Handover Management Techniques for Heterogeneous Cellular Networks

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Declaration

The candidate confirms that the work submitted is his own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others. Most materials contained in the chapters of this thesis have been previously published in research articles written by the author of this work (Mohanad Dhahir Jameel Alhabo), who appears as lead (first) author in all of them. The research has been supervised and guided by Dr Li Zhang, and she appears as a co-author on these articles. All the materials included in this document is of the author's entire intellectual ownership.

A) Details of the publications which have been used (e.g. titles, journals, dates, names of authors):

In Chapter 3:
"Unnecessary handover minimization in two-tier heterogeneous networks", *IEEE 2017 Wireless On-demand Network Systems and Services (WONS)*, **Published**. Co-author: Li Zhang. (DOI: 10.1109/WONS.2017.7888692).

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In Chapter 5:
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B) Details of the work contained within these publications which is directly attributable to Mohanad Dhahir Jameel Alhabo:
With the exceptions detailed in section C, the published work is entirely attributable to Mohanad Dhahir Jameel Alhabo: the literature review necessary to construct and originate the ideas behind the published manuscripts, the novel ideas presented in the papers and all the work necessary in the editing process of the manuscripts.

C) Details of the contributions of other authors to the work:
Dr Li Zhang is the co-author for all the publications listed above. These publications have been written under her supervision, benefiting from excellent technical advice and editorial, patient guidance and valuable feedback.

Naveed Nawaz, Obinna Oguejiofor and Hayder Al-Kashoash performed proofreading to the final drafts of the papers that their names appeared on.

I wish to dedicate this thesis to...

My

Beloved Father

My

Late Mother

My

Little Son

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Abstract

The rapid growth in the mobile users of cellular networks has brought big challenges for the networks and their providers in tackling the coverage extension and capacity boosting. The Heterogeneous Networks (HetNets) is considered as one of the best solutions to meet the ever increasing data rate and coverage demands. The HetNets consists of the deployment of smaller base stations (known as small cells) overlaying the traditional macrocells. Indeed, small cells can cover some areas where it is not possible to be covered by the macrocells.
Despite the potential benefits of deploying small cells along with the traditional macrocell, the ultra-dense deployment brought the concerns of interference and mobility management. As a result of mobility, users will have to perform handover between base stations to maintain service continuity. However, the ultra-dense small cells will cause a huge number of frequent handovers resulting in many issues including high signalling overhead, handover failures, unbalanced load distribution and high energy consumption. Unfortunately, these issues will limit the benefits of deploying small cells.

In summary, the purpose of this thesis is to investigate the existing literature works and then propose techniques to address the problems mentioned above in HetNets.

Firstly, a handover technique is proposed to reduce the number of target small cells for the user and to minimize the unnecessary handovers in the HetNets which eventually enhances the overall quality of service delivered to the end user.

Then, we considered both of the unnecessary handover and handover failure where the number of target small cells is also reduced by considering interference, predicted time that a user may stay in the coverage area of a small cell and the small cell capacity.

Additionally, a novel handover technique is proposed to improve the throughput and load balancing is proposed where an offloading strategy, by forcing the handover considering the load and interference, is considered to derive a han-

dover margin. The margin is then used to perform the handover to the target base station.

Moreover, the multiple attribute decision making principle is used to model the handover problem in HetNets and to address the user energy efficiency. First, we propose a handover mechanism to minimize the unnecessary handover and radio link failure, in addition to enhancing the throughput. This is obtained by deploying multiple attribute decision making weighted methods, Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS), in which selected handover parameters are weighted to evaluate their importance prior to the handover process. Second, a user-energy efficient handover mechanism is investigated via multiple attributes decision making weighted strategy, Grey Rational Analysis (GRA), which accounts for the minimization of the unnecessary handover and radio link failure, in addition to enhancing the user experience in terms of reducing its power consumption.

Finally, a game theory framework is used to manage the handover problem in terms of energy efficiency. First, we propose a novel handover method for energy efficiency in HetNets where a game theory approach is used to manage the transmission power of the base stations by reducing/halting the transmission power for light-loaded base stations prior to the handover process. The game is solved mathematically using the principle of ε-coarse correlated equilibrium. The Regret Matching-based Learning is deployed to learn the equilibrium in this game. Second, a non-cooperative game approach is formulated where base stations behave selfishly to obtain higher gain. The payoff function is defined to consider the gain from increasing the base station transmission power (the utility function) against the cost resulted from energy consumption, base station load and unnecessary handovers performed to this base station. In order to solve the game, we proved the existence of at least one Nash equilibrium.

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List of Abbreviations

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
ABS	Almost Blank Subframe
AHP	Analytical Hierarchy Process
BER	Bit Error Rate
CAC	Call Admission Control
CCE	Coarse Correlated Equilibrium
CDMA	Code Division Multiple Access
CE	Correlated Equilibrium
CoMP	Coordinated Multi-point Transmission/Reception
CSG	Close Subscriber Group
DSL	Digital Subscriber Line
EHO-GT	Efficient Handover Game Theoretic
eICIC	enhanced Inter Cell Interference Coordination
E-UTRAN	Evolved Universal Terrestrial Radio Access
FAP	Femtocell Access Point
FDD	Frequency Division Duplex
FLOPs	Floating Points Operations
GPS	Global Positioning System
GRA	Grey Rational Analysis
GRC	Grey Relation Coefficient

GSM	Global System for Mobile communications
HeNB	Home evolved NodeB
HetNets	Heterogeneous Networks
HGW	Home evolved NodeB Gateway
HHM	Handover Hysteresis Margin
HO	Handover
HOF	Handover Failure
ICIC	Inter Cell Interference Coordination
IHO	Inter-cell Handover
IoT	Internet of Things
KKT	Karush Kuhn Tucker
LPN	Low Power Node
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
MADM	Multiple Attribute Decision Making
MC	Macro Cell
MEW	Multiplicative Exponential Weighted
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MUE	Macro Cell User
NCL	Neighbour Cell List
NE	Nash Equilibrium
OPEX	Operational Expenditure
PDF	Probability Density Function
PE-TOPSIS	Proposed Entropy-TOPSIS
PoA	Point of Attachment
PRB	Physical Resource Block
PSD-TOPSIS	Proposed Standard Deviation-TOPSIS
QoS	Quality of Service
RB	Resource Block

RIP	Received Interference Power
RLF	Radio Link Failure
RRC	Radio Resource Control
RRH	Remote Radio Head
RSRP	Reference Signal Received Power
RSQ	Received Signal Quality
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
SAW	Simple Additive Weighting
SC	Small Cell
SD	Standard Deviation
S-GW	Serving Gateway
SINR	Signal to Interference plus Noise Ratio
SIR	Signal to Interference Ratio
SNR	Signal to Noise Ratio
SON	Self Organizing Networks
TDD	Time Division Duplex
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
ToS	Time of Stay
TTT	Time To Trigger
UE	User Equipment
UHO	Unnecessary Handover
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

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Chapter 1

Introduction

1.1 Motivation

Recently, the world is witnessing a rapid growth in the mobile data traffic demands due to the exponentially increased number of smart phones, laptops and tablets. Based on a recent study by Cisco, the mobile data traffic is expected to exceed 49 exabytes by year 2021 [1]. Additionally, an expected increase on the existing 4G network capacity is about 1000x [2]. Therefore, the mobile network providers are facing a new challenge to cope with this ever increasing demand for data traffic.

The existing homogeneous networks, which consists of macrocell-only (MC) base stations, will be incapable of tackling this problem due to an exponentially increased mobile users, in addition to the difficulties and cost of installing new MC base stations [3]. Therefore, an alternative solution is a must to replace the MC base stations deployment.

The concept of small cells (SCs) base stations is introduced to coexist with the already deployed MCs for a new paradigm under the term heterogeneous networks (HetNets) [4]. From their name, the SCs are small base stations which are cheap and consume less power compared to the traditional MCs. The SCs are overlaid with the MCs to boost the network capacity and increase its coverage.

There are different types of SCs, such as mircocells, picocells and femtocells. Each type differs from the others in terms of its transmission power, capacity of users and coverage area. SCs can serve the users in places where it is not possible for the MC to do so. Furthermore, the low cost of SCs deployment is considered as one of the main advantages over that of MCs. Moreover, and due to their small coverage area, the distance between SC and its users is short compared to that of the MC, and hence, a reduction in the path loss is experienced by the users which eventually enhance their overall performance [3]. Studies show that the average users stay about 60% of their time in an indoor environment, %50 of the conversational calls and almost 80% of data traffic are originated from indoor [5]. This makes the increase of SCs indoor deployment necessary. Additionally, the SCs backhaul connection to the main core network is usually DSL or fibre optic [3]. Therefore, this paves the way to efficiently offload the heavy traffic from the MC base stations to the newly deployed SCs.

Despite their huge benefits, the high densification of SCs arises critical issues ranging from interference, mobility management, frequent unnecessary handovers, handover failure, energy efficiency and uneven load distribution between the MC tier and SCs tier. Therefore, when dealing with the ultra-dense SCs in HetNets, it is necessary to consider these issues to get the anticipated gain of SCs for the users and the network service providers.

1.2 Objectives

In order to ensure a service continuity, the users on the move have to handover between base stations. In MC-only networks, the user can handover to the neighbour MC when it arrives the cell edge. However, in dense SCs HetNets, this mechanism can cause so many unnecessary handovers, handover failure and load balancing issues. Robust and seamless mobility in ultra-dense SCs HetNets is a big challenge. Indeed, the influence of handover failures and unnecessary handovers in HetNets is larger than that of the homogeneous networks. Therefore, it is an important strategy to develop different mobility management mechanisms that can deal with handover problems in HetNets. These mechanisms need to consider the characteristics and nature of the HetNets. The main objectives of this thesis are listed below:

a) To minimize the unnecessary handover, improve network throughput and reduce the signalling overhead due to scanning process of dense SCs.

b) To jointly reduce the unnecessary handover and handover failure by reducing the number of target SCs.

c) To enhance the load balancing in dense SCs environment.

d) To reduce the unnecessary handover, radio link failure and to improve the user experience in terms of enhanced delivered throughput.

e) To enhance the user experience in terms of reduced power consumption and also account for the minimization of the unnecessary handover and radio link failure.

f) To optimize the transmission power of the SCs aiming to reduce the power consumption due to dense SC deployment.

1.3 Major Contributions

This thesis addresses the handover problems in dense SCs HetNets and propose approaches that solve the following aspects:

a) Managing the unnecessary handover by reducing the number of target small cells and limiting the handover to small cells for users with low mobility states.

b) Reducing the unnecessary handover and handover failure by using a predicted residence time for the mobile user in the coverage area of the small cells, after minimizing the number of target small cells.

c) Designing a handover mechanism that can manage the load balancing in HetNets by using a load and interference dependent handover margin in which the handover to the small cell is forced to balance the load between MC tier and SC tier.

d) Designing a handover mechanism to reduce the unnecessary handover and radio link failure, in addition to improving the user experience in terms of enhanced delivered throughput. This is accomplished by deploying multiple attribute decision making weighted methods in which selected handover parameters are weighted to scale their importance prior to the handover process.

e) Designing a user-energy efficient handover mechanism, to save the energy of mobile user's battery, via multiple attribute decision making weighted strategy which accounts for the minimization of the unnecessary handover and radio link failure, in addition to enhancing the user experience in terms of reduced power consumption.

f) Designing an energy efficient handover mechanism for dense small cells to manage the transmission power of the small cells by deploying a game theoretic approach.

1.4 Structure of Thesis

This thesis is organized as follows.
Chapter 2 gives an introduction to the HetNets and the concept of SCs, in addition to the challenges associated with dense SCs deployment. It then gives a general literature review on the current works regarding the problem of handover in HetNets.
Chapter 3 studies the problem of unnecessary handover. A handover method is proposed to reduce the number of target SCs for the user, and hence, minimizing the unnecessary handover in the network which eventually enhances the overall QoS delivered to the end user.
Chapter 4 considered both of the unnecessary handover and handover failure where the number of target SCs in the neighbour cell list is also reduced. Then, by considering interference, estimated time that a user may stay in the coverage area of a SC and the capacity of SC, a compromise between unnecessary handover and handover failure is obtained.
Chapter 5 proposes a novel handover method to enhance the overall experience in terms of throughput and load balancing. First, the number of target SCs is optimized using the interference and estimated time of stay. Then, an offloading strategy, by forcing the handover, which considers the level of interference and the traffic load on a base station to derive a handover margin is used.
Chapter 6 uses the multiple attribute decision making principles to manage the process of handover in HetNets. First, The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS), is used to model the handover problem. Two methods are proposed and both of them use the user angle of movement, time of stay and signal to interference plus noise ratio (SINR) as handover metrics

(attributes). The first method weights the attributes via entropy weighting technique. While, the second proposed method uses the standard deviation weighting technique to assign weights to the attributes. We draw a conclusion that when the complexity is an issue in the application, then the first method would be a good solution otherwise the second method can be used. Second, the handover problem is modelled using Grey Rational Analysis (GRA) technique to address the user energy efficiency. The proposed method adopts the combination of the Analytical Hierarchy Process (AHP) technique to obtain the weight of the handover metrics and GRA method to rank the available cells for the best handover target.
Chapter 7 proposes two handover methods. First, a novel handover method for energy efficiency in HetNets is proposed where a game theory approach is used to manage the transmission power of the base stations, by reducing/halting the transmission power for light-loaded base stations, prior to the handover process. The game is solved using the principle of ε-coarse correlated equilibrium. Second, a game theoretical handover method is proposed where base stations behave selfishly to obtain higher gain. The payoff function is defined to consider the gain from increasing the base station transmission power (the utility function) against the cost. We proved the existence of at least one Nash equilibrium which is the solution of the game.
Finally, Chapter 8 highlights the main conclusions of the thesis and identifies future direction of the research.

1.5 List of Publications

The work undertaken in this thesis has resulted in the following publications.

1. M. Alhabo and L. Zhang, "Unnecessary handover minimization in two-tier heterogeneous networks", **Published** in Wireless On-demand Network Systems and Services (WONS), 2017 13th Annual Conference on. IEEE, 2017, pp. 160164.

2. M. Alhabo, L. Zhang, and N. Nawaz, "A trade-off between unnecessary handover and handover failure for heterogeneous networks", **Published** in European Wireless 2017; 23th European Wireless Conference; Proceedings of. VDE, 2017.

3. M. Alhabo, L. Zhang, and O. Oguejiofor, "Inbound handover interference-based margin for load balancing in heterogeneous networks", **Published** in Wireless Communication Systems (ISWCS), 2017 International Symposium on. IEEE, 2017.

4. M. Alhabo and L. Zhang, "Interference-based Load-dependent Margin Handover for Throughput Enhancement and Load Balancing in Heterogeneous Networks", **Submitted** to IEEE Transactions on Mobile Computing on 6/4/2018.

5. M. Alhabo and L. Zhang, "Multi-Criteria Handover Using Modified Weighted TOPSIS Methods for Heterogeneous Networks", **Published** in IEEE Access Journal.

6. M. Alhabo and L. Zhang, "GRA-based Handover for Dense Small Cells Heterogeneous Networks", **Submitted** to Elseveir Journal of Physical Communication on 27/3/2018.

7. M. Alhabo and L. Zhang, "Energy Efficient Handover for Heterogeneous Networks: A Non-Cooperative Game Theoretic Approach", **Submitted** to IEEE Global Communications Conference 2018 on 26/4/2018.

8. M. Alhabo, L. Zhang and H. Al-Kashoash "A Game Theoretic Handover Optimization for Dense Small Cells Heterogeneous Networks", **Submitted** for IEEE transactions on Vehicular Technology journal on 22/6/2018.

Chapter 2

Background and Literature Review

2.1 Introduction

This chapter presents an introduction to the heterogeneous cellular networks with a comprehensive literature review on the existing handover techniques. To this extent, the reminder of this chapter is organized as follows. Section 2.2 gives a general introduction for heterogeneous networks. Section 2.3 defines the features of heterogeneous networks. In Section 2.4 the concept of small cell base stations is explained. Section 2.5 briefly defines the common deployment scenarios and challenges for small cells. The most used handover metrics are provided in Section 2.6. Section 2.7 gives the handover types. The femtocell architecture is detailed in Section 2.8. The handover procedures in homogeneous macrocell networks are explained in Section 2.9. Section 2.10 explains the handover procedures in heterogeneous networks. The handover performance indicators are given in Section 2.11. The desirable features for handover algorithms are illustrated in Section 2.12. Section 2.13 gives a comprehensive literature review on the handover in heterogeneous networks. Finally, Section 2.14 draws the conclusions.

2.2 Heterogeneous Cellular Networks

Wireless system deployment has reached practical limits in many dense urban areas while data traffic continues to increase rapidly. This leaves wireless operators with few options to increase the most important metric: which is area spectral efficiency. Densifying the macrocell base stations (MCs) is not a practical solution to fix this problem [6] because there are different scenarios where the MCs could not provide the optimum coverage and capacity solutions. One scenario is the large indoor zones with heavy traffic, such as shopping malls, airports, and tube stations, where it is difficult for MC to tackle the users' data demands. Another scenario is the small indoor zones with coverage gaps, such as apartments, houses, and small offices, where MC coverage is too week to cover the entire gaps in this type of scenario [4,6,7]. Studies reveal that almost 70% of data traffic and 50% of voice traffic are originated from an indoor environment [3]. Thus, it is important to develop a technology that can satisfy this huge indoor traffic demand. Therefore, wireless network providers are revisiting conventional cellular system topologies and are considering a new paradigm to cope with this problem.

The concept of Small cells (also known as Low Power Nodes (LPNs)) is a solution to avoid the problem of MCs densification [4]. Small cells are overlaid under the coverage area of the MCs in order to boost the capacity and extend the coverage area of wireless networks. Small cells include remote radio heads, pico cells base stations, micro cell base stations, and femtocell access points [6]. A network that includes several base stations overlapping with each other, where each one has different transmission power, is called a heterogeneous networks (HetNets). Generally, the main reasons behind switching to the concept of HetNets are listed below:

- Difficulty of installing macrocell base stations in urban areas.
- Limited efficiency and performance at cell edge due to interference.
- Reduced cost of installation and maintenance.
- Fast and flexible deployment.
- Low power consumption.
- Provides different capability such as data rates and quality of service (QoS).

In addition to the small cell technology, which increases the coverage and capacity, nowadays network providers are using different techniques, such as the increasing of frequency spectrum and multiple-input-multiple-output (MIMO) antenna techniques.

2.3 Heterogeneous Network Features

The heterogeneous networks (HetNets) that incorporate the small cell (SC) technology, as depicted in Fig.2.1 [8], is a promising solution for enhancing the network performance in terms of coverage and capacity. However, the different characteristics of base stations involved in the network raise new challenges that could degrade the network performance and ending up with a low QoS delivered to the end users. The most challenging problems are the interference and mobility management [6, 7]. HetNets have many features that recognize them from their homogeneous networks counter part. Mainly, these features are load balancing, interference management, self organizing networks, and mobility management.

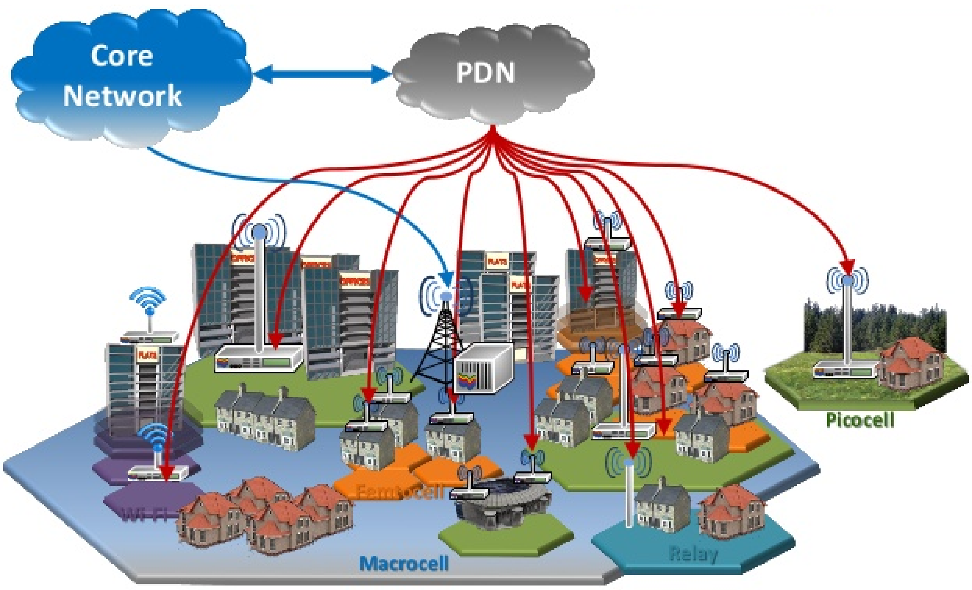

Figure 2.1: Heterogeneous Cellular Network [8]

- **Load Balancing**: The load balancing is considered as one of the significant benefit of SCs deployment. It means to distribute the user equipment (UE) evenly among all base stations in the network so that the resources are fairly shared. According to the offloading metric used to handover the UE from MC to SC, the amount of traffic offloaded can be specified [6]. Indeed, the basic homogeneous network metric for offloading, i.e. the downlink received power, does not perform a proper offloading due to the huge difference in power transmission between MC and SC. This eventually will lead to a poor SCs utilization.

- **Interference Management**: HetNets with SCs deployment is likely to increase the level of interference in the network. Therefore, interference enhancing schemes are required to eliminate or mitigate the interference. There are different types of interference scenarios in HetNet with SCs. For instance, when close access SCs (will be explained later in Section 2.4) are used, they could cause an interference to the UEs that are close to them but cannot connect to them because these UEs are not members in the SCs allowed access lists. Another interference scenario is when an UE associated with a MC switches to a SC with cell expansion (in order to offload the network traffic), here the UE will suffer from inter cell interference [6]. SC expansion means adding an offset power to the SC's received signal strength (RSS) so as to enhance its coverage area [9].

  Different kinds of interference mitigations techniques have been proposed in HetNets. In LTE release 8, frequency domain schemes were proposed where interference is managed between two cells in frequency domain. While in LTE release 10 and 11, schemes are proposed in time domain. Interference is mitigated in time domain techniques by making cells to mute some of their transmitted frames. Moreover, in LTE release 12, SCs dynamically activate or deactivate according to their load and interference level. Coordinated multipoint transmission/reception (CoMP) technique is also utilized to reduce the interference in HetNets where MCs and SCs work together to provide service for the UE [6].

- **Self Organizing Networks**: MC-only homogeneous networks parameters are manually configured by network operators. Manual configuration for HetNets with SCs is not possible and inefficient process because it increases the operational expenditure (OPEX). Therefore, self organizing networks (SON) is used as a feature of HetNets where SCs automatically coordinate and configure their metrics, such as power gains, and cell ID. SON enhances adjusting network parameters to control interference and traffic load balancing in the network which in turn optimize the network performance and enhance the end user QoS. Automatic parameter adjusting decreases the overall network OPEX. The huge data traffic demands is driving the telecommunication industries towards 5G SON HetNets [6].

- **Mobility Management**: Handover in HetNets with SCs is a big challenge. It is performed to assign an UE to the proper base station. UEs periodically measure the received signal from their neighbour cells and switch to the proper cell that has a level of signal greater than the level of the current serving cell plus an offset. This condition must hold for a certain time, named time to trigger (TTT), and thus the UE sends a measurement report to its serving cell which in turn will start the handover procedures. Unlike homogeneous network, which has a fixed value for the offset and TTT for all cell, HetNets have different offset for different cell [6].

2.4 Small Cell Base Stations

Small cells are defined as the wireless coverage area of a base station (i.e. small cell base station). An SC is considered as an equivalent base station to the MC base station with smaller coverage and capacity. Generally, SCs are deployed indoor to enhance the network capacity and extend the coverage areas where it is difficult for the MC to accomplish. SCs are connected to the main cellular network via an Internet connection, such as fibre optic cable or DSL [7]. Because of their beneficial specifications, SCs have acquired potential interest in both telecommunication industry and academic research fields. There are different types of SCs including, pico cell, micro cell, remote radio heads, and femtocell access points. Basically, the SCs are recognised by their transmit powers, coverage, radio propagation models, and sizes [10]. A cell is defined as the coverage area of a base station. For example, a pico cell means the coverage area of a pico cell base station [11]. The SCs can be categorized into the following types:

- **Micro Base Stations**: Micro base stations are typically base stations transmitting at a power lower than that of the MC. They are used for outdoor deployment to provide coverage for hotspots. The transmission power of micro cells are in the range of 5-10 W. Micro cell are coordinated to the MCs via X2 interface [10]. Omnidirectional and direct antennas could be used in micro cell [10].

- **Pico Base Stations**: Pico base stations are low power base stations deployed either in indoor or outdoor environment. For indoor, their transmit power is usually less than 100 mW. While for outdoor, the transmit power range is 250 mW to 2 W. Similarly to micro cells, pico cells provide coverage for hotspots. Omnidirectional and direct antennas could be used in pico cells. Pico cell are coordinated to the MCs via X2 interface. Pico cells provide high data rates for indoor users and they are usually deployed in locations like shopping malls and airports where there is a lack of capacity. Usually, the pico cells are installed and maintained by the network operator [10].

- **Remote Radio Heads**: Remote radio heads (RRHs) or distributed antenna system (DAS) typically used to expand the MC capabilities. RRHs are connected to MC base stations via fibre optic cable and therefore they consume more power and are usually expensive compared to other types of SCs. The transmission power of RRHs is scenario dependent [10].

- **Femtocell Access Points**: Femtocell access point (FAPs) are low power cells installed indoor by the user and are connected to the mobile network via wired broadband connections or optic fibre cable. FAPs are deployed indoor to compensate the lack of coverage in MCs [7]. The antenna used in femtocells is omnidirectional. On the other hand, the transmission power of femtocells are 100 mW and less which is lower than the power of the cellular phone. The reason behind the lower power used in femtocells is to mitigate the level of interference. In LTE, femtocell is named as Home evolved NodeB (HeNB). HeNBs are managed by Home evolved NodeB Gateway (HGW) which connects them to the MC base station network [10]. Femtocells are deployed by end user and they are capable of configuring themselves automatically. Based on their capacity, femtocells are divided into two types, home FAP, with capacity of 3-5 users, and enterprise FAP, with capacity of 8-16 users [11]. Femtocells have three access modes; open, close and hybrid.

  Table 2.1 illustrates the main node specifications of HetNets with SCs. The need to restrict the access mode of SCs is usually subscriber's big concern. Limiting the number of users who could gain access to the SC is very important to control the capacity and avoid at some extent the effect of interference. SCs generally and femtocells in particular have three access modes which can be classified into: open, close and hybrid [6, 7]:

Table 2.1: Specifications of different SCs in HetNets [9]

Types of Cells	Transmit power	Coverage area	Backhaul
Macrocell	46 dBm	Few km	S1 interface
Picocell	23-30 dBm	< 300 m	X2 interface
Femtocell	< 23 dBm	< 50 m	Internet IP
RRH	46 dBm	Few km	Fibre optic

1. **Open access mode**
   In this type, any mobile device can connect to the femtocell without restrictions. Efficient bandwidth utilization is expected to be achieved in open access femtocells. This is done on the expenses of increasing the security threats on the network and degrading the QoS [7].
2. **Close access mode**
   In close access femtocells, only specific number of mobile user devices, Close Subscriber Group (CSG), are permitted to gain access [10]. This type of femtocell is denoted as a CSG cell in the concept of the third generation partnership project (3GPP) [12]. Interference level is expected to increase in this mode [11].
3. **Hybrid access mode**
   In this type, the CSG users have priority to access the femtocell while the un-registered users have limited access. This type of femtocell is denoted as a hybrid cell in the concept of 3GPP [12].

2.5 Small Cell Deployment Scenarios and Challenges

To efficiently gain the full benefits of SCs, their deployment scenarios have been described by 3GPP release 12 [6, 13]:

- **First scenario**
  SCs and MC are deployed using the same operating frequency F1, where SCs are deployed under the MC coverage area.

- **Second scenario**
  SCs and MC are deployed using different frequencies F1 and F2, where SCs are deployed under the MC coverage area.

- **Third scenario**
  Standalone SC deployment scenario, where MC coverage area is not present.

Close access SCs may create coverage holes if they use the same frequency as the MC because UEs will not always be able to connect to the cell with strong signal power. Open access SC could solve this issue on the expense of increasing the number of handovers and also increasing security threats on the network [10].

HetNets deployment challenges vary from mobility, self-organizing networks, intercell interference, and energy efficiency. In terms of SCs deployment, the most challenging issues are interference and mobility, both of which will be addressed in the following Subsections 2.5.1 and 2.5.2 respectively.

2.5.1 Interference

Deploying SCs under the MC coverage area is likely to increase the interference in the network. Therefore, interference elimination/mitigation techniques must be used in order to make use of SCs capabilities. Different interference scenarios are facing the SC deployment. For example, when CSG femtocells are deployed, they will cause interference to the nearby UEs that are not members in the CSG list. Another interference scenario is when pico cell with cell range expansion deployment, when an UE is connected to an MC and then handed over to a pico cell for load balancing, this UE will experience high level of intercell interference which is higher than the received signal. This would in turn decrease the overall performance of the network. In order to mitigate the intercell interference, different time and frequency techniques have been proposed. In LTE Release 8, frequency domain techniques were adopted where two adjacent cells are cooperating to coordinate interference and data sending in the frequency domain. The dense deployment of SCs increases the interference specially when both MC and SCs are using the same carrier frequency [6]. Inter-Cell Interference Coordination (ICIC) technique proposed in 3GPP LTE Releases 8. MC eNBs exchange information (load and interference information) utilizing ICIC via X2 interface so as to decrease the interference for UE located at cell edges. UEs senses the

interfering cells in its coverage area and reports this to its serving cell which in turn cooperates with the interfering cell by coordinating the resources, such as power and frequency. The MCs and picocells are connected via X2 interface.
Enhanced version of ICIC (eICIC) was introduced in LTE Release 10 to support HetNets with SC deployments. In LTE Releases 10 and 11, time domain techniques were used (named Almost Blank Subframe (ABS)) where a cell mutes its subframes to eliminate the interference to its adjacent cell [6,14]. Generally, eICIC interference mitigation techniques are divided into time domain techniques, frequency domain techniques, and power control techniques [15]. In LTE Release 12, SCs could automatically turned on/off according to their load and interference [6].
In HetNets, being connected to the cell with the strongest received signal is not necessarily a proper association because UE will always connect to the MC and will not connect to the shortest path distance cell. Therefore, user connected to MC will strongly interfere with all SCs located within its coverage area in the uplink. This is illustrated in part (3) in Fig.2.2 where the interference scenario is caused by power differences between MC and picocell [9]. Part (4) in Fig.2.2 describes the interference caused by range expansion in picocells where users in uplink transmit good signal quality in terms of interference but users in downlink suffer from low SINR because they are not connected to the cell that provides the best RSS [9].

2.5.2 Mobility

Due to its mobility in HetNets, UE needs to perform the handover between base stations. Handover process is performed in wireless network to ensure that the UE is receiving a sufficient service from the proper cell in the network. Handover is necessary in wireless networks to maintain the ongoing call or data session for the UE, enhance the network capacity and load balance the network traffic. Basically, the handover process is accomplished based on the following basic steps. A UE calculates the RSS of the adjacent cells. In case if the RSS of the adjacent cell is greater than that of its serving cell plus HO hysteresis margin (HHM) for a specific time interval TTT. In this case, the UE will send a measurement report to its serving cell which in turn will initiate the handover (HO) [6]. In macrocellular networks all UEs use the same hysteresis margin and TTT values for HO.

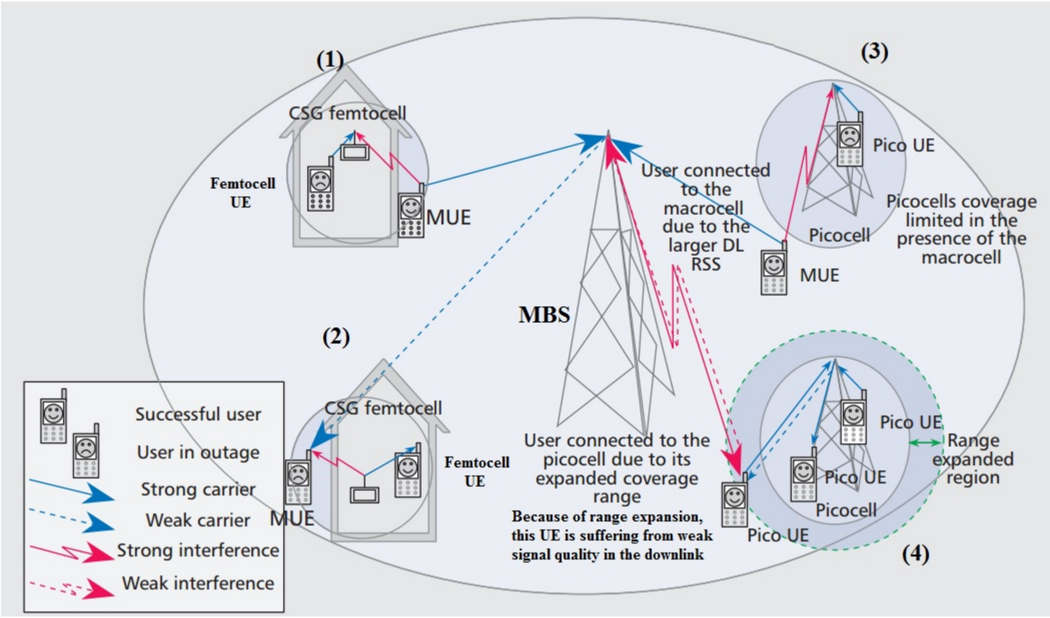

Figure 2.2: Interference scenarios for downlink and uplink in HetNets [9]

This assumption would not work in HetNets with SCs because high speed users with small coverage area will cause many HO failures which in turn degrade the network performance. Unlike the HO in homogeneous networks, different metrics have to be considered in HO for HetNets. Because of the limited capabilities of SCs, the HO mechanism must not cause a huge signalling overhead on the back-haul links e.g. frequent HOs. Therefore, in 3GPP LTE, TTT values are 0; 0.04; 0.064; 0.08; 0.1; 0.128; 0.16; 0.256; 0.32; 0.48; 0.512; 0.64; 1.024; 1.28; 2.56; 5.120 in seconds [16]. Optimal values for HHM and TTT are mainly depending on the UE speed, network scenario, network load and the propagation model. When using high values of TTT and HHM, the UE usually performs HO to the MC [17]. Mobility management is one of the most challenging issues in HetNets. There are two major parts in mobility [18]: location and HO management as depicted in the diagram of Fig.2.3.

