4.14) - (4.18), respectively. Thus system capacity function of Operators with non-roaming cases can be written mathematically as follows in the form of throughput with assumption and initial conditions expressed mathematically. The Operators play non-cooperative, repeated games in order to improve their current underachieved system throughput, as described in the next section.

$$Ta = \sum_{\mu=1}^{\mu_a} \log \left(\sum_{\mu=1}^{\mu_a} Y_{\mu,m} \log_2 (1+\gamma_a)\right) \qquad 4.14$$

Where,

$\mu_{a,}\mu_b$ = are average traffic loads of two MNOs respectively

γ_a = Are SINR of UEs in the access area and considers same for all users

M = rate of RAN resource

$$Ta = \mu_{a,}\, log\ \left(\frac{M}{2}\frac{1}{\mu_a} log_2\ (1+\gamma_a)\right) \qquad 4.15$$

Signal-to-noise ratio (considered the same for users in operators A and B) and each operator consists of one bastion for the sake of simplicity. Which is the same for Operator B, we can define the system capacity function in terms of throughput mathematically as

Follows:

$$Tb = \mu_{b,}\, log\ \left(\frac{M}{2}\frac{1}{\mu_b} log_2\ (1+\gamma_b)\right) \qquad 4.16$$

In the above Figure 4.5 the average throughput of two MNOs is expressed as the average throughput for both users once we have obtained the system capacity of each user served by each and every BS in the access region.

$$Tab = Ta + Tb \qquad 4.17$$

Mathematically expressed as

$$Tab \;=\; \mu_{a,}\, log\, (\frac{M}{2}\frac{1}{\mu_a} log_2\ (1+\gamma_a)) + \mu_{b,}\, log\, (\frac{M}{2}\frac{1}{\mu_b} log_2\ (1+\gamma_b\ )) \qquad 4.18$$

4.7. Roaming based multi-operator system throughput maximization using repeated non-cooperative game

Roaming based dynamic RAN sharing between two operators, the proposed model assumptions and problem formulations of the two operators have symmetric and asymmetric traffic ($\mu_{a=}\ \mu_{b,}\mu_{a,}{>}\mu_b$)

In the first scenario, ($\mu_{a,}{>}\mu_b$) Operator A is the high-load operator, so certain traffic should be transferred to Operator B to increase system capacity and prevent service outages for UEs from their home operators. To that end, operator A gets more resources from operator B to avoid congestion and blocking probability. A certain partition of resources ΔM is shared with the gust operator from the host one. Considering that ΔM amount of resources are transferred to high load operator OA from low load operator OB at the end of the stapes of a game from non-roaming, ΔM, the proposed average throughputs of the two operators during game GA and GB are:

4.7.1. Scenario 1: Asymmetric load($\mu_a > \mu_b$) Case between Operators

The case of operator A is a high-loaded operator($\mu_a > \mu_b$), so from the proposed game, it needs more resources to overcome congestion and use system capacity effectively. Then the new respective average throughputs of the operators during the game, GA and GB, were expressed as:

Average throughput calculation of highly loaded operator A with received ΔM resources from lightly loaded operatorB

$$T_{otalG_A} = ((\ \frac{M}{2} + \Delta M) + \frac{1}{\mu_a} log_2\ (1+\gamma_a)) \qquad 4.19$$

Where, sharing factor $(F(\Delta m)) = (1 + 2\Delta M/M)\ \mu_a\ (1 - 2\Delta K/K)\mu_a - 1$

Average throughput calculation of low loaded operator B which gives $-\Delta M$ resources for higher loaded operatorA

$$T_{otalG_B} = ((\frac{M}{2} - \Delta M) + \frac{1}{\mu_b} log_2\ (1+\Gamma_b)) \qquad 4.20$$

$$F(\Delta m) = (1 + 2\Delta M/M)\ \mu_b\ (1 - 2\Delta K/K)\mu_b - 1$$

In the two described mathematical equations, above the gain of the game for an overloaded operator OA that gains more throughput due to roaming and gains additional resources. In Figure 4.5 above the average throughput of two MNOs is expressed as the average throughput for both users once we have obtained the system capacity of each user served by each and every BS in the access region in the proposed game expressed as

$$T_{otalG} = T_{otalG_A} + T_{otalG_B} \qquad 4.21$$

The following mathematical definition also applies to this:

$$T_{otalG} = ((\frac{M}{2} + \Delta M) + \frac{1}{\mu_a} log_2\ (1+\Gamma_a)) + ((\frac{M}{2} - \Delta M) + \frac{1}{\mu_b} log_2\ (1+\Gamma_b)) + ((\frac{M}{2} + \Delta M)) \qquad 4.22$$

But only if the game's average throughput exceeds the aforementioned average throughput of non-roaming cases can we argue that the game is profitable, i.e. Benefit of the game compare to conventional (non-Roaming approach).

$$T_{otalG} > Tab \qquad 4.23$$

Please see appendix A for proof.

4.7.2. Scenario 2: Symmetric load ($\mu_a = \mu_b$) Case between operators

In this incident operator A and B having equal traffic loads ($\mu_a = \mu_b$) in this scenario, path loss and distance between UEs and bastions of the two operators are the main concerns during the sharing of the proposed game to avoid service outages from home operators and use system capacity effectively. Then the new respective average throughputs of the operators during the game, GA and GB, were expressed as:

The average throughput calculation of operator A with received resources from the distance-based roaming cell edge area of the BS of operator A and at the cell of central environmental zone of operator B is expressed as:

$$T_{otalG_A} = \left(\left(\frac{M}{2} + \Delta M\right) + \frac{1}{\mu_a} log_2\ (1+\Gamma_a)\right) \qquad 4.24$$

The average throughput calculation of operator B with received resources from the distance-based roaming cell edge area of the BS of operator B and at the cell core zone of operator A is expressed as:

$$T_{otalG_B} = \left(\left(\frac{M}{2} + \Delta M\right) + \frac{1}{\mu_b} log_2\ (1+\Gamma_b)\right) \qquad 4.25$$

Average throughput of two MNOs is expressed as the average throughput for both users once we have obtained the system capacity of each user served by each and every BS in the access region in distance-based roaming in the game proposed.

$$T_{otalG} = T_{otalG_A} + T_{otalG_B} \qquad 4.26$$

Mathematically expressed as

$$T_{otalG} = \left(\left(\frac{M}{2} + \Delta M\right) + \frac{1}{\mu_a} log_2\ (1+\Gamma_a)\right) + \left(\left(\frac{M}{2} + \Delta M\right) + \frac{1}{\mu_b} log_2\ (1+\Gamma_b)\right) \qquad 4.27$$

With the aforementioned average throughput of non-roaming cases, can we argue that the game is profitable, i.e., the benefit of the game compares to a conventional (non-roaming) approach).

$$T_{otalG} > Tab \qquad 4.28$$

Please see appendix B for proof.

In general, in this section, we addressed the issue using roaming-based dynamic RAN sharing with different scenarios that gain or lose average system throughput with a repeated non-cooperative game.

4.8. Tit-for-tat (TFT) algorithm

"Tit-for-tat" refers to a tactic in a repeating game (or a sequence of related games) in the framework of game theory. The 'cooperate' action is selected in the first stage of play using the 'tit-for-tat' method, and the action selected by the opposing player in the former step is selected in the subsequent rounds.

The objective is to rely on TFT algorithms to reach an incentive and secure negotiation between interested participants exclusively for individual gain and common incentive gains. In our situation, a continuous TFT technique is practicable. Recall that a TFT policy's guiding idea is to pair a partner's cooperative observation with a cooperative response. The aim is to encourage behaviors of mutual cooperation while ensuring that they are not exploited. In the continuous version of the TFT, the choices of actions represent degrees of cooperation. If we suppose that at each step t, a player A observes from a player B a degree of cooperation, then the players can choose their response according to the following strategy [41].

$$TFT_{\alpha,\beta,\mathrm{r0},c0}(t, at-1, bt-1), rt = \begin{cases} co, ro & s_i,\ \mathrm{t}=0 \\ \alpha at-1+(1-\alpha)\,(\mathrm{r\ t}+(1-\mathrm{rt})\ \mathrm{bt}-1), & \\ [(\mathrm{rt}-1+\beta\,(bt-1-at-1)] & s_i,\ \mathrm{t}>0 \end{cases} \quad 4.29$$

Where,

TFT α: simply includes an inertia coefficient to smooth the reactions, as well as a constant incentive rate r0. The parameters β and γ are zero.

TFT β: addition of the coefficient β which makes it possible to dynamically adapt the rate rt depending on the positive or negative reaction of the partner. The coefficient γ is zero.

TFT γ: addition of the stochastic coefficient γ. It allows probability γ to reset the rate rt to r0 if it has become zero.

$bt-1$: Previous action of operator B

4.8.1 Architecture of TFT RAN sharing model

Our model consists of four steps, as indicated in the following Fig. 4.6: -

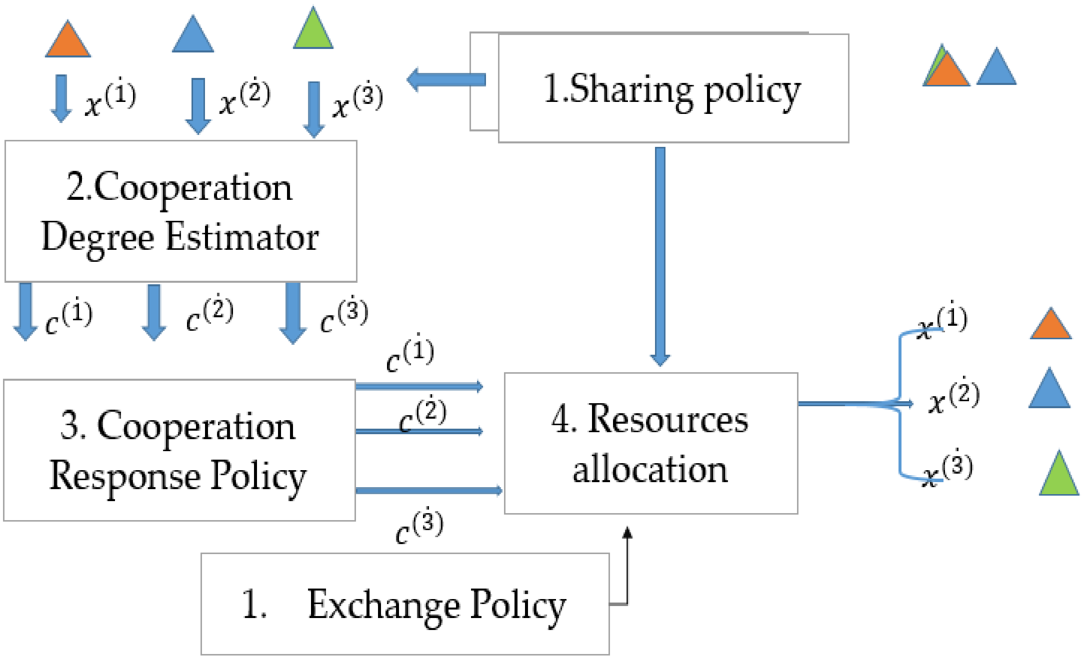

Figure 4. 6: Architecture of TFT RAN sharing model

Where,

Cooperation rate c i, j degree of cooperation of agent Ai with respect to agent A j

(0 for total defection and 1 for total cooperation).

$x^{(i)} .. x^{(3)}$ *are* Actions of each operators [remaining ON/OFF]

$c^{(i)} .., c^{(3)}$ cooperation degree of each operators [States]

▲ ▲ ▲ are symbolized of BSs of three mobile network operators.

CHAPTER FIVE

5. Simulation Results and Discussions

5.1. Simulation Scenario and parameters

We have developed a gametheortic TFT algorithm with Python programming to validate an infrastructure sharing scheme for multi-operator mobile networks to quantify the expected cost gains in terms of energy efficiency for the network operation and maximize system throughput. The proposed BSs switching off scheme and Roaming-based cooperation of the two MNOs under the above-proposed scheme.

We performed simulations in MATLAB to examine the performance of the proposed algorithm. The generated system-level simulation results of the proposed schemes in the previous section were presented. The BS switching of techniques among three operators is considered and investigated in contradiction to conventional approaches. In this section, we present the considered simulation scenario and the respective simulation results. The generated system-level simulation results of the proposed schemes in the previous section were presented. The BS switching of techniques among three operators is considered and investigated in contradiction to conventional approaches. In this section, we present the considered simulation scenario and the respective simulation results.

5.1.1. Simulation Scenario

We consider a network topology with three operators covering the same geographical area as described in Chapter 4, Figure 4.3. And this area is divided into 7 cells. Cells that have the lowest traffic switch off their BSs and roam their traffic to neighboring active cells or BSs. This interaction, cooperative among the operators, is applied mathematically with non-cooperative gametheortic approaches to cost-based functions to minimize number of active bastions in the clustered access areas to increase incentive costs between operators in different scenarios.

In this thesis, we focus on cases where N = 3 MNOs. In total, there are 21 BSs in the clustered accessed geographical areas in all 7 cell clusters (i.e., M = 7), of six peripheral cells and one central cell that always remains on, 3 BSs per cell of each 3 MNOs (op1, op2, and op3), and 200 UEs are considered in high traffic and 20 UES in low traffic per cell. UEs are uniformly distributed in the cell area [7], [15].