- **Location Management**
  Location management supports the network to know the current Point of Attachment (PoA) of the UE. Location management contains two steps, location update and call delivery. Location update allows to authorize the UE and update the UE's position. In location management, the UE frequently forwards

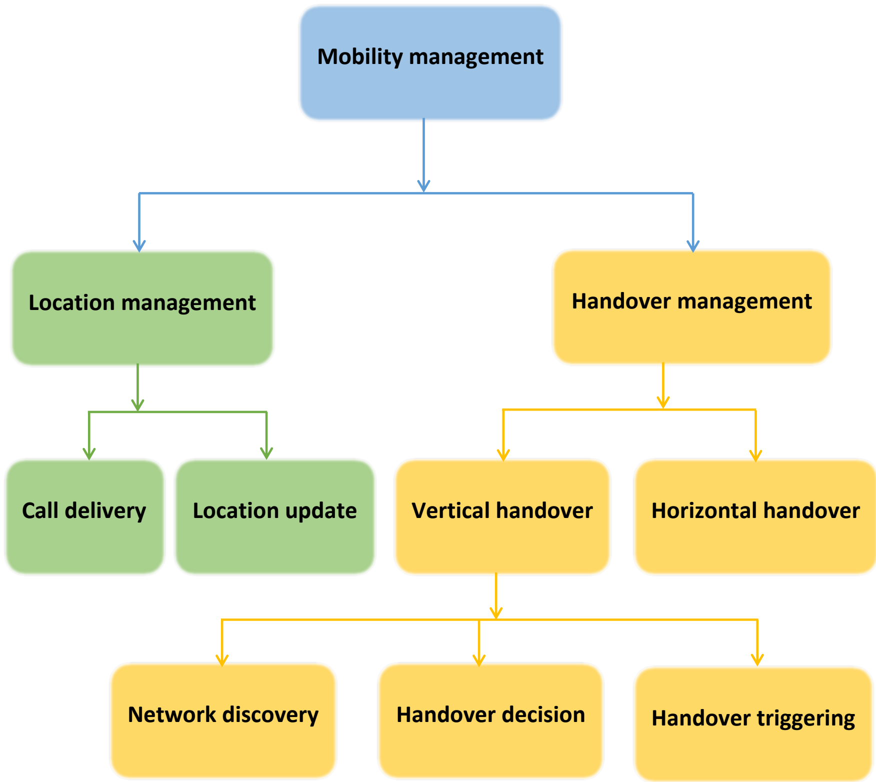

Figure 2.3: Mobility Management in HetNets

its current PoA to the network. Call delivery on the other hand, is in charge of database queries. Here, the network is questioned about the UE position and the UE's current location is acquired [18].

- **Handover Management**
  Different generations of mobile wireless networks (i.e., 1G, 2G and 3G) were based on the use of licensed or unlicensed radio spectrum. 4G mobile wireless networks incorporate a number of wireless networks forming the HetNets. The 4G wireless HetNets provide high data rates, high bandwidth, and seamless HO [19,20]. Seamless HO means changing of PoA without disturbing the user's ongoing call (i.e. no or tolerable service interruption). In the concept of 4G networks, the process of enabling the user to keep utilizing its mobile phone whilst moving from on cell to another is called a HO process [20]. Handover or handoff procedures involve three stages: decision, radio link transfer, and

channel assignment. Handover decision includes the choosing of the target PoA based on a certain algorithm. While radio link transfer means establishing a new link to the new PoA. Channel assignment on the other hand involves the allocation of network resources [18].

2.6 Commonly Used Handover Criteria

Different types of HO decision algorithm criteria have been used in HetNets. Algorithms are basically categorized according to their primary HO initiation criterion. The most widely used criteria for HO decision algorithms in HetNets are listed below:

a) **Received Signal Strength (RSS)**: RSS is the received signal strength at the end user considering the path loss defined in LTE. It is the most widely used HO metric in homogeneous network. However, RSS is not suitable for HO decision in SCs networks because of the large power difference between MC and SC. In LTE-A, the RSS used is Reference Signal Received Power (RSRP) [21] [22].

b) **Received Interference Power (RIP)**: RIP is the total power received from UEs or cells. When measured at the UE, the RIP refers to received signal strength indicator (RSSI). On the other hand, when measured at the cell side it refers to RIP [21].

c) **Received Signal Quality (RSQ)**: RSQ is the ratio of the target cell RSS to the UE RIP. It can also be utilized to predict the signal to interference plus noise ratio (SINR) upon receiving the signal from a target cell [23]. In LTE-A, RSQ relates to Reference Signal Received Quality (RSRQ) measured at the UE [21].

d) **UE speed**: it is the most used metric to minimize the unnecessary HO due to fast moving users in the coverage area of SCs. Taking this parameter as a metric for HO decision will improve the HO experience at the cost of slightly increasing the signalling overhead in the network [21, 24, 25].

e) **Traffic type**: it is used to improve the inbound HO to SCs. Current traffic types include voice, video and data traffic [21] [26].

f) **Bandwidth**: this metric is the measure of the remaining resources in the target cell. If used prior to HO admission, the HO failure probability can be reduced. Cell capacity and cell load are two major bandwidth correspondent parameters [21]. The number of residing UEs in the target cell can also be used as a load measurement indicator [27].

g) **UE residence time**: also named as time of stay (ToS). It is the expected time an UE would spend in the coverage area of a cell. Combined with the UE speed, this metric can be used to eliminate/reduce the unnecessary HOs [21, 26].

2.7 Handover Classification Factors

Small cells are deployed under the coverage area of MCs in HetNets. This means that cells are overlapped with each other which makes the UE receiving multiple signals from different cells. UEs usually tend to connect to the closest cell based on its RSS. The issue of choosing the proper target cell for HO among so many cells is a big challenge. Handover is performed in different ways depending on different factors which means that there are some classifications factors for HO. As depicted in Fig.2.4, HO can be classified into different types [20]:

2.7.1 Network Type Involved

This is the main type of HO classifications. Network type HO can be subdivided into two types namely vertical and horizontal HO [28].

a) **Horizontal HO**: Horizontal or intra-system HO is accomplished between two base stations that belong to the same network technology. Usually the horizontal HO happens smoothly and effectively [20]. For example, the HO between two wireless local area network (WLAN) access points.

b) **Vertical HO**: Vertical or inter-system HO is accomplished between two base stations that belong to different access network technologies [20]. For example, the HO between WLAN access point and 3G base station. In HetNets environment the vertical HO is implemented. Different specifications

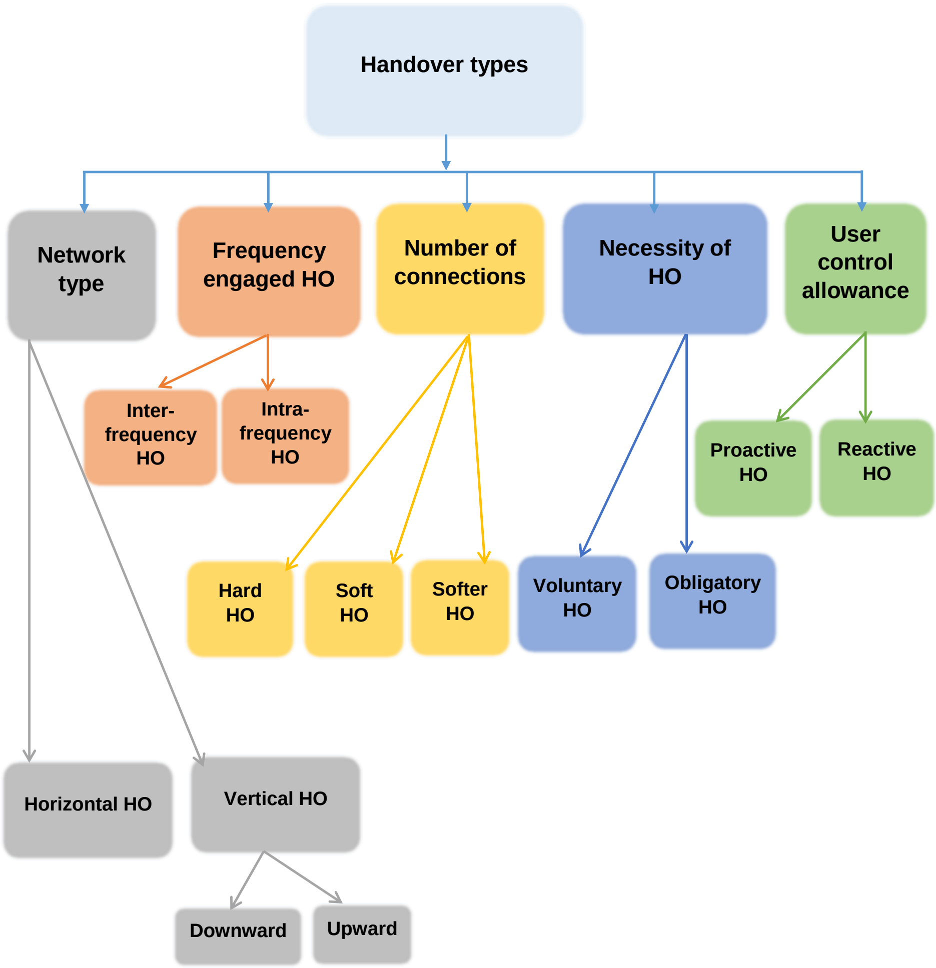

Figure 2.4: Handover Classification Factors

of different wireless access networks make the use of vertical HO a challenging [29]. Generally, the vertical HO includes upward and downward HO. In upward vertical HO, the UE releases its connection with the network that provides faster access but smaller coverage (such as WLAN) and associate with a network that provides slower access but larger coverage. While in downward vertical HO, the UE releases its connection with the network that provides wide coverage and associate with a network that provides smaller coverage but faster access service [20].

An example of HetNets vertical and horizontal HO is depicted in Fig.2.5 below:

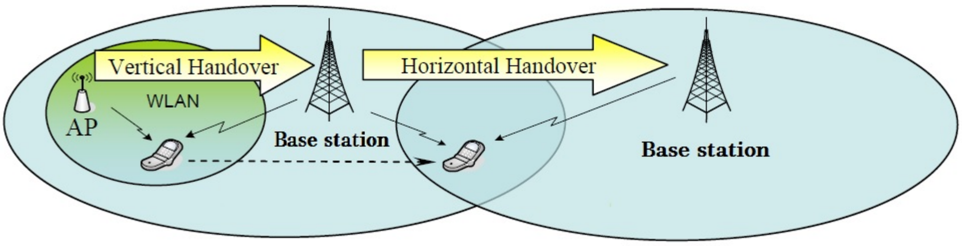

Figure 2.5: Heterogeneous network vertical and horizontal handover

2.7.2 Frequency Engaged Handover

Considering the number of engaged frequencies, this kind of HO includes both intra-frequency and inter-frequency HO as illustrated below [20]:

a) **Intra-frequency HO**: It is the HO between two PoAs that operate using the same frequency. Intra-frequency HO is utilized in code division multiple access (CDMA) with frequency division duplex (FDD).

b) **Inter-frequency HO**: Unlike intra-frequency HO, the inter-frequency HO is used to HO the UE across PoAs that operate using different frequencies. In global system for mobile communications (GSM), the inter-frequency HO is the only supported type of HO.

2.7.3 Number of Connections Involved

According to the number of connections, this type of HO includes hard, soft and softer HO, all of which are described below:

a) **Hard HO**: Hard HO or break-before-make. In this type of HO, the UE can be connected to only one base station at a time. This means that the old radio link is terminated before establishing a new one [20, 29]. LTE only supports hard HO [30].

b) **Soft HO**: Soft HO or make-before-break, means that the UE can be associated with at least two base stations at the same time. This means that the UE at any overlapped coverage area is capable of connecting to a new base station while it stills connected to the old one. Soft HO is applicable to cells that utilize the same frequency [20, 29].

c) **Softer HO**: Softer HO is the same as soft HO, except that the UE changes its radio channel in the same base station [20].

Generally, SCs only support hard HO and do not support soft HO. Therefore a short service interrupt in the call is expected to occur [31].

2.7.4 Necessity of Handover

Based on the necessity, HO can be subdivided into obligatory and voluntary [20].

a) **Obligatory HO**: The UE has to HO to another PoA so as to prevent service failure.

b) **Voluntary HO**: This is an optional HO and performing it could or could not enhance the overall QoS.

2.7.5 User Control Allowance

This category includes proactive and reactive HO.

a) **Proactive HO**: In proactive HO, the HO is initiated before the RSS received at UE side drops below a certain threshold. This strategy would reduce the call drops at the expenses of increasing the average number of HOs which in turn degrades the overall network performance [26]. Proactive HO reduces the HO time which in turn provides seamless mobility in the network.

b) **Reactive HO**: Unlike proactive HO, the reactive strategy delays the initiation of HO process as long as possible even after the RSS received at UE side drops below a certain threshold. This strategy would reduce the number of HOs while increasing the probability of call drops [26].

In order to obtain the full advantages of both proactive and reactive HO, there should be a compromise between the two types.

2.8 Femtocell Network Architecture

The architecture of LTE with femtocell is shown in Fig.2.6. The X2 interface interconnects two eNBs to coordinate with each other. This means that X2 is considered as logical point-to-point interface between two eNBs. The implementation of a logical interface is usually done on physical connections. Different medium are possible to realize the X2 interface algorithms. The selection of a certain medium must take into account the latency and throughput that are resulted from using the medium (wireless, fibre optic, or DSL) [6]. Mobility Management Entity (MME) is an important control node in LTE system. MME is in charge of signalling exchange between the user and the core network, MME's main function is mobility management and HO control. Serving Gateway (S-GW) is responsible for packet routing and forwarding. In dense femtocells deployment, operation costs of MME/S-GW is very high because the broadband is used as backhaul to connect the femtocells to the MC. Additionally, the security issue is also a challenge in this case. Therefore, in E-UTRAN femtocell architecture an entity named FAP-GW is introduced as an intermediate device between the femtocells and the mobile core network. The FAP-GW is in charge of connecting large number of femtocells to the mobile core network. The main function of FAP-GW is to distribute and organize the traffic flow of the femtocells within its vicinity. FAP-GW is seen as virtual eNB to the MME and as virtual MME (which connect femtocells to core network) to the femtocells. Unlike eNB-to-eNB interface, there is no dedicated X2 interface between adjacent femtocells. S1 interface is used to interconnect the FAP-GW with femtocells and to connect FAP-GW to MME/S-GW [32]. In 2013, it has been declared that femtocells represent 56% of the all deployed base stations globally [6]. Femtocells, which can be connected to the mobile operators core network using digital subscriber line (DSL), can be used to handle the huge indoor traffic originated from internet of things (IoT) applications, such as smart water meters and temperature monitoring sensors, in 5G networks [33].

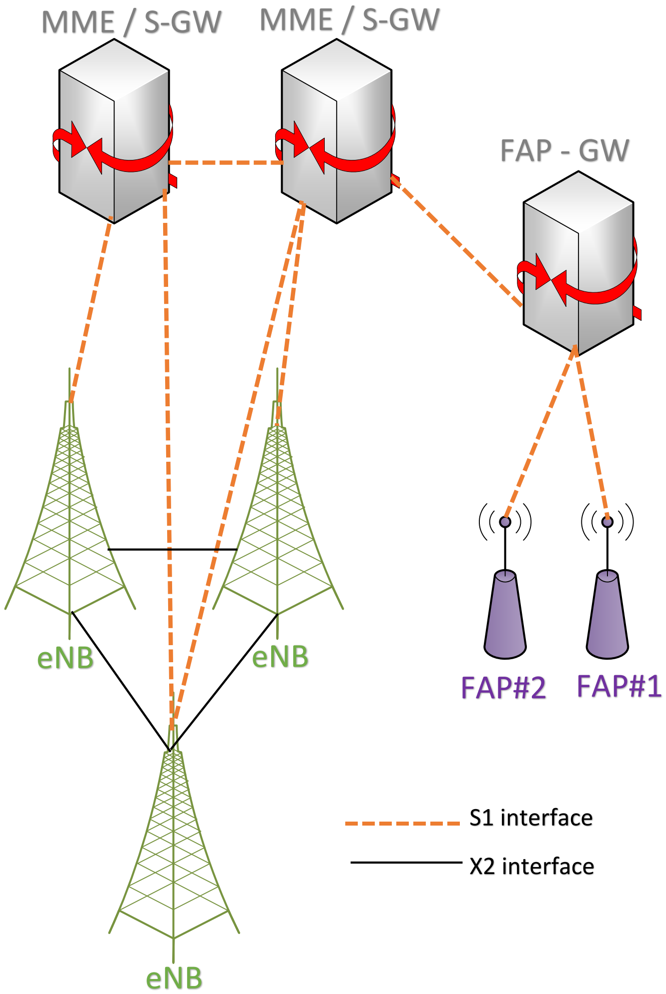

Figure 2.6: Femtocell network architecture [34]

2.9 Handover in Macrocell-Only Networks

The HO process is performed in four steps as shown in Fig.2.7. The UE periodically receives a downlink signals from the nearby MCs. The UE measures and compares the received signals and sends the measurement report to the serving MC. According to the measurement report, the serving MC decides to HO to the target cell [26]. In the context of 3GPP LTE, the HO is triggered based on various events. The leading triggering event is so-called A3 event [35]. Fig.2.8 depicts the A3 event [17]. Serving cell sends command to UE to calculate the RSRP of the neighbouring cells. The UE periodically measures the RSRP of the received cell

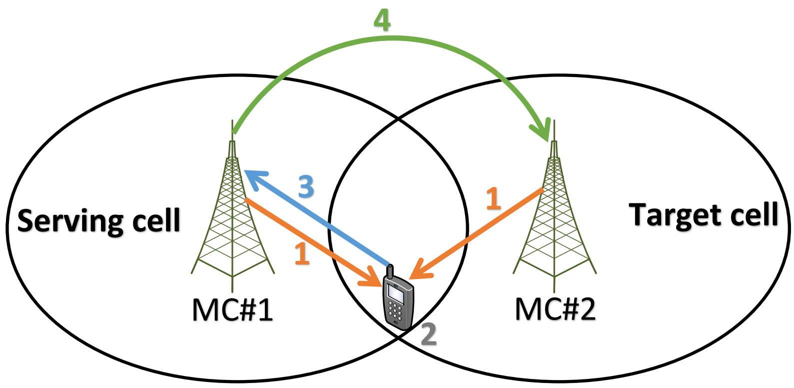

Figure 2.7: Macrocell-only HO process

list and sends back a measurement report to its serving cell. According to the measurement report received, the serving cell requests a HO to the target cell that satisfies the HO initiation condition. Target cell acknowledges the request to serving cell. Then, the serving cell commands the UE to start the HO to the target cell. At time slot (t_6) in Fig.2.8, the RSRP of serving cell A starts to drop below the RSRP of cell B. The RSRP of target cell B should be greater than RSRP of serving cell A plus HHM. HO will not be executed until this condition holds for TTT period. Then the HO to target cell is executed after TTT expires [16].

The standard HO procedures for homogeneous MC-only networks diagram is depicted in Fig.2.9 where the HO procedures are subdivided into three parts including: HO preparation, HO execution and HO completion [34] as explained in the following:

- **Handover preparation**

  In this part, the HO to the target MC is prepared. The UE, the serving MC and the target MC exchange message in this part including the following:

  Message 1, the serving MC sends control information to the UE to measure them.

  Message 2, the UE calculates the required information and responds with a measurement report to the serving MC.

  Messages 3 and 4, based on the received report, the serving MC sends a HO request to the target MC.

  Messages 5 and 6, the target MC performs admission control and responds with HO request acknowledgement if its resources are available to serve the

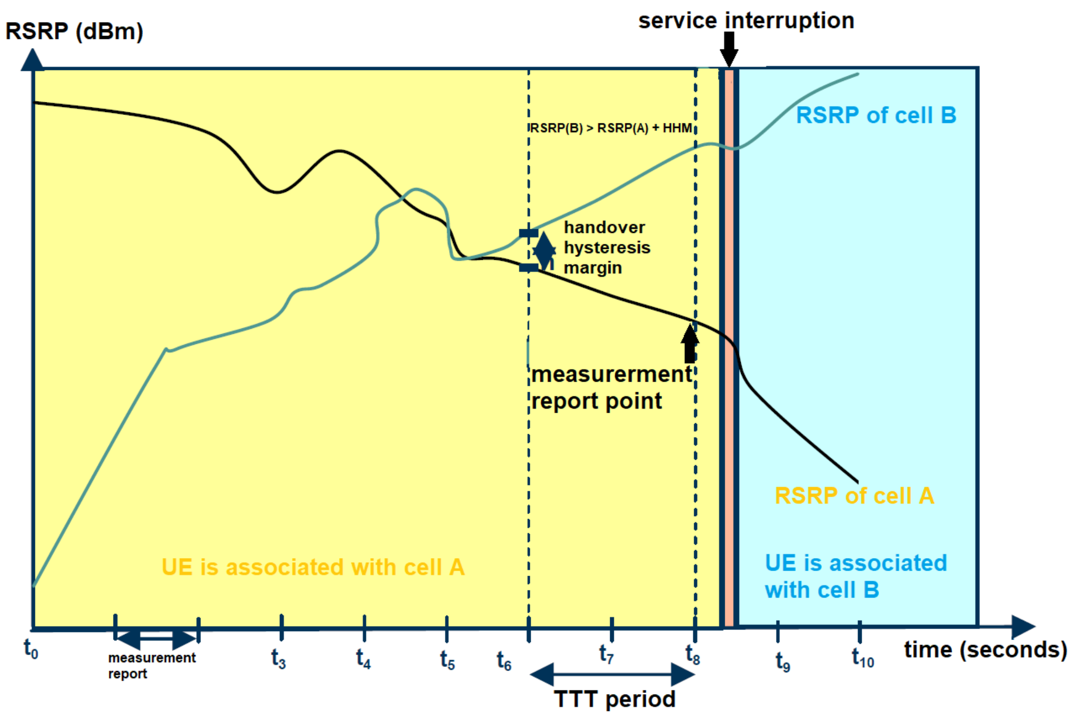

Figure 2.8: A3 handover triggering event [17]

UE, otherwise admission is not permitted.
Message 7, the serving MC commands the UE to HO to the target MC.

- **Handover execution**
  In this part, the HO is executed according to the following messages:

  Messages 8, 9 and 10, detaching from the serving MC and synchronization to the target MC is performed. The UE accesses the target MC.

- **Handover completion**
  The HO procedures are finished in this part. Message exchanges in the HO completion phase are as follows:
  Message 11, the UE sends configuration connection complete message to indicate that the UE has completed the HO. After message 11, data packet is possible to be exchanged between the UE and the target MC.
  Message 12, the target MC sends path switch message to the MME informing that the UE has changed its PoA.
  Message 13, the MME requests an update to the user plane from the serving

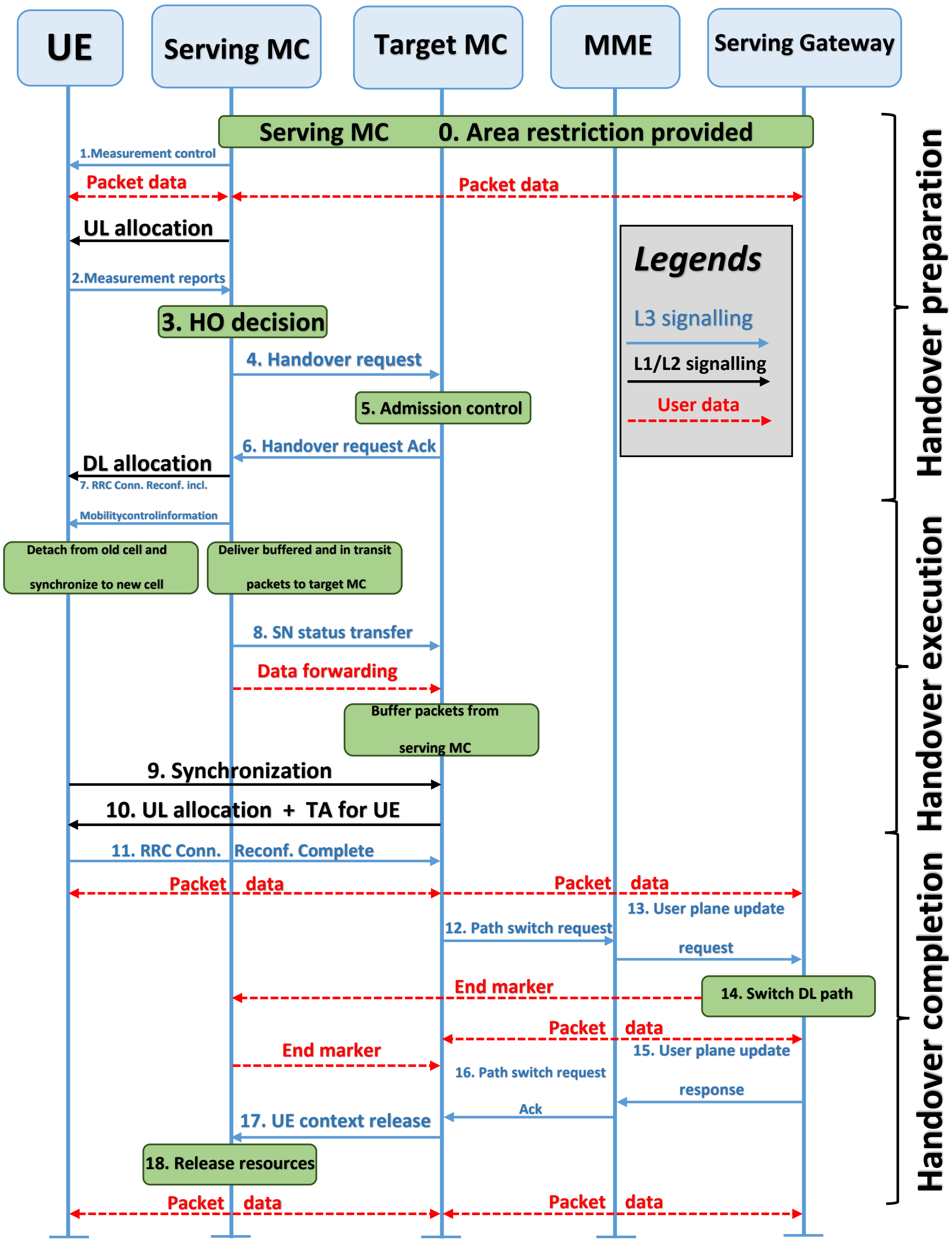

Figure 2.9: Macrocell-only network handover procedures [34]

gateway.

Message 14, the serving gateway changes the downlink data path to the target MC.

Message 15, the serving gateway responds to the response in message 13.

Message 16, the MME sends a path switch acknowledgement to the target MC.
Message 17, the target MC confirms to the serving MC the HO success.
Message 18, serving MC resources that were assigned to the UE are released.

2.10 Handover in Networks with Small Cells

Handover in SC environment is largely affected by the SC access mode. High number of HOs are expected in open access SC while it is minimized in closed and hybrid access SCs [36]. When deploying SCs in HetNets, a HO can be subdivided into three categories: hand-out, hand-in and inter-SC HO as depicted in Fig.2.10, all of which are explained in the following subsections below:

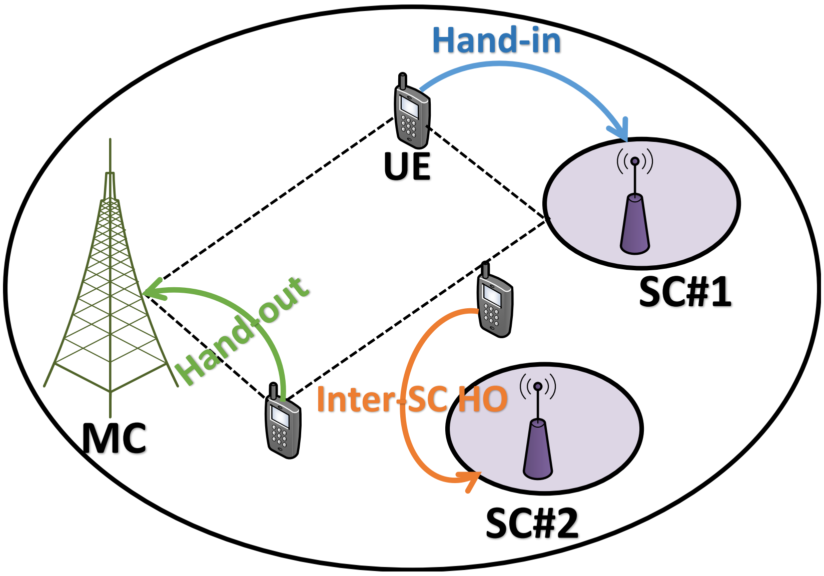

Figure 2.10: Handover scenarios in HetNets

2.10.1 Hand-in (Inbound-HO)

The hand-in or inbound HO is done when the UE moves from the MC coverage area and enters the SC coverage and performs HO to this SC. This scenario is considered as the most complicated HO scenario because there are thousands of target SCs. Moreover, the interference level should also be considered in this HO scenario and authorization is also required particularly when close access SCs are deployed [37]. Signal flow procedures for inbound HO from MC to SC is depicted in Fig.2.11

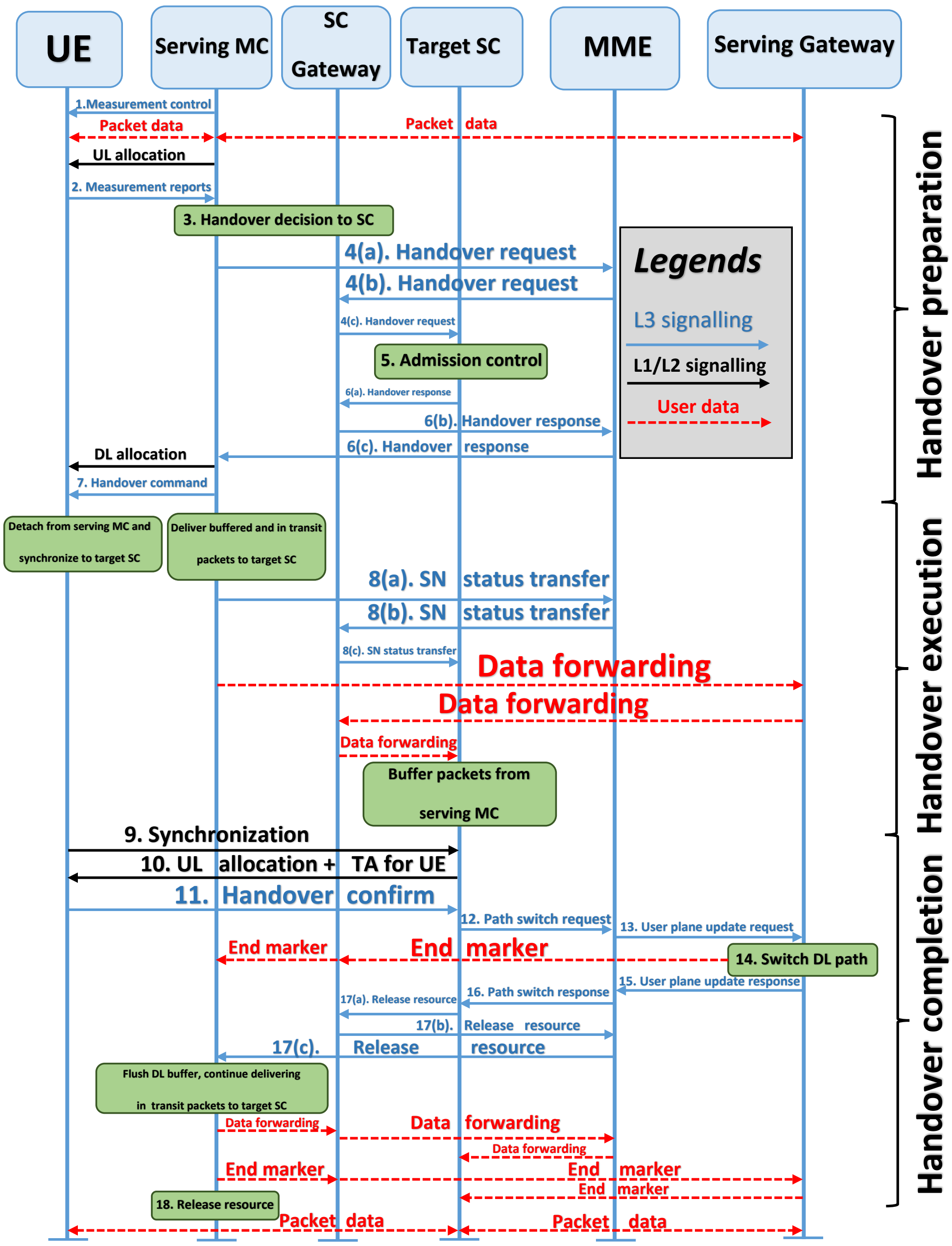

Figure 2.11: Inbound handover procedures from MC to SC [34]

2.10.2 Hand-out (Outbound HO)

This type of HO is accomplished when the UE moves away from the SC coverage area towards MC coverage area. The hand-out is not as complex as the hand-in because the UE has only one target MC base station to connect to. Unlike the hand-in scenario, interference level and authorization are not complicated in this scenario. The UEs perform HO to the MC when the latter's RSS is stronger than that of the SC. This type of HO is also called outbound HO [37]. Signal flow procedures for outbound HO from SC to MC is depicted in Fig.2.12.

2.10.3 Inter-SC Handover

This scenario is similar to the hand-in scenario since there are thousands of target SCs. Interference level and authorization are to be checked in this type of HO [38].