We focus our study on the low traffic hours (night zones where all operators have low traffic) of the day (3 a.m.–7 a.m.). Which were described in the earlier section in Figure 4.4. Both MNOs assume orthogonal LTE communication with a bandwidth of B_j = 20 MHz [26]. Regarding the technical and all essential parameters, they are taken from the gametheortic mathematical model from the above section, Ethiotelecom engineering and optimization, and ITU and 3GPP release documents of literature aided. We assume a service rate of 4096kb/s for data terms, while we deliberate two different communication power levels for the BSs, equal to 40 and 46 dBm for normal and extended processes, respectively [15][36].

For financial analysis, literature aided by ITU and 3GPP workshop reports cost analysis of infrastructure sharing between operators and considers a fixed operational cost (C_{const}) 500$, while the cost for transmission and the power increase can take different values depending on the traffic level, i.e., (C_{tr}∈ [10, 500] $ and (C_{inc} ∈ [15, 583] $[7]. Further, we have adopted a price of 0.1 $/kWh for the electricity charge, and the roaming cost factor has been set equal to α = [0, 1] [7]. We have also considered tune both standard (α = 0.5, r0 = 0.2, β = 0) and non-zero (dynamic) TFT configuration help to less exploited among operators [41].

To evaluate the performance of our scheme, we compare the proposed game theoretic BSs switching off scheme with switching of probabilities taking into account individual and cooperative incentives costs due to bastion switching of strategies. Bastion switching off strategies (probabilities $i.e\ s_{i,j}.$) taking into consideration as a mixed strategies rather than pure strategies.

5.1.2. Simulation Parameter

Details of the proposed system parameters are given in Table 5.2 below. The abovementioned parameters and cross ponding values described in this section were taken from

Third Generation Partnership Programmed (3GPP) and ITU recommendations, mainly [42], [43] [15] [7], [41]. In addition to that, the considered parameters were also taken from the Ethiotelecom engineering and optimization sections.

The effects are offered for a 10-stage game occurrence, produced based on the parameters mentioned in Table (5.2), before examining the actual simulation results. Initially, all operators use their own resources independently.

From ITU and 3GPP work shop documents, the sample BSs share expected costs of parameter values in 24h described in [7]. Expected payoff E [C] with described actions of three operators (A, B, and C) under different states is described in table 5.1 below.

The traffic variations during night zone are negligible and, as a result, the C_{const} can be considered constant $C_{const} \approx 500\$$

Cost of C_{tr} and C_{inc} depends on traffic level

$C_{tr} \in [10, 500]$ $

$C_{inc} \in [15, 600]$ $

α is the roaming cost factor [0,1]

Cost of roaming $(C_{roam}) = \alpha * (C_{const} + C_{tr})$ with $\alpha \in [0, 1] = 0.5$

We have taken value of (α= 0.5) for our mathematical calculations

$= 0.5 * (500) + (150) = 400\$$

Table 5. 1: Expected cost calculation of different states - under different MNO actions

States	**Action of MNOs**	**Expected payoff E[C]**
Scenario 1	BSs of All operators ON	$(C_{tr}) + (C_{const})$ $(150) + (500) = 650\$$
Scenario 2	Operator A is ON and subset of operators in Player B are OFF	$C_{const} + (\bar{N}_{\text{roam}}+1)C_{tr} - \bar{N}_{\text{roam}} \cdot C_{roam}$ $500 + (2+1)*150 - 2 * 185 = 545\$$
Scenario 3	Operator A is OFF at least one operator in OB or OA is ON	$(C_{roam}) = \alpha * (C_{const} + C_{tr})$ $0.5 * (465) + (150) = 400\$$
Scenario 4	All operators are OFF : expected cost/payoff	(C_{inc}) 250$

From the above table, the mathematical analysis of the proposed game

- Scenario 1: In this case, all BSs in each cell are active to serve the traffic loads, so the expected cost of the clustered network is high and not optimal strategies.
- Scenarios 2 and 3: Are the best joint strategies BS switching off from the above the expected cost E [C] is symmetric and stable.
- Scenario 4: In this situation, the expected payoff E[C] is lower than in the other scenario. Due to all peripheral cells switching off their BSs, the transfer of their traffic to the central cell might compromise the offered QOS in high traffic load conditions.

From the proposed game, we can conclude that infrastructure sharing amongst MNOs modelling a strategic non-cooperative game is significant for reducing the operational costs of cellular networks that MNOs operating in the similar environmental area. In addition to that financial parameters were includes in the simulation scenarios depending up on traffic conditions.

Table 5. 2: Simulation parameters mainly [41] [36] [7], [15]

Parameters	**Values**
Geographical settings	
Number of MNOs	3
Number of BSs per cell	3
Total number of BS access areas of the 3MNOs	21
Average number of users per cell	(20-200)
Simulation Area[Km2]	2*2
Traffic Model	
Cell radius(km)	0.5-1.6
Data rate R(kbps)	4096
Bandwidth [MHz]	20
SNIR min[dB]	[-4,13]
Max/min transmit power [dB]	[46,37]
BS idle power [dBm]	20

Hyper parameters	Values
Number of T per episode	10
TFT(TIT for TAT) model parameters(β, α, r0 and c0)	[0,1]
Roaming cost coefficient	[0,1]
Bastion switching off strategies (probabilities)	
OFF/OFF	0
ON/ON	1

5.2. Simulation results and analysis

In this section, we provide the analytical and simulation results, considering a low traffic profile (20 users per cell) for the downlink. Our scenario consists of three operators (operator 1, operator 2, and operator 3) serving in the same environmental region during low traffic duration (night zone) with varying traffic intensities and expressed in Fig. 4.5.

Fig. 5.1 shows simulation results to examine the proposed game behavior of the BS switch on/off probability with the incentive costs of operators in both cooperative and individual cases. In our simulation result, bastion (BSs) switching off probability in each cell increases with incentive costs due to extra BSs switching off during low traffic durations. In this situation, the traffic of the three BSs in each cell is the similar, and for the sake of simplicity in our simulation, we have used 20 users for each cell. As we can see from our simulation results in figure 5.1, each pair of curved lines and dotted points of the three operators, which are denoted with different colors, represents the best response strategy or Nash equilibrium (NE) of the game. In the NE, each operator follows the same strategy to switch off more BSs in their proposed access area, and their expected individual as well as cooperative costs are the same. Three MNOs' NE BS switching off probability and strategies by deactivating an additional number of BSs, which are not required during low traffic periods in Nash equilibrium, it is possible to achieve the best expected payoff for individual and cooperative MNOs (scenarios 2 and 3 in the previous section). Each player in a non-cooperative game is believed to be aware of the equilibrium strategies of the other players, and no player stands to gain by altering merely his or her own strategy. A coordinated switching-off technique called Nash equilibrium maximizes operator profitability while preserving UE QOS. Generally, in Fig. 5.1, NE BS switching off probabilities are 50% to achieve the optimal expected payoff for individual and cooperative MNOs (scenarios 2 and 3 in the proposed game).

The Tit-for-Tat (TFT) algorithm, which is regarded as a "robust" approach that necessitates cooperation from the competitive operator, was the foundation for the game formulations addressed by this thesis. And we have used two types of TFT hyper parameter configurations in our simulation. These are standard TFT (α = 0.5, r0 = 0.2, β = 0) configurations and dynamic or non-zero TFT (α = 0.5, r0 = 0.2, β =0.3) configurations [41]. The purpose is to boost behaviors of common cooperation while ensuring that they are not exploited. In Figs. 5.1 and 5.2, all operators follow an optimal strategy with standard TFT configuration to increase cooperation among operators.

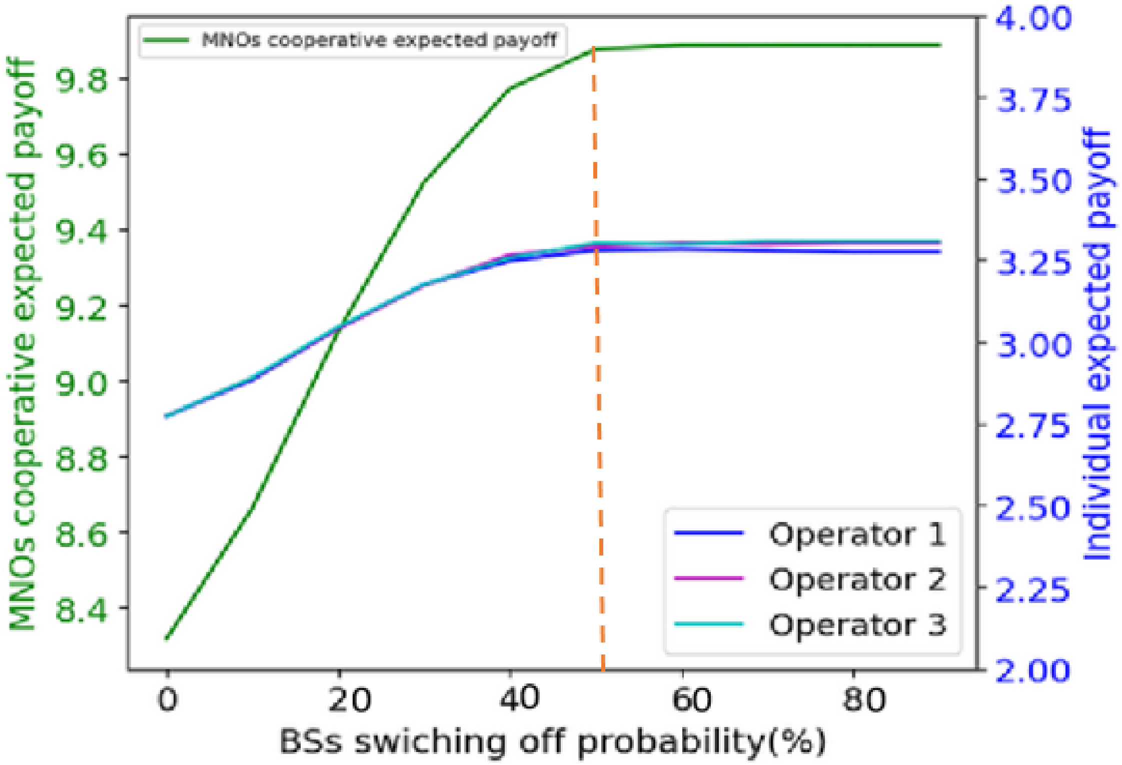

Fig 5. 1: Expected payoff vs BSs switching off probability and three TFT operators with (α = 0.5, r0 = 0.2, β = 0) standard TFT configuration

Cooperation steps among competitive and cooperative three TFT operators were articulated in Figure 5.2 in a 10-step game simulation in a symmetric cost function expressed as operators exchange traffic (operator 1 sending and receiving traffic and the same to other operators during the game in a continuous manner). The simulation result shows that the step of the game increases between operators with optimal state resources sharing in a cooperative manner (step 6 is stable strategies taken from a single iteration stage). After certain steps of the game, it stable states (converges) and returns to its initial state randomly.

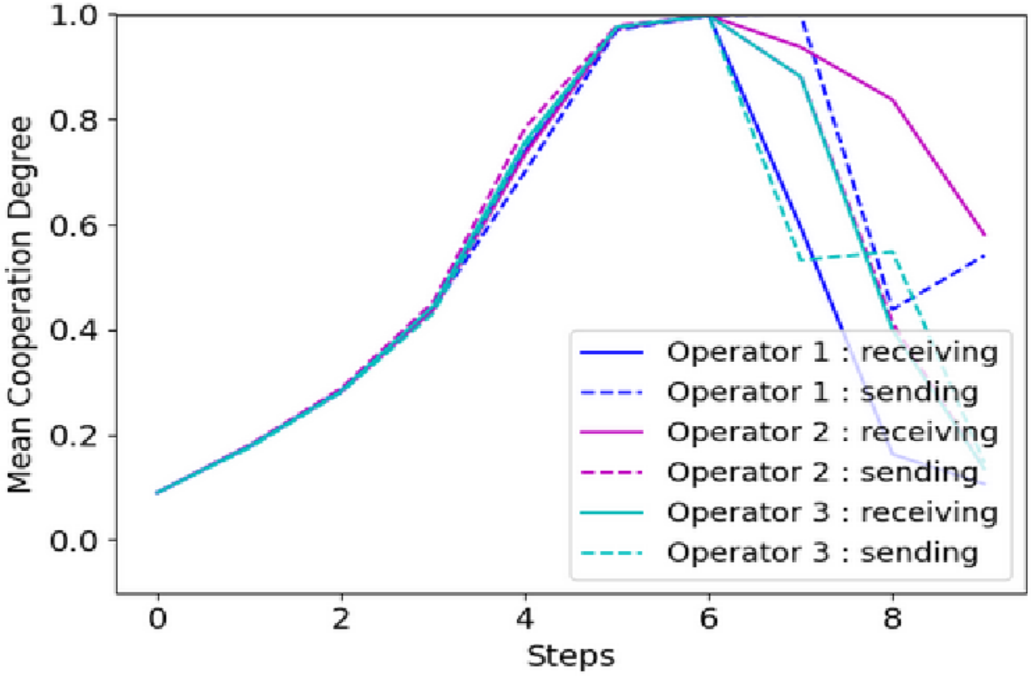

Fig 5. 2: Mean cooperation degrees of exchanging traffic between three TFT operators with (α = 0.5, r0 = 0.2, β = 0) standard TFT configuration

The simulation results for two TFT operators with the average cooperative traffic exchange and one Sel1fish operator (*op1) are shown in Figure 5.3. And we have examined the performance of the proposed scheme with different BS switch ON/OFF probabilities between operators. The simulation result shows that expected gains increase with BS switching off probabilities; this shows our proposed scheme is significant for BS switching off among different cooperative and competitive operators that operate in the same geographical area.

Operators 2 and 3 follow optimal strategy, or Nash equilibrium (NE), in addition to that they follow TFT (a= 0.5, r0 = 0.2, β = 0) standard configuration in our proposed algorithm of the game, but the strategy or probability of Operator 1 (s1, j) mathematically expressed from eq. (4.1) in Section 4 is greater than the probability in NE, which is 57% BSs switching off probability, as shown in our simulation results. That means more of operator 1's BS in each cell is deactivated without QOS degradation. Due to this, the expected individual cost of operator 1 was higher than operators 2 and 3. These two operators are exploited by MNO1. Even though the two operators are exploited by selfish operators (1), the cooperative expected payoff is greater than that of NE strategies, which shows that Nash equilibrium is non-optimal. Operators have no incentive to cooperate compared to other strategies.

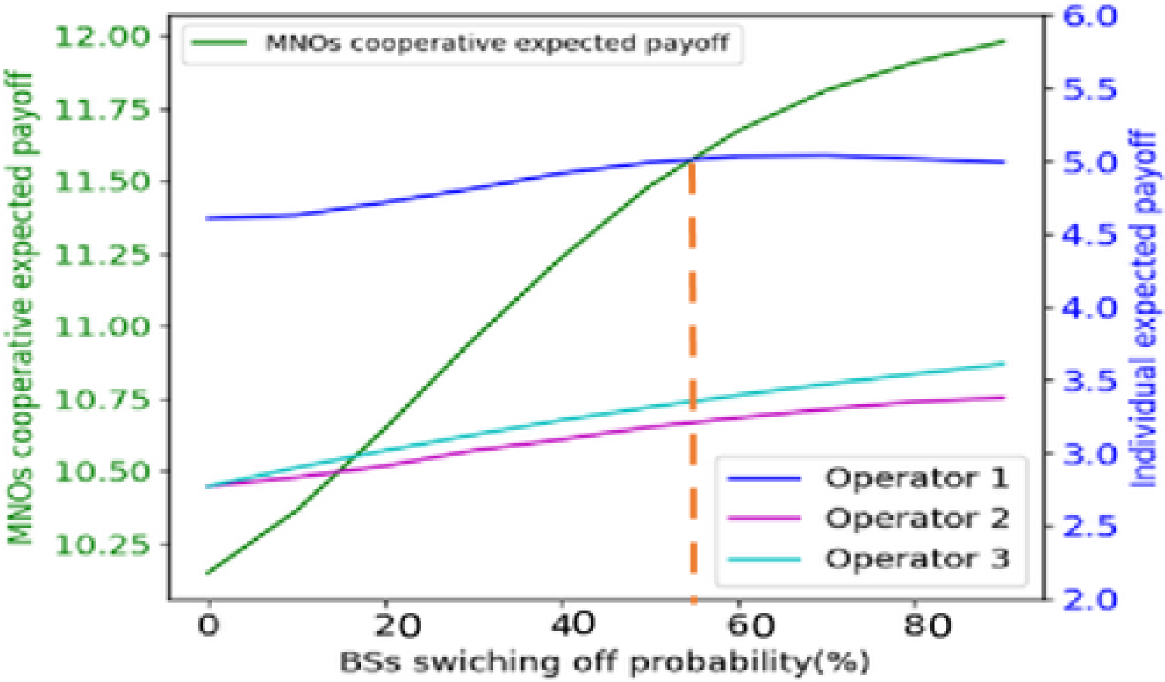

Figure 5.3: Expected payoff vs BSs switching off probability with two TFT operators with (α = 0.5, r0 = 0.2, β = 0) standard TFT configuration and one selfish operator (*op1)

In Figure 5.4, the simulation results for two TFT operators with a pure tit-for-Tat configuration of (**α** = 0.5, r0 = 0.2, **β** = 0) and one Sel1fish operator (*op1) of average cooperation components of traffic exchange are described. Due to the occurrence of selfish operator (*op1) between operators' the average cooperation degree throughout the game (10 stage games) is only 40%.

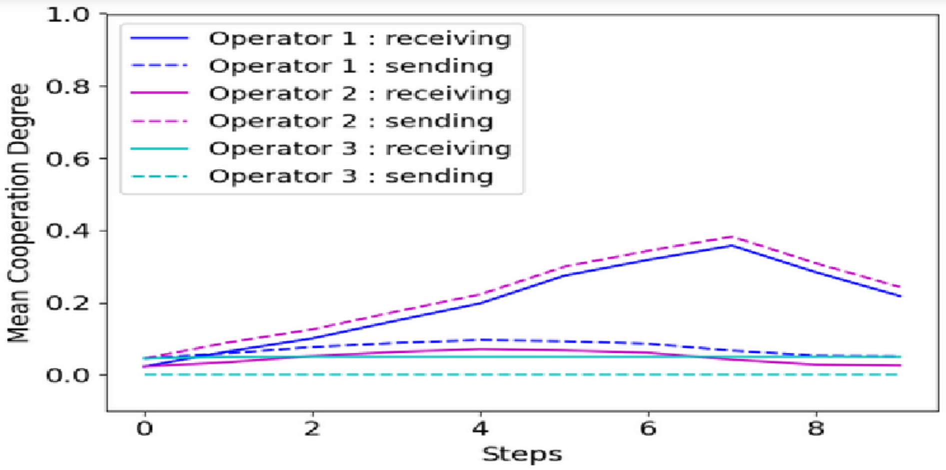

Figure 5.4: average cooperation units of exchanging traffic between two TFT operators with (α = 0.5, r0 = 0.2, β = 0) standard TFT configuration and one sel1fish operator (*op1)

5.2.1. The Effect of TFT Parameters

As described in the preceding section, two types of TFT configuration out of this nonzero adaptive allow the operators to be less exploited by the pure defector (operator 1).

The simulation results described in Figure 5.5 are similar in Figure 5.4, but with adaptive TFT algorithmic parameters (α = 0.5, r0 = 0.4, β = 0.3). Due to this, the BS switching off probability (s1, j) of operator 1 is lower than the NE, which is 30%, as we can see from Fig. 5.5. This indicated that more base stations of Operator 1 remain active (with the highest traffic load) and have a lower individual payoff than the other two. In these scenarios, both individual and cooperative expected payoffs are greater than those of the exploded and NE strategies, which shows that Nash equilibrium is non-optimal compared to the other two strategies expressed in this thesis. We draw attention in fact that the probability of a BS remaining on drops as traffic demand does. Lower switch-on probability results in more BSs being switched off, which increases energy gain.

The simulation results for two TFT operators with average traffic exchange cooperation mechanisms of (α = 0.5, r0 = 0.4, and β = 0.3) are defined in Figure 5.6. The dynamic setup of our algorithm reduces operator exploitation, resulting in an average collaboration degree over the course of the game (10 stage games), which is better than operator exploitation.

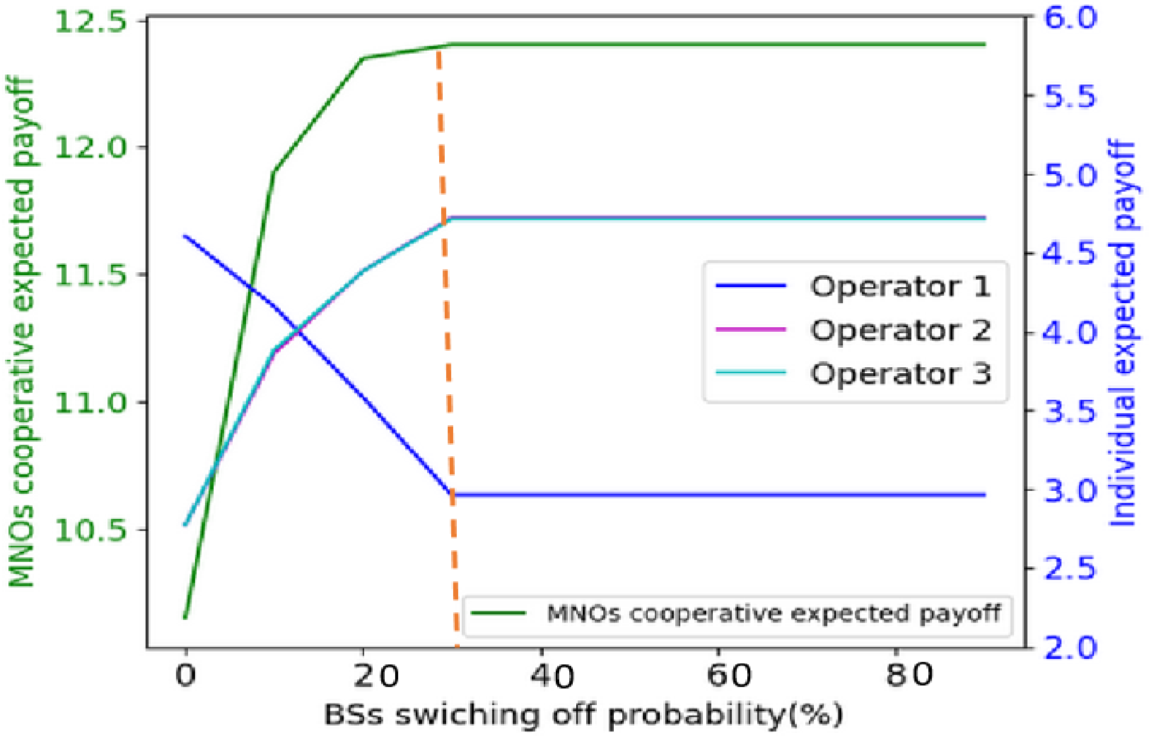

Figure 5.5: Expected payoff vs BSs switching off probability and Two TFT agents one selfish operator1 have a coefficient nonzero adaptive β: TFT (α = 0.5, r0 = 0.2, β = 0.3).

The simulation results for two TFT operators with average traffic exchange cooperation mechanisms of (α = 0.5, r0 = 0.4, and β = 0.3) are defined in Figure 5.6. The dynamic setup of our algorithm reduces operator exploitation, resulting in an average collaboration degree of up to 55% over the course of the game (10 stage games), which is better than operator exploitation.

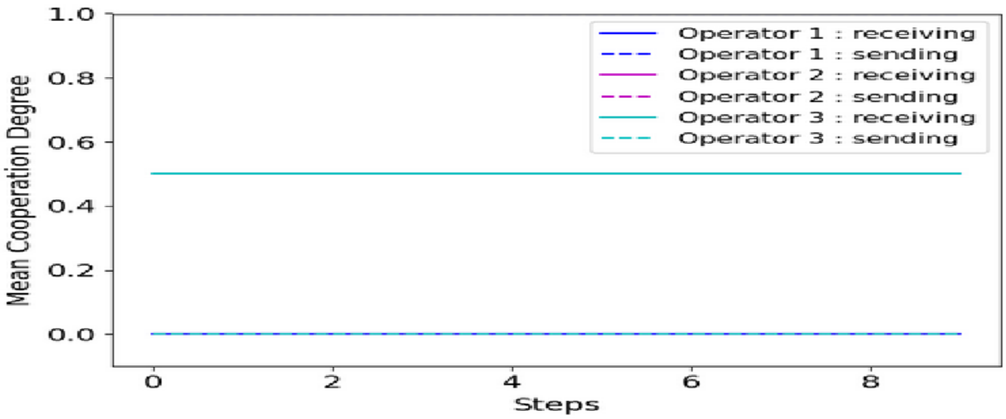

Figure 5.6: Average cooperation units of exchanging traffic between three TFT operators with dynamic (α = 0.5, r0 = 0.4, β = 0.3) configuration

5.3. Simulation Results and Analysis of Roaming-Based Multi-operator System Throughput Maximization Framework

5.3.1. Simulation Scenario

We assume a small cell LTE network topology comprising two operators each with one BS and a Poisson-distributed mean load of 10 and 30 users in their given access area in lower and higher traffic load respectively. The BSs are deployed in small areas (0.5*0.5km2), and the users are uniformly distributed within the operator's access area. The case we consider to deploy these topologies is RAN resource efficiency, which can also be described as how massive a data rate (in Mbps) can be successfully sent per unit spectrum (Hz).

The BSs' locations and coverage areas are illustrated in Fig. 4.5. Produced a mean system-level simulation presented with the MATLAB results of the proposed frame work has been presented in the previous sections. i.e., the roaming-based dynamic RAN sharing systems between two players are investigated and examined over non-roaming scenarios with varying Load factors.