2.11 Handover Performance Indicators

Handover performance indicators usually include HO failure, unnecessary HO and Ping-Pong HOs.

a) **Handover Failure**
Unreliable radio link may cause a handover failure. At the physical layer, a radio link failure is detected when the quality of the received signal is very poor to guarantee a reliable communication. If this case continues for a certain time, then a radio link failure takes place causing a call drop [39]. According to the reason for radio link failure, a handover failures are divided into three types: too early HO, too late HO and HO to wrong cell [39] [40]:

- **Too early handover**
It happens when a UE enters into a target cell too early and the connection is lost at once as a result of poor channel quality after a successful HO. In other words, too early HO triggering time means that the UE receives low signal from the target cell resulting in message exchange failure between the UE and the target cell. Therefore, the UE modifies the state to radio link failure (RLF), and re-associates to the source cell. The source cell considers this as a too early HO where

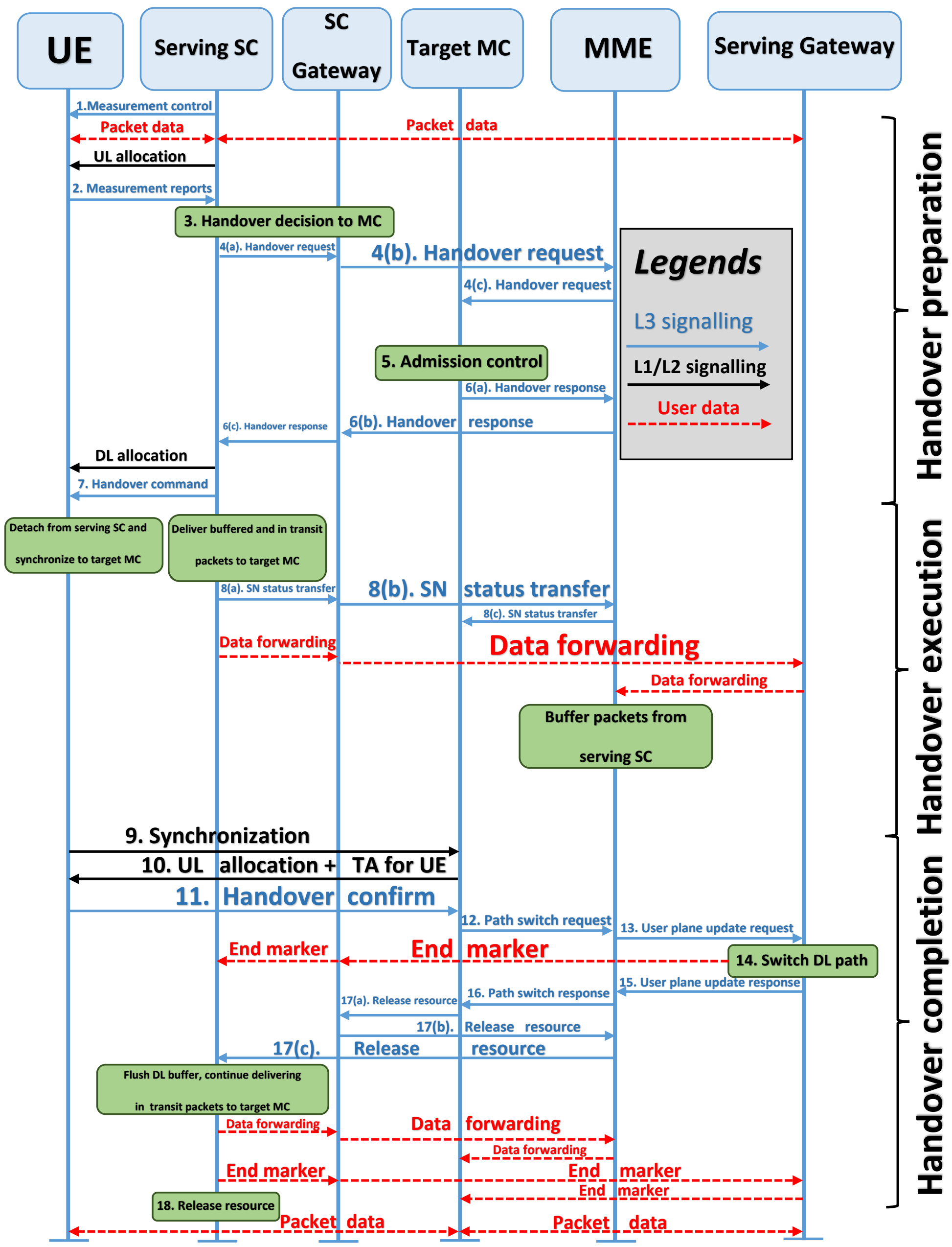

Figure 2.12: Outbound handover procedures from SC to MC [34]

there is no need to notify the target cell about it. Fig.2.13 shows the too early HO scenario and detection mechanism.

- **Too late handover**

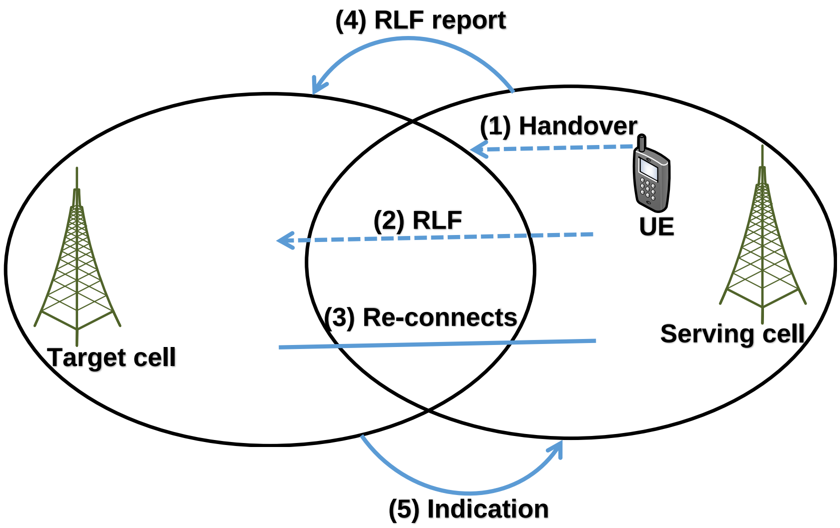

Figure 2.13: Too early handover scenario [10]

It happens when a UE moves very fast so the HO process at the serving cell begins very late. This phenomena causes a too late HO when a RLF occurs in the serving cell during or after the HO process due to a poor signal quality from the source cell. Once the UE discovers the RLF, it connects to the target cell and the target cell reports the RLF to the serving cell via X2 interface. The serving cell will consider this as a too late HO. Too late HO scenario and its detection mechanism is depicted in Fig.2.14.

- **Handover to wrong cell**
  Handover to wrong cell is considered as failure. In this type of HO failure, there are three cells involved: source cell, target cell and wrong cell. The HO to wrong cell happens when a UE enters to an unexpected cell (i.e., the wrong cell). A wrong cell HO is discovered when there is a RLF just immediately after a successful HO to a target cell, then a UE associates to another cell that neither the source nor the target cell. The wrong cell reports this to the target cell which in turn considers this as a RLF and reports it back to the source cell. Fig.2.15 shows the HO to wrong cell scenario and its detection mechanism.

One of the significant causes for HO failures in wireless system is the uplink

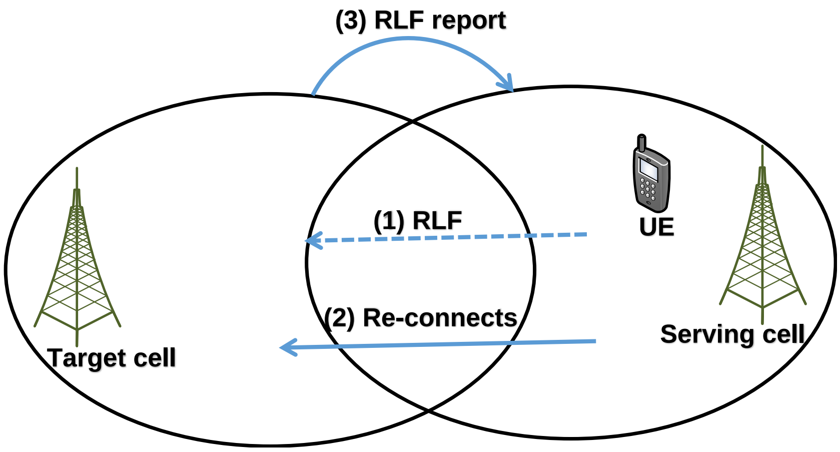

Figure 2.14: Too late handover scenario [10]

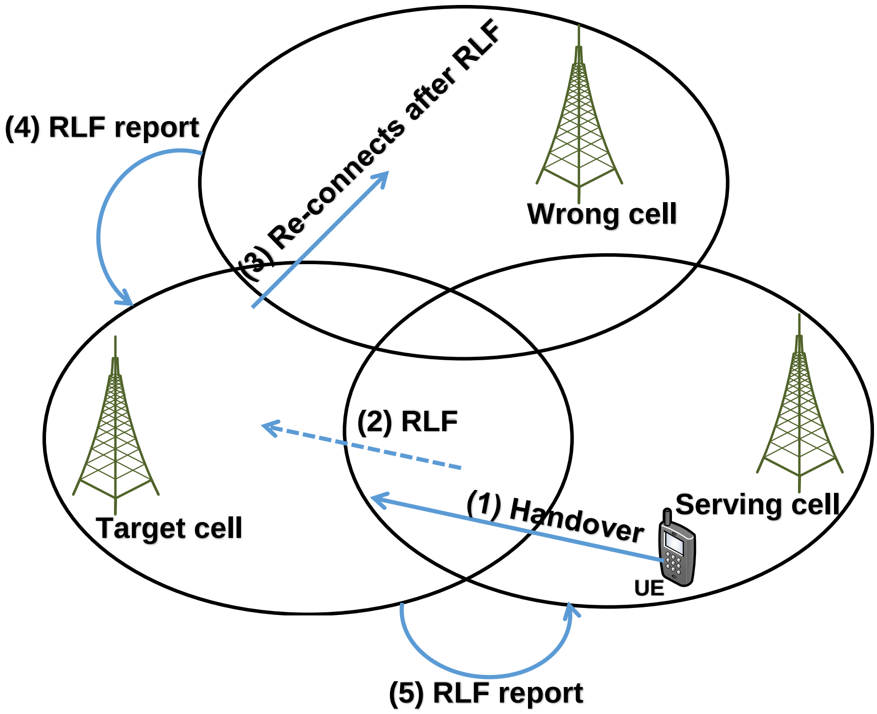

Figure 2.15: Wrong cell handover scenario [10]

transmission of the HO measurement report. This is because the downlink is more resourced than uplink [17]. A robust mobility management would minimize the probability of HO failures to a tolerable level.

b) **Unnecessary and Ping-Pong Handovers**
High dense deployment of SCs is expected to increase the number of unnecessary HOs. High speed users passing by the SCs coverage area are causing very frequent HOs that burden the network and degrade the overall QoS. Ping-Pong HO happens when the UE frequently switches between two cells back and forth in a short period, named time to stay. The time to stay begins when the UE transmits a HO complete notification to a PoA and finishes when the UE transmits a HO complete notification to another PoA. Ping-Pong HO is considered as an unnecessary HO and is calculated as the ratio of the ping pong HOs to the total number of HOs [10, 16].

2.12 Handover Algorithms Desirable Features

The desirable HO decision algorithm features, according to [20] [41], are given in Fig.2.16. A good function algorithm must combine most of these features that are listed below:

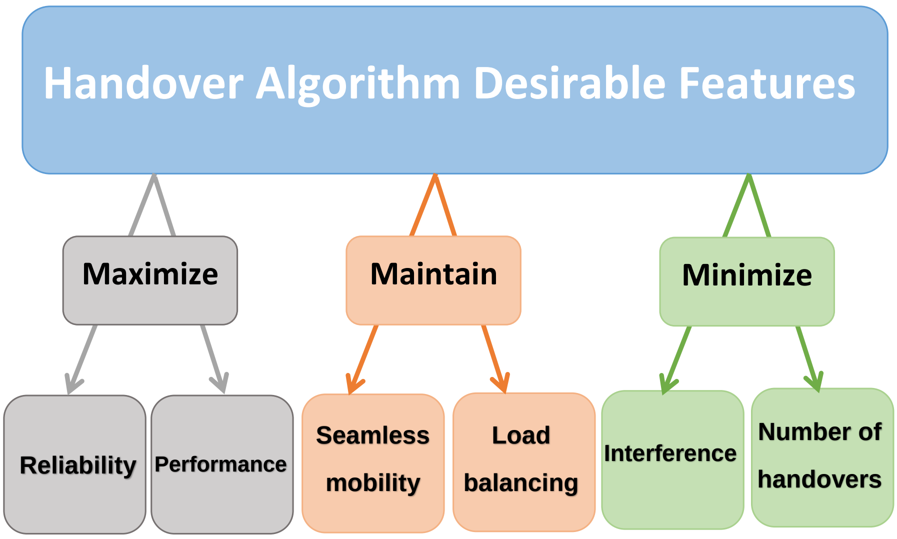

Figure 2.16: Handover algorithm desirable features

a) **Reliability**
This feature means that the HO algorithm must maintain an efficient call quality after the HO. Different metrics specify the quality of the HO target cell such as RSS, signal-to-interference ratio (SIR) and bit error rate (BER).

b) **Seamless Mobility**
The HO process must be performed as fast as possible so that the UE will not suffer from service interruption or call drops due to slow HO process.

c) **Load Balancing**
A HO algorithm must load balance the data traffic among base stations. Load balancing will minimize the probability of call dropping due to lack of resources on heavily-loaded base stations.

d) **Interference Elimination**
Interchannel interference, which is caused by equipments sending signals on the neighbouring channels, and co-channel interference, which is caused by equipments sending signals on the same channel, have negative impact on the data transfer rate of the network. Small cells deployment has also introduced different scenarios of interference as depicted in Fig.2.2. The elimination/mitigation of interference is an important characteristic of a robust HO algorithm.

e) **Number of Handovers**
An extensive number of HOs is a major challenge for dense SCs HetNets. A robust HO algorithm should reduce the number of HOs, and hence, reduce the signalling overhead on the network backhaul. Indeed, the frequent unnecessary HOs is one of the most critical concerns of dense SCs deployment.

2.13 Literature Review on Existing Handover Methods for HetNets

Most of the available HO methods use multiple parameters for HO decision. Basically, the HO metrics are ranging from RSS, UE speed, interference and etc. Therefore, the HO algorithms can be classified into the following major types based on the metrics defined in Section 2.6:

1. **RSS Based Handover Algorithms**
2. **UE Speed Based Handover Algorithms**
3. **Cost Function Based Handover Algorithms**
4. **Interference Based Handover Algorithms**
5. **Energy Efficiency Based Handover Algorithms**
6. **Multiple Criteria Handover Based Algorithms**

Selected methods of each category have been reviewed and described in this chapter.

1. **RSS Based Handover Algorithms**

   Handover decision is basically based on RSS. Dense SCs deployment is a challenge when it comes to mobility management. Most works in the literature did not account for HO in dense SC scenarios. Instead works are focusing at large extent on less complicated scenarios.

   Authors in [42] and [43] proposed an algorithm to create a neighbour cell list (NCL) with reduced number of cells for the purpose of HO. The authors also proposed a CAC (Call Admission Control) mechanism to control various calls. A large number of femtocells require an effective network management to control the HO processes. SON properties can help to solve this issue, and therefore it was suggested to handle the high dense femtocell deployment in this research. Self-optimization feature of SON for femtocell networks incorporates the optimization of power, coverage, NCL and mobility. The HO between MC and femtocell and between femtocell and femtocell in high dense networks is a complex issue because the UE should choose a femtocell among a huge number of neighbour femtocells. Scanning all available femtocells for HO is a power consumption process. Therefore, creating an optimized NCL is a solution to reduce the scanning process and in turn optimize the HO. NCL is an essential issue to support seamless mobility for UE. Considering only RSS in creating a NCL will produce a very large lists and may exclude any hidden femtocell (even if it is very close to the UE) from the list due to a barrier (e.g. wall). In their scenario shown in Fig.2.17 below, the UE cannot receive a signal from FAP#1, although they are very close to each other, because of the obstacle. Serving FAP and FAP#1 are both unable to communicate. By deploying SON optimization feature, FAP#1 and FAP#2 can coordinate with each other and therefore FAP#2 can forward FAP#1's location to the serving FAP. In this case the NCL will include a very close FAP which was not in the list because of the obstacle. The UE is therefore able to initiate the pre-HO process with the hidden FAP#1 and complete the HO with this FAP once the HO condition accomplished ($\text{RSS}_{serving} < \text{RSS}_{FAP\#1} + \text{HHM}$). The inclusion of the hidden

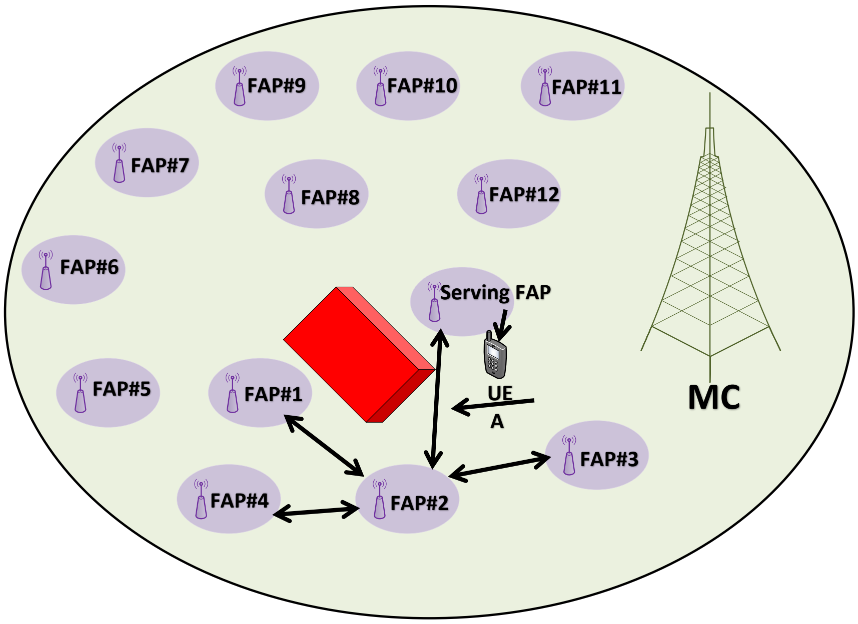

Figure 2.17: High dense femtocell deployment scenario [42, 43]

FAPs in the NCL will minimize the HO failure that may occur in the network. To avoid interference, they considered that two neighbour FAPs do not use the same frequency. Femtocell access mode is also considered in the design. Two mechanisms were used to generate the NCL. First mechanism considers that the UE is initially connected to a FAP. While the second mechanism considers the UE is initially connected to an MC. Two signal strength thresholds were considered: S_{T0} is the minimum value of the RSS that indicates the availability of an FAP (discovered by a UE). $S_{T1} < S_{T0}$ was used to produce the NCL. The density of FAPs is used as a criterion to choose the value of S_{T1}. Increasing both of S_{T1} and FAP density will shrink the size of NCL which in turn minimize the unnecessary HOs. Optimum NCL was constructed by using not only the RSS. Four factors were used for this case RSS, frequency used by serving FAP and neighbour FAP and location information (of a hidden FAP). Densifying the number of femtocells had reduced the possibility that a hidden FAP is out of the neighbour cell list. With this, HO failure rate is reduced in this algorithm. Also the unnecessary HO for this scheme had been minimized compared to the traditional scheme that uses only RSS for NCL creation.

In [44], a single-MC single-SC scenario is considered where a UE tries to perform inbound HO from MC to SC. The goal of this method is to combine the RSS of both MC and SC so as to adjust the big difference of their transmission power. The authors used an exponential window function to eliminate the rapid RSS changing rate:

$$S_m^{'}(t) = w(t) \cdot RSRP(m, t), \tag{2.1}$$

$$S_{sc}^{'}(t) = w(t) \cdot RSRP(sc, t), \tag{2.2}$$

where $RSRP(m, t)$ and $RSRP(sc, t)$ represent the RSS of MC and SC at time t, respectively, and $w(t)$ is the window function. $S_m^{'}(t)$ and $S_{sc}^{'}(t)$ are the filtered RSSs of MC and SC respectively. They are combined into the following HO decision equation:

$$S_{pro}^{\alpha} = S_{sc}^{'}(t) + \alpha \cdot S_m^{'}(t), \tag{2.3}$$

where α represents a factor introduced to adjust the big difference of transmission power between SC and MC. The proposed method allows an UE to perform inbound HO to the SC if one of the following conditions is satisfied:

a) $S_{sc}^{'}(t) > RSRP_{threshold}$ and $S_{pro}^{\alpha} > S_m^{'}(t) + HHM(c)$,

b) $S_{sc}^{'}(t) < RSRP_{threshold}$ and $S_{sc}^{'}(t) > S_m^{'}(t) + HHM(c)$,

where $HHM(c)$ is the HO hysteresis margin of a cell c. The performance evaluation of this algorithm takes into account the probability of HO. The simple network scenario is considered as one of the drawbacks of this algorithm, in addition to neglecting the interference that could degrade the QoS by delivering low throughput. Hence, this method cannot be applied to dense SCs network deployment.

In [45] and [46], single-MC and multiple-SCs are considered. An intercell HO (IHO) principle is introduced. IHO is a unique type of HO where the serving and target cell is the same (channel changing). The authors introduce an algorithm that optimizes the HO and the interference in SC networks. The proposed method uses the scenario where the UE is connected to the MC and it receives interference from the neighbouring SCs. The major point in this method is to make an IHO to the serving MC or broadcast an IHO to all neighbouring SCs when an MC UE suffers from cross-tier interference. The IHO process is initiated when the SINR received at the UE decreases below a predefined SINR threshold. Then, the serving MC commands the UE to calculate the RSS of the neighbouring SCs. According to these calculations, the serving MC constructs a list of interfering SCs by using RSS with hysteresis margin procedures. If there is no interfering channel, the MC ends the IHO process. If there is interfering channels, the MC sends an IHO message to all neighbouring SCs. The neighbouring interfering SCs in turn assign a new channel to their interfering users. The performance evaluation of these algorithms takes into account the probability of HO failure and network throughput. Reassigning the interfering SC users to an alternative channel is likely to increase the interference in neighbouring SCs and users, which in turn would degrade the overall network performance.

2. **UE Speed Based Handover Algorithms**

   In this type of algorithms, the UE speed is used as the main HO metric. UE speed algorithms usually include another metrics for HO decision making, such as RSS and capacity of target cell. Speed based HO methods tend to reduce the probability of HO for high speed users.

   Authors is [26] used proactive and reactive HO decision strategies (see their definition in 2.7). In proactive method, a HO is triggered before the RSS of the serving cell goes down below a HO hysteresis threshold. The UE residence time estimation in the serving cell is used to obtain this. Proactive HO minimizes the HO decision delay and is used for real time traffic. While in reactive HO method, a HO is triggered when the minimum required RSS to maintain a call is reached. Reactive HO reduces the probability of unnecessary HOs and is used for non-real time traffic. One of the obvious features of this method is the using of UE speed with mobility prediction, which minimizes the probability of HO for fast moving users. Multiple-MC and multiple-SCs scenario is considered in this algorithm. If the speed of UE is greater than 10km/h, the algorithm does not perform inbound HO to SC. Instead it performs HO with classic RSS based decision. If the speed of UE is in the range 5km/h and 10km/h, the algorithm predicts the mobility and performs proactive HO for real time traffic or performs reactive HO for non-real time traffic. On the other hand, when the speed is less than 5km/h, the algorithm does not predict the mobility and performs proactive HO for real time traffic or reactive HO for non-real time traffic. The performance evaluation of this algorithm takes into account the number of HOs. The influence of reactive HO on the throughput and interference of neighbouring SCs have not been investigated here.

Multiple parameters for HO decision have been used in [25]. Parameters include RSS of serving and target cell, UE speed, interference at the target cell, capacity of the target cell and the traffic type. The network scenario considers a single-MC single-SC. If the serving cell is SC, the method performs outbound HO to MC if the following conditions satisfied:

a) $\text{velocity}_{ue} > \text{velocity}_{threshold,1}$ and MC has enough capacity, or

b) $\text{RSRP}_{serving\ small\ cell}$ goes down and MC has enough capacity.

If the serving cell is a MC and the UE is not a member in CSG of target SC, the inbound HO to SC is performed if the following conditions satisfied:

a) Interference at target cell is higher than interference threshold,

b) $\text{velocity}_{ue} < \text{velocity}_{threshold,2}$,

c) The target SC has enough capacity.

If the serving cell is a MC and the UE is a member in CSG of target SC, the inbound HO to SC is performed using the parameters:

a) RSS with HO hysteresis margin,

b) UE speed,

c) Traffic type.

Similarly, the avoidance of dense SCs deployment scenario in this work is the obvious drawback, in addition to the neglecting of incorporating the interference in HO decision. Signalling overhead and delay may also occur in this work due to the use of large number of parameters for a HO decision.

Handover algorithm that considers RSS and UE speed has been presented in [47]. Single-MC multiple-SCs scenario is considered. Speed is prioritized on RSS in HO decision making to eliminate the unnecessary HO during UE mobility. The algorithm works under the following rule assumptions sequentially:

a) if velocity$_{ue}$ $\geq$ velocity$_0$, then BS$_{ue}$=BS$_M$,

b) if velocity$_{ue}$ $<$ velocity$_0$, and RSS$_{ue}(i)$ $\geq$ RSS$_0$ then BS$_{ue}$=BS(i),

c) if velocity$_{ue}$ $<$ velocity$_0$, RSS$_{ue}(i)$ $\geq$ RSS$_0$, and RSS$_{ue}(j)$ $\geq$ RSS$_0$ then BS$_{ue}$=BS(j),

d) if RSS$_{ue}(j)$ $<$ RSS$_m$, then BS$_{ue}$=BS(i),

e) if BS$_{ue}$=BS(i), then interchange i and j,

where velocity$_{ue}$ is the UE speed, velocity$_0$ is the maximum HO velocity limit, RSS$_{ue}$(i) is the RSS from i^{th} SC, RSS$_0$ is the minimum received RSS, RSS$_m$ is the HO RSS limit (RSS$_0$ $<$ RSS$_m$), BS$_{ue}$ is the UE's serving cell, BS$_M$ is the MC, BS(i) is the i^{th} current serving SC, and BS(j) is the j^{th} SC. The performance evaluation of this algorithm takes into account the probability of HOs and system throughput.

3. **Cost Function Based Handover Algorithms**

Handover decision parameters used in this category may include a combination of various metrics such as RSS, UE speed, traffic type and target cell load. All of these parameters are combined in one cost function which is used to make the HO decision.

Authors is [27] proposed a cost function based algorithm for inbound HO to SC where a scenario of single-MC single-SC is considered. The UE is initially connected to the MC and moves toward the SC coverage area. The cost function $F(c)$ is based on either RSRP or RSRQ, that is

$$F(c) = \frac{F^{'}(c) \cdot C_{max}(c) \cdot G(c)}{\log(e \cdot k(c) + UEs(c))}, \tag{2.4}$$

where $F^{'}$(c) is the RSRP or RSRQ of a cell c (MC or SC), $k(c)$ is cell type adapted factor, $C_{max}(c)$ is the maximum capacity of cell c, $G(c)$ is the adjusting factor for the cost function and $UEs(c)$ is the total number of users residing in the cell c. This algorithm computes the cost function of both serving MC and target SC. The algorithm keeps running if the output cost function of serving MC $F(m)$ is less than a predefined threshold $F_{threshold}$ (i.e., $F(m) < F_{threshold}$) or if the output cost function of target SC $F(sc)$ is higher than the cost function of MC plus margin ($F(sc) > F(m) + HHM(c)$). When the UE speed is higher than 30km/h no HO to SC is performed. On the other hand, the algorithm continues to run if:

a) velocity$_{ue}$ < 15km/h (real or non-real time traffic) or
b) 15km/h < velocity$_{ue}$ < 30km/h and the traffic is real time traffic

The algorithm waits TTT time before checking if the condition ($F(sc) > F(m) + HHM(c)$) is still verified. If the condition is still verified, the target SC bandwidth is checked and inbound HO is performed. This method used bandwidth and speed of UE to minimize both the probability of HO failure and unnecessary HOs for fast moving users. In addition to the simple network scenario, the used values of $G(c)$ and $k(c)$ have not been justified.

Similarly to the scenario given in [27], the authors in [48] proposed a cost function based algorithm for inbound HO to SC. Single-MC single-SC is considered. The UE is initially associated with the MC and moves toward the SC coverage area. Different from [27], the cost function takes two parameters into considerations: traffic type and UE speed. The proposed method obtains the RSQ of the target SC, processes the UE speed and checks the traffic type. The method compares the RSQ of serving MC with that of the target SC, compares the UE speed with a predefined threshold and identifies the traffic type. The integration of UE speed and traffic type is likely to minimize the probability of HO for fast moving users. The proposed algorithm did not use the hysteresis margin when calculating the RSQ which may increase the probability of HO because of the wireless medium variations.

Authors in [26] proposed HO procedures for SCs. Unlike the work in [27], the maximum used UE speed in [26] is 10km/h. The probabilities of unnecessary HOs and HO failure have been reduced using proactive and reactive HO schemes. The performance evaluation of this algorithm takes into account the number of HOs in the network.

In [49], the authors proposed an adaptive method to optimize the probability of HO failure. A weighted cost function is introduced containing metrics correspondent to UE speed, load of a cell and number of UE connections. Each of these metrics has a cost function F_v, F_l and F_s respectively. The related weights for each metric are denoted by w_v, w_l and w_s respectively. The final outcome cost function $F_{v,l,s}$ is combined using the following normalized form:

$$F_{v,l,s} = w_v \cdot F_v + w_l \cdot F_l + w_s \cdot F_s \tag{2.5}$$

When the HO triggering condition is satisfied, the algorithm makes the following measurements:

a) Finds the number of real-time and non-real-time connections of a specific UE

b) Calculates the UE speed

c) Finds the load of both serving and target cell

By using the above calculations, the algorithm can then find the values of F_v, F_l and F_s:

$$F_v = -2 \cdot \frac{\text{velocity}_{ue}}{\text{velocity}_{max}} + 1 \tag{2.6}$$

$$F_l = \text{load of candidate cell} - \text{load of serving cell} \tag{2.7}$$

$$F_s = \frac{\text{Number of non real time connections} - \text{Number of real time connections}}{2} \tag{2.8}$$

Then, the final outcome cost function $F_{v,l,s}$ is obtained. Finally, the HO decision is taken if the following condition satisfied:

- $RSRP_{candidate\ cell} > RSRP_{serving\ cell} + HHM(c) + \alpha \cdot F_{v,l,s}$, where α is the adjusting factor. Using the load metric in this algorithm is expected to balance the load between the serving and the target cell. The incorporating of UE speed is likely to minimize the probability of HO for fast moving users. The performance evaluation of this algorithm takes into account the probability of HO failure. Despite that this algorithm shows to minimize the signalling overhead by reducing the number of HO failures, however, performance evaluation regarding the enhancement in the throughput is not considered which raise a doubt in the efficiency of this algorithm.

4. **Interference Based Handover algorithms**

   This category takes into considerations the interference level at the UE side or cell sites. Parameters used in this type of methods include SINR, RIP and RSQ.

   Authors in [50] and [51] proposed HO algorithms to minimize the transmission power of an UE in HetNets. Multiple-MC multiple-SC scenario is used. The algorithm finds an approximation of UE transmission power per target cell basis based on a specific SINR of a target cell. The output of this operation is used to HO to target cell that consumes less power. The algorithm is combined in the RSS-based process by using the adaptive HO hysteresis margin HHM. Fixed HHM value is utilized so as to eliminate the effect of UE mobility and to minimize the Ping-Pong. When a HO is initiated, the serving cell sends a request to the target cells to obtain the RIP at the cell and the transmit power at downlink. The UE transmit power at the serving cell is measured using RSRP and the specified SINR target:

$$P_{ue \to s} = \frac{\gamma_{target} \cdot P_{RS}(s) \cdot I_s}{RSRP_{s \to ue}}, \tag{2.9}$$

   where γ_{target} is the target SINR of the target cell, $P_{RS}(s)$ is serving cell transmit power at downlink and I_s is the RIP at the serving cell. Based on the operation band of the target cell, the HHM is calculated for each candidate target cell:

$$HHM_{target}^{UTRP} = \begin{cases} 10 \log \frac{P_{RS}(target) \cdot \left(I_c - P_{ue \to s} \cdot \frac{RSRP_c}{P_{RS}(c)} \right)}{P_{RS}(s) \cdot I_s} \\ 10 \log \frac{P_{RS}(target) \cdot I_c}{P_{RS}(s) \cdot I_s}, \end{cases} \tag{2.10}$$

   where HHM_{target}^{UTRP} is the proposed HHM for HO decision algorithm and I_c is the RIP at the target cell. Finally, the HO is performed to the cell that satisfies the HO condition (i.e. HO to a cell that reduces the UE transmit power):

- $RSRP_c > RSRP_s + HHM_{target}^{UTRP} + HHM_{target}$

where HHM_{target} is the HHM required to eliminate the negative impact of UE mobility. This algorithm tends to minimize the UE transmit power and reduce the interference at cell and UE sites. The performance evaluation of this algorithm takes into account the probability of HO, impact of the HHM and average interference power.

Handover decision algorithm to minimize the probability of unnecessary HOs in HetNets is presented in [23]. Single-MC and single-SC is considered, the UE is being served by MC and is moving towards the coverage area of SC. Three parameters were used for HO condition, RSRP, RSRQ and bandwidth at the target SC. The method periodically checks the RSRQ and RSRP of the target cell and examines at least one of the conditions below:

a) $RSRP_{sc} < RSRP_{threshold\ 2}$

b) $RSRP_{sc} \leq RSRP_{threshold\ 2}$ for specific time interval T

c) $RSRQ_{sc} < RSRQ_{threshold\ 2}$

Based on the above measurement checking, the algorithm performs inbound HO to the target SC if the following conditions satisfied:

a) $RSRP_{mc} < RSRP_{threshold\ 1}$

b) $RSRQ_{sc} > RSRQ_{mc}$

c) SC has enough capacity to deliver service to the UE

The HO is also performed if the above conditions *b* and *c* satisfied. The utilizing of call admission control before HO process has a great effect on minimizing the HO failure and unnecessary HO probabilities. The performance evaluation of this algorithm takes into account the probability of unnecessary HOs.

Similar to [23], the works and scenarios in both [52] and [37] are almost the same.

In [53] the authors proposed an adaptive hysteresis margin algorithm to minimize the probability of unnecessary HOs in HetNets. Single-MC single-SC scenario is considered where the UE performs inbound HO to SC. The algorithm compares the RSRQ of the serving MC and target SC by using an adaptive

HHM method. The HHM is evaluated with correspondent to the RSRQ at UE side and the measured path loss. The algorithm periodically measures RSRQ of both serving and target cells. The HHM is calculated as follows:

$$HHM = max\left\{HHM_{min}, HHM_{max} \cdot \left(1 - 10^{\frac{RSRQ_c - RSRQ_{min}}{RSRQ_{min} - RSRQ_{max}}}\right)^x\right\} \tag{2.11}$$

where HHM_{min} and HHM_{max} are the minimum and maximum HHM values respectively. x is the path loss exponent, $RSRQ_{min}$ is the minimum value of RSRQ that is required to ensure a continuous service and $RSRQ_{max}$ is method introduced metric. The inbound HO to the target SC is performed if the following condition is satisfied:

- $RSRQ_{sc} > RSRQ_{mc} + HHM$

The performance evaluation of this algorithm takes into account the probability of HO, the effect of HHM (which reduces the ping pong effect) and the throughput.

5. **Energy Efficiency Based Handover Algorithms**
   The main HO metric used in this type is either UE battery power level or UE expected power consumption. Energy efficient methods usually related to interference based methods because the power consumption is mainly affected by the interference level in the network.

   Authors in [54] proposed a HO method for energy efficient in HetNets. It has been shown that increasing the number of SCs in the network would enhance the network performance in terms of energy efficiency by minimizing the power consumption. However, this work do not consider the dense SCs scenario and the complexity involved if applying this technique to such scenario.