Throughout the simulation, the number of UEs follows a Poisson distribution with a mean traffic load (μ_a) for mobile network operator A and (μ_b) for Mobile network operator B. We deliberate two scenarios where two operators have equal unequal mean traffic loads in the assumed access area of both operators. The minimum mandatory data rate of 4096 kbps was applied in our system-level simulation [39]. The simulation has been concentrated on the downlink power allocation, keeping the user sensitive to worse SINR. We consider a simple power-law distance-based propagation path loss model for a carrier frequency of 2.4 GHz. The signal power attenuates or diminishes distance-based path loss in the free space area. The distance D between bastions and users

The degree of roaming-based RAN sharing between MNOs depends on inter-operator traffic load variations, which played a significant role in this simulation. The objective function in terms of system throughput maximization for the game were expressed as equations (4.14 to 4.18) for each stage and (4.19) for the entire game, as stated in chapter (4). The game has two operators, and the strategy is Tit for Tat to achieve the maximum reward behavior [41]. Considering that a particular number of stages that can be used to simulate the game. For the purposes of simulations, we have used 200 duration stages of games, and examine the outcome.

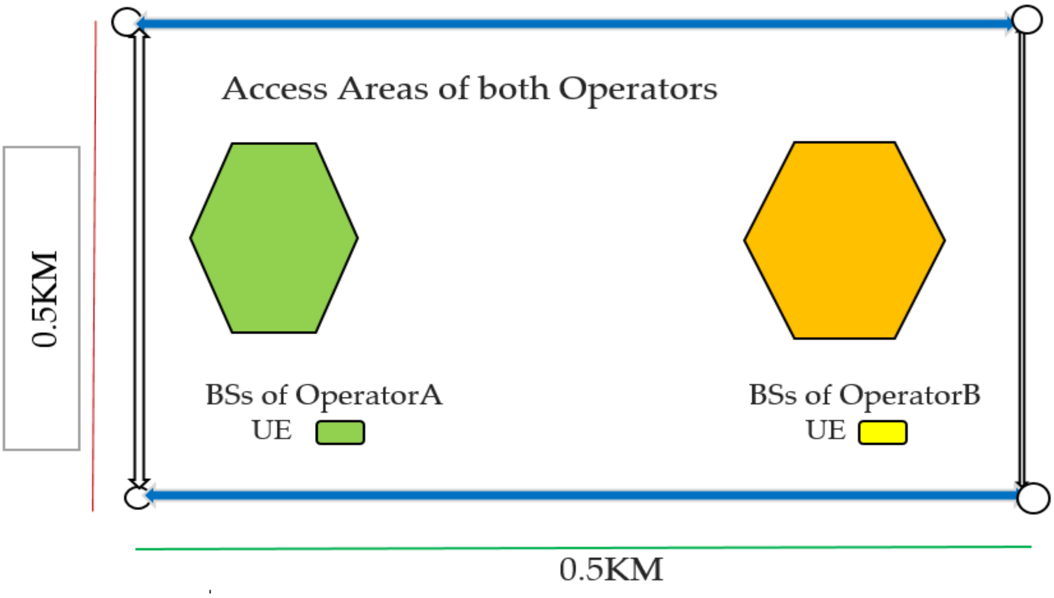

Figure 5.7: Two operator deployment scenario

5.3.2. Simulation Parameter

All necessary proposed system parameters are specified below in Table 5.3. The aforementioned parameters and cross ponding values defined in this section remained from 3GPP and ITU recommendations, mainly [39] [40] [28].In addition to that, the considered parameters were also taken from the Ethiotelecom engineering and optimization sections. The effects are obtainable for a 200-stage game occurrence, produced based on the parameters mentioned in Table (5.3), before examining the actual simulation results. Initially, both operators use their own resources independently.

Simulation scenarios and parameters are depicted in Fig.4.5 which includes:

- Traffic load variation
- Percent of shared resources (partition resources) from host operators to gust operators to serve the roamed traffic
- Equal and unequal mean loads
- Simulation area size

- No. of Operators
- Game iteration (steps) for sharing mechanism

The remaining parameters for simulation are as follows:

Table 5. 3: Simulation Parameter values according to ITU and 3GPP release documents

Parameters	Values
Geographical settings	
Number of mobile operators in the access areas	2
Number of UEs per operator	Poisson Distribution Load with mean number of 10 or 30 users
Number of BSs of the two operators	2
Simulation Area[Km2]	0.5*0.5
Fixed path loss D [dB].	-35
The reference distance r0 [m]	10

Parameters	Values
Game iteration number(steps)	200
SNIR Min/Max for all UEs in the system[dB]	[-4,13]
Carrier frequency	2.6e9
Max transmit power Pr, max[dB]	37
Noise power N0 [dBm/Hz].	-174
Antenna patterns	Omni directional
Bandwidth for each operator is B[MHz]	10
Required data rate for each UE is C [Mb/s]	0.1

5.4. Simulation results and analysis

In this section, we present the simulation findings that we used to examine the effects of roaming amongst MNOS on system throughput. In order to verify and assess the power of roaming, our proposed model is compared with a non-roaming instance in this section.

Different UE traffic loads (symmetric and asymmetric situations), the percentage of shared resources from the total amount of shared resources, and coverage areas are used to compare the roaming and baseline non-roaming models. The baseline system is a non-cooperative mobile network with each operator supporting only its own UEs and no roaming between operators. The identical resources distribution technique is applied in both schemes. In the suggested model, the proportion of user data rate is determined using various distances between BSs. In order to maximize total system throughput for mobile network operators, we implement the TFT algorithm with realistic setup parameters, as discussed in system model 4.5 in the preceding sections. Additionally, an illustration is shown of how the cell central range affects the roaming zones between operators. Also presented the ideal cell core radius. The overall system throughput is a multiple of the symmetric or asymmetric traffic load factor, which correlates to the SINR, and the roaming resources factor Δm, which correlates to the cell coverage, as was previously stated in this work. Eqn (4.14-4.19). The first is the effect of UE loads on power usage in roaming and non-roaming situation (from a capacity perspective), which is the basis for the comparison. The second is how (from a coverage standpoint) the two situations' respective power usage is impacted by the coverage region.

Simulation results are discussed and established on different setups, i.e., the simulation range distances between each BS and random distribution users, roaming factor percent of shared resources to achieve maximum throughput in the system, and the above-mentioned parameters. In figure 5.8, simulation results of users randomly distributed in the proposed access area shows bastions of path loss as a function of distance between users and BSs. In figure below shows, that path loss increases as the distances between BS and users increase.

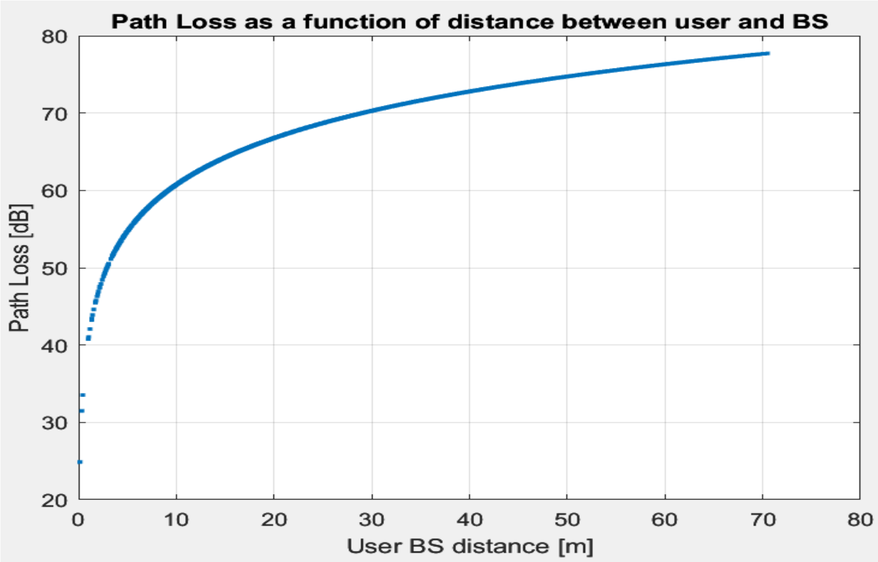

Figure 5.8: Path loss as a function of distances between BS and users

5.4.1. Equal user traffic load between operators ($\mu_a = \mu_b$)

Simulation results for the considered roaming based sharing model achieved in the conditions of two operators, OPA and OPB, have equal average user traffic ($\mu_a = \mu_b = 30$) for the simplicity of our simulation in the access environmental region. Simulation in 200-step games with the same average load is explained in Figure 5.4. That shows the entire amount of RAN resources of both operators in every single step iteration is available to roam their traffic based on distance.

The mathematical outcome of the ordinary gain throughput of two MNOs (OPA and OPB) with equal traffic for proposed roaming-based inter-operator throughput maximization using repeated non-cooperative games compared to the non-roaming scheme expressed in the above proposed mathematical game illustrations

In our simulation, we gained throughput with equal traffic when comparing roaming with non-roaming mechanisms in the case of simulation area sizes. In this thesis, we have designed two operator network topologies with (0.5 [km] * 0.5 [km]) deployment cases. The performance of the proposed game roaming strategy outperformed the non-roaming strategy regardless of the results in deployment access area sizes.

Figure 5.9 shows the simulation effects of non-roaming scenarios and the proposed roaming-based dynamic RAN distribution framework that illustrates MNOA. The access area average throughput gain is similar to MNOB, as roaming setups have similar mean users. The decision criteria for roaming for both MNOs are chosen randomly based on the core distance, and the system throughput function measures the level of system performance. With mean throughput for both operators, MNOA and MNOB, equal mean loads, and 50 to 70% recovery of repeated non-cooperative 200 game stages of the pool resources shown in Figs. 5.9 and 5.10 below, the proposed algorithm for both MNOs compares favorably with the roaming model and non-roaming scenarios. In both situations, our approach performs better as bassline scenarios.

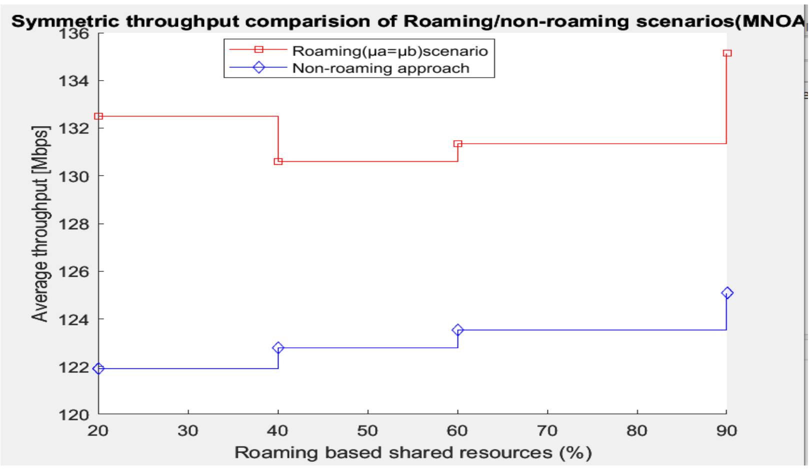

Figure 5.9: Throughput comparison with roaming and non-roaming approaches with equal UEs (μ_a = μ_b = 30) setups for MNOA

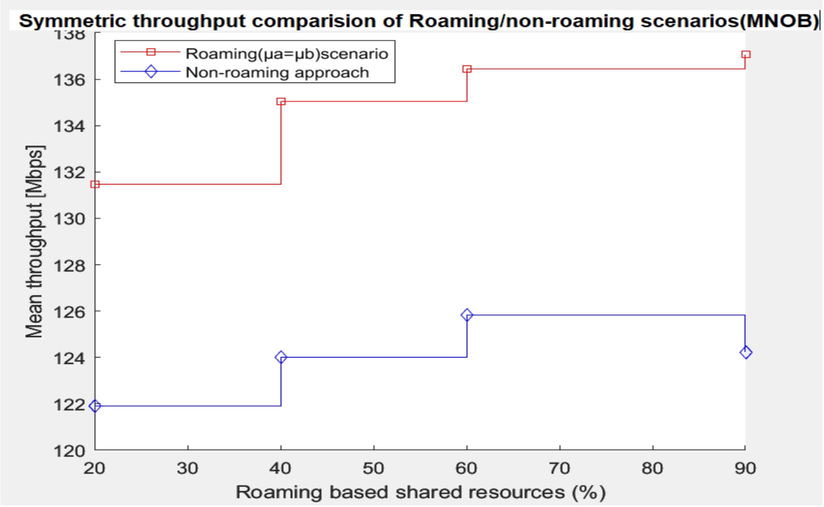

Figure 5.10: Throughput comparison with roaming and non-roaming approaches with equal UES (μ_a = μ_b = 30) scenarios for MNOB

5.4.2. Asymmetric Traffic load Between Operators ($\mu_{a} < \mu_{b}$)

Simulation set-up when MNOs have different numbers of UEs over the given operating specific environmental area. The results obtained for Operator A and Operator B with a mean number of users ($\mu_{a=10}$ and $\mu_{b=30}$) and vice versa by considering temporal traffic variation. Our study demonstrates that the proposed infrastructure sharing scheme uses a roaming scheme with asymmetric and random distribution of users and two mobile network operators. This simulation implements high UEs for operator B and low user traffic for cross-ponding competitive or cooperative operator A. For simplicity's purpose, we have used simulation parameters and cross-ponding values, which are represented in table 5.3 and deployment scenarios described in figure 5.7. The expected roaming-based RAN sharing with non-cooperative repeated games between the operators i.e. MNOA and MNOB are implemented with 200 game iterations in each step of the game exchange traffic simultaneously in the proposed region of the two MNOs. In this simulation, the proposed gametheortic algorithm (TFT) considers the resource sharing factor Δm which ranges from Δm=1 up to Δm=10 described in the above equations (4.20 - 4.29), as a utility function for system capacity maximization with repeated game approaches by both operators.