   Authors in [55] proposed a green policy HO algorithm to minimize the UE power consumption and reduce the probability of unnecessary HOs. The proposed method rejects to perform a HO request for fast moving UE (using CAC mechanism to control the HO for fast moving UEs) and accepts HO request that does not increase the target cell transmission power (only UEs that increase the network performance in term of SINR are permitted to perform inbound HO to SC). The algorithm works based on UE speed as follows:

a) velocity$_{ue}$ > 10km/h, then the inbound HO to SC is refused,

b) velocity$_{ue}$ < 5km/h, then the inbound HO to SC is accepted,

c) 10km/h ≥ velocity$_{ue}$ ≥ 5km/h, then only UEs that increase the network performance in term of SINR are permitted to perform inbound HO SC.

The performance evaluation of this algorithm takes into account the number of HOs and network throughput.

6. **Multiple Criteria Handover Based Algorithms**

There are some HO algorithms that can not be categorized based on the previous four type. Therefore, we review some of these algorithms in this subsection.

In [56] the authors presented a HO distance-based method in HetNets to minimize the probabilities of HO failure and unnecessary HOs. Fig.2.18 shows the system model scenario. The UE at point X is being served by the MC. The

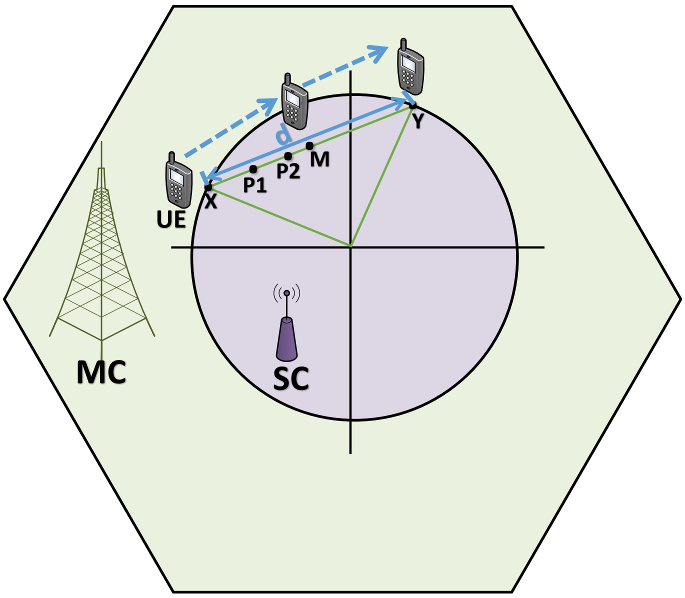

Figure 2.18: System model scenario of [56]

UE moves in a straight line towards the coverage area of SC. The distance d between entry point X and exit point Y of the SC can be calculated using path loss model and RSS samples at points $P1$ and $P2$ as presented in the following equation [56]:

$$\Delta RSS = \left| \frac{RSS_{P2} - RSS_{P1}}{t_{P2} - t_{P1}} \right|, \tag{2.12}$$

where RSS_{P2} and RSS_{P1} are the RSS samples at points $P2$ and $P1$ respectively, t_{P2} and t_{P1} are the time slots at which the UE measures RSS_{P2} and RSS_{P1} respectively. The distance d is compared against a threshold $t_{threshold}$ to reduce the probability of unnecessary HOs. If $d < t_{threshold}$ means that the UE will stay a very short time in SC coverage area and the HO is unnecessary and will not be performed. Otherwise a HO condition to SC is accomplished and the UE switches to the target cell. Thus the traveling distance and the threshold are estimated using the following equations:

$$d = \frac{R^2 - l_{os} + v_{ue}^2 (t_s - t_x)^2}{v_{ue}^2 (t_s - t_x)}, \tag{2.13}$$

$$t_{threshold} = \frac{2R}{v_{ue}} \sin\Big(\arcsin\big(\frac{v_{ue} \cdot \tau}{2R}\big) - \frac{\pi}{2} P \Big), \tag{2.14}$$

where R is SC radius, l_{os} is the distance between SC and where UE takes an RSS sample, v_{ue} is UE speed, t_s is the time at which RSS is taken, t_x is the time at which UE enters the SC coverage area, τ is the HO delay from MC to SC and P is the maximum allowed HO failure or unnecessary HO probability in the network. The performance evaluation of this algorithm takes into account the probability of HO failure. The algorithm depends on taking RSS samples and averaging them. These processes are expected to increase the HO delay which in turn will affect the number of unnecessary HOs.

System model and algorithm procedures and principles in [57] and [58] are similar to that in [56].

In [59], the authors proposed a HO method for hybrid access SC network to minimize the probabilities of HO failure and unnecessary HOs taking into account various metric including RSS, UE speed and interference. The algorithm considers outbound and inbound HO scenarios. For outbound HO, the UE speed is compared against threshold $V_{threshold}$ if it exceeded the threshold a HO to MC is performed providing that the later has enough capacity to serve the UE. Otherwise if UE speed is below the threshold, the RSS will be used for HO decision. For inbound HO, if the UE belongs to a CSG, RSS and velocity conditions are used ($RSS_{macrocell} < RSS_{threshold}$ or $RSS_{small\ cell} > RSS_{macrocell} + HHM$), (velocity$_{ue} < V_{threshold}$). If the two conditions satisfied, a HO is performed to SC. On the other hand, if the UE does not belong to a CSG, it only only preforms inbound HO to SC if there is enough capacity available.

Authors in [52] proposed a method to reduce the probability of unnecessary HOs in HetNets. A CAC mechanism is introduced to mitigate the negative effect of HO process on the network. HO metrics used in this method include RSS, the time by which the UE keeps the required RSS for service continuity and SINR. The inbound HO to the SC is performed if the following two conditions satisfied:

a) $SINR_{small\ cell} > SINR_{macrocell}$

b) $RSS_{small\ cell} > threshold$

The performance evaluation of this algorithm takes into account the probability of unnecessary HOs. In addition to the strict CAC policy that could result in HO failure, this method has not been evaluated under dense SCs deployment in which the HO problem is a crucial factor.

In [60] and [61], authors proposed methods to increase network capacity while maintaining fairness among UEs and minimizes the probability of unnecessary HOs. The performance evaluation of this algorithm takes into account the average number of HOs in the network.

Authors in [62] proposed a HO method to optimize the TTT and HHM parameters so that to enhance the network performance by reducing the HO failure and ping-pong HOs. Results show an improvement in the HO performance in terms of minimizing the HO failure and ping-pong effects compared to the traditional HO method. However, the global impact of TTT and HHM for a specific cell has not be investigated.

Authors in [63] proposed a HO method that adjusts the HHM and TTT parameters to enhance the HO performance in terms of ping-pong HOs and HO failure, in addition to load balancing consideration.

The authors in [64] analyzed the SC range expansion effect on the HO performance (including HO failure and ping-pong HOs). The SC range expansion involves the enlargement of SC coverage area (by adjusting its transmission power) for different reasons such as in traffic load balancing. The performance evaluation of this work considered the HO failure and ping-pong HO rate. Authors argued that the concept of SC range expansion must be adopted with the consideration of the influence on HO failure and ping-pong HO so as to improve the proper utilization of SC deployment.

In [65], the authors proposed a theoretical analysis HO method for HetNets where the authors expressed the relationship between HO failure and ping-pong HO as a function of different parameters including HHM, UE velocity, TTT and SC range expansion. The authors derived theoretical expressions for the HO failure and ping-pong HO rates.

In [66], the authors adopted a double threshold HO mechanism to reduce the HO signalling overhead and satisfying the UEs QoS. The two adopted thresholds include a cell specific HHM for MC and HHM for SC. These two thresholds are adjusted according to the networks HO performance such as average HO times, call drop rate and the load of a cell. The performance evaluation show a reduction in the average number of HOs and call dropping rates. However, the extensive signalling resulted from adjusting the two thresholds may cause a degraded QoS due to the required time to acquire the parameters needed for thresholds adjusting.

A HO failure probability is expressed as a function of sampling period (i.e., Layer 3 filtering) utilized by the UE to collect measurements from the neighbouring cells as presented in [67]. Handover measurements are filtered using layer 3 filtering, where the UE monitors the HO entry condition at discrete samples of layer 3 filter.

In [68], the authors address the influence of SC deployment in HetNets on HO performance. This method studied the impact of the HO parameters HHM and TTT, in addition, considering to switch-off the MC as a result of capacity increase by dense SC deployment. Authors argued that for a high dense SCs and low speed UEs, the MC can be switched off to save energy. However, the authors neglected to evaluate the performance in terms of energy efficiency.

Authors in [69] studied the HO failure performance in HetNets considering the multipath fading and shadowing. This work investigates how the mobility management parameters affect the HO performance. Results show that the fading can cause degradation in HO performance for all UE velocities.

In [40], authors proposed an algorithm to optimize the HO parameters when there is a change in UE mobility. The serving cell initiates the HO when event A3 [70] holds for TTT time period (the UE sends a measurement report to serving cell). Mobility change of UE (change in trajectory and/or speed) influences the measurement report sending time which in turn will result in HO failure. Therefore HO parameter adjusting is needed. Adjusting TTT for each cell is not possible while the adjusting of HO margin for each individual cell is likely to solve the issue. The performance evaluation of this algorithm takes into account HO failure rate.

In order to reduce the radio link failure, authors in [71] proposed a HO method that uses the UE mobility state prediction to classifies the UEs into different groups and assigns fixed TTT value for each group. In this way, the high speed UEs are kept connected to the MC while low speed UEs can perform inbound HO to the SC. Performance evaluation show a reduction in the radio link failure and number of HOs.

In [72], authors presented a HO method which saves energy and supplies a load balancing in HetNets. The method relays on two parameters: UE speed and traffic type. The UEs moving with a speed higher than threshold and require a real time traffic will not be permitted to perform inbound HO to SC. In this case the probability of unnecessary HO is reduced. On the other hand, SCs are kept idle when there is no UEs in their coverage area. This property saves the energy. The performance evaluation of this algorithm takes into account the probability of HO and energy consumption cost. However, this method failed to present a strategy that put the SCs back into active mode when there is any UE in their coverage area which may cause a HO failure.

A novel HO decision algorithm for HetNets is presented in [73] where a UE is connected to a MC and moves towards SC coverage area. The algorithm combines the RSS of both MC and SC to produce new HO criteria. The received

RSS of MC and SC can be expressed as follows

$$RSS_m(k) = P_m - PL_m(k) - u_m(k) \tag{2.15}$$

$$RSS_{sc}(k) = P_{sc} - PL_{sc}(k) - u_{sc}(k) \tag{2.16}$$

where RSS_m and RSS_{sc} are MC and SC RSSs. P_m and P_{sc} are MC and SC transmit powers. PL_m and PL_{sc} are MC and SC path losses. u_m and u_{sc} are log-normal shadowing with zero mean and variances σ_m^2, and σ_{sc}^2 respectively. An exponential window is used to weight the RSSs based on [74] [75]:

$$RSS_m^{'}(k) = w(k) * RSS_m(k) \tag{2.17}$$

$$RSS_{sc}^{'}(k) = w(k) * RSS_{sc}(k) \tag{2.18}$$

A combination factor α is used to compensate the large variation in RSS of MC and SC:

$$RSS_{pro}^{\alpha}(k) = \alpha RSS_m^{'}(k) + RSS_{sc}^{'}(k) \tag{2.19}$$

Therefore, the inbound HO to SCs works under either of the following conditions:

a) If $RSS_{sc}^{'}(k) > RSS_{sc,threshold}$ and RSS_{pro}^{α}(k) $> RSS_m^{'}$(k) + $HHM(c)$, or
b) If $RSS_{sc}^{'}(k) < RSS_{sc,threshold}$ and $RSS_{sc}^{'}(k) > RSS_m^{'}$(k) + $HHM(c)$.

On the other hand, the outbound HO to MC works under either of the following conditions:

(a) If $RSS_{sc}^{'}(k) > RSS_{sc,threshold}$ and RSS_{pro}^{α}(k) $< RSS_m^{'}$(k) + $HHM(c)$, or
(b) If $RSS_{sc}^{'}(k) < RSS_{sc,threshold}$ and $RSS_{sc}^{'}(k) < RSS_m^{'}$(k) + $HHM(c)$.

The performance evaluation of this algorithm takes into account the number of HOs.

In [76], a two-step method is proposed to enhance the HO performance in terms of HO failures and ping pong HOs. Early HO preparation ensures that the HO command is transmitted before the HO failure occurs. On the other hand, ping pong avoidance ensures to delay the HO execution to minimize unnecessary HOs.

Authors in [77] proposed a distributed mobility robustness optimization method to reduce the HO failure by controlling the two HO parameters TTT and HHM. This method adaptively adjusts the HO parameters according to the reason of HO failure for each cell in the network. Performance evaluation results show that this method tends to reduce the HO failure by optimizing the two HO parameters compared to the conventional HO method.

In [78], an analysis of HO failure probability in SC network has been presented. A scenario where an UE passes its serving cell coverage area before his TTT expires, without switching to his target cell. An expression of HO failure as a function of fading, TTT, velocity and distance has been provided.

2.14 Summary

The dense deployment of small cells in future 5G networks (i.e., HetNets) is expected to be a very effective technology to improve the overall network performance in terms of capacity boosting and coverage extension. Mobile users moving in this type of networks with dense small cells need to perform the handover process to maintain the ongoing call or data session.

The handover in homogeneous networks is a straight forward process where a user switches from the serving cell to the target cell upon arriving at cell edge. However, the handover in heterogeneous cellular networks, where the small cells are densely deployed, is a very complex process. Frequent unnecessary handovers, which cause a huge signalling overhead and service interruption on the backhaul, and handover failures are the major concerns in heterogeneous cellular networks handover. In addition to the uneven load distribution due to the improperly handover management. Therefore, some base stations will suffer from heavy congestion and other base stations will have a light load. Furthermore, the energy efficiency as a result of handover is also another challenge for future 5G ultra-dense small cells network. Therefore, a seamless handover mechanism in heterogeneous cellular networks is an important strategy to properly utilize the small cells. According to the reviewed research works in this chapter, we can come to a conclusion that RSS is the most common handover decision metric used in the literature. The speed of UE is also widely used metric to express the user mobility. Traffic type and cell capacity are used to minimize the HO failures and reduce service interruption for real time traffic. Incorporating of HO hysteresis margin plays a significant role in RSS comparison which could reduce the ping pong HOs to some extent. Proactive and reactive HO schemes are less frequently used in the literature.

However, most of the research works use simple network scenarios like single macrocell single small cell networks (i.e. dense small cell deployment is not widely investigated in terms of unnecessary handovers, handover failure, proper load distribution and energy efficiency). To this extent, this thesis focuses on the handover problem in dense small cells heterogeneous cellular networks aiming to address the following aspects:

a) To reduce the unnecessary handover by reducing the number of small cells in the target cell list and limiting the inbound handover to small cells for users with low mobility states.

b) The unnecessary handover and handover failure are reduced by using a predicted residence time for the mobile user in the coverage area of the small cells, after reducing the number of target small cells in the neighbour cell list.

c) To improve the load balancing in the network by using a load-dependent interference-based handover margin in which the handover to the small cell is forced to balance the load between base stations in the network.

d) Designing a handover technique to minimize the unnecessary handover and radio link failure, in addition to improving the user experience in terms of enhancing the delivered throughput. This is done by using multiple attributes decision making weighted strategy in which selected handover decision metrics are weighted to scale their importance prior to the handover decision making.

e) Designing a multiple attribute decision making weighted strategy handover technique that accounts for reducing the unnecessary handover and radio link failure, in addition to improving the user experience in terms of reduced energy consumption.

f) To improve energy efficiency in dense small cells by controlling the transmission power of the small cells by using a game theoretic approach.

Throughout this thesis, all the used competitive methods in the literature (i.e., in Chapters 3, 4, 5, 6 and 7) have been implemented in simulation tools and compared against our proposed solutions so as to verify and validate the obtained results.

Chapter 3

Unnecessary Handover Minimization in Dense Small Cell Environment

3.1 Introduction

Data traffic demand around the globe is sharply increasing due to the increasing number of smart UE equipments. Increasing the number of MC base stations is usually costly and inefficient to deal with this demand. Also, the traditional MC base stations are inadequate to coping with the explosive mobile data traffic demand [10]. For example, in large indoor environments with high traffic demand about 70%, such as underground stations, shopping malls and airports, it is impossible to cover this demand with MC-only networks. One of the most recent methods for capacity boosting and coverage extension is the deployment of SCs [6] [10].

Ultra-dense deployment of SCs can be foreseen in 5G network under the coverage area of the MC. A mobile UE should be able to discover adjacent SCs to perform the HO. This process can be done by frequent neighbour cell list (NCL) scanning. However, extensive scanning for every SC in a dense deployment scenario is a resource wasting strategy, which results in a power dissipation of the UE battery and also lowers the throughput gain. This also means that a high number of SCs would be available for the UE to HO to. For instance, when the UE scans a big number of SCs in the neighbourhood, the processing time to find the best target for HO will in turn increase leading to a significant consumption in the energy of the UE's battery. In addition, the probability of unnecessary HO will increase and in turn cause a degradation in the UE's QoS.

Unlike the HO in homogeneous cellular networks, where the UE switch the base station when arriving at the edge of the serving one so as to maintain the ongoing call, the HO in dense SCs HetNets is a challenge. This is due to the vast number of HOs experienced by the UE within a short period of time which basically causes an increase in the service interruption as a result of transferring the UE from the serving to the target cell. Therefore, it is important to develop a mechanism to reduce the number of SCs in the neighbour cell list and also minimizing the unnecessary HOs in dense SC environment.

This chapter aims to minimize unnecessary HOs in two tier heterogeneous network with dense deployment of SCs. In the proposed method, we utilize the actual distance between the UE and the SCs and the UE angle of movement to construct a shortened candidate NCL which helps in reducing the signal overhead of scanning and the number of unnecessary HOs. UE's movement velocity threshold based on average human walking speed is used to control the HO to the SC. Distance and angle can practically be estimated using the Global Positioning System (GPS) or from the variation of the received signal strength. Simulation results show that the proposed algorithm outperformed the conventional HO method with reduced unnecessary HOs and increased throughput for the network particularly for medium to high speed UEs resulting in good UE QoS. Results also show that the average energy consumption due to the simplified scanning process is reduced in the proposed method as compared to the performance of the conventional method.

The main contributions in this chapter can be briefly given as follows:

- Reducing the NCL prior to the HO. This is accomplished by utilizing the velocity of the UE, the distance between the UE and the SC and the angle between the UE and the SC. A NCL is modelled as a circle whose center is the UE location and its radius is a distance threshold (which is a function of SC radius). Then, any SC in the circle, which is not on the moving trajectory of the UE, is omitted from the NCL where the UE performs the HO to the SC with the highest signal to noise ratio. Due to the ultra-dense SC deployment, it is unlikely that the NCL will become empty.

- Implement, evaluate and compare the proposed method with the conventional one in terms of NCL reduction, unnecessary HO probability, throughput and average energy consumption.

The rest of this chapter is organized as follows. In Section 3.2 some of the related works are given. Section 3.3 describes the network system model. Section 3.4 illustrated the proposed unnecessary HO minimization method. While Section

3.5 discusses and compares the performance of the proposed method with that of the conventional method. Finally, Section 3.6 concludes the chapter.

3.2 Related Works

Despite their huge benefits in providing network coverage in the gaps that could not be covered by MCs and their promising capacity enhancements, the dense deployment of SCs is expected to introduce a very high number of HOs because of the mobility of UEs. Hence, the overall QoS of the mobile network would be degraded. There have been some works accomplished to address this problem in the two-tier heterogeneous network. The majority of HO algorithms use RSS metric for HO decision.

In [79], authors proposed a HO based method which uses the predicted UE velocity and location. A GSM system model were utilized to evaluate their method where results reveal a reduction in the unnecessary HOs.

Authors in [44] used an exponential window function to eliminate the rapid RSS changing rate between MC and SC. The two windowed RSS of MC and SC are then combined to form a HO decision criteria. One of the drawbacks of this algorithm is that the optimization of its performance in real life network deployment is a challenge.

In [24] the authors proposed a single-MC single-SC scenario for inbound HO to SC when the RSRP of SC is offset greater than that of the MC and the velocity of the UE is below a predefined threshold. Compared to the traditional methods, this method tends to minimize the probability of unnecessary HO for fast moving UEs. However, the choice of the speed threshold has not been justified.

Authors in [25] proposed a multiple metrics method for HO in SC network. Metrics include RSS of serving MC and target SC, UE velocity, capacity of the target SC and the traffic type. A simple scenario is considered where a single-MC single-SC are deployed. If the serving cell is SC, the method performs HO to MC if the UE velocity below a predefined threshold and the MC has enough capacity. On the other hand, when the serving cell is a MC, the HO to SC is performed based on the RSS of SC and UE velocity.

A HO method that considers RSS and UE velocity has been proposed in [47]. Single MC multiple SC scenario is considered in this work. UE velocity is prioritized on RSS in taking the HO decision so as to eliminate the unnecessary HOs during UE mobility. The method works under the following assumptions: high velocity UEs are kept connected to MC. On the other hand, low velocity UEs are directed to HO to the SC when its RSS is greater than a predefined signal threshold. However, both of the deployed scenarios in [25] and [47] are very simple and did not account for dense SC environment.

In our proposed solution, which is descried in this chapter, the actual distance between the UE and the SCs and the UE angle of movement are used to extract a shortened candidate list to reduce both scanning process and unnecessary HOs. In addition, signal to noise ratio (SNR), and velocity threshold, which is based on average human walking speed, are used to minimize the unnecessary HO. The time of stay metric is used to evaluate the performance of the proposed method in terms of unnecessary HO.

3.3 Network System Model

The network system model in this chapter considers two-tier dense SC HetNet which consists of 7 hexagonal MCs as illustrated in Fig.3.1, and dense open access mode SCs. Indoor SCs are deployed randomly under the MC coverage area. The mobility model of the UE follows a random way point model [80] where each UE selects a random destination in the MC coverage area and moves towards this destination with a speed chosen randomly and uniformly from the range $[V_{ue}^{min} = 0; V_{ue}^{max} = 50]$ km/h and random direction. The velocity and direction of UE movement are independent of each other. When the UE reaches its intended destination it stops for a pause time (very short time, in this scenario $T_{pause} =$ 100ms). After the expiry of the pause timer the UE selects another destination and repeats the same process until the simulation ends. The random way point mobility model is a simple and widely used model in many network simulators where it is considered a good model to represent the pedestrians movement [80] particularly for low to medium speeds [81]. The path loss between a UE and a cell is different in different scenarios as detailed in [82]. When a MC UE is outdoor, the path loss between the MC and the UE is

$$\delta = 128.1 + 37.6 \ \log_{10}(d_m), \tag{3.1}$$

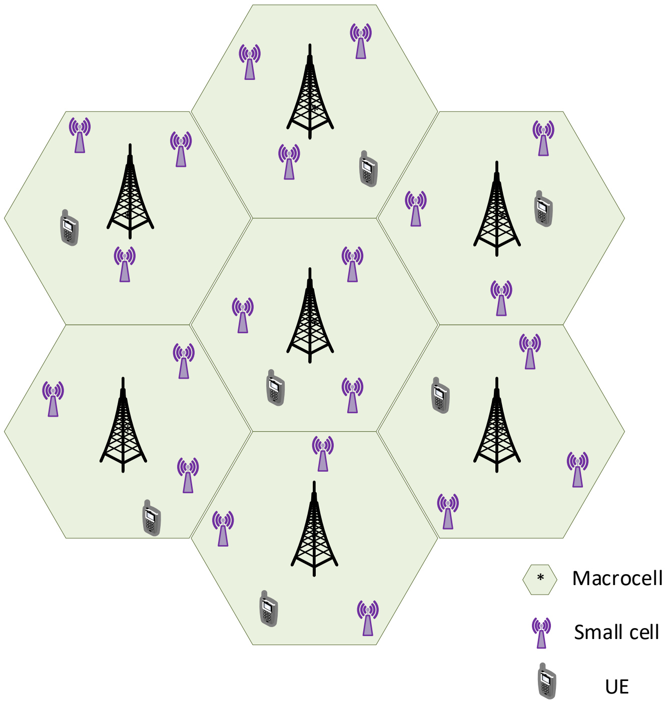

Figure 3.1: Network System model

where d_m is the distance between the UE and the MC in kilometres. And its path loss to the SC is calculated as

$$\delta = 37 + 20\ \log_{10}(d_{sc}) + q_{sc} \cdot W + L, \tag{3.2}$$

where d_{sc} is the distance between the UE and the SC in metres, q_{sc} is the number of walls between the SC and the UE, W is the wall partition loss and L is the outdoor penetration loss. When the UE is inside a house (SC UE), its path loss to the SC is

$$\delta = 37 + 20\ \log_{10}(d) + q_{sc} \cdot W. \tag{3.3}$$

The downlink reference signal received power (RSRP) is

$$P^r_{i \to ue_j} = p^t_{i \to ue_j} + g_{bs} - \delta_{i \to ue_j} - \xi_{i \to ue_j}, \tag{3.4}$$

where $P^r_{i \to ue_j}$ is the measured RSRP of the target cell i at UE j, $p^t_{i \to ue_j}$ is cell transmitting power, g_{bs} is the base station antenna gain, $\delta_{i \to ue_j}$ is the path loss between UE j and base station i and $\xi_{i \to ue_j}$ is the shadow fading with a log-normal distribution with zero mean and 3 dB standard deviation [16]. The radius of each SC i, R_{sc_i}, could be estimated when the UE enters the coverage area of the SC [57] i.e. when the UE starts receiving the minimum required signal for service continuity (P_{th}), as defined below

$$R_{sc_i} = (\frac{p^t_{i \to ue_j} \; 10^{\xi/10}}{P_{th}})^{\frac{1}{\beta}}, \tag{3.5}$$

where β is the path loss exponent. From the geometry of Fig.3.2 we can see the expected distance UE stays inside the cell is between A and B. Where A and B are respectively the entry and the exit points of the UE to and from the SC. The UE's angle of entry to the SC, θ, is measured as in (3.6)

$$\theta = \arctan\left(\frac{y_2 - y_1}{x_2 - x_1}\right). \tag{3.6}$$

The estimated distance of UE j inside SC i, $d_{ue_j \to sc_i}$, is

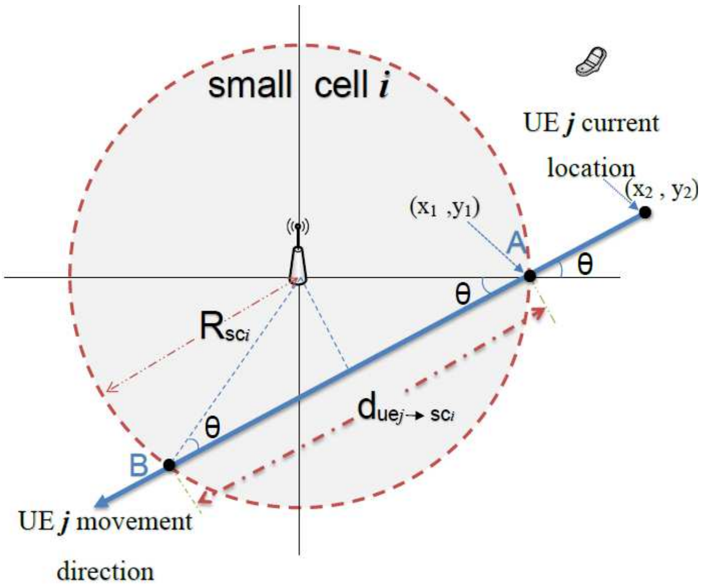

Figure 3.2: Small cell ToS measurement

$$d_{ue_j \to sc_i} = 2R_{sc_i} \cdot \cos(\theta), \tag{3.7}$$

3.4 Proposed Unnecessary Handover Minimization Method

In this section, we explain the proposed method to minimize the probability of unnecessary HO and to reduce the NCL scanning for SC heterogeneous network.

The proposed method uses shortened SC list and different metrics for HO decision including SNR, velocity and the actual distance between the UE and the SC denoted as ($d_{act}^{ue_j \to sc_i}$). The proposed method pseudo code is shown below in Algorithm 1.

Algorithm 1 Proposed Unnecessary Handover Minimization Method

if Strong neighbor SC **detected** with $P^r_{i \to ue_j} > P_{th}$ **then**
  Put the SC in a shortened candidate NCL
  V_{ue_j} **monitoring**
  if $V_{ue_j} \leq V_{th}$ **then**
    if $\big((d_{act}^{ue_j \to sc_i} \leq d_{th}) \wedge (\mid \alpha_{ue_{ji}} \mid \leq \alpha_{in,th})\big)$ **then**
      Keep SC sc_i in the shortened candidates NCL
    else
      Remove SC sc_i from the shortened candidates NCL
    end if
  end if
  if maximum ($SNR^r_{sc_i \to ue_j}$) in the NCL is $> SNR^r_{m \to ue_j}$ **then**
    Handover to SC
  end if
end if

where V_{ue_j} is the velocity of the UE, V_{th} is the HO velocity threshold, d_{th} is the distance threshold to form the SC NCL, $\alpha_{ue_{ji}}$ is the angle between UE j and the SC i, $\alpha_{in,th}$ is the angle threshold at which the SCs are included in the candidate NCL, $SNR^r_{m \to ue_j}$ is the signal to noise ratio received from the MC at the UE side and $SNR^r_{sc_i \to ue_j}$ is the signal to noise ratio received from SC at the UE side. From the geometry of Fig.3.3 we can calculate the angle between UE j and SC i, $\alpha_{ue_{ji}}$, based on $\vec{u}$ and $\vec{v}$ vectors as

$$\alpha_{ue_{ji}} = \arccos\big(\frac{x_u \cdot x_v + y_u \cdot y_v}{\sqrt{x_u^2 + y_u^2} \cdot \sqrt{x_v^2 + y_v^2}}\big), \forall i = 1, 2, ..., N^*_{sc} \tag{3.8}$$

where $x_u = x_2 - x_1$, $x_v = x_3 - x_1$, $y_u = y_2 - y_1$, $y_v = y_3 - y_1$, and N^*_{sc} is the total number of SCs that are located within d_{th} distance from the UE.

The algorithm starts by checking the neighbouring SCs, if their received RSRP are greater than a threshold, P_{th}, a shortened SCs NCL is formed containing all of these cells. Then, the UE's velocity is checked, if it exceeds the threshold, V_{th},

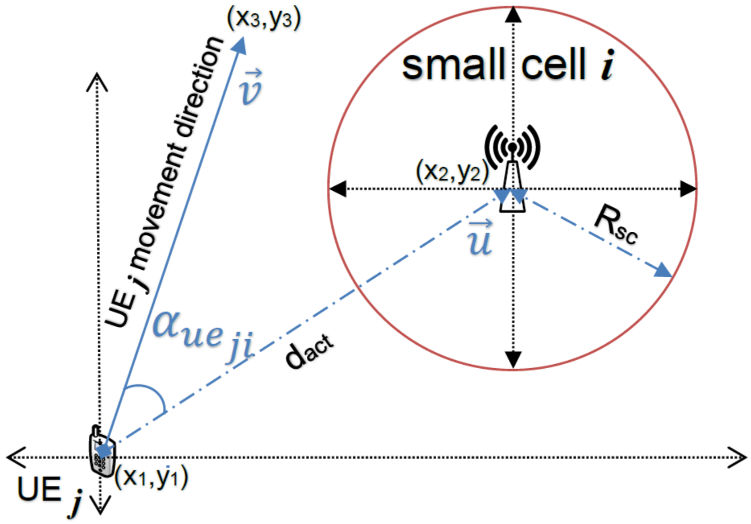

Figure 3.3: UE angle of movement

which means that the UE is moving very fast and will potentially stay very short time in the SC coverage area, then the UE keeps associated to MC. On the other hand, if the UE's moving velocity is equal to or below the threshold, we form a circle, i.e. model the SC candidate NCL as a circle, whose center is the UE location and its radius is d_{th}. Then, all SCs, within this circle, that are not located within an angle range of $[-\alpha_{in,th}, \alpha_{in,th}]$ from the circle center (i.e. UE location) will be removed from the circle as shown in the blue shaded area of Fig.3.4. Therefore, only SCs that are located at UE trajectory are left in the NCL as shown in the white unshaded area of Fig.3.4. Hence, the scanned number of SCs by the UE for HO target is reduced. The larger the angle threshold $\alpha_{in,th}$ the larger the number of SCs in the NCL. The evaluation of the actual distance between the UEs and the SCs, in one MC, can be described in the following matrix

$$d_{act}^{ue_j \to sc_i} = \begin{pmatrix} d_{act}^{ue_1 \to sc_1} \cdots d_{act}^{ue_1 \to sc_{n-2}} \cdots d_{act}^{ue_1 \to sc_n} \\ \vdots \quad \ddots \quad \vdots \quad \iddots \quad \vdots \\ d_{act}^{ue_2 \to sc_1} \cdots d_{act}^{ue_2 \to sc_{n-2}} \cdots d_{act}^{ue_2 \to sc_n} \\ \vdots \quad \ddots \quad \vdots \quad \iddots \quad \vdots \\ d_{act}^{ue_m \to sc_1} \cdots d_{act}^{ue_m \to sc_{n-2}} \cdots d_{act}^{ue_m \to sc_n} \end{pmatrix}, \tag{3.9}$$

where n = 1, 2,..., N_{sc}^*, m = 1, 2,..., N_{ue}, N_{ue} is the total number of UEs, the rows represent the UEs and the columns represent the SCs. Each element in the

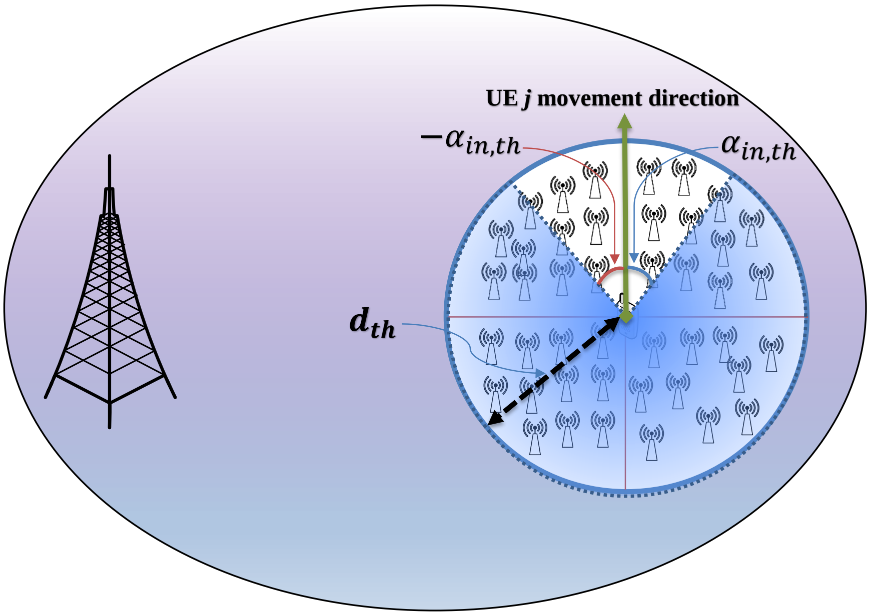

Figure 3.4: Removing small cells from the NCL

matrix is compared against its correspondent SC radius to construct the shortened candidates NCL. Thus, we can define the set of candidate SCs for UE j in one MC, which is denoted as S_{sc}, using the following

$$S_{sc} = \Big\{ sc_i \in N_{sc} \mid (d_{act}^{ue_j \to sc_i} \leq d_{th}) \wedge (\mid \alpha_{ue_{ji}} \mid \leq \ \alpha_{in,th}) \Big\}, \tag{3.10}$$

where N_{sc} is a set represents all SCs in one MC base station. The HO is performed to the SC, sc_i from the set S_{sc}, with the maximum SNR providing that this SNR is greater than the serving one i.e. $SNR^r_{sc_i \to ue_j} > SNR^r_{m \to ue_j}$. Since the SC radius, R_{sc_i}, is environment-dependent i.e. depends on the path loss, shadowing distribution and the transmit power, then the distance threshold, d_{th}, is also environment-dependent as $2R_{sc_i}$. In this way, the UEs only need to initiate the HO to a certain SC in a shortened NCL which only contains certain number of SCs that have a sufficient RSRP level and are located in the UE's movement trajectory. Hence, the possibility of unnecessary HO will be reduced. The introduction of shortened SC NCL has an obvious effect on the performance of the proposed method. Many unnecessary HOs have been avoided because fewer number of target SCs are available for HO unlike the conventional method which considers RSRP level only for candidate NCL extraction (which means that the conventional SC NCL contains all nearby SCs).

The UE expected time of stay (ToS) inside the SC is measured to evaluate the probability of unnecessary HO. The ToS is compared against the time threshold $T_{threshold}$. When the UE's ToS is less than the $T_{threshold}$, the HO is considered as unnecessary HO. The expected time of stay inside a SC i for UE j, denoted as $ToS_{UE_{ji}}$, can be calculated using UE velocity, V_{ue_j}, and the expected traveling distance, $d_{ue_j \to sc_i}$, and is expressed as

$$\begin{aligned} ToS_{UE_{ji}} &= \frac{d_{ue_j \to sc_i}}{V_{ue_j}} \\ &= \frac{2R_{sc_i} \cdot cos(\theta)}{V_{ue_j}}. \end{aligned} \tag{3.11}$$

Depending on the hand-in and hand-out times, the time threshold is chosen so that it is equal to the sum of two HO times (hand-in and hand-out). The RSRP measurement and HO execution take about 360ms. Therefore, two HOs time (hand-in and hand-out) is approximately equal to 720ms.

3.5 Performance Evaluation and Results Analysis

System level simulations have been carried out to evaluate the performance of the proposed algorithm. Table 3.1 gives a summary of simulation parameters used.

We define the number of HOs per MC, HO_n, as

$$HO_n = \sum_{i=1}^{N_{sc}} HO_{n \to i}, \tag{3.12}$$

where $HO_{n \to i}$ is the number of HOs from MC n to SC i. Whereas the number of HOs in all deployed MCs, NHO_m, will be

$$NHO_m = \sum_{n=1}^{N_m} HO_n, \tag{3.13}$$

where N_m is the total number of MC base stations in the network. For high-speed UEs, the HO is happening between two neighbouring MC following the

Table 3.1: Basic Simulation Parameters

Parameter	Value
System bandwidth	5 MHz
Macrocell antenna gain	15 dBi
Macrocell transmit power	45 dBm
Macrocell radius	500 m
Small cell antenna gain	0 dBi
Small cell transmit power	2 dBm
Number of SCs within MC	100
Outdoor penetration loss (L)	10 dB
Number of walls (q_{sc})	Random
P_{th}	-70 dBm
V_{th}	5, 15, 20 km/h
d_{th}	$2R_{sc_i}$
$\alpha_{in,th}$	20^0,30^0,60^0

strongest received power strategy. Therefore, the number of HOs for high-speed UEs, $NHO_{m\to m}$, is expressed as

$$NHO_{m\to m} = \sum_{k=1}^{N_m} HO_{m,k}, \tag{3.14}$$

where $HO_{m,k}$ is the number of HOs between two adjacent MC base stations. Finally, the total number of the HOs in the network, HO_{total}, is

$$HO_{total} = NHO_m + NHO_{m\to m}. \tag{3.15}$$

We express the probability of successful HO to SCs, P_{HO}, as

$$\begin{aligned} P_{HO} = \mathbb{P}\Bigg[& V_{ue_j} \leq V_{th} \;\; \wedge \;\; d_{act}^{ue_j\to sc_i} \leq d_{th} \;\; \wedge \\ & \mid \alpha_{ue_{ji}} \mid \leq \;\; \alpha_{in,th} \;\wedge\; SNR^r_{sc_i\to ue_j} > SNR^r_{m\to ue_j}\Bigg]. \end{aligned} \tag{3.16}$$

Note that equation (3.16) can be evaluated analytically using tools such as stochastic geometry. The probability of unnecessary HO, P_{unHO}, is defined as

$$P_{unHO} = \mathbb{P}\Big[ToS_{UE_{ji}} \leq T_{threshold}\Big], \tag{3.17}$$

where $T_{threshold}$ is the minimum time required for hand-in and hand-out.

In this section, we compare the performance of our proposed HO algorithm with that of the conventional method. The evaluation takes into account the ratio of the SCs in the shortened candidate HO NCL, the probability of HO, the unnecessary HO probability, the throughput and the average energy consumption due to the scanning process prior to selecting the target HO cell. The HO for the conventional method happens when the RSRP of the target cell, $P^r_{sc_i \to ue_j}$, is greater than the RSRP of the serving cell, $P^r_{m \to ue_j}$, i.e. ($P^r_{m \to ue_j} < P^r_{sc_i \to ue_j}$) and can be described as

$$\eta := \Big\{sc_i \mid P^r_{sc_i \to ue_j} > P^r_{m \to ue_j}\Big\} \tag{3.18}$$

$$sc^*_{conv} = \arg\max_{sc_i \in \eta} P^r_{sc_i \to ue_j}, \tag{3.19}$$

where η represents the set of all SCs within the candidate NCL circle of d_{th} radius, and sc^*_{conv} is the best SC in set η in term of downlink received power.

Whereas the HO criteria of our proposed method can be presented as

$$\zeta := \Big\{sc_i \mid SNR^r_{sc_i \to ue_j} > SNR^r_{m \to ue_j}\Big\} \tag{3.20}$$

$$sc^*_{pro} = \arg\max_{sc_i \in \zeta} SNR^r_{sc_i \to ue_j}, \tag{3.21}$$

where ζ represents the set of all SCs within the white unshaded area of Fig.3.4, and sc^*_{pro} is the optimal SC in set ζ which satisfies the conditions in lines (5) and (11) of Algorithm 1.

3.5.1 The Ratio of the Small Cells in the List

We evaluate the ratio of the candidate SCs in a NCL as a function of the distance threshold, d_{th}, taking into account the SC radius. Given that d_{th} is defined as a function of R_{sc_i}, we can define the ratio of the SCs in a shortened candidate NCL, denoted ρ_{sc}, as

$$\rho_{sc} = \frac{Number\ of\ candidate\ small\ cells\ within\ [-\alpha_{in,th}, \alpha_{in,th}]}{Total\ number\ of\ small\ cells} \times 100\% \quad (3.22)$$

As depicted in Fig.3.5, the ratio of the candidate SCs in the conventional method is always the higher compared to our proposed method, because its shortened NCL contains all the SCs within the UE range (i.e. all SCs within a circle of d_{th} radius). On the other hand, our proposed method has reduced the number of candidate SCs in the NCL for different $\alpha_{in,th}$ values. The higher the value of $\alpha_{in,th}$ the higher the ratio of SCs. The impact of the SC NCL radius, d_{th}, is obvious in Fig.3.5, the ratio of SCs slightly increases with the increase in d_{th}. We can clearly see from Fig.3.5 an achieved improvement of the ratio of the candidate SCs in our proposed method compared to the conventional method. For example at $d_{th} = 3R_{sc}$, we have an improvement of 20%, 25%, and 27% when setting $\alpha_{in,th}$ to 60^0, 30^0, and 20^0 respectively. Depending on the distribution of the SCs, we can have different ratio of SCs in the candidate list. For example, when Poisson distribution is used, the ratio will have different performance than that of uniform distribution.

3.5.2 Probability of Handover

The probability of HO is depicted in Fig.3.6. Generally, the probability of HO for the two methods increases with the increase in velocity. The conventional method validation result in Fig.3.6 validates our proposed method. The conventional method [17] has the highest increase owing to the fact that it depends only on RSRP for HO decision. As can be noticed from Fig.3.6, the probability of HO is comparable until the velocity threshold, however, the proposed method shows a sharp reduction in the probability of HO at the velocity threshold enhancing the performance by limiting the number of HOs for fast moving users (i.e., users with velocities above the threshold). At the velocity limits, 5km/h, 15km/h and 20km/h, we can see that the probability of HO for the proposed method sharply goes down before it starts to climb again very slightly because the HO to SC only happens for the UEs with a velocity less than or equal to the velocity threshold. For high-speed UEs, above the velocity threshold, the HO is happening between

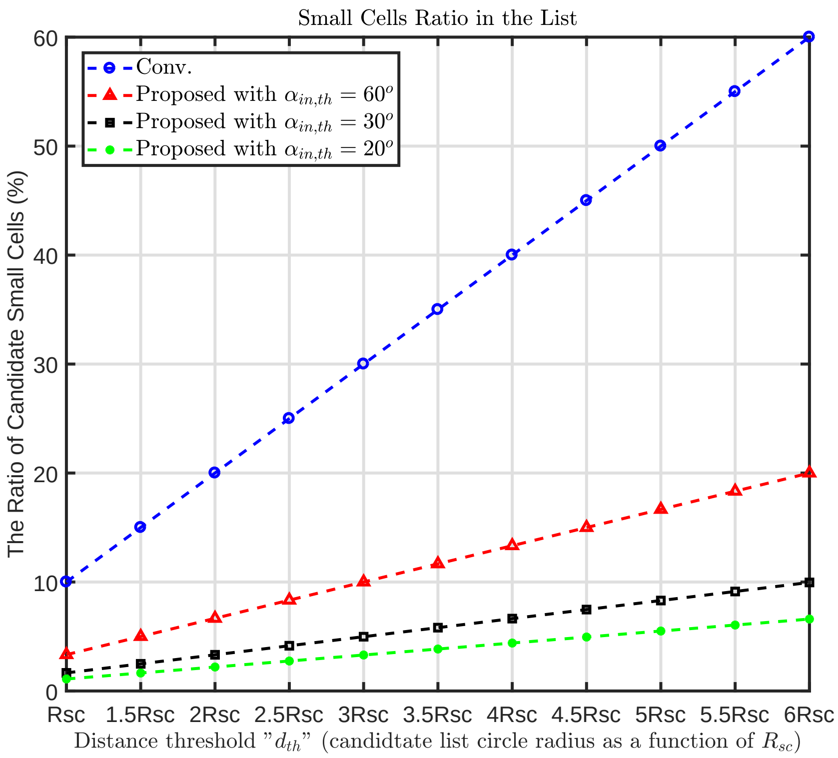

Figure 3.5: Ratio of the Candidate Small Cells in the List as a Function of d_{th} with Different Values of $\alpha_{in,th}$

two adjacent MC base stations. In the proposed method, the effect of the velocity threshold is obvious, fewer HOs are taking place for low-speed UEs with a lower velocity threshold (5 km/h). Moreover, the proposed method shows lower level of HO probability (for all $V_{ue} < V_{th}$) because of the introduction of shortened SC NCL. Hence, fewer HO target cells will result in lower HO probability and will also reduce the extensive scanning for neighbouring SCs which will eventually reduce the UE battery power consumption.

3.5.3 Unnecessary Handover Probability

Fig.3.7 illustrates the probability of unnecessary HO for both the conventional and the proposed methods. The performance of the proposed method outperformed that of the conventional one by showing a lower level of unnecessary HO probability. The conventional method shows a higher level of unnecessary HOs

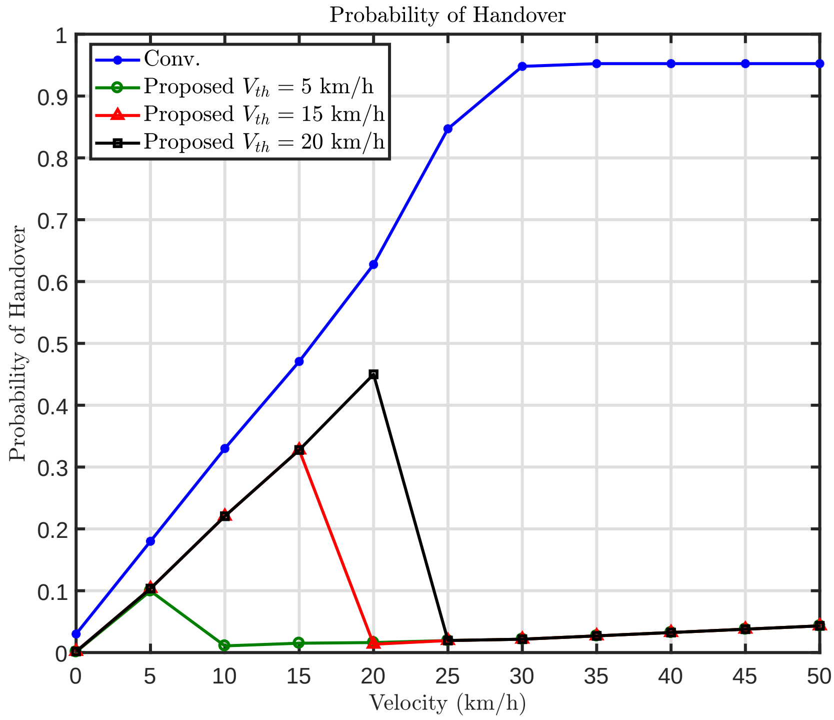

Figure 3.6: Probability of Handover with $\alpha_{in,th} = 30^0$

and this level slightly increase when the velocity of the UE increases owning to the fact that the conventional method depends only on the RSRP level for neighbourhood scanning and HO decision which degrades the end UE QoS by consuming the UE's battery power. The introduction of shortened SC NCL has a great influence on the performance of the algorithm. By using this NCL a plenty of unnecessary HOs have been avoided because a fewer number of target SCs are nominated and the one with highest SNR is selected as a possible HO target making the scanning process less power consuming. As clearly shown in the figure, when using different velocity thresholds in the proposed method the unnecessary HOs are very low for SC UEs compared to the conventional method. The utilization of the angle, $\alpha_{in,th}$, has reduced the number of SCs in the shortened NCL and in turn minimizes the unnecessary HO for different velocity thresholds. For example, when adjusting the velocity threshold to 5km/h, fewer unnecessary HOs are happening for low to medium-speed UE (0km/h-to-25km/h). The higher the velocity threshold, the higher the unnecessary HO for low to medium-speed UEs (0km/h-to-25km/h). Thus, our method has increased the proper utilization

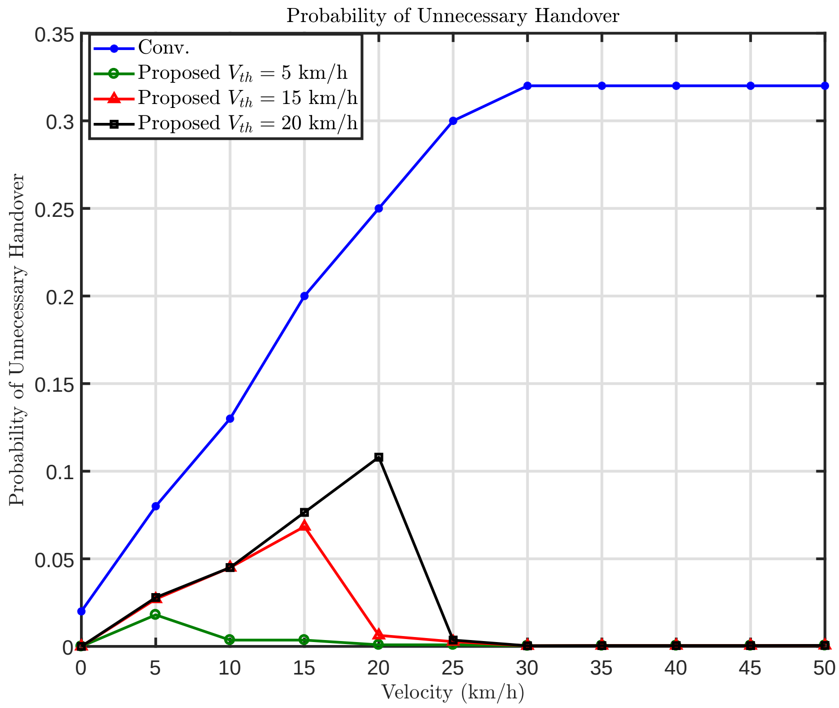

Figure 3.7: Probability of Unnecessary Handover with $\alpha_{in,th} = 30^0$

of SCs and prevented the unnecessary HO from MC UEs to the SC (i.e. has eliminated the HO for fast UEs). Fig.3.8 shows the influence of different angle thresholds, $\alpha_{in,th}$, on the probability of unnecessary HO. As clearly illustrated in Fig.3.8, for different velocity thresholds, the unnecessary HO for lower angle threshold is lower than that of the higher angle threshold (almost 50% reduction in the unnecessary HO is achieved with lower angle threshold). This is due to the fact that lower angle threshold will produce shorter SC NCL and hence low unnecessary HO.

3.5.4 Throughput

Fig.3.9 illustrates the network throughput for both the proposed and the conventional methods against the velocity. For both methods, the throughput decreases with the increase in velocity. The conventional method has always the lowest throughput compared to the proposed method. The proposed method has outperformed the conventional method in terms of throughout by holding higher

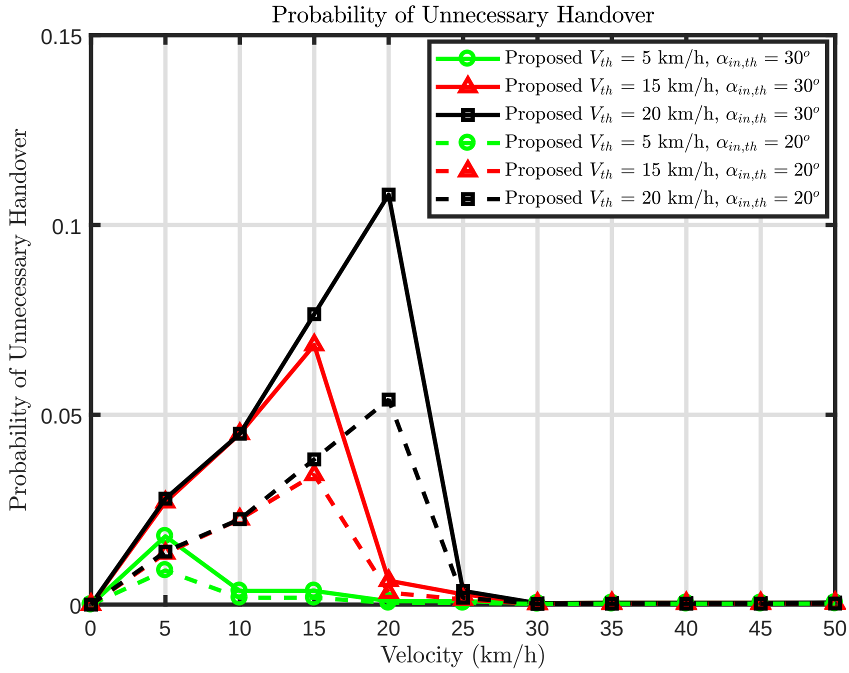

Figure 3.8: Probability of Unnecessary Handover for Different Values of $\alpha_{in,th}$

capacity for fast moving UEs because the fast moving UEs do not have to perform frequent HOs to the small coverage area SC. Fig. 3.9 reveals that our proposed method, in addition to the unnecessary HO reduction, has increased the network throughput. At (5km/h) velocity, the throughput of the proposed method is about 23Kbps higher than that of the conventional method. Moreover, the proposed method continues to produce higher throughput for high-speed UEs, e.g. at (50km/h), the throughput is 46Kbps higher than the conventional method because the high-speed UEs are always associated to the MC. Hence, higher capacity is held for fast moving UEs because the signal to noise ratio for these UEs (served by MC) are nearly steady and are not fluctuated due to high-speed mobility.

3.5.5 Average Energy Consumption

According to [83], the average energy consumption due to scanning the neighbourhood for SCs can be expressed as

$$E_{avg} = N_{avg}^{c} \cdot \lambda_{scan}, \tag{3.23}$$

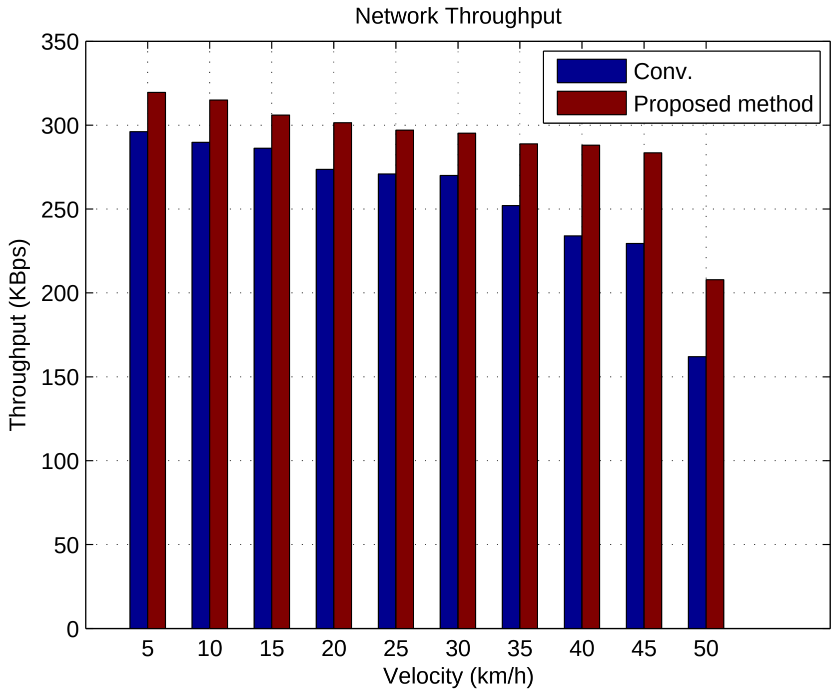

Figure 3.9: Network Throughput with $\alpha_{in,th} = 30^0$

where N^c_{avg} is the average number of scanned cells and λ_{scan} is the average energy consumption per one scanning of one cell and is set to 3 mWs as per [83]. The energy consumption due to the scanning of neighbouring cells is depicted in Fig.3.10. In line with Fig.3.5, the energy consumption increases with the increase in the distance threshold i.e. it is linearly increases with the increase in the number of SCs in the NCL as the distance threshold increases. The proposed method has outperformed the conventional method by producing less energy consumption due to scanning process.

Apparently, smaller values of the angle threshold $\alpha_{in,th}$, e.g. 20^0, can reduce the number of scanned SCs, unnecessary HO and also the energy consumption. However, bigger values of $\alpha_{in,th}$ may increase the throughput. Therefore, a trade-off between choosing smaller values of $\alpha_{in,th}$ and bigger values can depend on the network service provider requirement in terms of tolerable SC scanning, unnecessary HO and the energy consumption, in addition to the desired throughput.

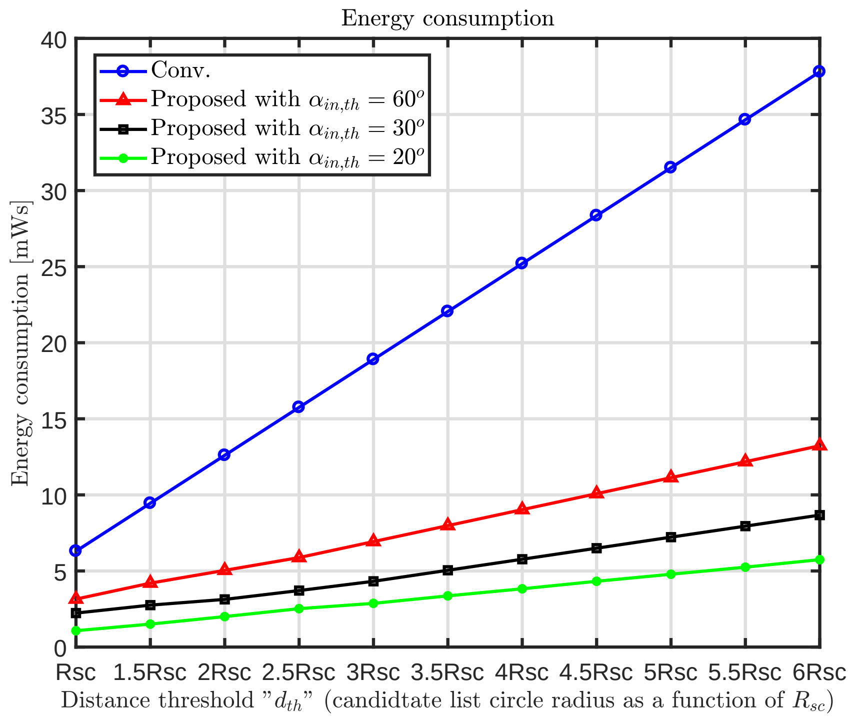

Figure 3.10: Average Energy Consumption with Different Values of $\alpha_{in,th}$

3.6 Summary

In this chapter, a HO method for two-tier heterogeneous network was proposed and compared against the conventional HO method which builds the NCL considering all of the neighbouring SCs and depends only on RSRP for HO decision. Different velocity thresholds are used to control the HO to SC. In order to identify the shortened candidate SC NCL, the actual distance and SC radius, in addition to the UEs angle of movement, were used to form the most realistic SC HO targets. Simulation results showed that our proposed method reduces the number of candidate SCs in the shortened NCL. The proposed method also shows a low number of HOs for all UE's velocities compared to the conventional method. On the other hand, the probability of unnecessary HOs for the proposed method is less than the conventional method due to the incorporation of the shortened SC NCL which in turn reduced the overall scanning for neighbouring SCs. Hence, reducing the UE battery power dissipation. Results show, the network throughput also increased for the proposed method comparing to the conventional method. In addition to that, the proposed method reduced the average energy consumption due to the scanning process compared to the conventional method.

Chapter 4

Management of Unnecessary Handover and Handover Failure in Dense Small Cell HetNets

4.1 Introduction

Despite their huge benefits in providing network coverage in the gaps, that could not be covered by MC base stations, and their promising capacity enhancements, dense SC deployment is expected to introduce the problems of unnecessary handovers (UHO) and handover failures (HOF) in future 5G wireless networks which in turn would degrade the end users' QoS due to the high-speed users, which connect to the SC for a very short time [6] [10]. When the UE performs the HO to a SC and within a short time it performs another HO to the source cell or different SC this is known as ping-pong HO or UHO. On the other hand, when a UE initiates a HO to a SC but the SINR from both the source and target cell drops below a predefined threshold during the HO execution, then a failure in the cell switching happens and this leads to a HOF.

In this chapter, we introduce our proposed method that aims to reduce the UHOs and the HOF in a SC HetNets. Time metric is used to find a compromise between UHO and HOF. In order to reduce the target SC list for HO, the estimated time of stay is used to avoid long NCL. Interference from different base stations is taken into account through the use of SINR metric. The proposed method consists of two procedures. The first one involves the reduction of the number of candidate SCs for HO by removing the SCs that could result in short time of stay phenomena from the NCL. While the second procedure performs the HO to the SC that satisfies the SINR and capacity conditions. Simulations are performed to evaluate the performance of the proposed method. Results show that the proposed method outperformed the competitive methods presented in the literature with a lower level of UHOs and HOFs.

The reminder of this chapter is organized as follows. The related works are given in 4.2. Section 4.3 describes the network system model. Section 4.4 illustrated the proposed HO method to reduce the UHO and HOF. While Section 4.5 evaluates, compares and analyses the performance and results of the proposed method with other methods in the literature. Finally, Section 4.6 concludes the chapter.

4.2 Related Work

Because the MC transmits at much higher power compared to the SCs, the UEs will always tend to HO to MC rather than a SC which makes it difficult to achieve the benefit of utilizing the SCs. Many works have been accomplished in the literature to address this problem of HO management in heterogeneous networks.

Authors in [37] proposed a method to reduce UHO in HetNet with hybrid access SCs. The HO decision is taken by utilizing the RSRP measurements and available bandwidth. However, the neglecting of using the HHM during RSRP comparison is expected to introduce many UHOs due to channel variation. Also, they utilized a fixed time threshold metric to control the HO to SC (e.g 10 and 30 sec) which is not practical in HetNets with SC.

In [84], an RSS and path loss based HO method was proposed. The scenario used in their work consists of a single-MC and a single-SC where a window function is applied to the RSRP of both SC and MC. A Ping-Pong HO is expected to occur in this scenario because the path loss of a cell may fluctuate due to the rapid variations of the network.

Authors in [85] proposed a CAC mechanism and resource management method to minimize the probability of UHOs in WiMAX SC network. Metrics used to design the CAC include RSS, UE speed, time required for UE to maintain minimum RSS for service continuity and duration that UE spends in cell coverage area. Three levels of UE speed are considered low, medium and high. High speed UE will not be permitted to HO to SC and medium speed UE will only be permitted to continue HO procedures if the traffic is real time traffic. Low speed UE continues the HO procedures by checking signal level. The evaluation of this method takes into account the number of HOs in the network.

In [86], location prediction and mobility are used to prevent UEs from performing HO to SC if they are temporary visitors which in turn will minimize the UHOs. The UE enters the coverage area of SC and estimates its next trajectory based on the current one. This information is sent to a server that stores the histories and generates mobility patterns according to certain rules. If the RSS of a target SC is greater than a threshold, the UE predicts its next trajectory. If the next trajectory movement are inside the SC coverage area for enough time, the UE will HO to SC, otherwise it will stay connected to its current serving cell.

Authors in [53] proposed an adaptive hysteresis margin method to reduce the probability of UHOs to a SC. This method compares the RSQ of the target and serving cells by using an adaptive HO margin. The HM is calculated according to the path loss and the RSQ at the UE side.

When the UE spends very short time in the SC after performing the HO, this will result in high number of UHOs and even HOF if the quality of the signal from the serving and target cells dropped simultaneously before the completion of the HO process. However, most of the existing works focus on minimizing the UHO in the SC networks and they did not account for the phenomena of the short time of stay and the HOF. In this work, we propose a HO method which accounts for the avoidance of short time of stay in SCs and hence reducing the UHO and HOF in SC HetNets. We used different metrics for HO including RSRP with HM, UE's ToS, a time threshold, SINR and the capacity of the target HO SC.

4.3 Network System Model

The system model used in this chapter considers two-tier HetNets scenario which consists of one MC base station as depicted in Fig.4.1, with dense SCs and UEs. SCs are deployed randomly under the MC coverage and are likely to overlap due to their dense deployment. UEs are also distributed randomly and uniformly within the MC coverage area. The mobility of the UEs is considered as a Gauss model where the UE velocity and direction are generated with a normal distribution. The mobility of the UE can be expressed using two parameters: UE velocity, V_k, and UE direction, θ_k. These two parameters can be defined as Gaussian distribution

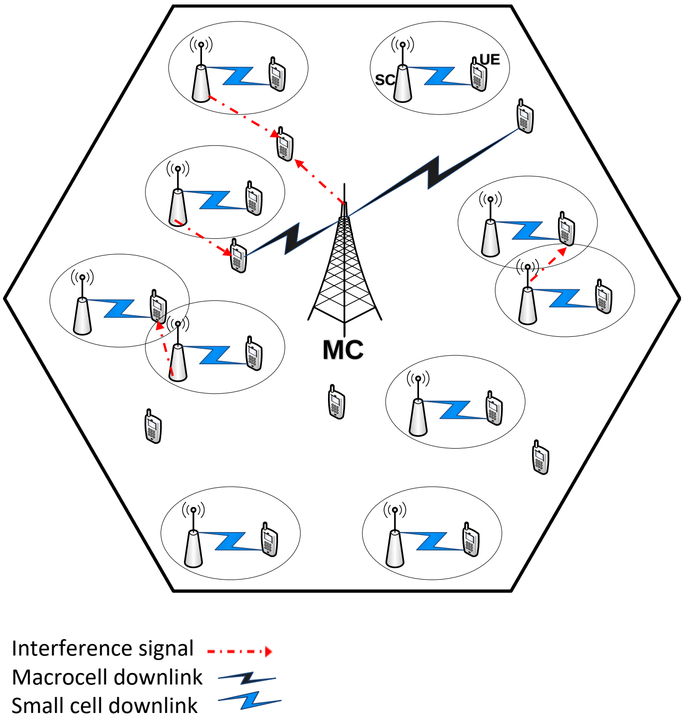

Figure 4.1: Two-Tier Network System model

and are updated accordingly by the following two equations [11]

$$V_k = \mathcal{N}(V_m, V_{std}), \tag{4.1}$$

$$\theta_k = \mathcal{N}\Big(\theta_m, 2\pi - \theta_m \tan(\frac{\sqrt{V_k}}{2})\Delta t\Big), \tag{4.2}$$

where V_m represents the UE's mean velocity, V_{std} denotes the UE's velocity standard deviation, θ_m is the UE's previous direction, Δt is the period between two updates of the mobility model, and $\mathcal{N}(x, y)$ is a Gaussian distribution with mean x and standard deviation y. The Gauss mobility model is a widely used model to represent the mobile user movement, particularly for medium to high speeds (e.g., vehicular speed) [81].

Taking into account the heterogeneous network architecture, different path loss models defined in [87] were used. The path loss between the MC and the UE is as given in (3.1).

On the other hand, the path loss between the UE and the SC is used as per [87]. If the UE is outside the coverage area of SC i, its path loss to SC i is as follows

$$\delta_{sc_i \to ue_k} = \max\Big(15.3 + 37.6\ \log_{10}(d_{sc_i \to ue_k}), 37 + 20\ \log_{10}(d_{sc_i \to ue_k})\Big) + qW + L, \tag{4.3}$$

where $d_{sc_i \to ue_k}$ is the distance between the UE and SC i in meters, q is the number of walls between the SC and the UE where $q \in \left\{0,1,..., \left\lfloor \frac{d^p_{sc_i \to ue_k}}{d} \right\rfloor\right\}$, $\lfloor x \rfloor$ means the floor of x, i.e. the largest integer less than or equal to x, $d^p_{sc_i \to ue_k}$ is the part of $d_{sc_i \to ue_k}$ inside SC i coverage area, d is chosen to be $2m$ [87], W is the wall partition loss and L is the outdoor penetration loss.