In Figures 5.11 and 5.12, consider that Operator B is experiencing a high load while Operator A has a low load, i.e., (μb > μa). Now, two approaches arise: either in high traffic load, operator B gets more RAN resource usage in terms of a resource sharing factor (Δm) from low traffic load operator A, or vice versa over the next 200 iteration games

(t + 1) With traffic variations between both operators of μa = 10 and μb = 30.Throughput is plotted for both operators with respective Poisson-distributed mean loads of 10 and 30 UEs for operators A and B, respectively. We have considered load reversal approaches to evaluate the power of algorithm with varying traffic loads.

Figure 5.11 shows the simulation result contrast of the roaming-based RAN distribution framework and non-roaming approaches for low-loaded traffic for operator A. Our interpretation based on simulation results is that the throughput gain of the proposed game in low-loaded operators (A) is not significant compared to non-roaming cases, and in operator

B (high traffic), the main case is that this low-loaded operator loses its RAN resources in the form of (-Δm) to serve the competitive operators traffic. Taking into account that participating in the game is always beneficial, in the given access area, the average throughput gain between operators is not similar to the case of asymmetric user traffic.

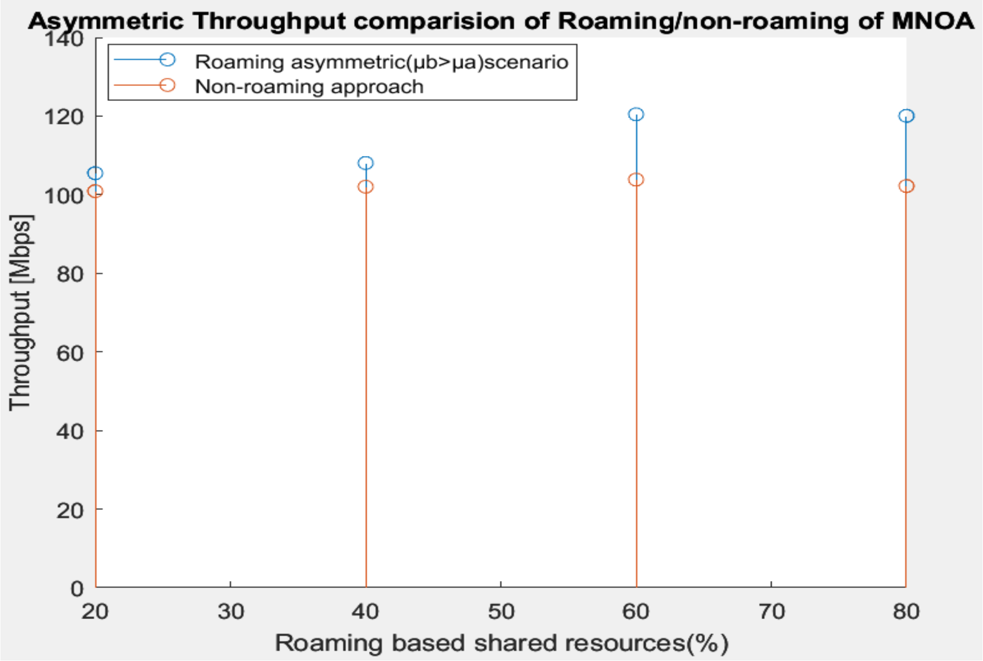

Figure 5.11: Throughput comparison with roaming and non-roaming approaches with unequal UEs (μb > μa) setups for MNOA

The second simulation scenario is roaming infrastructure sharing with high traffic load **μb** =30 operator (B), which is described in figure 5.12. In these scenarios, this operator can increase its throughput in comparison to low traffic load (A) and also non-roaming cases due to the use of high RAN resources, up to 60–70% shared from low-loaded μa=10 MNOA in 200 repeated games. The access region also has a maximum resource sharing factor Δm=7 implemented in MNOB.

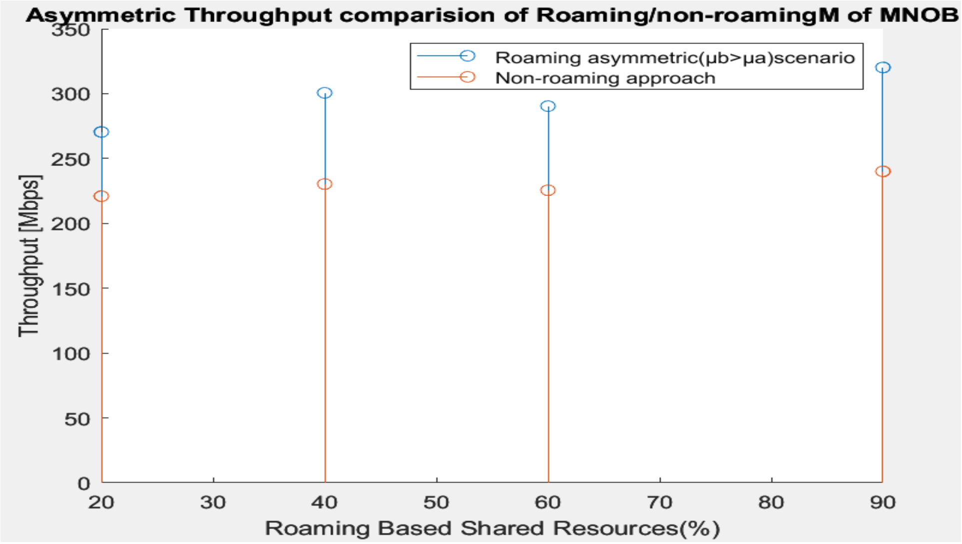

Figure 5.12: Throughput comparison with roaming and non-roaming approaches with unequal UEs (μb=30 and μa = 10), setups for MNOB

Simulation result indicates that properly modelled games provide a gain in terms of system-level throughput with respect to traffic-dependent roaming system network sharing scenarios over time. Importantly, we can conclude the proposed algorithm outperforms the baseline approaches and provides significant gains (i.e., 350 Mbps of our proposed game gains and 250 for the conventional approach for two MNOs in a 0.5 km*0.5 km game) when number of UEs served by an operator is relatively large in the asymmetric manner described in figure 12. The system performance of the game is strongly dependent on several system parameters, such as the number traffic, SINR, and sharing factor.

In Figure 5.13, Throughput and traffic exchange during simulation in each game iteration are shown. The shared resources (%) increase with user data rate by arbitrary points and converge to their initial state. In these repeated games, the average throughput gain is up to 35–37 Mbps per game iteration, considering temporal load variations.

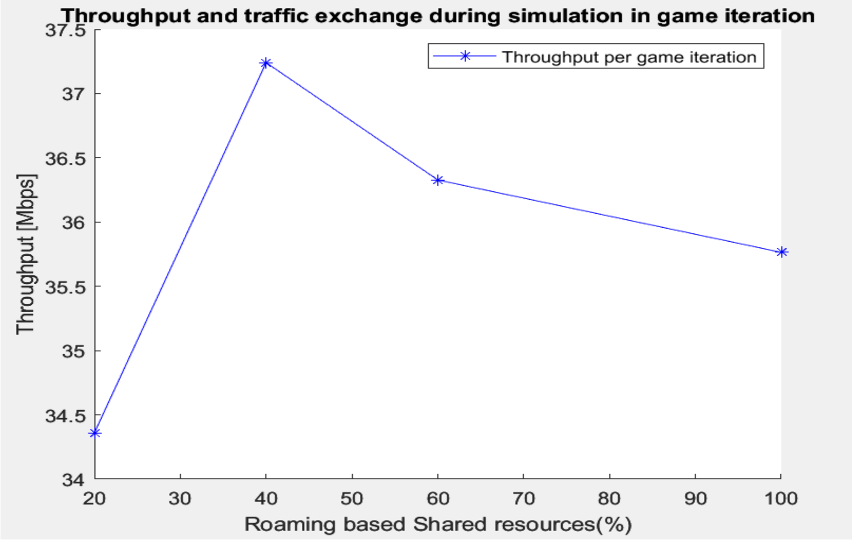

Figure 5.13: Throughput and traffic exchange during simulation in each game iteration

The overall proposed game throughput gains are significant when traffic load is asymmetric and MNOs average traffic loads are relatively high, as shown in 200 game steps in comparison with non-roaming (the conventional approach in figure 5.14) and the gains up to 100 Mbps. System throughput for non-roaming is almost the same, but in roaming, throughput gain is dependent on traffic loads.

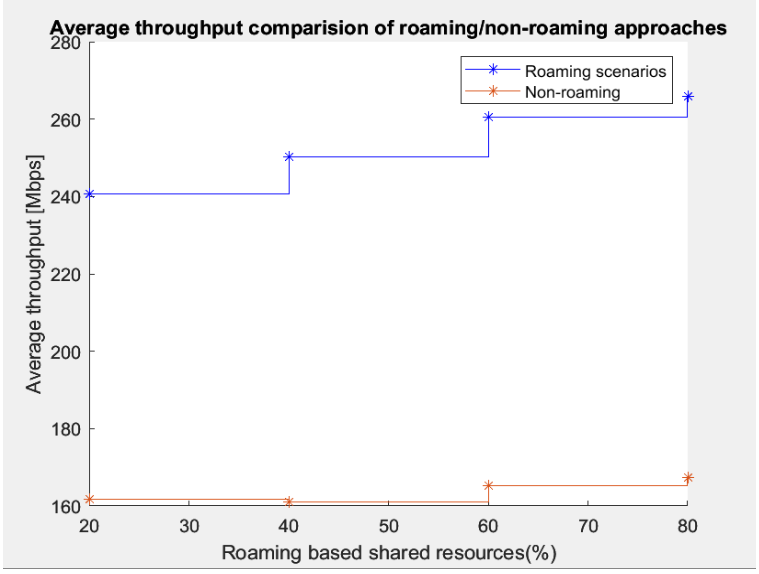

Figure 5.14: Throughput comparison of the proposed scheme and non-roaming cases of the system

CHAPTER SIX

6. Conclusion, Recommendation and Future Works

This chapter begins with an overview of the research work of the study and ends with some recommendations and ideas for future work directions.

6.1. Conclusion

In this thesis, we investigated the possible energy savings introduced by the existence of redundant BSs in multi-operator environments. Motivated by the coexistence of several MNOs in the same area, we introduced the concept of roaming-based infrastructure sharing among MNOs, which offers additional possibilities to the operators for having their traffic served in regions where they decide to switch-off their BSs. We proposed a mathematical model based on strategic non-cooperative game theory and a novel collaborative framework to adopt more suitable BSs switched off in low-traffic scenarios. Implementing this framework enables the operators to decrease their individual operating costs by approximating their steady-state probabilities.

In simulation analysis, our framework outperforms state-of-the-art solutions by providing up to 50% BS switching-off probabilities while keeping QOS. In the case of operational costs, the operators provide the necessary individual and cooperative incentives to participate in network infrastructure sharing. But Nash equilibrium is non-optimal solution, and operators have no better incentive to cooperate compared to other strategies provided in this thesis.

In this paper, we have also investigated roaming-based infrastructure sharing between two MNOs. To maximize the system capacity and QOS of the MNOs that operate in the same geographical region. We have proposed a repeated non-cooperative game scheme and discussed in different scenarios, namely I) distances between users and BSs and II) symmetric and asymmetric traffic load cases, to show roaming effects under the proposed scheme. Based on a coordination protocol of tit-tat-strategy for exchanging traffic during equal and unequal loads to use resources efficiently and enhance system capacity.

Our simulation results describe that the proposed model provides a gain in terms of system-level throughput, comparable with roaming and non-roaming cases. In all scenarios, our model performs better than non-roaming models. Innocently, throughput gains are significant for operators that have asymmetric cases and serve large users relatively well; the gains are up to 100 Mbps, which was approved in our simulation. As a result, we think that using this approach to analyze cooperative energy-saving and maximize system capacity scenarios could have significance.

6.2. Future Work and Recommendation

The study conducted for this thesis could be expanded in several areas; thus, we do not expect it to be complete.

- In this thesis, I have generated various hypothetical cellular network environmental parameters (MNOs, users, and BSs) mathematically using game theory due to the unavailability of realistic data about infrastructure sharing currently in our country. But it's possible to extend it by collecting realistic continuing data, e.g., power consumption and user data rate.
- In this simulation, we considered a small urban area deployment scenario for the sake of simulation with minimum UEs and cross-ponding BSs. But it's possible to model and extend the game for densely populated areas, including shadowing with more than three operators.

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APPENDICES

APPENDIX A

Proof, simplifying of sharing factor $(1+2\frac{\triangle m}{m})^{\mu_a}\ (1-2\frac{\triangle m}{m})^{\mu_b} > 1$ 4.30

ΔM resources transfer to highly loaded operator from lightly loaded using TFT algorithm $T_g\ (M^{t+1}) > T_g\ (M^t)$, where M^{t+1} and M^t are game step resources.

Operator OPA T_{ga}, accordingly, $T_{ga}\ (\frac{M}{2}+\triangle m) > U_{ga}(\frac{M}{2})$ 4.31

$$\mu_{a,}\log\ (\frac{M}{2}+\triangle m)\ \frac{1}{\mu_a}\log_2\ (1+\gamma a) - p1\ (\ e^{p2(\frac{\frac{m}{2}+\triangle m}{m})}\ -1)\ >$$

$$\mu_{a,}\log\ (\frac{M}{2}\ \frac{1}{\mu_a}\log_2\ (1+\gamma a)) - p1(\ e^{p2(\frac{\frac{m}{2}}{m})}-1) \qquad 4.32$$

$\mu_{a,}\log\ (\frac{M}{2}+\triangle m)\ -\ \mu_{a,}\log\ (\frac{M}{2}) > p1\ (\ e^{p2(\frac{\frac{m}{2}+\triangle m}{m})}\ -1)\ -\ p1(\ e^{p2(\frac{\frac{m}{2}}{m})}\ -1)$ Similarly, operator OPB checks its throughput, U_{gb} ,

Accordingly, $U_{gb}(\frac{M}{2}-\triangle m) > U_{gb}(\frac{M}{2})$

$$\mu_{b,}\log\ (\frac{M}{2}-\triangle m)\ -\ \mu_{b,}\log\ (\frac{M}{2}) > p1\ (\ e^{p2(\frac{\frac{m}{2}-\triangle m}{m})}\ -1)\ -\ p1\ (\ e^{p2(\frac{\frac{m}{2}}{m})}\ -1) \qquad 4.33$$

APPENDIX B

Two scenarios of the proposed game proof and simplify

Case I: High traffic operator $0P_a$ obtains more from low load

Operator OP_b game t + 1,

$$G_a^{t+1} > \widehat{L_a^t}$$

$$L_b^{t+1} < \widehat{G_b^t} \qquad 4.34$$

Case II: Low traffic operator OP_b gets resources from high load operator OP_a at

Game step t + 1

$$G_b^{t+1} > \widehat{L_b^t} \qquad 4.35$$

$$L_a^{t+1} < \widehat{G_a^t}$$

$$G^{t+1} = \text{N} \log \left(\frac{M^{t+1}}{N} \log_2 (1+\gamma)\right) - \text{N} \log \left(\frac{M^t}{N} \log_2 (1+\gamma)\right)$$

Where M^t is current resource of current game, M^{t+1} is the next resources ($M^{t+1} > M^t$), γ is the SNR and N is the load an operator. Simplifying G,

$$G^{t+1} = \text{N} \log \left(\frac{M^{t+1}}{M^t}\right) \qquad 4.36$$

Immediate loss for an operator (with $M^{t+1} < M^t$) can be shown as

$$L^{t+1} = \text{N} \log \left(\frac{M^t}{M^{t+1}}\right) \qquad 4.37$$

It is observable in both G^{t+1} and L^{t+1} larger for high load N, with $N_a > N_b$

$M_a^t = M_b^t$ =M/2, M_a^{t+1} = (M/2) + x and M_b^{t+1} = (M/2) - x

Where 0 < x < (m/2) it can be implied that

$$G_a^{t+1} > L_b^{t+1} \qquad 4.38$$

M_b^t / M_b^{t+1} is slightly superior than M_a^{t+1} / M_a^t

Game Theoretic Frame Work Based Energy Efficient RAN Infrastructure Sharing in Multi-Operator Mobile Networks

Tewodros Misgan
School of Electrical and Computer Engineering. AAiT
Addis Ababa, Ethiopia
tewodrosmisgan13891@gmail.com

Dr.–Eng. Yihenew Wondie (PhD)
School of Electrical and Computer Engineering. AAiT
Addis Ababa, Ethiopia
yihenew.wondie@aait.edu.et

Abstract *Key word*

This thesis explores roaming-based infrastructure sharing among three mobile network operators (MNOs) to reduce energy and cost by switching off their base stations and roaming traffic to neighboring BSs during low-traffic periods, while maintaining Quality of Service (QOS).

We have proposed mathematical models all over this thesis based on novel non-cooperative game theoretic strategies to model and evaluate competitive interactions among MNOs. This strategy is modelled as an integrated cost-based objective function by applying different scenarios to determine which base stations should remain active. In this method, operators share infrastructure and dynamically roam their traffic to maximize throughput. We have implemented the Tit-for-Tat (TFT) algorithm to share a portion of their network and optimized it with three MNOs operating in the same area with varying traffic loads and distance (D) between UEs and BSs. We also implemented the TFT algorithm's hyper parameters. A MATLAB simulation tool was employed to evaluate the performance of proposed scheme. We demonstrate simulation results in different scenarios to quantify the financial benefits due to energy savings from our proposed scheme, which provides up to 50% BS switching of probability to MNOs and throughput gains up to 100 Mbps with roaming-based traffic load variations compared to baseline approach.

Key word ---- *Infrastructure Sharing, Roaming, Game Theory, BSs Switching-Off, Nash Equilibrium, Multi-operator*

I. INTRODUCTION

Globally, mobile data traffic has been growing exponentially in recent years, and the number of cellular network subscribers has been increasing at an exponential rate. According to [1], at the end of 2021, there will be around 8.2 billion mobile subscriptions. This number will increase to around 9.1 billion by the end of 2027. been increasing at an exponential rate.

According to a forecast by Ericsson mobility, global mobile data traffic would increase by a factor of 5 from 58 exabytes (EB) per month at the end of 2020 to 300 EB per month in 2026 [2]. The forecast also reveals that by the end of 2026, 5G will lead traffic growth with 53% of the total mobile data traffic. Cooperation between operators, by sharing their resources, tends to be required to achieve reductions in energy consumption and financial cost. It is usually necessary for operators to work together and share resources in order to reduce energy usage and costs.The common trend among network operators is to continually implement infrastructure expansion mechanisms, but energy and operating expenditure (OPEX) costs are a great challenge for cellular network infrastructure enhancement.In [3] and [4], mobile data consumption is expected to grow at a faster rate, and capacity challenges will continue to exist in Ethiopia for future.

II. PROBLEM STATEMENT

Telecom operators, including Ethiotelecom, deploy their networks considering peak traffic volume to undertake QOS in high traffic scenarios, but in low traffic scenarios, the minimum amount of BSs is enough to solve the traffic. Existing BSs are underutilized and redundant, especially with low traffic on the network. And the major challenges are energy consumption, waste of RAN resources, CAPEX, and OPEX costs of cellular networks [5]. The base station (BS) consumes 60-80% of cellular network power, especially at high traffic loads, and energy consumption increases proportionally with traffic load. This research addresses energy consumption issues in Ethiopia with multiple network operators.

To overcome the above problems, we have proposed multi-operator infrastructure sharing techniques among operators that operate in the same geographical area. In this thesis, we have proposed i) BSs switching off framework work between multi-operators and serving a certain geographical area jointly during low traffic periods (night zone), when the base station capacity is underutilized, to reduce operational costs and energy efficient [6]. Means that operators switch off their bastion and roam their traffic to active neighboring operators during low traffic cases. ii) Roaming-based infrastructure sharing between operators during RAN resources is underutilized when the load conditions of neighboring operators are subjected to temporal traffic variations. In this scenario, a high-load operator could transfer its traffic to a low-load operator by using the dynamic infrastructure sharing (roaming) technique to increase system capacity and QOS between operators. The interaction among operators can be modelled and analyzed using game theory.

III. LITERATURE REVIEW

This paper reviews studies on infrastructure sharing among network operators in the same geographical areas, focusing on passive and active network sharing. It discusses strategies for improving energy efficiency and effective resources utilization through cognitive radio or cooperative spectrum sharing.

In [7] the rapid expansion of mobile networks has increasing costs and energy consumption for operators. To address underutilization during low traffic, a novel game-theoretic framework for infrastructure sharing has been proposed, allowing MNOs to independently estimate switching-off probabilities, reducing conflicting interests.

In [8], the study suggests that multi-operator connectivity can enhance reliable communication by providing redundancy and implementing super quantiles. However, this can lead to lower spectral efficiency, particularly in high-demand networks, which can increase demand for scarce resources, potentially decreasing the capacity offered to subscribers.

The game-theoretic methodology introduced by Bousia et al [9], Enables the MNOs to independently estimate the switching off probability that lower their expected financial cost. Regarding the switch-off pattern, choose the one that balances the switch-off time periods, roaming expenses, energy savings, and quantity of energy saved to greatest extent possibly up to 35%

Marsan and Meo propose two BS sleeping schemes for multi-operator situations: roaming-to-one and roaming-balanced. The first uses one BS during low traffic, while latter switching off BSs to balance costs. Both strategies reduce energy consumption [10].

This thesis proposes infrastructure sharing with three operators in the same geographical area to increase efficient RAN resource utilization during low traffic periods, mainly in the night zone. MNOs aim to collaborate to benefit from resources, resulting in closer or lower load. Study considers clusters of three operator cells and their interaction in a non-cooperative tit-for-tat strategy game.

IV. SYSTEM MODEL AND PROBLEM FORMULATION

This section takes into account a region covered by three operators. Each operator's BSs completely cover the area, and the network is sized to accommodate peak traffic volumes. Therefore, BSs can occasionally be redundant, especially when the network's traffic load is very low. We propose an energy-efficient mechanism in which the three operators work together to switch off/on number of BSs and pool their resources to serve the area together during times of low traffic [7], [12].The behavior of users, which varies greatly during the day, has a direct impact on the traffic load of cellular network. As a result, a typical cellular network's traffic load drastically changes during a day. The real network traffic load will vary dramatically over the course of a single day, with highest traffic load occurring from 10:00 AM to 18:00 PM and lowest traffic load being from 2:00 AM to 6:00 AM at midnight according to figure 1 which is a general telecom traffic trends

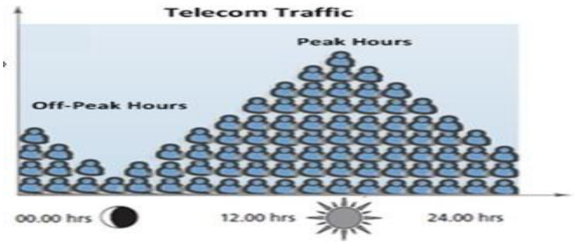

Fig.1. daily traffic load variations during 24-h [12]

A portion of the BSs will be idle when traffic load is very low because operators currently deploy their BSs in accordance with peak traffic demand to give comprehensive coverage of an entire area regardless of variable traffic loads [12].The main contribution lies on the following:-

(i) We propose a game-theoretic algorithm used in real, multi-operator centralized networks.

(ii) Operators decide if infrastructure sharing will be viable, we outline the cost analysis clearly accounting for operational, roaming, and overhead costs.

(iii) The study presents an analytical probabilistic model assessing network performance, demonstrating how our technique enhances network energy efficiency without compromising QOS.

A. System Modelling and Assumption

In this thesis, we have considered a geographical area served by three different MNOs. This area consists of a seven-cell cluster among three mobile network operators, as shown in figure 2. Each cell is covered by three BSs from three MNOs. Such a system is the most energy-efficient with the minimum number of BSs [9]. The central BS is always on to ensure QoS [7], whereas the six surrounding cells (j) are subject to the switching-off algorithm. To agree whether they would be switched off or not. Once three BSs in the same cell select to switch off at the same time, the central BS will increase its transmission power, expanding the communication coverage to the surrounding cells where both BSs are switched off. The traffic load of the switched-off BSs will be roamed to the central BSs. The three steps in the switch-off scheme:-

Step1: Three operators' BSs calculate operational costs, including unique roaming and overhead expenses, and assume X2 interface access for traffic load data in the same cell [7].

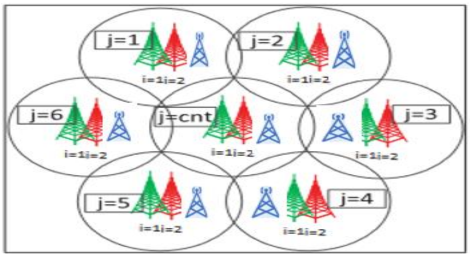

Fig.2. Seven - cell cluster of three MNOs [9]

Step 2: The BSs use a non-cooperative game theoretic scheme to choose whether or not to switch off their BSs based on cost functions.

Step 3: Cells with some BSs that need to be turned off are stacked on top of the other cells to create a list of the six cells. To switch cells with the same number of BSs, the ones that receive the least overall traffic are switched-off first. Following the BSs at the top are switch-off, and the remaining BSs handle their traffic. Optimize the objective function until maximum number of switched-off BSs is reached without degrading QOS; step 3 is repeated

B. Game Formulation

In our case, reducing energy use is the main objective. Maintaining QoS that diminishes if all BSs are turned off. Base station switching on/off method as a static non-cooperative game with complete information where each operator

I in each cell j chooses the strategy that minimizes its own cost, to evaluate this contradicting scenario. The proposed game has three major components:

G = (N, A, E [Ci, j]) [7], [9]

Set of operators: N = three operators, analogous to BSs of the 3 operators in each cell, i = 1, 2, 3. and j cells j=1, 2, 3,4,5,6 and 7

Set of actions: Each operators has two possible actions: remain on or switch off, i.e., A = (ON, OFF).