When the UE is inside the SC i coverage area, its path loss to the SC i is calculated as

$$\delta_{sc_i \to ue_k} = 37 + 20\ \log_{10}(d_{sc_i \to ue_k}) + qW. \tag{4.4}$$

If the UE is inside the coverage area of SC i, its path loss to SC j ($j \neq i$) is as follows

$$\delta_{sc_j \to ue_k} = \max\Big(15.3 + 37.6\ \log_{10}(d_{sc_j \to ue_k}), 37 + 20\ \log_{10}(d_{sc_j \to ue_k})\Big) + qW + 2L, \tag{4.5}$$

where $d_{sc_j \to ue_k}$ is the distance between the UE and SC j in meters, $q \in \left\{0,1,..., \left\lfloor \frac{d^p_{sc_i \to ue_k} + d^p_{sc_j \to ue_k}}{d} \right\rfloor\right\}$, and $d^p_{sc_j \to ue_k}$ is the part of $d_{sc_j \to ue_k}$ inside SC j coverage area. The pilot RSRP is calculated as follows

$$P^r_{i_p \to ue_k} = \frac{p^t_{i \to ue_k} g_i g_{ue_k}}{lo_i lo_{ue_k} \xi_{i \to ue_k} \delta_{i \to ue_k}}, \tag{4.6}$$

where $P^r_{i_p \to ue_k}$ is the pilot RSRP received from a target cell i at UE k, $p^t_{i \to ue_k}$ is the transmitting power of the base station i, g_i is the antenna gain of the base station i, g_{ue_k} is the antenna gain of UE k, lo_i is the base station i equipment loss, lo_{ue_k} is the UE equipment loss, $\xi_{i \to ue_k}$ is the shadow fading with a log-normal distribution with zero mean and 3 dB standard deviation [16] and $\delta_{i \to ue_k}$ is the path loss between base i station and UE k.

The UE measures RSRP every 40 ms and averages it over 5 samples i.e. every 200 ms [10] so that

$$P^r_{i \to ue_k} = \frac{1}{5} \sum_{s=1}^{5} P^r_{i_p \to ue_k}(s), \tag{4.7}$$

where $P^r_{i\rightarrow ue_k}$ is the average RSRP over 5 samples.

Whereas the interference power received by UE k from its adjacent base stations is expressed in the following equation

$$P^r_{j\rightarrow ue_k} = \frac{p^t_{j\rightarrow ue_k} g_j g_{ue_k}}{lo_j lo_{ue_k} \xi_{j\rightarrow ue_k} \delta_{j\rightarrow ue_k}}, \tag{4.8}$$

where $P^r_{j\rightarrow ue_k}$ is the power received from the interfering base station j, $p^t_{j\rightarrow ue_k}$ is the transmitting power of the interfering base station j, g_j is the antenna gain of the interfering j, lo_j is the interfering base station equipment loss, $\xi_{j\rightarrow ue_k}$ represents the shadow fading between interfering base station and UE k and $\delta_{j\rightarrow ue_k}$ is the path loss between the interfering base station j and UE k.

The SINR measured at UE k is obtained as follows

$$\gamma_{i\rightarrow ue_k} = \frac{P^r_{i\rightarrow ue_k}}{\sum_{j=1,i\neq j}^{n_j} P^r_{j\rightarrow ue_k} + \sigma^2}, \tag{4.9}$$

where n_j is the total number of interfering base stations and σ^2 is the noise power.

Substituting (4.7) and (4.8) in (4.9), we get the final SINR as follows

$$\gamma_{i\rightarrow ue_k} = \frac{\frac{1}{5}\sum_{s=1}^{5} P^r_{i_p\rightarrow ue_k}(s)}{\sum_{j=1,i\neq j}^{nj} \frac{p^t_{j\rightarrow ue_k} g_j g_{ue_k}}{lo_j lo_{ue_k} \xi_{j\rightarrow ue_k} \delta_{j\rightarrow ue_k}} + \sigma^2} \tag{4.10}$$

The realistic cell border is neither circular nor hexagonal, but it depends on different factors such as interference, geographic environment and obstacles. The shape of the cell coverage area is highly affected by these factors. Therefore, the radius of the SC, R_i, could be estimated when the UE enters the coverage area of the SC [57] i.e. when the UE starts receiving the minimum required signal power indicated by service continuity, (P_{th}), hence, we can express the SC radius as

$$R_i = \Big(\frac{p^t_{i\rightarrow ue_k}\ 10^{\xi/10}}{P_{th}}\Big)^{\frac{1}{\zeta}}, \tag{4.11}$$

where $p^t_{i\rightarrow ue_k}$ is defined in mW, ξ is a Gaussian distribution random variable with zero mean and 12 dB standard deviation and ζ is the path loss exponent selected between 2 and 4.

In order to find the expected traveling distance of the UE inside the SC coverage area, d_s, we use the geometry shown in Fig.4.2. The expected UE traveling

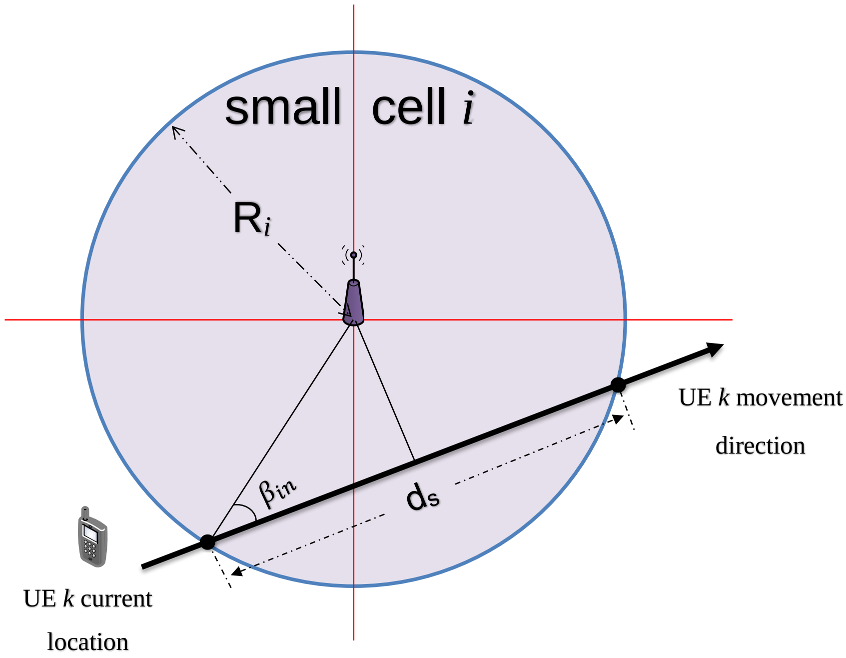

Figure 4.2: Estimated ToS measurement

distance inside the SC can be expressed as

$$d_s = 2R_i \cos(\beta_{in}). \tag{4.12}$$

The expected time of stay of UE k, $ToS^{est}_{ue_k}$, can then be calculated using the UE velocity, V_k, and the traveling distance, d_s, and is expressed as

$$\begin{aligned} ToS^{est}_{ue_k} &= \frac{1}{\pi}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{d_s}{V_k} d\beta_{in} \\ &= \frac{1}{\pi V_k}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} 2R_i\cos(\beta_{in})d\beta_{in} \\ &= \frac{4R_i \sin(\frac{\pi}{2})}{\pi V_k} \\ &= \frac{4R_i}{\pi V_k}. \end{aligned} \tag{4.13}$$

Instead of considering a fixed HM for all cells and to make sure that the ping-pong HO (which is the type of UHO between the serving and destination cells back and forth) is highly reduced, we modified the used expression in [53] to calculate the HM, to be dynamic, such as the following

$$HM = \left(1 - 10^{P^r_{sc \to ue_k} - P_{th}}\right)^{\epsilon}, \tag{4.14}$$

where $P^r_{sc \to ue_k}$ is the RSRP from the SC received at UE k and ϵ is a constant exponent set to 4 as per [53].

4.4 Proposed Method to Manage the Unnecessary HO and HO Failure

The proposed method uses multiple metrics for HO decision in order to control both UHOs and HOFs in the dense SC HetNet environment. These metrics are RSRP with HM, ToS, a time threshold, SINR and SC capacity. The ToS is an effective metric to reduce the size of the NCL and both SINR and SC capacity are used to HO to the best cell and ensure to reduce the HOF. The proposed method is described in the pseudo code Algorithm 2, where $P^r_{m \to ue_k}$ is the RSRP from the MC received at UE k, TC_{th} is the critical time threshold (which is equal to two HO times i.e. hand-in and hand-out and set to 720ms), $\gamma_{m \to ue_k}$ and $\gamma_{sc_i \to ue_k}$ are the SINR received at UE k from the MC and SC i respectively and finally γ_{th} is the outage threshold ($\gamma_{th} = 5$dB [88]).

The proposed method begins when a MC UE moves towards the SCs coverage area. High-speed UEs usually stay in the SC coverage area for a very short time, thus, the received RSRP from the SC fluctuates rapidly resulting in UHOs and HOFs. Therefore, we introduce the expected UE's ToS and a time threshold metrics to control this issue. The time threshold will ensure that the UE selects a proper target for HO with sufficient signal level i.e. the UE must stay in the SC coverage area for a sufficient time that worth to HO to the SC.

The UE then starts monitoring the RSRP received from the surrounding SCs. The UE's expected ToS in the SC is measured and compared against the critical time threshold TC_{th}. If the UE's ToS is at least higher than the critical time threshold, we mark this SC as one of the HO targets. Hence, we can define a set of HO target SCs, denoted as M_{set}, at this stage as

$$M_{set} = \left\{ sc_i \in N_s \mid ToS^{est}_{ue_k} > TC_{th} \right\}, \tag{4.15}$$

Algorithm 2 Proposed Method to Manage the UHO and HOF

1: **Procedure Starts**
2: MC UE k **moves** to SC coverage area
3: SC RSRP **monitoring**
4: **Evaluate** $P^r_{sc \to ue_k}$
5: **Estimate** $ToS^{est}_{ue_k}$
6: **if** $ToS^{est}_{ue_k} > TC_{th}$ **then**
7:     **Include** this SC in HO target cell list for UE k
8: **end if**
9: **if** maximum ($P^r_{sc \to ue}$) from the list is $> P^r_{m \to ue} + HM$ **then**
10:     **Evaluate** $\gamma_{i \to ue}$
11:     **if** $\gamma_{m \to ue_k} < \gamma_{th}$ and $\gamma_{sc_i \to ue_k} > \gamma_{th}$ **then**
12:         **Check** capacity C_{sc_i}
13:         **if** $C_{sc_i} < 1$ **then**
14:             **HO** to SC i
15:         **end if**
16:     **end if**
17: **end if**
18: **end procedure**

where N_s is a set representing the total number of SCs in the network. Which means that the number of possible target SCs in the NCL is reduced by omitting all SCs that could cause a short ToS. Then, the maximum received RSRP from the SC list must be offset greater than the current serving MC RSRP $\left(P^r_{sc \to ue_k} > P^r_{m \to ue_k} + HM\right)$. It is worth noting that this condition (line 9 in Algorithm 2) is to make sure that the SC downlink received signal still strong enough and has not been fluctuated due to shadow fading.

Then, UE k measures the SINR received from both MC, $\gamma_{m \to ue_k}$, and SC, $\gamma_{sc_i \to ue_k}$, and compare them against a predefined threshold γ_{th}. When $\gamma_{sc_i \to ue_k}$ exceeds $\gamma_{m \to ue_k}$ and γ_{th}, the HO is performed to this SC providing that this SC has enough capacity (resources) to serve this UE. This process will offload the traffic from the congested MC and increase the network capacity. SC capacity (see the proposed method Algorithm 2, line (12)) here means the number of UEs that can be served by the SC. Here we assume that the maximum number of UEs that can be served by a SC is 20 [10]. Hence, the capacity of SC i, denoted as

C_{sc_i}, can be expressed as

$$C_{sc_i} = \frac{\sum_{ue} N_{ue,sc_i}}{N^{max}_{ue,sc_i}}, \tag{4.16}$$

where N_{ue,sc_i} is the current number of UEs camping in SC i and N^{max}_{ue,sc_i} is the maximum capacity of SC i in terms of the number of UEs which is set to 20. When C_{sc_i} is equal to 1, this means that SC i is fully-loaded and is unable to deliver services to any new incoming UEs.

4.5 Performance Evaluation and Results Analysis

In this section, we compare the performance of our proposed method with that of the conventional method [17] and the methods presented in [37] and [85]. For the sake of simplicity, we abbreviate the competitive methods' names based on the authors' initial, method in [37] is abbreviated as KL and method in [85] is referred to as SOA.

All methods are evaluated in terms of the total number of HOs, UHO probability and the HOF probability. Table 4.1 gives a summary of simulation parameters used. Simulations have been carried out to evaluate the performance of the proposed and competitive methods.

The probability of HO in the conventional methods (denoted as P^{conv}_{ho}) is RSS-dependent, i.e. UE performs HO to the base station with the strongest downlink received signal, and is given by the following form

$$P^{conv}_{ho} = \mathbb{P}\Big[RSS^r_{m\rightarrow ue_k} < RSS^r_{sc_i\rightarrow ue_k}\Big], \tag{4.17}$$

where $RSS^r_{m\rightarrow ue_k}$ and $RSS^r_{sc_i\rightarrow ue_k}$ are the received signal strength from the serving MC and the target SC base stations respectively.

According to our system model, we can describe the HO criteria for the conventional method to select the best SC as

$$\chi := \Big\{sc_i \mid RSS^r_{sc_i\rightarrow ue_k} > RSS^r_{m\rightarrow ue_k}\Big\}, \tag{4.18}$$

$$sc^{tar}_{conv} = \arg\max_{sc_i\in\chi} RSS^r_{sc_i\rightarrow ue_k}, \tag{4.19}$$

Table 4.1: Basic Simulation Parameters

Parameter	Value
Bandwidth	10 MHz
MC antenna gain	14 dBi
MC Transmit power	43 dBm
MC Radius	800 m
SC antenna gain	0 dBi
SC Transmit power	23 dBm
Number of SCs within MC	50
Outdoor penetration loss (L)	10 dB
Wall partition loss (W)	5 dB
P_{th}	-70 dBm
γ_{th}	5 dB
V_m	3 km/h
V_{std}	1 km/h
Δt	1 sec
ζ	3.5

where χ corresponds to the set of all SCs in the network with $RSS^r_{sc_i \to ue_k} > RSS^r_{m \to ue_k}$, and sc^{tar}_{conv} is the conventional method's best SC within the set χ in terms of strongest RSS.

The KL method [37] performs the HO to SC if its RSS is greater than a predefined threshold, RSS_{th}, for a specific time, T, and the SC's bandwidth is sufficient enough to support the UE HO. Therefore, the HO criteria for KL method can be give as

$$\Upsilon := \Big\{ sc_i \mid RSS^r_{sc_i \to ue_k} > RSS_{th} \text{ for } 'T' \text{ time } \wedge \text{ BW available} \Big\}, \tag{4.20}$$

$$sc_{kl}^{tar} = \arg\max_{sc_i \in \Upsilon} RSS_{sc_i \to ue_k}^{r}, \tag{4.21}$$

where Υ corresponds to the set of all target SCs in the network that satisfy the conditions in the brackets, and sc_{kl}^{tar} is the KL method's best SC within the set Υ.

The SOA method [85] performs the HO to SC if the UE speed is slow, below a threshold V_{th}, the SC's bandwidth is sufficient enough to support the UE HO and SC's RSS is greater than that of the serving MC for a period of time T. Thus, the HO criteria for SOA method can be also simplified as

$$\Omega := \Big\{ sc_i \mid V_k < V_{th} \ \wedge \text{BW available } \wedge RSS_{sc_i \to ue_k}^{r} > RSS_{m \to ue_k}^{r} \text{ for } 'T' \text{ time} \Big\}, \tag{4.22}$$

$$sc_{soa}^{tar} = \arg\max_{sc_i \in \Omega} RSS_{sc_i \to ue_k}^{r}, \tag{4.23}$$

where Ω corresponds to the set of all target SCs in the network that satisfy the conditions in the brackets, and sc_{soa}^{tar} is the SOA method's best SC within the set Ω.

The probability of successful HO to a SC i in our proposed method (denoted as P_{ho}^{pro}) is

$$\begin{aligned} P_{ho}^{pro} = \mathbb{P}\Big[& \ ToS_{ue_k}^{est} > TC_{th} \ \wedge \ P_{sc \to ue_k}^{r} > P_{m \to ue_k}^{r} + HM \ \wedge \\ & \gamma_{m \to ue_k} < \gamma_{th} \ \wedge \ \gamma_{sc_i \to ue_k} > \gamma_{th} \ \wedge \ C_{sc_i} < 1 \Big], \end{aligned} \tag{4.24}$$

Similarly, we can define the HO criteria for our proposed method to select the best SC as

$$\omega := \Big\{ sc_i \mid (\gamma_{sc_i \to ue_k}^{r} > \gamma_{m \to ue_k}^{r}) \wedge [C_{sc_i} < 1] \Big\} \tag{4.25}$$

$$sc_{pro}^{tar} = \arg\max_{sc_i \in \omega} \gamma_{sc_i \to ue_k}^{r}, \tag{4.26}$$

where ω represents a set of all SCs, within the set M_{set}, which satisfies the conditions (11) and (13) of Algorithm 2, $[\cdot]$ is the Iverson bracket which denotes one if the condition in the bracket is true or denotes zero otherwise, and sc_{pro}^{tar} is the optimal SC in the set ω which satisfies all the conditions of the proposed method.

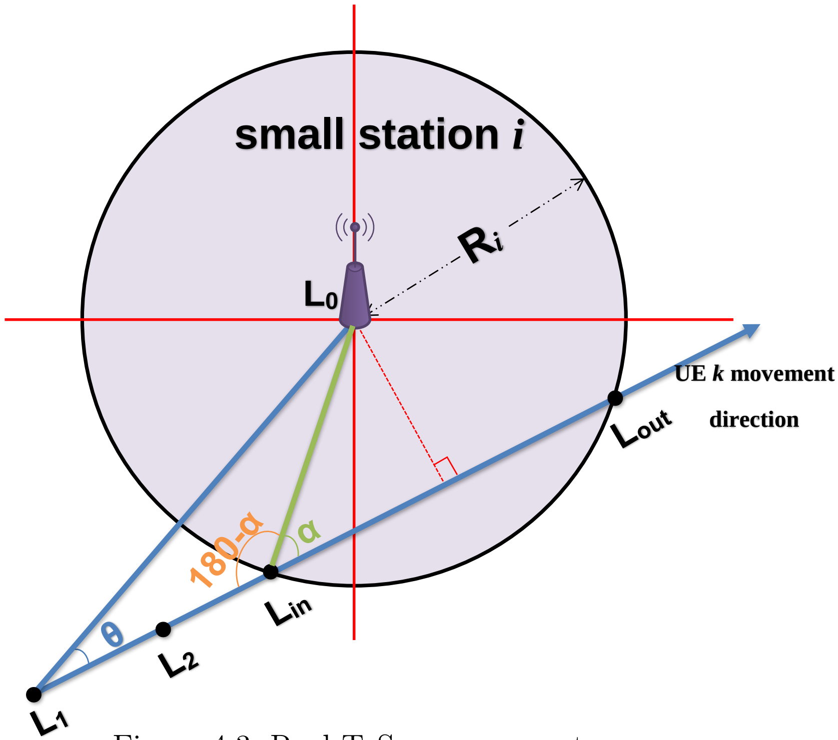

Figure 4.3: Real ToS measurement

The probability of UHO is measured based on the real time of stay, denoted $ToS^{real}_{ue_k}$, that UE k will actually spend inside SC i after HO and the critical time threshold TC_{th}. In our proposed method, we defined the HO as unnecessary when the UE's real ToS, $ToS^{real}_{ue_k}$, is less than or equal to the critical time threshold TC_{th}. Then, the UHO probability, P^{pro}_{uho}, is

$$P^{pro}_{uho} = \mathbb{P}\Big[ToS^{real}_{ue_k} \leq TC_{th}\Big]. \tag{4.27}$$

Based on Fig.4.3 we can measure the real ToS as

$$\begin{aligned} ToS^{real}_{ue_k} &= \frac{\mid \overrightarrow{L_{in}L_{out}} \mid}{V_k} \\ &= \frac{2R_i \cos(\alpha)}{V_k}, \end{aligned} \tag{4.28}$$

where L_{in}, and L_{out} are respectively the entry point of UE to SC, and the exit point of UE from SC. We can get the following from Fig.4.3

$$\frac{\mid L_1 L_0 \mid}{\sin(180-\alpha)} = \frac{R_i}{\sin(\theta)}, \tag{4.29}$$

where L_0, and L_1 are respectively the SC location, and the previous location of the UE. Rearranging (4.29), we get

$$\sin(\alpha) = \frac{\mid L_1 L_0 \mid \sin(\theta)}{R_i}, \tag{4.30}$$

and thus

$$\cos(\alpha) = \sqrt{1 - \frac{\big(\mid L_1 L_0 \mid \sin(\theta)\big)^2}{R_i^2}}. \tag{4.31}$$

The angle between the UE trajectory and the SC, θ, can also be calculated as shown in Fig.4.3

$$\theta = \arccos\left(\frac{\overrightarrow{L_1 L_0} \cdot \overrightarrow{L_1 L_2}}{\mid \overrightarrow{L_1 L_0} \mid \times \mid \overrightarrow{L_1 L_2} \mid}\right), \tag{4.32}$$

where L_2 is the current location of the UE.

Finally, we substitute (4.31) and (4.32) in (4.28) to get the real time of stay as

$$ToS^{real}_{ue_k} = \frac{2R_i\sqrt{1 - \frac{\left(|\overrightarrow{L_1 L_0}| \cdot \sin\left(\arccos\left(\frac{\overrightarrow{L_1 L_0} \cdot \overrightarrow{L_1 L_2}}{|\overrightarrow{L_1 L_0}| \times |\overrightarrow{L_1 L_2}|}\right)\right)\right)^2}{R_i^2}}}{V_k}. \tag{4.33}$$

The probability of HOF for our proposed method, P^{pro}_{hof}, happens when the HO to a SC i is initiated (as UE k departs the vicinity of MC coverage area i.e. $\gamma_{m \to ue_k} < \gamma_{th}$) but $\gamma_{sc_i \to ue_k}$ suddenly goes below the threshold for a period of TC_{th}. Thus, we define the probability of HOF as

$$P^{pro}_{hof} = \mathbb{P}\Big[\gamma_{m \to ue_k} < \gamma_{th} \;\; \wedge \;\; \gamma_{sc_i \to ue_k} < \gamma_{th} \;\; \text{for} \;\; TC_{th} \text{ time}\Big] \tag{4.34}$$

4.5.1 Total Number of Handovers

Fig.4.4 depicts the total number of HOs between the MC and SCs for all four methods. The results in Fig.4.4 validate our proposed method. As depicted in Fig.4.4, when the number of users is 8, the number of HOs for KL [37], SOA [85] and the proposed method is very similar. After that the proposed method starts to outperform the other methods. The number of HOs for the conventional method linearly increases when the number of UEs moving towards the SCs increases because all UEs have to perform the HO from the MC to SC according to the received signal power RSS. Whereas the number of HOs for our proposed

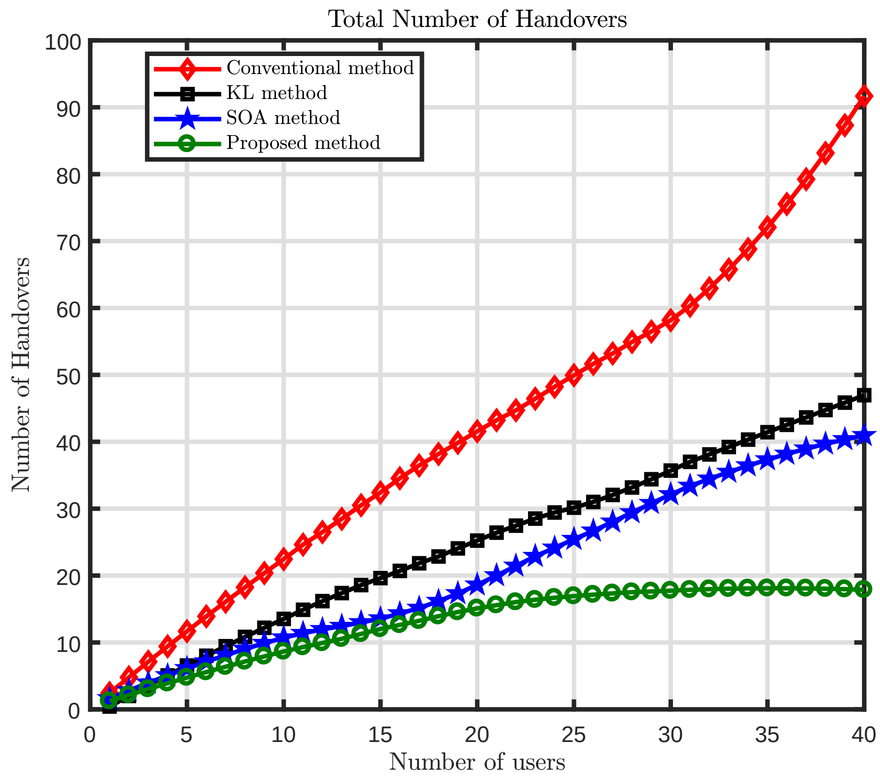

Figure 4.4: Total Number of Handovers

method is much lower (when UE density is 30, about 40%, 15% and 11% reduction in the number of HOs is achieved in our proposed method comparing to the conventional, KL and SOA methods respectively) because the UEs do not have to perform HO frequently due to the incorporation of UE's ToS and the critical time threshold as HO triggering criteria. Due to the limited capacity of the SCs, the number of HOs in our proposed method reaches a steady level with the increase in the number of UEs moving to the SCs coverage area.

4.5.2 Unnecessary Handover Probability

The probability of UHO is shown in Fig.4.5. In our method, we defined the HO as unnecessary when the UE's real ToS, $ToS^{real}_{ue_k}$, is less than or equal to the critical time threshold TC_{th} as defined in (4.27). For both the conventional and KL methods, the UHOs increase with the increase in the number of UEs traveling

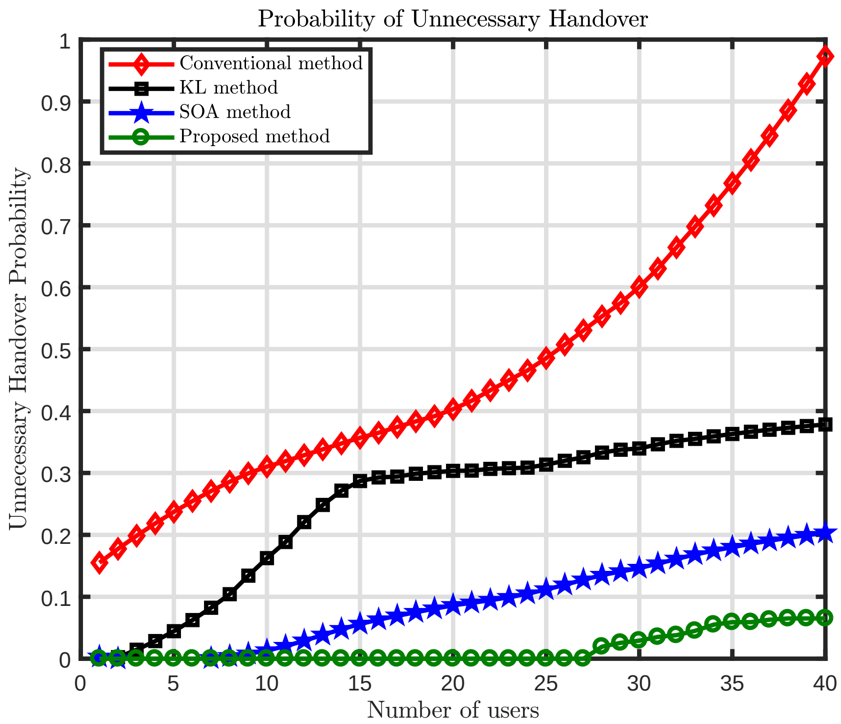

Figure 4.5: Unnecessary Handover Probability

to the SC coverage area. We noticed that the conventional method has the highest increase due to the fact that it depends on the signal strength level only for HO decision. Whereas our proposed method has the lowest level of UHO due to the restrictions of the UE's ToS. When the number of UEs is 30, there are nearly 60%, 35% and 15% of UHOs respectively when the conventional, KL and SOA methods are used. On the other hand, using our proposed method, the probability of UHO is reduced to almost 4%. The main reason for UHO reduction in our proposed method is the use of UE's predicted ToS as a triggering condition for HO, which means that high-speed users will not usually HO to the SC because they will spend very short time compared to the threshold TC_{th} in the SC coverage area. Even in the presence of interference, our proposed method ensures that the received signal from the SC is sufficient for HO through the use of SINR metric, thus, this procedure has reduced some of the UHOs in the network.

4.5.3 Handover Failure Probability

The probability of HOF is depicted in Fig.4.6. As given in (4.34), the HOF in our proposed method will take place when the SINR received from both the serving MC and the target SC drops below a predefined threshold at the same time i.e. the TC_{th} is triggered and the HO is initiated but a radio link failure occurs before TC_{th} expires, which means that neither the serving MC nor the target SC is able to serve the UE. From Fig.4.6 we can see that the HOF probability for the conventional method is increasing rapidly when the number of UEs moving to the SC coverage area increases due to the high-speed mobility users in the dense SC deployment area and capacity shortage in the target SC. Hence, the HO will be initiated based on RSS but will be interrupted due to the short time that the user will spend inside the SC resulting in HOF. While the proposed method shows a much lower level of HOF because of the time threshold metric. Our proposed method also outperformed KL and SOA methods, by showing few HOFs as the number of UEs increases due to the considered interference measurements. Most of the HOFs in our proposed method will probably happen at the MC edge due to the hight interference power near the MC coverage area border. One reason for this low HOF in the proposed method is that the incorporating of capacity metric, hence, UEs will not initiate a HO process to a SC without sufficient resources.

Fig.4.7 shows the probabilities of UHO and HOF vs. variable values of time threshold (this result is when the density of the UEs is 30). High-speed UEs may pass through the SC coverage area before TC_{th} expires leading to HOF due to the degradation of SINR. Whereas high-speed UEs crossing the SC coverage area and HO to the SC causing frequent UHO. Therefore, small values of TC_{th} may cause too early HO which results in UHO. While large values of TC_{th} may cause too late HO which in turn leads to HOF. As clearly indicated in Fig.4.7, a trade-off between HOF and UHO can be achieved with a time threshold metric of 1.97 seconds.

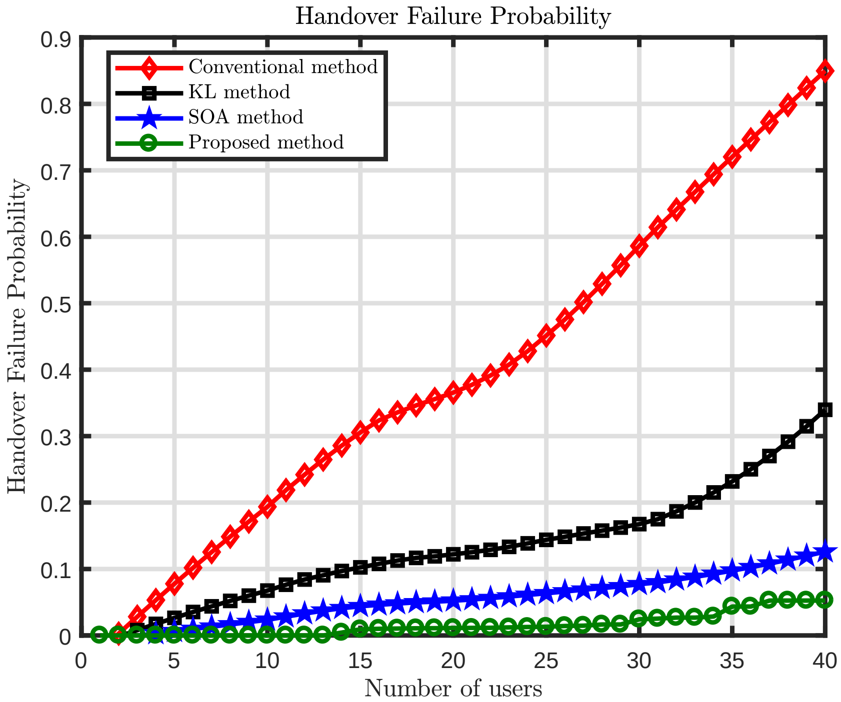

Figure 4.6: Handover Failure Probability

4.5.4 Comparing the Estimated with the Real Time of Stay

To further analyse the accuracy of the used time of stay in the proposed method, where it has been used to reduce the number of SCs in the NCL, we compared the estimated ToS measured in (4.13) with the real ToS measured in (4.33) which is used to evaluate the unnecessary HO probability. In this scenario, we considered one UE with one SC, where the UE moves towards the SC with constant velocities from the range [0:5:50]. As depicted in Fig.4.8, for all velocities the estimated ToS is slightly higher than the real ToS. This indicates that the utilization of estimated ToS is sufficient to properly reduce the number of SCs in the NCL.