Set of cost functions: Cost of an action as a real number. Each MNOs has an individual cost function E [Ci, j] that includes both the roaming and the operational energy consumption costs of each BS, thus focusing on the energy aspect of the problem. The strategy si, j of the BS of operator i in a cell j determines its switch on/off probability. In particular, si, j = 0 denotes BS switch-off, whereas si, j = 1 denotes the operator staying on. The game features 3 MNOs in each cell, with a cost function representing operational costs, roaming, and central BS power increase. As a result, the proposed game is symmetric by definition, enabling us to:

i) To formulate the problem with two macro-players (player A is a given $MNOi$, while player B consists set of remaining (N-1) MNOs

ii) To study the problem from the operator A point of view, generalizing the findings for every player; and,

iii) To formulate problem with two major-players, thus from the view point of operator A, and the other operators B and C.

In a strategic game, stable states, also known as Nash Equilibria, define players' actions. These states provide a certain payoff (response .cost) that cannot be increased or decreased if players unilaterally alter their decision. The study explores mixed strategies in real systems, addressing the challenge of selecting a pure strategy. The expected cost function for player A is defined as

E [Ci,j] = f (si, Sj, N,$Cost_k$), where $Cost_k$ represents the respective costs in each of the four different cases. The expected cost function includes four costs: fixed cost for BS operation (C_{const}) cost for serving traffic (C_{tr}), cost for increasing central BS power (C_{inc}), and cost for roaming traffic to another operator in the same cell (C_{roam}). C_{roam} [7]. Table. I, including different cost functions.

TABLE I. Cost matrix of the propose game [7]

Operator B and C

		ON	OFF
Operator A	ON	$C_{const} + C_{tr}$	$C_{const} + (\bar{N}_{\mathrm{roam}}+1)C_{tr} - \bar{N}_{\mathrm{roam}} \cdot C_{roam}$
	OFF	$C_{roam} = \alpha * (C_{const} + C_{tr})$	C_{inc}

Where, $\bar{N}_{\mathrm{roam}}$ The number of roaming BSs.

α is the roaming cost factor

Total estimated cost paid by those three operators in the above cost matrix of the propose game expressed as:

Expected cost, E [$C_{(\mathrm{i,j})}$], operators (A, B and C) = {(1, 2), (2, 1)} is given by:

$$E\,[C_{(\mathrm{i,j})}] = \bar{s}_{\mathrm{A},j} \cdot \bar{s}_{\mathrm{B},j} \cdot (C_{const} + C_{tr}) + \bar{s}_{\mathrm{A},j} \cdot s_{B,\mathrm{j}} \cdot (C_{const} + (\bar{N}_{\mathrm{roam}} + 1)\, C_{tr} - \bar{N}_{\mathrm{roam}} \cdot C_{roam}) + s_{\mathrm{A,j}} \cdot \bar{s}_{B',j} \cdot (C_{roam}) + s_{\mathrm{A},j} \cdot \bar{s}_{C',j} \cdot C_{inc} \qquad (1)$$

In the above equation, the first term represents the average cost when all BSs are switched off, the second and third term is the average cost when one of the BSs is switched off, and the fourth term is the average cost when all BSs remain on where, i and j are indexes of operators and cells respectively.

$s_{A,j} . \bar{s}_{B,c\,j}$ Strategies of the operators (ON/ON =1, OFF/OFF = 0 ON/OFF =0)

Si, j is the complementary probability equal to $\bar{s}_{i,\,j} = 1 -$ si, j

E $[C_{(i,j)}]$ is all expected costs paid by game player operators

From table I. We have generated four scenarios of BSs on/off states

Scenario 1: Player A is ON, and Player B's operators are all ON. The fixed operational cost for the BS (Cconst) and the variable cost for serving its traffic (C_{tr}) are both included in the total cost for the MNO under investigation.

Scenario 2: Player A is ON, but a portion of Player B's operators are OFF: The switched-off BSs must move their traffic to the active ones in this situation. Typically, player A is permitted to serve N_{roam} BSs on average. As a result, player A's total cost must account for the increased operational expense of accommodating the more traffic (N_{roam} + 1) C_{tr}.

Scenario 3: Player A is OFF, but Player B has at least one operator ON. Although the operator under study has no operational expenses, it is nonetheless required to pay the active operator that handles its traffic (C_{roam}).

Scenario 4: Player A is not playing; Player B's operators are also not playing. In this instance, each MNO is responsible for the additional energy costs increasing the power of BS (C_{inc}) to cover the region of a switched-off BS

C) Objective Function

Operators playing non-cooperative games do not have to maintain the same utility or be aware of the utility of other operators. The utility function is occasionally defined as

$$E[Ci,j] = f\,((s_i, s_j, N, (Cost_k) \qquad (2)$$

Where f represents the objective or optimize function, Operators play strategies to continuously maximize their utility function. $Cost_k$, k ∈ {1, 2, 3, and 4} denote the individual cost in each of the four different cases described above. The probability that minimizes the cost function incessantly

$$\underset{k1\,....k4}{Min}\ \hat{}\ E[Ci,j]\ s.t\ k_i \in K \qquad (3)$$

V. SYSTEM MODELING AND PROBLEM FORMULATION OF ROAMING BASED INFRASTRUCTURE SHARING

In a metropolitan area, two MNOs dynamically serve each other's network traffic to increase capacity and reduce interruptions. Sharing strategies depend on distance, path loss, and traffic load conditions, with roaming criteria governing roaming across cooperative providers.

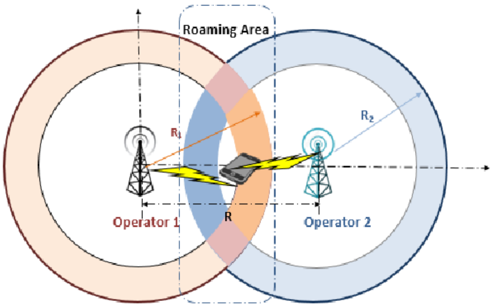

Fig 3. System model of two operators roaming layout [13]

A) Mathematical description of the game

Mathematical analysis of the cooperative game between two mobile network operators, and its network topology and collaboration, which is shown in Figure 3.with roaming-based RAN sharing based on user, BS, and traffic load factor distances. In order to understand how the algorithm behaves, we create the following hypotheses for the sake of simplicity:

- Operators, OPA and B, has its own BS and traffic load.
- The SINR is same for each user in BS's access region.
- Shadowing has not been taken into account;

The system sum rate in terms of traffic load, SINR, and sharing factor, as well as the anticipated throughput of both operators.

$$Ta = \sum_{\mu=1}^{\mu_a} \log \left(\sum_{\mu=1}^{\mu_a} Y_{\mu,m} \log_2 (1+ɼ_a)\right) \qquad (4)$$

$\mu_{a,}\mu_b$ = are average traffic loads of two MNOs respectively

$ɼ_a$ = Are SINR of UEs in the area and same for all users

M = rate of RAN resource

$$Ta = \mu_{a,}\, log\, (\frac{M}{2}\frac{1}{\mu_a} log_2\, (1+ɼ_a)) \qquad (5)$$

Signal-to-noise ratio (considered the same for users in operators A and B) and each operator consists of one bastion for the sake of simplicity. Which is the same for Operator B, we can define the system capacity function in terms of throughput mathematically as follows:

$$Tb = \mu_{b,}\, log\, (\frac{M}{2}\frac{1}{\mu_b} log_2\, (1+ɼ_b)) \qquad (6)$$

In the above figure 3. The average throughput of two MNOs is expressed as the average throughput for both users once we have obtained the system capacity of each user served BSs of its region.

$$Tab = Ta + Tab \qquad (7)$$

Mathematically expressed as

$$Tab = \mu_{a,}\, log\, (\frac{M}{2}\frac{1}{\mu_a} log_2\, (1+ɼ_a)) + \mu_{b,}\, log\, (\frac{M}{2}\frac{1}{\mu_b} log_2\, (1+ɼ_b)) \qquad (8)$$

The proposed model assumes dynamic RAN sharing between two operators with symmetric($\mu_{a=}\mu_b$) and asymmetric traffic ($\mu_{a,}$>μ_b). Operator A transfers traffic to Operator B to increase system capacity and prevent service outages. A partition of resources ∆M is shared with the gust operator. The proposed game average throughputs for GA and GB are calculated.

B) Asymmetric load($\mu_a > \mu_b$) Case between Operators

The proposed game requires more resources for operator A ($\mu_a > \mu_b$), a high-loaded operator, to overcome congestion and effectively use system capacity. The average throughputs of GA and GB are calculated. Average throughput calculation of highly loaded operator A with received ∆M resources from lightly loaded operator B

$$T_{otalG_A} = ((\frac{M}{2} + \Delta M) + \frac{1}{\mu_a} log_2\ (1+ɼ_a)) \qquad (9)$$

Where, sharing factor (F (∆m)) = (1 + 2∆M/M) μ_a (1 − 2∆K/K)μ_a − 1

Average throughput calculation of low loaded operator B which give −∆M resources for higher loaded operatorA

$$T_{otalG_B} = ((\frac{M}{2} - \Delta M) + \frac{1}{\mu_b} log_2\ (1+ɼ_b)) \qquad (10)$$

$$F (\Delta m) = (1 + 2\Delta M/M)\ \mu_b\ (1 - 2\Delta K/K)\mu_b - 1$$

The mathematical equations show that an overloaded operator gains more throughput due to roaming and additional resources, while the average throughput of two MNOs is expressed as the average throughput for both users.

$$T_{otalG} = T_{otalG_A} + T_{otalG_B} \qquad (11)$$

The following mathematical definition also applies to this:

$$T_{otalG} = ((\frac{M}{2} + \Delta M) + \frac{1}{\mu_a} log_2\ (1+ɼ_a)) + ((\frac{M}{2} - \Delta M) + \frac{1}{\mu_b} log_2\ (1+ɼ_b)) + ((\frac{M}{2} + \Delta M)) \qquad (12)$$

But only if the game's average throughput exceeds the aforementioned average throughput of non-roaming cases can we argue that the game is profitable, i.e. Benefit of the game compare to conventional (non-Roaming approach).

$$T_{otalG} > Tab \qquad (13)$$

C) Symmetric load ($\mu_a = \mu_b$) Case between operators

The main concerns during the sharing of a proposed game are operator A and B's equal traffic loads, path loss, and distance between UEs and bases. The new average throughputs, GA and GB, are calculated using resources from the distance-based roaming cell edge area and central environmental zone.

$$T_{otalG_A} = ((\frac{M}{2} + \Delta M) + \frac{1}{\mu_a} log_2\ (1+ɼ_a)) \qquad (14)$$

The average throughput calculation of operator B with received resources from the distance-based roaming cell edge area of the BS of operator B and the cell core zone of operator A is expressed as:

$$T_{otalG_B} = ((\frac{M}{2} + \Delta M) + \frac{1}{\mu_b} log_2\ (1+ɼ_b)) \qquad (15)$$

Average throughput of two MNOs is expressed as the average throughput for both users once we have obtained the system capacity of each user served by each and every BS in the access region in distance-based roaming in the game proposed.

$$T_{otalG} = T_{otalG_A} + T_{otalG_B} \qquad (16)$$

Mathematically expressed as

$$T_{otalG} = ((\frac{M}{2} + \Delta M) + \frac{1}{\mu_a} log_2\ (1+ɼ_a)) + ((\frac{M}{2} + \Delta M) + \frac{1}{\mu_b} log_2\ (1+ɼ_b)) \qquad (17)$$

With the aforementioned average throughput of non-roaming cases, can we argue that the game is profitable, i.e., the benefit of the game compares to a conventional (non-roaming) approach).

$$T_{otalG} > Tab \qquad (18)$$

VI. SIMULATION RESULTS AND DISCUSSIONS

A gametheortic TFT algorithm was developed using Python to validate an infrastructure sharing scheme for multi-operator mobile networks. The algorithm quantifies expected cost gains in energy efficiency and maximizes system throughput. Simulations were performed in MATLAB, examining the performance of the proposed schemes. The simulation scenarios and results contradict conventional approaches, potential of this algorithm.

A. Simulation Results and Analysis of Base Stations Switching Off Algorithm

In this thesis, we focus on cases where N = 3 MNOs. In total, there are 21 BSs in the clustered accessed geographical areas in all 7 cell clusters (i.e., M = 7), of six peripheral cells and one central cell that always remains on, 3 BSs per cell of each 3 MNOs (op1, op2, and op3), and 200 UEs are considered in high traffic and 20 UES in low traffic per cell. UEs are uniformly distributed in the

Cell area [7], [9].We focus our study on the low traffic hours (night zones where all operators have low traffic).