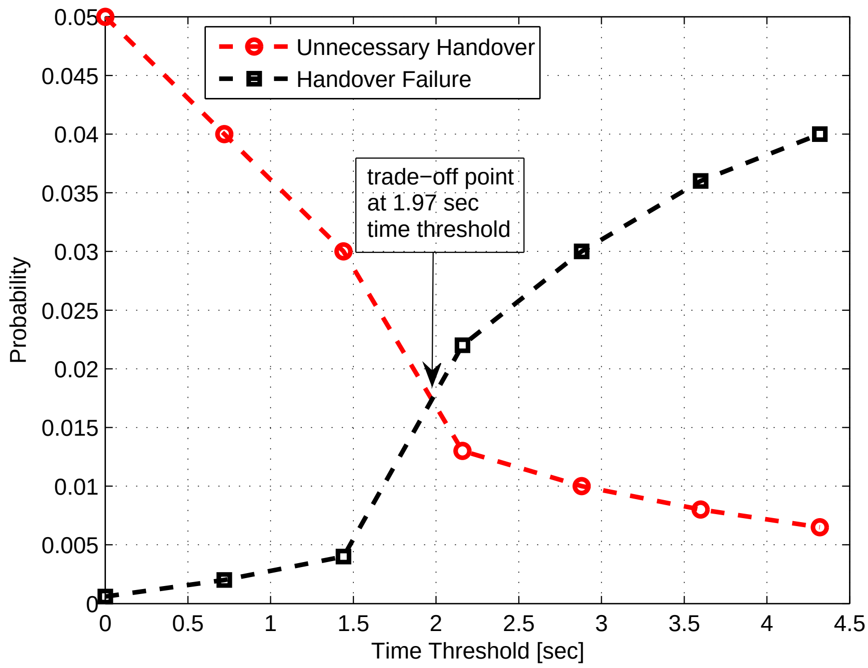

Figure 4.7: A Trade-off Between Unnecessary Handover and Handover failure

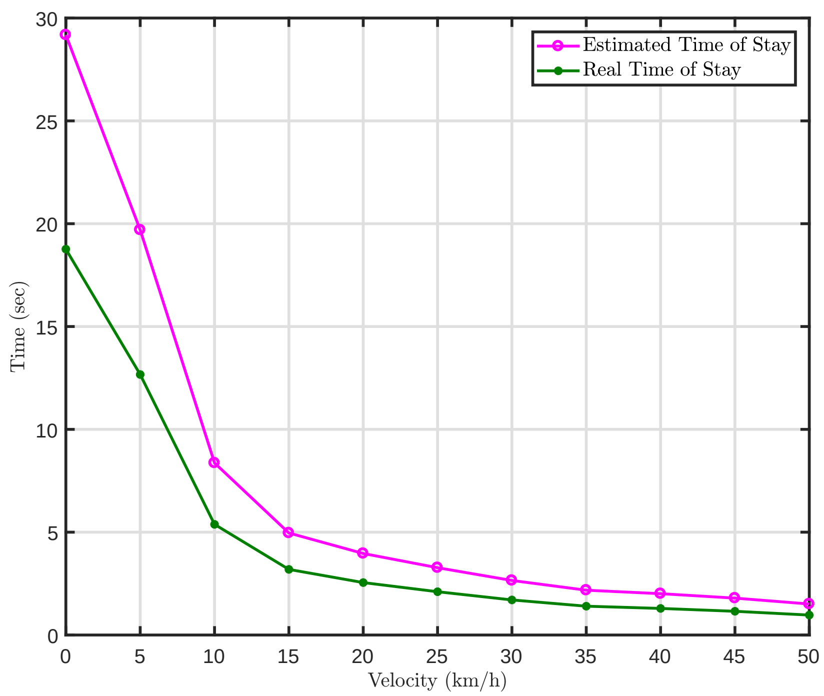

Figure 4.8: Comparing the Estimated with the Real Time of Stay

4.6 Summary

In this chapter, we proposed a HO method to minimize the UHO and HOF in HetNets. The proposed method is applied to a scenario of one MC base station and dense SCs. The MC UEs travel to SCs coverage areas and perform HO according to the proposed method. The predicted time of stay, $ToS^{est}_{ue_k}$, is used to reduce the UHOs and to avoid long small cell list. Moreover, the interference and SC capacity are utilised as major metrics to minimize the UHOs and HOFs. Simulation results show that the probability of UHO is reduced compared to the conventional, KL and SOA methods. Moreover, our proposed method also outperformed all methods by producing a very low probability of HOF. The time threshold along with the SINR are used to find a compromise between UHO and HOF and the results show that it is possible when using a time threshold metric of 1.97 seconds.

Chapter 5

Interference-based Load-dependent Handover Margin for Load Balancing and Throughput Enhancement

5.1 Introduction

The robustness of mobility is a critical aspect in HetNets. The mobility states are either in Radio Resource Control (RRC) idle mode or in RRC-active mode. The RRC-idle mobility mode is related to the cell selection and reselection. While the mobility in the RRC-active mode involves the process of HO so as to maintain the ongoing call or data session. Therefore, the HO is a critical process that affects the services delivered to the UE because it happens during the data transmission between the UE and the base station [10].

Inbound HO or hand-in is done when the UE performs HO from an MC to a SC. While the outbound HO or handout is done when a UE hands over from SC to MC. On the other hand, the inter-SC HO is done when a UE performs HO between two SCs. The outbound HO is not as complex as the other two types because the UE has only one HO target base station i.e., the MC. Therefore, in this chapter, we only consider the inbound and inter-SC HO types.

Given the traditional HO scheme for HO to SCs as [89]

$$P^{r}_{m\rightarrow ue_k} < P^{th}_{min} \text{ and } P^{r}_{sc_i\rightarrow ue_k} > P^{r}_{m\rightarrow ue_k} + HM, \tag{5.1}$$

where $P^{r}_{m\rightarrow ue_k}$, $P^{r}_{sc_i\rightarrow ue_k}$, represent the downlink received signal from the MC and SC respectively, P^{th}_{min} is the minimum required signal power threshold to guarantee QoS and HM is the HO hysteresis margin.

Due to the big difference in the transmission power of both MC and SC, it is unlikely to achieve the above criteria. In particular, when the SC is positioned in the inner area of MC coverage, the UE will always be associated to the MC despite that $P^{r}_{sc_i\rightarrow ue_k}$ being strong enough. This will lead to a severe congestion in the MC tier because of the improper SC utilization and eventually ends up with a lower network throughput. Therefore, it is definitely efficient to consider other parameters for HO that account for different UE speeds, cell load balance and interference levels introduced by a large deployment of SCs because the achievable data rate of the UE is largely affected by the interference level in the network as well as the distance between the base station and the UE in addition to the load of each cell.

For a UE to perform HO, the list of HO target cells is saved in each cell in a specific list known as a NCL, which includes all of the neighbouring cells for this base station. Upon the HO to this base station, the UE obtains the NCL. Then, the UE measures the signal quality of the cells stored in this NCL for the purpose of the next HO process [90]. With the dense deployment of SCs in the future 5G network, it is not efficient to consider a NCL containing a very large number of SCs. A shorter NCL means lower signal overhead, proper SC utilization, faster HO and lower energy consumption.

When the UE connects to a SC for a very short time of stay (ToS), less than a predefined time threshold, this will result in frequently unnecessary HOs and also increase service interruption, which in turn will degrade the end UE QoS. In this chapter, we propose a novel HO method for the purpose of throughput enhancement and load balancing in HetNets. The impact of interference from both MC and SC tiers is considered so that the UE is offloaded from the congested cell and forced to perform the HO to the SC tier that supplies a sufficient data rate by selecting the proper SC target, which has the highest SINR, from a reduced NCL. The NCL is optimized using the SINR threshold and ToS criteria. The proposed method uses a modified A3 HO triggering condition taking into account the interference and cell load. The conventional A3 HO condition is described in Section 2.9 and Fig.2.8. The SINR can be practically estimated upon the service reception using the RSQ [21] described in Section 2.6. Results show that our proposed method can perform UE HO while keeping the throughput to the maximum level. Moreover, the proposed method has significantly minimized the inbound and inter-SC HOs and radio link failures compared to the existing methods. Under different network conditions and load factors, simulation results show that the proposed method can provide significantly better performance, in terms of number of unnecessary HO and throughput for the UE and the network as well.

The major contributions of this chapter can be summarized as follows:

- Propose a novel HO method for the purpose of throughput enhancement and load balancing in HetNets.
- This work considers to increase the efficient utilization of SCs and in turn increase the end UE QoS by offloading the UEs from the MC base station to the SCs. Considering the end UE QoS, UEs will be offloaded from the congested cells and forced to perform HO to the SC that provides higher data rate and has enough resources compared to the MC by applying our proposed HO triggering event that takes into account the interference and cell load.
- A modified A3 HO triggering condition is proposed by considering the traffic load in the serving base station and an equivalent SINR received from an SC within the reduced NCL, which gives a better data rate compared to the serving MC.

This chapter is organized as follows. Section 5.2 presents the related works. The network system model is given in Section 5.3, while Section 5.4 presents the proposed interference-based load-dependent HO margin method. In Section 5.5 the performance of the proposed method is evaluated and compared with other works in the literature and the results are analysed. Finally, Section 5.6 concludes the chapter.

5.2 Related Works

In [91], the authors proposed a method to automatically adjust the HM for outbound HO from SC to MC. This method adjusts the HM according to the UE speed so that for fast moving UE the HM is decreased (avoiding late HO), and for the low speed UE the HM is increased (avoiding early HO). The method has helped in avoiding late and early HOs in addition to the reduction in the radio link failures for different UE speeds. However, no mechanism for adjusting the traffic load between the SC and MC tier is considered, which may lead to a severe congestion in the MC tier, hence a high call dropping rate is expected.

Authors in [92] proposed a method to minimize the unnecessary HOs by reducing the number of scanned SCs. The building of the SC list is based on the downlink received power and ToS criteria, which avoids the SCs with a short time of stay. The UE performs HO to the SC with the strongest downlink received power from the list. However, the interference scenario and cell load are not taken into account in this work, which may lead to a throughput unaware HO strategy and radio link failures.

In [93], the authors present an algorithm for inbound HO to reduce the scanning of neighbouring SCs. The cell is considered in the list according to the HO probability to this cell and SINR at the UE side from its current serving SC. This process has highly reduced the scanning list, however, this work has not accounted for the problems of MC traffic offloading and SC utilization.

In [90], a mechanism to reduce the scanning process is presented. This mechanism uses the estimated distance between the SC and the UE to perform the scanning by considering the previously visited SCs. However, this mechanism can only be applied to SC with a CSG and can not be used for an open subscriber group SCs in addition to the traffic offloading problem.

A multiple HO criteria method is proposed in [94] to reduce the probability of HO and balance the load between the MC and the SCs. This method uses the estimated RSRP of the target cell, the transmit power of the UE and the target cell capacity as HO decision making metrics.

Authors in [95] proposed a dynamic cell association to increase the sum rate and considered a cell range expansion method for load balancing in HetNet. The principles of SC range expansion is a good strategy to offload the traffic from MC to SC by increasing the transmit power of the SC, hence, more UEs associate with the SC and eventually the load balancing is accomplished. However, using this method of offloading has limited achievements because the biasing of SC power increases the interference and degrades the SINR received at the UE. Therefore, controlling the power biasing is a critical issue.

In [96], the authors proposed a HO load balancing method for HetNet. The UEs are forced to perform the HO to the SCs when their speed is low and the capacity of the SC is available. However, these UEs are also permitted to connect to the MC temporarily if the capacity of the SC is not sufficient, so as to reduce the HO failure. On the other hand, high speed UEs are connected to the MC. However, this method is not efficient if deployed in a dense SC HetNet, which may result in a high number of SC in NCL, high number of unnecessary HOs and signalling overhead.

The proposed method in this chapter aims to reduce the congestion in the HetNet by forcing the HO to SCs, hence, balancing the load between the MC and SC tiers in addition to increasing the throughput by increasing the SCs utilization.

5.3 Network System Model

For the sake of clarity, we first define the major symbols used in this chapter in table 5.1.

Network system model in this chapter is based on a two-tier HetNets, which consists of SCs overlaid under the coverage area of the MC base station, as depicted in Fig.5.1. MC is deployed as a hexagonal shape with three sectors (120^o each). SCs are deployed randomly according to uniform distribution and the number SCs in each MC sector is fixed. The MC and SCs are deployed on the same frequency. The minimum distance constraint between the MC tier and SC tier is taken into account to reduce the influence of the interference and hence improve the anticipated capacity of the SCs. The minimum distances in meters are set as follows [10]: MC site to SC site is 75m and MC to UE is 35m. The UE mobility follows a Gauss distribution model described in Section 4.3.

According to Shannon's capacity equation, the maximum data rate, $r_{i\to ue_k}$, is given as

$$r_{i\to ue_k} = \mathrm{BW}\log_2(1+\gamma^r_{i\to ue_k}), \tag{5.2}$$

where BW is the carrier bandwidth and $\gamma^r_{i\to ue_k}$ is the SINR received at UE k from base station i. The SINR from SC i and MC received at UE k can be written as

$$\gamma^r_{sc_i\to ue_k} = \frac{P^r_{sc_i\to ue_k}}{P^r_{m\to ue_k} + \sum_{j=1,j\neq i}^{N_{sc}} P^r_{sc_j\to ue_k} + \sigma^2}, \tag{5.3}$$

$$\gamma^r_{m\to ue_k} = \frac{P^r_{m\to ue_k}}{\sum_{j=1}^{N_{sc}} P^r_{sc_j\to ue_k} + \sigma^2}, \tag{5.4}$$

where $\gamma^r_{m\to ue_k}$ is the SINR received from MC at the UE k, $\gamma^r_{sc_i\to ue_k}$ is the SINR received from SC i at the UE k, σ^2 is the noise power and finally N_{sc} is a set representing the total number of SCs in the network.

Table 5.1: Definition of Symbols

Symbol	Definition
$\mathcal{N}(\cdot,\cdot)$	Gaussian distribution with mean and standard deviation
$r_{i\rightarrow ue_k}$	maximum data rate from cell i
$\gamma^r_{i\rightarrow ue_k}$	the SINR received at UE k from cell i
$ToS_{ue\rightarrow sc_i}$	UE time of stay in SC i
HO^*_i	HO point
$\gamma^{r_{eq}}_{sc_i\rightarrow ue_k}$	is the SC's i SINR equivalent to that of the MC's/SC's j that gives at least the same data rate as compared to the MC/SC's j
$\gamma^{pro}_{m\rightarrow sc_i}$	is the proposed interference-based load-dependent margin to control the HO point for inbound HO
$\gamma^{pro}_{sc_j\rightarrow sc_i}$	is the proposed interference-based load-dependent margin to control the HO point for inter-SC HO
N_{sc}	total number of SCs in the network
N^*_{sc}	set of all SCs $\in N_{sc}$ with $\gamma^r_{sc_i\rightarrow ue_k} > \gamma_{th}$
N^{**}_{sc}	set of all SCs $\in N^*_{sc}$ with $ToS_{ue\rightarrow sc_i} > T_{th}$
L_{m_i}	load on MC sector i
L_{sc_j}	load on SC j
$RB^{ue}_{m_i}$	number of PRBs used by all active UEs in sector i
$RB^{ue}_{sc_j}$	number of PRBs used by all active UEs in SC j
RB_{tm}	total number of PRBs in MC
RB_{tsc_j}	total number of PRBs in SC j
L^{mr}_m	is the load-dependent parameter for inbound HO
$L^{mr}_{sc_j}$	is the load-dependent parameter for inter-SC HO

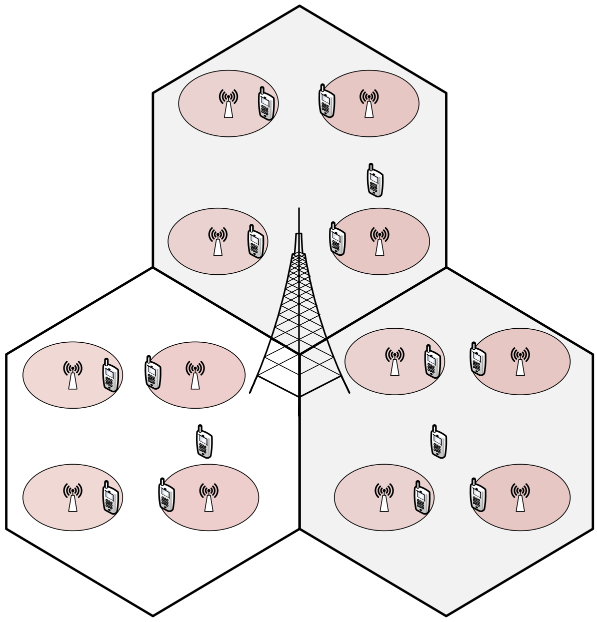

Figure 5.1: Two-tier HetNet system model

Taking into account the heterogeneous network architecture, the propagation model between the MC and the UE is defined as in [87] by

$$\delta_{m \to ue_k} = 128.1 + 37.6 \ \log_{10}(d_{m \to ue_k}) + \xi, \tag{5.5}$$

where $d_{m \to ue_k}$ is the distance between the UE and the MC base station in kilometres and ξ is a Gaussian distribution random variable with zero mean and 12 dB standard deviation [97]. For outdoor SC, the path loss is defined as in [22] by

$$\delta_{sc_i \to ue_k} = 38 + 30 \ \log_{10}(d_{sc_i \to ue_k}) + \xi, \tag{5.6}$$

where $d_{sc_i \to ue_k}$ is the distance between the UE and SC i in metres.

Given that the UE time of stay can be expressed using the velocity, v_{ue}, and the expected distance that the UE will spend inside the base station coverage area as shown in Fig. 5.2. The angle β_{sc_i}, which is the UE angle of entry to the SC, can be represented as a random variable, which is uniformly distributed and restricted to interval $[\frac{-\pi}{2}, \frac{\pi}{2}]$. This random variable has a constant density over the interval i.e., has a probability density function (PDF) $f_{\beta_{sc_i}}(\beta_{sc_i})$, as shown in Fig. 5.3 and equation (5.7).

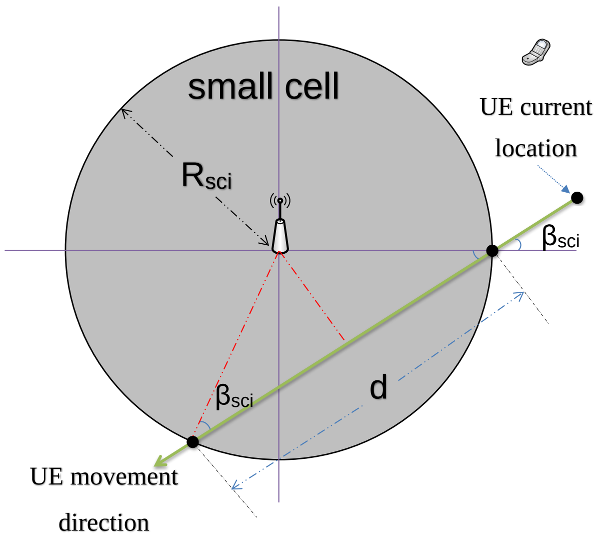

Figure 5.2: UE ToS measurement

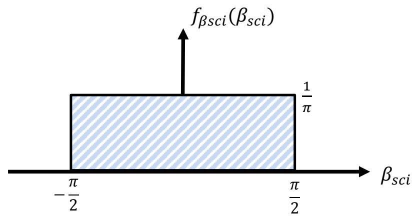

Figure 5.3: PDF of β_{sc_i}

$$f_{\beta_{sc_i}}(\beta_{sc_i}) = \begin{cases} \frac{1}{|\frac{-\pi}{2}-\frac{\pi}{2}|} & \text{if } \frac{-\pi}{2} \leq \beta_{sc_i} \leq \frac{\pi}{2} \\ 0 & \text{otherwise} \end{cases} \tag{5.7}$$

Thus, we can define the mean predicted ToS a UE will stay in the SC as

$$\begin{aligned} \mathrm{E}\Big[ToS_{ue\rightarrow sc_i}\Big] &= \mathrm{E}\left[\frac{2R_{sc_i}\cos(\beta_{sc_i})}{v_{ue}}\right] \\ &= \int \frac{2R_{sc_i}\cos(\beta_{sc_i})}{v_{ue}} f_{\beta_{sc_i}}(\beta_{sc_i}) d\beta_{sc_i} \\ &= \int_{\frac{-\pi}{2}}^{\frac{\pi}{2}} \frac{2R_{sc_i}\cos(\beta_{sc_i})}{v_{ue}} \frac{1}{\pi} d\beta_{sc_i} \\ &= \frac{4R_{sc_i}}{\pi v_{ue}}, \end{aligned} \tag{5.8}$$

where R_{sc_i} is the SC radius.

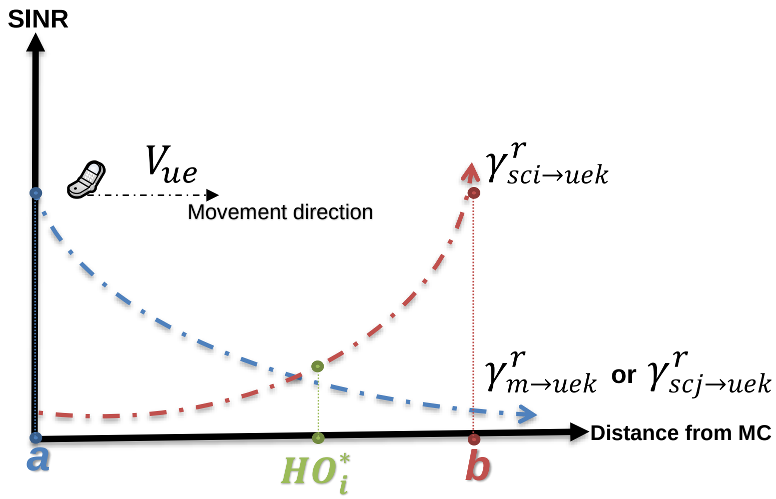

Figure 5.4: Handover point

As shown in Fig. 5.4, the blue curve represents the SINR of the serving cell (MC or SC j) and the red curve represents the SINR of the target cell (SC i). The HO takes place at point HO_i^*, which is the point at which the A3 HO event is satisfied. In other words, it is the point at which the HO should be performed.

The aim is to find HO_i^* $\forall i = 1, ..., N_{sc}$, to maximize the throughput and achieve traffic load balancing between the MC and SCs by forcing the HO to SC to distribute the load.

In the following subsections we explain the analysis and calculations of the loads, the equivalent SINR required to perform the HO to SC and the proposed interference-based load-dependent HO margin.

5.3.1 Resource Assignment and Load Calculations

The cell load factor is the amount of resource usage with respect to the available resources in the cell [98], i.e., a low load factor means that the base station is light-loaded; on the other hand, a high load factor means that the base station is heavily-loaded [99].

1. **For Inbound HO**

   For the i^{th} MC sector, the load L_{m_i} is defined as the number of physical resource blocks (PRBs) being used by all mobile UEs connected to the aforementioned sector divided by the total MC PRBs, that is

$$L_{m_i} = \frac{RB^{ue}_{m_i}}{RB_{tm}}, \tag{5.9}$$

where $RB^{ue}_{m_i}$ is the number of PRBs used by all active mobile UEs connected to the MC sector i and RB_{tm} is the total number of PRBs in the MC.

The number of PRBs used by all active mobile UEs connected to the MC sector i, i.e., $RB^{ue}_{m_i}$, can be expressed as

$$RB^{ue}_{m_i} = \sum_{k=1}^{N^{sec}_{ue}} RB_{m_i,k}, \tag{5.10}$$

where N^{sec}_{ue} is the number of UEs in the sector and $RB_{m_i,k}$ is the number of PRBs used by UE k.

2. **For Inter-SC HO**

   Whereas the load on the SC j is

$$L_{sc_j} = \frac{RB^{ue}_{sc_j}}{RB_{tsc_j}}, \tag{5.11}$$

where $RB^{ue}_{sc_j}$ is the number of PRBs used by all active mobile UEs connected to SC j and RB_{tsc_j} is the total number of PRBs in SC j.

The number of PRBs used by all active mobile UEs connected to SC j, $RB^{ue}_{sc_j}$, can be expressed as

$$RB^{ue}_{sc_j} = \sum_{k=1}^{N^{sc_j}_{ue}} RB_{sc_j,k}, \tag{5.12}$$

where $N^{sc_j}_{ue}$ is the number of active UEs residing in SC j and $RB_{sc_j,k}$ is the number of PRBs used by UE k.

5.3.2 Equivalent SINR Analysis

The HO point HO^*_i, see Fig. 5.4, is the point at which the data rate of the SC is equal or greater than that of the MC. In other words, it is the point at which $\gamma^r_{sc_i \to ue_k} = \gamma^r_{m \to ue_k}$ for inbound HO and $\gamma^r_{sc_i \to ue_k} = \gamma^r_{sc_j \to ue_k}$ for inter-SC HO.

1. **For Inbound HO**

   For a given SC i and MC, recall equations (5.3) and (5.4). We first apply the condition ($\gamma^r_{sc_i \to ue_k} = \gamma^r_{m \to ue_k}$) to the two equations

$$\frac{P^r_{sc_i \to ue_k}}{P^r_{m \to ue_k} + \sum_{j=1, j \neq i}^{N_{sc}^{**}} P^r_{sc_j \to ue_k} + \sigma^2} = \frac{P^r_{m \to ue_k}}{\sum_{j=1}^{N_{sc}^{**}} P^r_{sc_j \to ue_k} + \sigma^2}. \tag{5.13}$$

   Reordering equation (5.13) and after some simplifications we get

$$P^r_{sc_i \to ue_k} = \frac{A}{\sum_{j=1}^{N_{sc}^{**}} P^r_{sc_j \to ue_k} + \sigma^2}, \tag{5.14}$$

   where

$$A = P^r_{m \to ue_k} \big(P^r_{m \to ue_k} + \sum_{j=1, j \neq i}^{N_{sc}^{**}} P^r_{sc_j \to ue_k} + \sigma^2 \big). \tag{5.15}$$

   The UE will initiate the HO to the SC with the highest data rate, i.e., at HO point HO_i^*. In other words, we can say that the HO is triggered when the downlink received power from the SC satisfying the criteria in (5.14). Without loss of generality, we substitute (5.14) in (5.3) to obtain the equivalent SINR $\gamma^{r_{eq}}_{sc_i \to ue_k}$, for inbound HO from MC to SC i, that provides at least the same data rate as the current serving MC base station, that is

$$\begin{aligned} \gamma^{r_{eq}}_{sc_i \to ue_k} &= \frac{P^r_{sc_i \to ue_k}}{P^r_{m \to ue_k} + \sum_{j=1, j \neq i}^{N_{sc}^{**}} P^r_{sc_j \to ue_k} + \sigma^2} \\ \therefore \quad \gamma^{r_{eq}}_{sc_i \to ue_k} &= \frac{A / (\sum_{j=1}^{N_{sc}^{**}} P^r_{sc_j \to ue_k} + \sigma^2)}{P^r_{m \to ue_k} + \sum_{j=1, j \neq i}^{N_{sc}^{**}} P^r_{sc_j \to ue_k} + \sigma^2}, \end{aligned} \tag{5.16}$$

2. **For Inter-SC HO**

   Similarly, for a given SC i and SC j, we can derive an expression to find the equivalent SINR for the inter-SC HO from SC j to SC i, that is

$$P^r_{sc_i \to ue_k} = \frac{B}{\sum_{j=1}^{N_{sc}^{**}} P^r_{sc_j \to ue_k} + \sigma^2}, \tag{5.17}$$

   where

$$B = P^r_{sc_j \to ue_k} \big(P^r_{m \to ue_k} + \sum_{j=1, j \neq i}^{N_{sc}^{**}} P^r_{sc_j \to ue_k} + \sigma^2 \big). \tag{5.18}$$

Substituting (5.17) in (5.3) and after some simplifications, we get the equivalent SINR $\gamma^{r_{eq}}_{sc_i \to ue_k}$, for inter-SC HO from SC j to SC i, that provides at least the same data rate as the current serving SC j base station, that is

$$\gamma^{r_{eq}}_{sc_i \to ue_k} = \frac{B/(\sum_{j=1}^{N^{**}_{sc}} P^r_{sc_j \to ue_k} + \sigma^2)}{P^r_{m \to ue_k} + \sum_{j=1, j \neq i}^{N^{**}_{sc}} P^r_{sc_j \to ue_k} + \sigma^2}. \tag{5.19}$$

It is worth noting that the summation of the interference term, in equations (5.13) to (5.19), considers only the SCs in set N^{**}_{sc} (will be given in Section 5.4) as defined in (5.30), which will, in turn, reduce the computation complexity since we only have a reduced number of SCs in this set.

5.3.3 Proposed Interference-Based Load-Dependent Margin

When the serving base station (MC or SC j) suffers from heavy traffic load and the target SC i has a light traffic load, the serving base station will undergo a high rate of radio link failure when a UE tries to perform HO to this serving base station. To maintain mobility load balancing in general, if the serving cell is overloaded then it increases the HO margin so as to trigger the HO early to another cell. However, this unplanned increase may cause radio link failure and ping-pong HO issues, and hence, poor QoS is delivered to the UE. Therefore, these parameters should be adjusted dynamically according to the actual cell load to maintain the mobility robustness. For this reason, we aim to force the UE to HO to SC i, which has a lower load and hence lower resource utilization. The proposed method biases the HO point between the congested serving cell and the target SC i aiming to balance the load and limit the radio link failure.

Given the conventional A3 HO triggering condition, which depends on a power-based margin, when the power of the neighbouring SC i is offset greater than that of the serving MC for a period of TTT [10], that is

$$P^r_{sc_i \to ue_k} \geq P^r_{m \to ue_k} + HM_m - HM_{m,sc_i}, \tag{5.20}$$

where HM_m is the hysteresis parameter of MC and HM_{m,sc_i} is the SC i specific offset with respect to the MC (i.e., the hysteresis set by MC to HO to the SC

i). Indeed the parameter HM_{m,sc_i} controls the HO point and can be optimized based on the load of the serving MC.

Inspired by (5.20), we proposed to modify this criteria to facilitate an interference based load-dependent hysteresis margin. The proposed method considers the SINR instead of the downlink received power and replaces the power margin HM_{m,sc_i} with the interference-based load-dependent margin, denoted $\gamma^{pro}_{m\to sc_i}$, namely the proposed interference-based load-dependent margin to control the HO point between the MC and the SC i.

Since we are considering inbound and inter-SC HO, we need to find two margins. The first is $\gamma^{pro}_{m\to sc_i}$ for inbound HO from MC to SC i and the second is $\gamma^{pro}_{sc_j\to sc_i}$ for inter-SC HO from SC j to SC i.

1. **For Inbound HO**

   We can rewrite equation (5.20) based on our proposal as shown in (5.21) for inbound HO from MC to SC i

$$\gamma^{r}_{sc_i\to ue_k} \geq \gamma^{r}_{m\to ue_k} - \gamma^{pro}_{m\to sc_i}, \tag{5.21}$$

   For inbound HO, in order to balance the load, the HO point HO^*_i must be moved closer to the serving MC rather than being closer to the target SC i (the HO point HO^*_i will be shifted (i.e., changed) based on the current load on the MC tier so as to perform offloading to SC tier). To adjust the HO point for a UE trying to perform HO from MC to SC i, we must shift the HO^*_i point to the left as shown in Fig. 5.5, i.e., the HO point will be changed from the intersection point of the two curves $\gamma^{r}_{sc_i\to ue_k}$ and $(\gamma^{r}_{m\to ue_k} + \gamma_{th} - \gamma_{m\to sc_i})$ to the intersection point of the two curves $\gamma^{r}_{sc_i\to ue_k}$ and $(\gamma^{r_{eq}}_{sc_i\to ue_k} - \gamma^{pro}_{m\to sc_i})$, note that $\gamma^{r_{eq}}_{sc_i\to ue_k}$ is taken from (5.16). In other words, the congested MC adjusts the HO margin $\gamma^{pro}_{m\to sc_i}$ to allow the UE to perform early HO to SC i and preventing the UEs from performing HO to itself (i.e., to the MC) so as to avoid more congestion in the already congested MC. This is done by considering the load-dependent margin $\gamma^{pro}_{m\to sc_i}$.

   For Fig. 5.5, γ_{th} is the outage threshold and is set to 5 dB [88] and $\gamma^{max}_{sc_i}$ is the SINR from SC i when $\gamma^{r}_{m\to ue_k}$ is equal to γ_{th}. To maintain the radio link failure to a lower level, the hysteresis can be assigned according to the UE speed [10]. Therefore, we adjust the values of $\gamma_{m\to sc_i}$ and $\gamma_{sc_j\to sc_i}$ to 4 dB for low speed

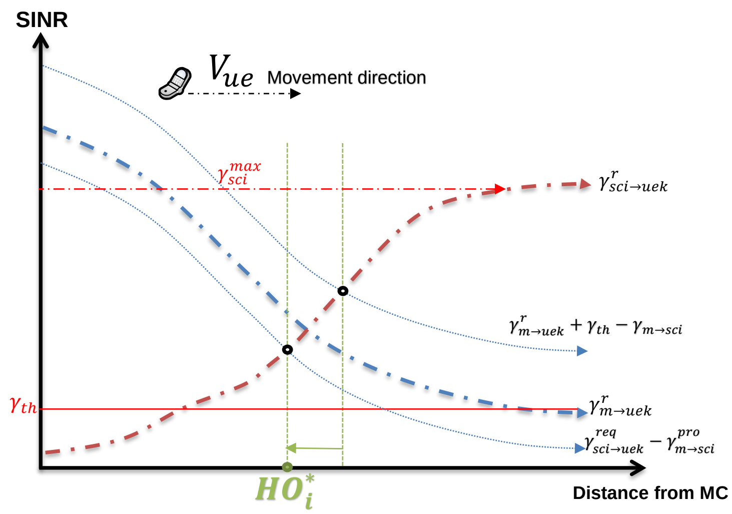

Figure 5.5: Handover point for inbound HO

UE ($v_{ue} \leq$ 20km/h), 3 dB for medium speed UE (20km/h $< v_{ue} \leq$ 50km/h) and 2 dB for high speed UE ($v_{ue} >$ 50km/h).

To incorporate the impact of the UE velocity on the proposed margin, we proposed to incorporate the margin $\gamma_{m \to sc_i}$ into equation (5.22) to find the load-dependent parameter, denoted as L_m^{mr}, which will be used later to calculate the proposed margin

$$L_m^{mr} = (1 - L_{m_i}) \cdot \gamma_{m \to sc_i}, \tag{5.22}$$

where L_m^{mr} is the load-dependent parameter for inbound HO. Finally, the proposed interference-based load-dependent margin can be calculated as

$$\begin{aligned} \gamma_{m \to sc_i}^{pro} &= \gamma_{m \to sc_i} - L_m^{mr} \\ &= L_{m_i} \cdot \gamma_{m \to sc_i}. \end{aligned} \tag{5.23}$$

The parameter L_m^{mr} depends on L_{m_i}: the higher the value of L_{m_i} the smaller the value of L_m^{mr} (as shown in Fig. 5.6), the higher the proposed margin and eventually the closer the HO_i^* point to SC i.

Lower the value of L_m^{mr} means that the serving MC is heavily loaded, hence, the HO point is moved closer to the MC so as to speed up the HO triggering, which will balance the traffic load by offloading it from the congested MC to SC i.