The simulation results show that bastion switching off probability increases with incentive costs due to extra BSs switching off during low traffic durations. In the Nash equilibrium (NE) of the game, each operator follows the same strategy to switch off more BSs in their proposed access area, resulting in the best expected payoff for individual and cooperative MNOs. The Tit-for-Tat (TFT) algorithm, a "robust" approach that requires cooperation from competitive operators, was used to formulate the game formulations. Two types of TFT hyper parameter configurations were used in the simulation: standard TFT (α = 0.5, r0 = 0.2, β = 0) and dynamic or non-zero TFT (α = 0.5, r0 = 0.2, β = 0.3) configurations. The aim is to boost common cooperation behaviors while ensuring they are not exploited. A coordinated switching-off technique called Nash equilibrium maximizes operator profitability while preserving UE QOS. Generally, in Fig. 4a NE BS switching off probabilities are $s_i*=$ 50% to achieve the optimal expected payoff for individual and cooperative MNOs. In NE strategies 50% BSs was switched-off in the proposed area that are not required during low traffic period (scenario 2&3 in proposed mathematical model)

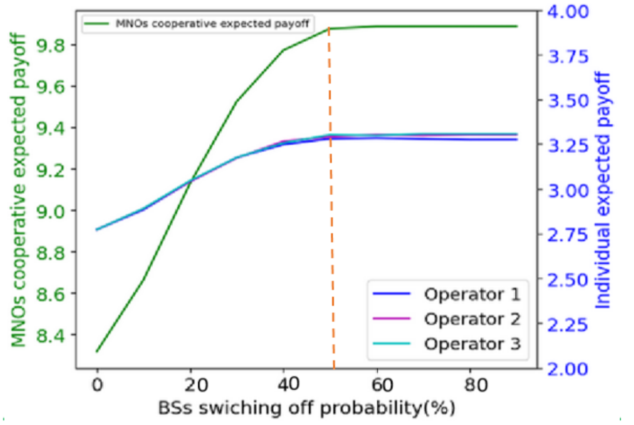

Fig 4a. Expected payoff vs BSs switching off probability and three TFT operators with (α = 0.5, r0 = 0.2, β = 0) standard TFT configuration

The simulation result shows in fig 4b NE strategies, the efficiency of mean cooperation degree among MNOs BS switching-off and traffic exchange is 0.95**.** We have applied three TFT configurations operators with (α = 0.5, r0 = 0.2, β = 0) standard TFT configuration

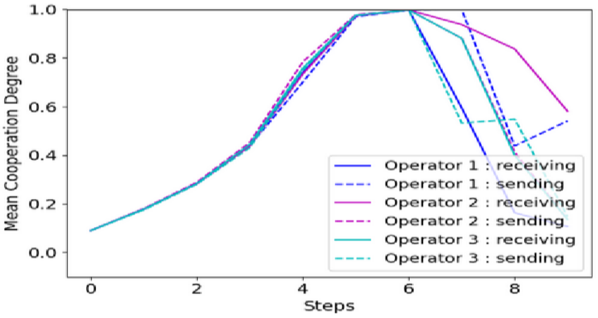

Fig 4b. Mean cooperation degrees of exchanging traffic between three TFT operators with (α = 0.5, r0 = 0.2, β = 0) standard TFT configuration.

Operators 2 and 3 follow the optimal Nash equilibrium strategy in the proposed game algorithm. However, Operator 1's probability is higher than the Nash equilibrium probability, i.e. $s_1*=$ 57% BSs switching-off probability resulting in a higher individual cost for Operator 1 rather than other operators. Despite being exploited by Operator 1, the cooperative expected payoff is greater than the Nash equilibrium, indicating NE are suboptimal in Fig below.

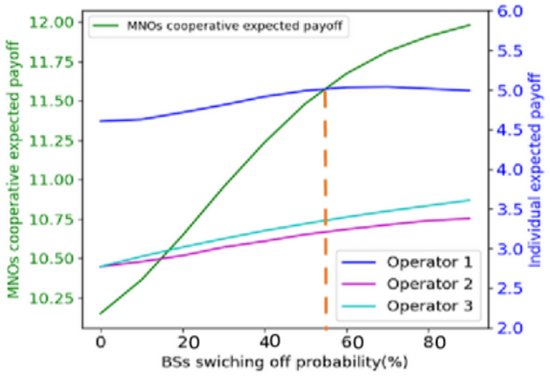

Fig 5a. Expected payoff vs BSs switching off probability two TFT MNOs with (α = 0.5, r0 = 0.2, β = 0) standard configuration and one selfish (*op1)

The simulation results for two TFT operators with a normal tit-for-Tat configuration of (**α** = 0.5, r0 = 0.2, **β** = 0) and one Sel1fish operator (*op1) of average cooperation components of traffic exchange are described. Due to the occurrence of selfish operator (*op1) between operators' the average cooperation degree throughout the game (10 stage games) is only 40% to switch off BSs and exchanging traffic b/n MNOs. Described in figure 5b.

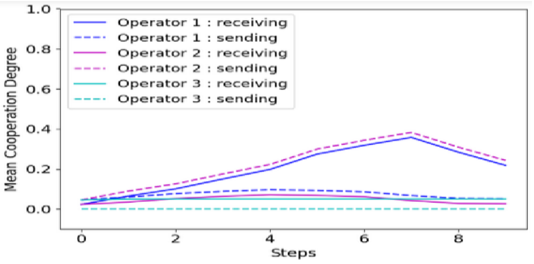

Fig 5b. Average cooperation for exchanging traffic two TFT MNOs with (α = 0.5, r0 = 0.2, β = 0) standard TFT configuration and one sel1fish MNO (*op1)

The simulation results described in Figure 6 are similar in Figure 5a, but with adaptive TFT algorithmic parameters (α = 0.5, r0 = 0.4, β = 0.3). Due to this, the BS switching off probability (s1, j) of operator 1 is lower than the NE, which is 30%. This indicated that more base stations of Operator 1 remain active (with the highest traffic load) and have a lower individual payoff than the other two. In these scenarios, both individual and cooperative expected payoffs are greater than those of the exploded and NE strategies, which shows that Nash equilibrium is non-optimal compared to the other two strategies expressed in this thesis. In general more BSs being switched off, which increases energy gain.

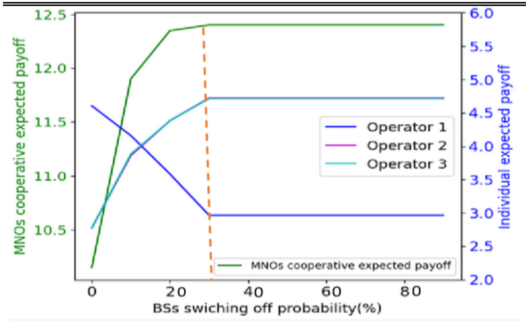

Figure 6: Payoff vs BSs switching off probability and Two TFT agents one selfish operator1 with nonzero adaptive β: TFT (α = 0.5, r0 = 0.2, β = 0.3).

In conclusion our simulation results in non-cooperative game NE is sub-optimal, Operators have no incentive to cooperate than other strategy.

B. Simulation Results and Analysis of Roaming-Based Infrastructure sharing to Maximize Throughput

This study examines the impact of roaming among MNOS on system throughput using simulation findings. The model is compared with a non-roaming instance, considering different UE traffic loads, shared resources, and coverage areas. The TFT algorithm is implemented to maximize total system throughput for operators. The study also highlights the impact of cell central range on roaming zones and ideal cell core radius. The overall system throughput is a multiple of traffic load and roaming resources factors

Equal user traffic load between operators ($\mu_a = \mu_b$):- The simulation results show that the proposed roaming-based inter-operator throughput maximization can be achieved with equal traffic (μ_a = μ_b = 30) between two operators, OPA and OPB. This is achieved through repeated non-cooperative games, comparing the throughput with equal traffic when comparing roaming with non-roaming mechanisms in the simulation area sizes.

The proposed roaming-based dynamic RAN distribution framework for MNOA and MNOB shows similar access area average throughput gain and system performance. In Fig. 7, simulation results of the average throughput comparison of roaming schemes and non-roaming approaches with two MNOs in symmetric loads illustrated. In symmetric load sharing strategies considered D b/n users and BSs.

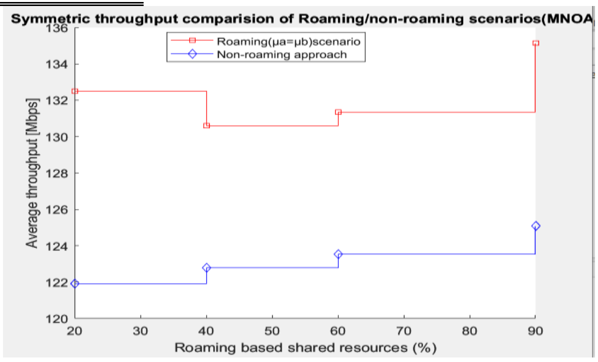

Fig 7. Throughput comparison with roaming and non-roaming approaches with equal UEs ($\mu_a = \mu_b = 30$) setups for MNOA

Asymmetric Traffic load Between Operators ($\mu_a < \mu_b$): The study investigates the proposed infrastructure sharing scheme using a roaming scheme with asymmetric and random distribution of users (μa =10) and μb =30) and two mobile network operators, considering temporal traffic variation.

Simulation result shows in Fig8 and 9 throughput gains are significant traffic load is asymmetric mean loads is relatively large Throughput gains of MNOB is better than MNOA due to high resources shared to high loaded operators from the lower operators.

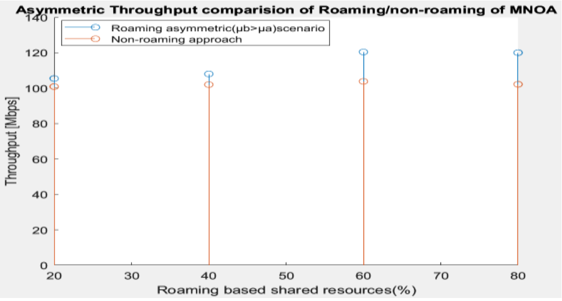

Fig 8. Throughput comparison with roaming and non-roaming approaches with unequal UEs (μb > μa) setups for MNOA

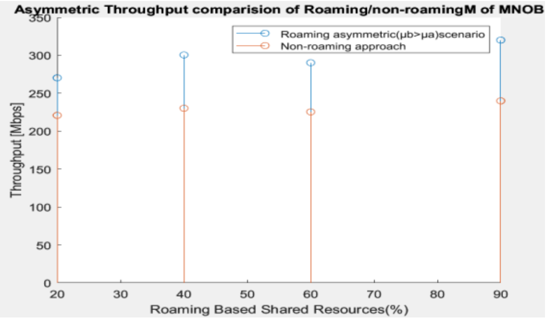

Fig 9. Throughput comparison with roaming and non-roaming approaches with unequal UEs (μb=30 and μa = 10), setups for MNOB

The overall proposed game throughput gains are significant when traffic load is asymmetric and MNOs average traffic loads are high, as shown in fig 10 in game steps comparison with non-roaming approach. In all scenarios the effect of roaming is significant but in asymmetric load cases the average throughput gains is up to 100Mbps in 200 game steps

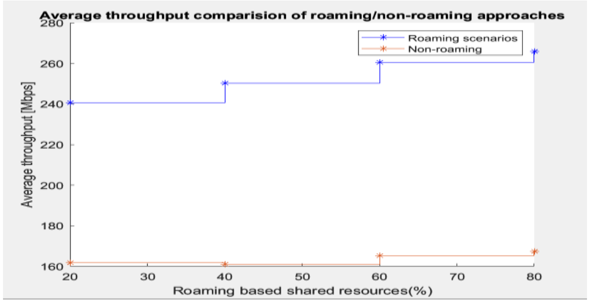

Fig 10. Throughput comparison of the proposed scheme and non-roaming cases of the system

VII. CONCLUSION

The thesis explores energy savings from redundant BSs in multi-operator environments, proposing roaming-based infrastructure sharing among MNOs. It proposes a mathematical model and collaborative framework using non-cooperative game for suitable BSs switched off in low-traffic scenarios, enabling operators to reduce operating costs.

In simulation analysis, our framework outperforms state-of-the-art solutions by providing up to 50% BS switching-off probabilities while keeping QOS. In the case of operational costs, the operators provide the necessary individual and co-operative incentives to participate in network infrastructure sharing. But Nash equilibrium is non-optimal solution, and operators have no better incentive to cooperate compared to other strategies provided in thesis.

This paper explores roaming-based infrastructure sharing between two MNOs to maximize system capacity and QOS. The authors propose a non-cooperative game scheme and discuss different scenarios, including distances and traffic load cases. The simulation results show that the proposed model provides system-level throughput gains, comparable to non-roaming models. The gains are significant for operators serving large users and are up to 100 Mbps.

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APPENDIX C Summary of Literature Review

references	Objectives	Methodologies	Results	Limitations
[7]	• Increase profits of MNOs • Enhanced QoS for the end user.	• Coalition game • Simulation parameters using MATLAB	• Cooperation among MNOs is always beneficial(QOS, Profits)	• Challenging of security and market conflict issues during collaboration
[8]	• Network reliability among multi operators	• Network redundancy • Super quantiles as a measure of reliability.	• Avoid service outages • Reliable communication between users.	• Requires high-demand networks due to the use of redundant resources
[9]	• Throughput maximization in C-RAN network	• Stochastic game • (DQL)algorithm	• higher sum rate compared to the existing baseline of a greedy search-based power allocation strategy	• focused on Throughput maximization instead of resources utilization
[10]	• Data rate , power consumption and • Handover control	• Cooperative game frame work • MATLAB	• power consumption minimization (45%) during low loaded traffic	• Handover and ping-pong b/n cells
[11]	• Improve network resource • Energy saving	• Markov game • RL algorithm	• Saves computational resources by enhancing users demand than fixed power allocation.	• Fixed and limited cellular data used.