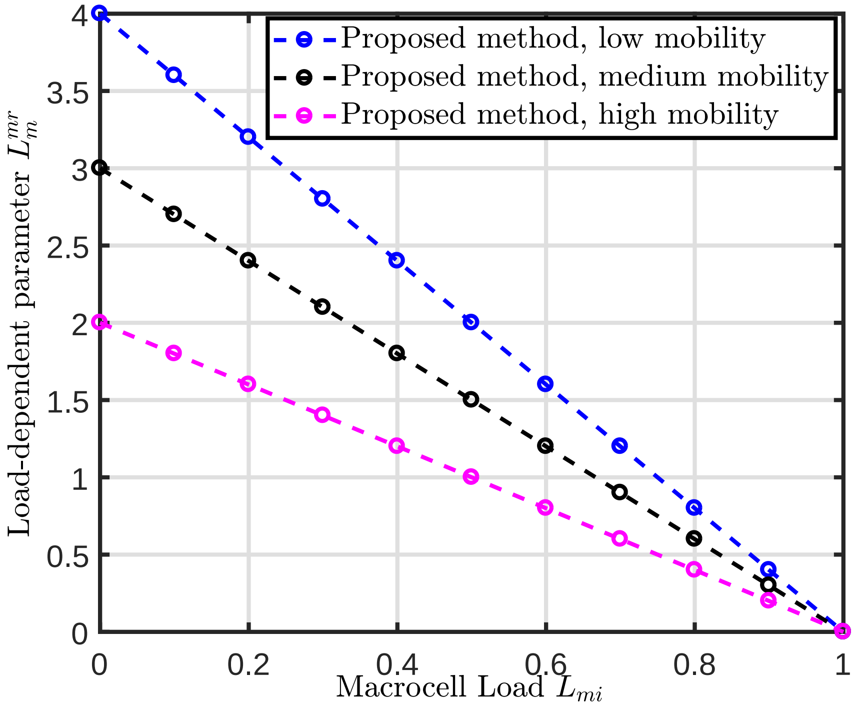

Figure 5.6: L_m^{mr} vs L_{m_i}

In fact, the term $(1 - L_{m_i})$ is the key parameter to control the proposed interference-based load-dependent margin. As depicted in table 5.2 for low, medium and high MC loads, the term $(1-L_{m_i})$ ensures that the load-dependent parameter L_m^{mr} is adjusted based on the current state of the load on the MC base station. For instance, when the load is high at (90%) with the mobility state also high, then the parameter L_m^{mr} is 0.2, which will make the proposed margin high at 1.8 dB, hence, the HO is performed earlier so as to offload the congested traffic from MC to SC. On the other hand, when the load is low at (10%) with the mobility state is low, then the parameter L_m^{mr} is 3.6 and the proposed margin is low at 0.4 dB, hence, the HO is not performed early.

2. **For Inter-SC HO**

   Also, we can rewrite equation (5.20) based on our proposal as shown in (5.24) for inter-SC HO from SC j to SC i

$$\gamma^r_{sc_i \to ue_k} \geq \gamma^r_{sc_j \to ue_k} - \gamma^{pro}_{sc_j \to sc_i}. \tag{5.24}$$

Table 5.2: L_m^{mr} and $\gamma_{m\rightarrow sc_i}^{pro}$ for different MC loads and different mobility states

Mobility state		**MC load**		
		(10%)	**(50%)**	**(90%)**
Low	L_m^{mr}	3.6	2	0.4
	$\gamma_{m\rightarrow sc_i}^{pro}$ [dB]	0.4	2	3.6
Medium	L_m^{mr}	2.7	1.5	0.3
	$\gamma_{m\rightarrow sc_i}^{pro}$ [dB]	0.3	1.5	2.7
High	L_m^{mr}	1.8	1	0.2
	$\gamma_{m\rightarrow sc_i}^{pro}$ [dB]	0.2	1	1.8

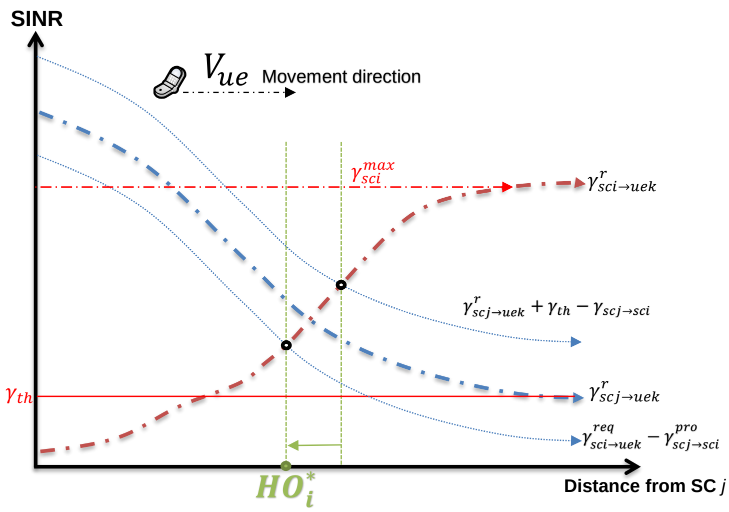

Figure 5.7: Handover point for inter-SC HO

Similarly for the inter-SC HO, the HO point HO_i^* must be moved closer to the serving SC j rather than being closer to the target SC i. Thus, we move the HO point for a UE trying to perform HO from SC j to SC i to the left as shown in Fig. 5.7, where $\gamma_{sc_i}^{max}$ is the SINR from SC i when $\gamma_{sc_j\rightarrow ue_k}^{r}$ is equal to γ_{th}, note that $\gamma_{sc_i\rightarrow ue_k}^{req}$ is taken from (5.19). Then, the margin in this case is calculated as

$$L_{sc_j}^{mr} = (1 - L_{sc_j}) \cdot \gamma_{sc_j\rightarrow sc_i}, \tag{5.25}$$

$$\begin{aligned}\gamma^{pro}_{sc_j \to sc_i} &= \gamma_{sc_j \to sc_i} - L^{mr}_{sc_j} \\ &= L_{sc_j} \cdot \gamma_{sc_j \to sc_i},\end{aligned} \tag{5.26}$$

where $L^{mr}_{sc_j}$ is the load-dependent parameter for inter-SC HO.

Now we have $\gamma^{r_{eq}}_{sc_i \to ue_k}$, $\gamma^{pro}_{m \to sc_i}$ and $\gamma^{pro}_{sc_j \to sc_i}$, then we can rewrite equation (5.21) to represent our proposed modified A3 HO triggering event for inbound HO as

$$\gamma^{r}_{sc_i \to ue_k} \geq \gamma^{r_{eq}}_{sc_i \to ue_k} - \gamma^{pro}_{m \to sc_i}. \tag{5.27}$$

While also rewriting equation (5.24) for inter-SC HO as

$$\gamma^{r}_{sc_i \to ue_k} \geq \gamma^{r_{eq}}_{sc_i \to ue_k} - \gamma^{pro}_{sc_j \to sc_i}. \tag{5.28}$$

The above conditions in (5.27) and (5.28) should hold for a period of TTT according to the UE speed [49] as depicted in table 5.3.

Table 5.3: TTT according to UE speed

UE speed (km/h)	$v_{ue} \leq 20$	$20 < v_{ue} \leq 50$	$v_{ue} > 50$
TTT (ms)	1280	512	256

5.4 Proposed Method

Algorithm 3 illustrates the proposed method procedures where $ToS_{ue \to sc_i}$ is the expected time of stay of the UE in the SC i coverage area, T_{th} is the time threshold for ToS and N^*_{sc} is a set that represents the total number of SCs with an SINR greater than the outage threshold.

First, the proposed method optimizes the NCL by reducing the number of target SCs. This is done by using γ_{th} and ToS metrics as illustrated in Algorithm 3 lines 3 through 11 and explained below.

The proposed algorithm begins by eliminating the SCs that could cause degradation in the UE QoS, i.e., SCs with SINR less than the outage threshold γ_{th}, resulting in a NCL N^*_{sc}, which is written as

$$N^*_{sc} = \Big\{ sc_i \in N_{sc} \mid \gamma^{r}_{sc_i \to ue_k} > \gamma_{th} \Big\}. \tag{5.29}$$

Algorithm 3 Proposed Method

```
1: Procedure Starts
2: User moves to SC coverage area
3: if γ^r_{sc_i→ue_k} ≤ γ_th then
4:    Exclude this SC from Handover target NCL (N*_sc)
5: end if
6: for i ← 1, N*_sc do
7:    Estimate ToS_{ue→sc_i}
8:    if E[ToS_{ue→sc_i}] > T_th then
9:       Keep SC i in the new Handover NCL (N**_sc)
10:   end if
11: end for
12: Convert γ^r_{m→ue_k} or γ^r_{sc_j→ue_k} to its equivalent γ^{req}_{sc_i→ue_k}
13: Calculate γ^{pro}_{m→sc_i} or γ^{pro}_{sc_j→sc_i}
14: Select the SC with the maximum γ^r_{sc_i→ue_k} from (N**_sc)
15: if γ^r_{sc_i→ue_k} ≥ γ^{req}_{sc_i→ue_k} - γ^{pro}_{m→sc_i} for TTT or
       γ^r_{sc_i→ue_k} ≥ γ^{req}_{sc_i→ue_k} - γ^{pro}_{sc_j→sc_i} for TTT then
16:   if RB^{ue}_{sc_i} < 1 then
17:      Handover the UE to sc_i
18:   end if
19: end if
20: end procedure
```

Then, for an active mobile UE k, a SC NCL is formed, denoted as N_{sc}^{**} set, containing all the SCs whose predicted mean UE ToS is greater than the time threshold T_{th}. Thus, we can rewrite the new NCL as

$$N_{sc}^{**} = \Big\{ sc_i \in N_{sc}^{*} \mid \mathrm{E}\big[ToS_{ue \to sc_i}\big] > T_{th} \Big\}. \tag{5.30}$$

After the NCL reduction, the second phase of the method is applied to obtain the equivalent SINR and calculate the interference-based load-dependent margin.

For inbound HO from MC to SC i, the UE uses the converted SINR, i.e., $\gamma_{sc_i \to ue_k}^{req}$ from (5.16). If the latter minus the proposed interference-based load-dependent margin $\gamma_{m \to sc_i}^{pro}$ is less than or equal to the actual SINR received from the SC i for TTT time, then the inter-SC HO checks line 16 in Algorithm 3. On the other hand, for inter-SC HO form SC j to SC i, the UE uses the converted

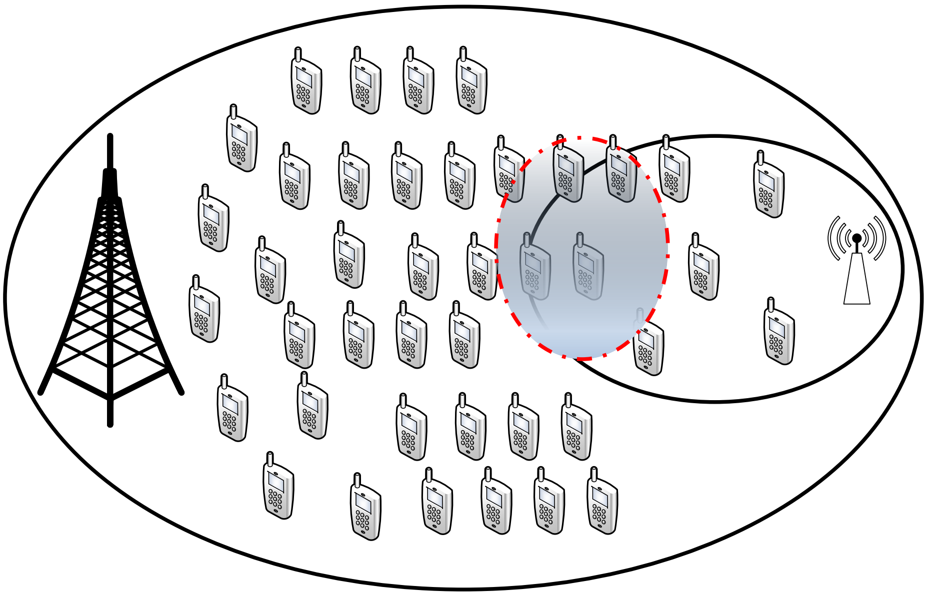

Figure 5.8: Inbound HO forcing to SC

SINR, i.e., $\gamma^{req}_{sc_i \to ue_k}$ from (5.19). If the latter minus the proposed interference-based load-dependent margin $\gamma^{pro}_{sc_j \to sc_i}$ is less than or equal to the actual SINR received from the SC i for TTT time (this is the proposed modified A3 HO condition), then the inter-SC HO checks line 16 in Algorithm 3. The HO is performed to SC i providing that the resources of this SC is sufficient enough to provide resources to the UE. In line (16) in Algorithm 3, the condition $RB^{ue}_{sc_i} < 1$, the value 1 means that the SC resources are all occupied by other UEs and it is not possible to perform the HO to this SC.

Fig. 5.8 simplifies the aim of the proposed interference-based load-dependent margins $\gamma^{pro}_{m \to sc_i}$ and $\gamma^{pro}_{sc_j \to sc_i}$. When the serving cell (MC or SC j) suffers from high load (congested cell), the margins $\gamma^{pro}_{m \to sc_i}$ and $\gamma^{pro}_{sc_j \to sc_i}$ will be adjusted to HO the UEs, located in the overlapped shaded region (i.e., in Fig. 5.8) between the serving and the target SC, to the target SC. This will attain the offloading purpose, increase the system throughput and eventually increase the proper utilization of SCs.

It is worth noting that the HO is only forced to the cell with SINR greater than the outage threshold, hence, the high throughput is expected with an acceptable HO signalling.

5.5 Performance and Results Analysis

The performance of our proposed method is compared against three competitive methods, namely the conventional method, the energy efficient and cell load balancing (ENCLB) method presented in [94] and the estimated time-of-stay-based cell selection (ETCS) method presented in [92]. We divide this section into three parts. The first part briefly introduces the competitive methods. The second part presents the performance evaluation metrics. While the results and discussions are given in the last part.

5.5.1 Competitive Methods

The three competitive methods defined in this part are the conventional method, the ENCLB method given in [94] and the ETCS method presented in [92].

In the conventional method, the UE periodically performs neighbourhood scanning, based on the downlink received power, to form the HO NCL. This means that the UE will spend a significant time period to select the proper target. Then, the UE performs the HO to the SC with the strongest downlink received power as shown in (5.1) without considering the interference and load balancing scenario, which means that the HO point HO_i^* for this method is downlink power dependent. This will cause an UE throughput reduction and wasting the battery power of the UE due to the frequent scanning measurement, especially in a dense SC environment. Therefore, the HO target SC for the conventional method, denoted as sc^t_{conv}, can be expressed as

$$sc^t_{conv} = \Big\{ sc_i \in N_{sc} \mid \; P^r_{sc_i \rightarrow ue_k} \; > \; P^r_{m \rightarrow ue_k} \Big\}. \tag{5.31}$$

The ENCLB method in [94], forms the HO NCL based on the predicted RSRP and the transmit power of the UE. The UE performs the HO to the SC, from the NCL, if its RSRP is offset greater than that of the serving cell and has enough capacity. Thus, the HO point HO_i^* is based on the power difference between the serving and the target cells with a fixed HO margin. The HO target SC for this method, denoted as sc^t_{enclb}, can be given as

$$\begin{aligned} sc^t_{enclb} = \Big\{ sc_i \in N_{sc} \mid \; & P^r_{sc_i \rightarrow ue_k} \; > \; P^r_{m \rightarrow ue_k} + HM_m \quad \wedge \\ & \gamma^{up}_{ue \rightarrow sc_i} \; > \; \gamma^{up}_{th} \; \wedge \quad RB^{ue}_{sc_i} < 1 \Big\}. \end{aligned} \tag{5.32}$$

where $\gamma^{up}_{ue \to sc_i}$ is the uplink SINR for the target SC i and γ^{up}_{th} is its threshold which is set to 3 dB.

Whereas the ETCS method in [92] forms the HO NCL based on the downlink received power and ToS criteria, which means to avoid the SC that could cause short time of stay phenomena. Then, the UE performs the HO to the cell with the strongest power from the list. In addition, the interference scenario and cell load balance are not considered in this method and the HO point HO^*_i is based on the power difference between the serving and the target cells. We can write the HO target SC, sc^t_{etcs}, for this method as

$$sc^t_{etcs} = \Big\{ sc_i \in N_{sc} \mid \ (\mathrm{E}\big[ToS_{ue \to sc_i}\big] > T_{th}) \ \wedge \ \ P^r_{sc_i \to ue_k} \ > \ P^r_{m \to ue_k} \Big\}. \tag{5.33}$$

In contrast, our proposed method forms the HO NCL based on the ToS criteria and interference constraint. Then, the UE performs the HO to the cell that gives a better data rate with load balancing considerations, providing that the resources are available, considering the proposed modified A3 HO triggering condition to ensure high QoS, which means that the HO point is interference and load based as given in (5.27) and (5.28).

5.5.2 Performance Evaluation Metrics

Based on the density definition in [100], the density of the number of SCs in a given coverage area can be obtained by using the density metric, D_{sc}, as

$$D_{sc} = \frac{\mid N_{sc} \mid \pi R^2_{sc_i}}{\pi R^2_m}, \tag{5.34}$$

where R_m is the MC radius. The denominator represents the MC coverage area. Thus, if the SC density metric D_{sc} is equal to 1, this means that the deployment of the SCs covers the whole area of the MC coverage area. While a higher than 1 value means that the SCs are covering the whole area of MC and an overlapping is ensured among the SCs. We set up the number of SCs to 100, which means that $D_{sc} \approx 1.56$ and hence, the dense SCs scenario is obtained.

In the case of inbound HO i.e., the UE is associated to MC and is trying to perform a HO to SC i or in case of inter-SC HO, i.e., the UE is associated to SC

j and is trying to perform a HO to SC i, then the probability of the UE is inside SC i vicinity is expressed as shown below

$$\mathbb{P}_{ue \text{ inside } sc_i} = \mathbb{P}\Bigg[P^{r}_{sc_i \to ue_k} \;\geq\; P^{th}_{min}\Bigg]. \tag{5.35}$$

The probability of inbound HOs to the SCs is given as

$$\begin{aligned} P^{in}_{HO} = \mathbb{P}\Bigg[&P^{r}_{sc_i \to ue_k} \;\geq\; P^{th}_{min} \;\wedge\; \mathrm{E}\big[ToS_{ue \to sc_i}\big] > T_{th} \;\wedge \\ &\gamma^{r}_{sc_i \to ue_k} \geq \gamma^{r_{eq}}_{sc_i \to ue_k} - \gamma^{pro}_{m \to sc_i} \text{ for } TTT \quad \wedge \quad RB^{ue}_{sc_i} < 1\Bigg]. \end{aligned} \tag{5.36}$$

In (5.36), the SINR $\gamma^{r_{eq}}_{sc_i \to ue_k}$ is taken from (5.16).

Whereas the probability of inter-SC HOs, i.e., SC j to SC i, is expressed as

$$\begin{aligned} P^{inter}_{HO} = \mathbb{P}\Bigg[&P^{r}_{sc_i \to ue_k} \;\geq\; P^{th}_{min} \;\wedge\; \mathrm{E}\big[ToS_{ue \to sc_i}\big] > T_{th} \;\wedge \\ &\gamma^{r}_{sc_i \to ue_k} \geq \gamma^{r_{eq}}_{sc_i \to ue_k} - \gamma^{pro}_{sc_j \to sc_i} \text{ for } TTT \quad \wedge \; RB^{ue}_{sc_i} < 1\Bigg]. \end{aligned} \tag{5.37}$$

In (5.37), the SINR $\gamma^{r_{eq}}_{sc_i \to ue_k}$ is taken from (5.19).

In fact, the performance of the network in terms of HO is expected to be enhanced with lower network load. Considering a constant network load, when we increase the number of SCs under the coverage area of the MC, the network load will be shared among the MC and the SCs. Thus, the load per cell is reduced resulting in a lower level of interference and hence reducing the radio link failure, which causes HO failure. The outage probability or the probability of transmission failure happens either when the UE initiates HO procedures but an interruption stops the process before completion (before the HO execution time expires) due to the degraded SINR from the serving and the target base stations, or when the SINR of the serving cell is degraded and the target SC has lack of resources. Therefore, we can define the outage probability as

$$\begin{aligned} P_{out} = \mathbb{P}\Big[&\gamma^{r}_{sc_i \to ue_k} < \gamma_{th} \;\wedge\; \gamma^{r}_{m \to ue_k} < \gamma_{th} \;\text{ for } t > T^{exe}_{ho} \\ &\vee \\ &\gamma^{r}_{m \to ue_k} < \gamma_{th} \;\wedge\; RB^{ue}_{sc_i} = 1 \;\text{ for } t \;>\; T^{exe}_{ho}\Big], \end{aligned} \tag{5.38}$$

where T^{exe}_{ho} is the time required to complete the HO process (including HO preparation time and HO execution time and is set to 1 second [90]).

5.5.3 Results and Discussions

Initially, the UE is connected to the MC and receive $\gamma^{r}_{m\rightarrow ue_k}$, which gives $r_{m\rightarrow ue_k}$. The MC UE is moving from the MC towards the SC coverage area at a speed of v_{ue}. Due to its mobility, the UE approaches the vicinity of the SCs and follows the proposed method to perform HO to a SC $\in N^{**}_{sc}$ considering the proposed interference-based load-dependent margin, and also has the available resources. The simulation parameters are listed in table 5.4 [92].

Table 5.4: Simulation Parameters

Bandwidth (BW)	10 MHz
Carrier Frequency (F_c)	2.5 GHz
Macrocell Transmit power	43 dBm
Macrocell Radius	800 m
Small Cell Radius	100 m
Maximum Small cell Transmit power	23 dBm
Number of Small cell within the Macrocell	100
Number of UEs within Macrocell sector (N^{sec}_{ue})	40
Maximum number of UEs per Small cell	5
Minimum required signal for service continuity (P^{th}_{min})	-70 dBm
Outage threshold (γ_{th})	5 dB
Handover completion time (T^{exe}_{ho})	1 sec
Mean velocity of the UE	{1,10,20,30, 40,50,60,70} km/h
Time threshold for ToS (T_{th})	5 sec

To practically evaluate the impact of the proposed interference-based load-dependent margin $\gamma^{pro}_{m\rightarrow sc_i}$, we used a numerical example which tests the margin against the MC load. Then we applied the HO condition in (5.27) by substituting the margin $\gamma^{pro}_{m\rightarrow sc_i}$. Here we assumed that $\gamma_{th} = 5$ dB [88], and the margin $\gamma_{m\rightarrow sc_i}$

is adjusted according to the mobility of the UE [10], i.e., low, medium, and high mobility as given in Section 5.3.3. Fig. 5.9 depicts the proposed HO margin with respect to the load on the MC. As illustrated in the figure, as the load on the MC increases the HO margin also increases linearly for all mobility states. Therefore, we expect an earlier HO to SC when the MC load increases since the HO condition subtracts the proposed HO margin from the SINR causing an early HO as the MC congests with a high load.

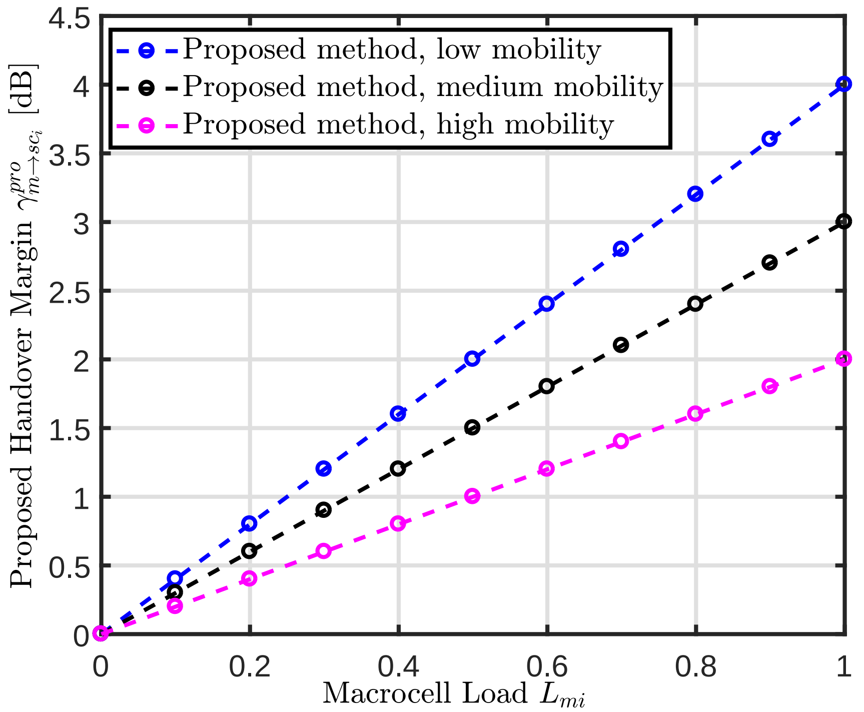

Figure 5.9: Proposed Handover Margin

The proposed new HO point, i.e. SINR at new HO point, against the proposed HO margin is shown in Fig. 5.10. As the proposed HO margin $\gamma^{pro}_{m \to sc_i}$ increases (meaning the load on MC increases), the location of the new HO point decreases (i.e., the HO is triggered earlier) for all mobility states, which means that the new HO point from MC to SC is forced to be closer to the MC, i.e., the new HO point should be before the point at which the SINR of both the MC and the SC is identical. It can be observed from Fig. 5.10 that the higher the proposed margin, the lower the new HO point for all mobility states. For example, when the proposed margin is 0.5 dB, then the new HO points for low, medium and high mobility states are respectively 17 dB, 16.2 dB and 14.5 dB. On the other hand, when the proposed margin is 1.5 dB, then the new HO points are 11 dB, 8.5 dB and 3.5 dB for low, medium and high mobility states respectively.

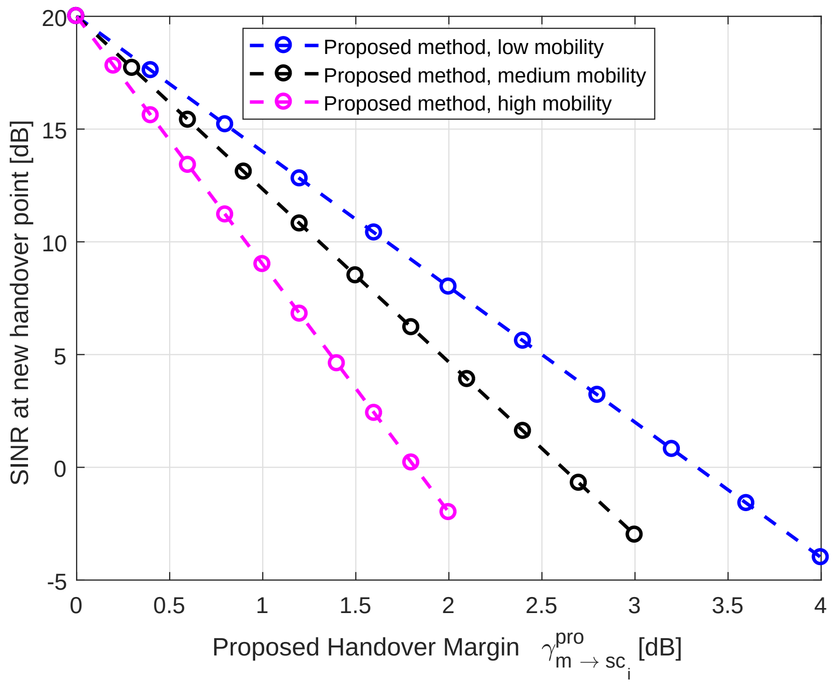

Figure 5.10: SINR at new handover point

5.5.3.1 Number of Handovers

The total number of HOs is depicted in Fig. 5.11. The results obtained in Fig. 5.11 validate the proposed method. At a velocity of 10 km/h, the performance of the proposed method is very similar to that of the conventional [17], ETCS [92] and ENCLB [94] methods. However, after 10 km/h, the proposed method outperformed the other methods by reducing the number of HOs. The conventional method has a higher rate of increase in the number HOs including inbound and inter-SC HOs. Generally, for both of the ETCS method and our proposed method, the number of HOs to SCs is highly reduced due to the reduction in the number of target SCs in the NCL owing to the ToS condition. Our proposed method outperformed the three methods by reducing the unnecessary HOs for different UE velocities since our method initiates the HO at a point when the data rate from the target SC is good enough with the consideration of the interference-based load-dependent modified A3 HO condition, unlike the other methods that depend on the downlink received power to initiate the HO to the SC via the classical A3 HO condition. We can observe the drop in the number of HOs for the proposed method from Fig. 5.11, e.g. at a velocity of 40 km/h. This is due to the reduced number of SCs in the NCL as the velocity increases which in turn cause a reduction in the number of HOs.

5.5.3.2 Number of Unnecessary Handovers

The HO is regarded as unnecessary, if the UE performs HO to a cell and then performs another HO to another cell before the expiry of the time threshold (5 seconds [92]). The proposed method minimizes the unnecessary inbound and inter-SC HOs as v_{ue} increases compared to the competitive methods because the final HO candidate NCL only contains a few SCs (the proposed method removes the SCs that cause the short time of stay phenomena from the HO NCL) as the velocity increases, hence, the reduction in HO occurs, e.g., after 40km/h as depicted in Fig.5.12. It can also be noticed from Fig.5.12 that a slight increase in the number of unnecessary HOs occurs in the proposed method, between 20km/h and 40km/h, due to the HO forcing to balance the load between cells. However, this increase is still below that of the other competitive methods.

5.5.3.3 Outage Probability

Fig. 5.13 shows the outage probability for all methods. The proposed method yields a lower link failure compared to the other three methods because the proposed method only initiates the inbound and inter-SC HOs when there is a sufficient data rate received from the target SC, which means that the HO is initiated with QoS consideration by considering the interference powers from the other neighbouring cells. The conventional and ENCLB methods have an instantaneous increase in the link failure owing to the fluctuated downlink received power due to the UE mobility in the HetNet, and the level of link failure increases rapidly with the increase in UE velocity. The difference in link failure between ETCS and the proposed method starts to be distinct at a speed of 20km/h and it increases as the speed increases because, in addition to the ToS criteria, the proposed method takes the interference from adjacent cells and the availability

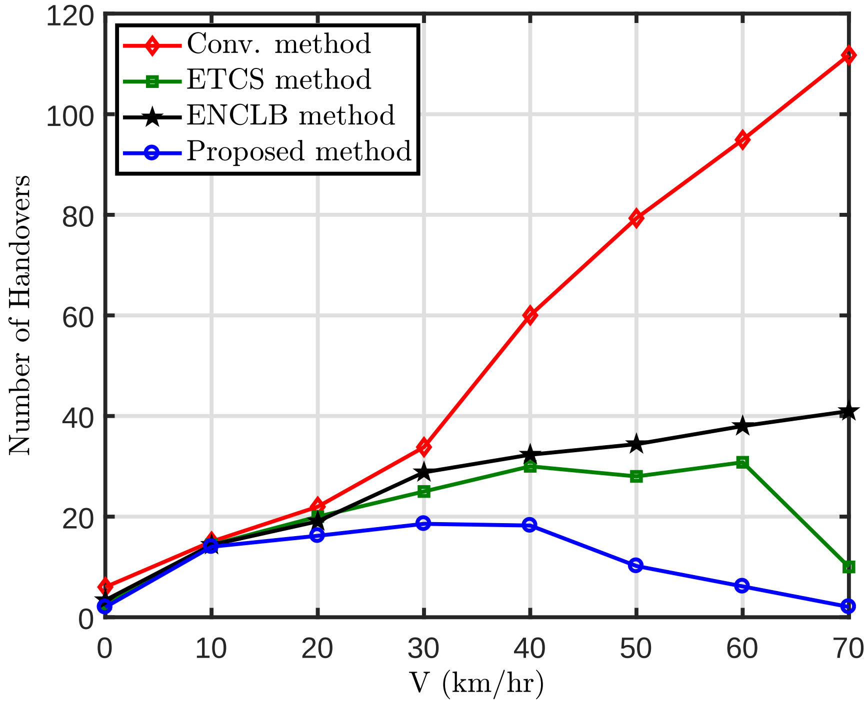

Figure 5.11: Total number of Handovers

of resources into account when performing the HO to SC, resulting in QoS HO process. This reduction in the outage probability emphasizes that the proposed load-dependent margins, $\gamma^{pro}_{m\rightarrow sc_i}$ and $\gamma^{pro}_{sc_j\rightarrow sc_i}$, have properly managed the load distribution among cells in the network.

5.5.3.4 Throughput

Fig. 5.14 depicts the UE's mean throughput with respect to different signal to noise ratio (SNR) values. The throughput is increased with the increase in the SNR. The proposed method consistently supplies the UE with the highest throughput compared to the other methods under different SNR values because the HO point for a UE trying to perform HO from an overloaded serving cell to a target SC is moved closer to the serving cell (i.e., the HO is triggered earlier), hence, the load is balanced between the two cells resulting in higher throughput.

For the range of MC load factors of 5% to 100% with an increment of 10%, Fig. 5.15 shows the UE mean throughput vs different load factors. Our proposed method outperformed the other three methods in terms of the average UE

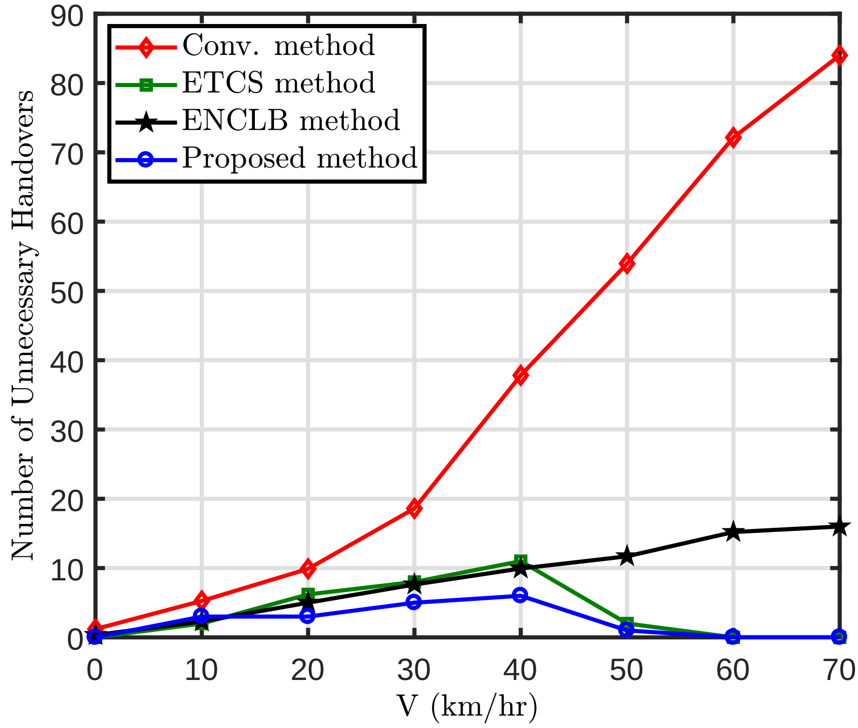

Figure 5.12: Number of Unnecessary Handovers

throughput at all load factors. When the load increases, the cell congests and its radio resources reduce, which in turn leads to the drop in the throughput gain. As the load goes towards 1 (100% load), the interference will increase, which in turn will reduce the SINR resulting in a lower UE mean throughput. From Fig. 5.15 we can also notice the sudden drop in the UE mean throughput for the ENCLB, the ETCS and the conventional methods since they trigger the HO to the target SC based on the downlink received power using the classical A3 event and also they do not apply the offloading policy, hence, higher dropping in calls is expected resulting in a lower throughput sudden decrease. On the other hand, the drop in the UE mean throughput for our proposed method is less than the other methods because the HO is performed upon the occurrence of our proposed modified A3 event where the UEs are offloaded from the MC to the SC by forcing the HO. Although there is a slight drop in the UE mean throughput for the proposed method as the load on the MC increases (due to the time needed for processing the HO from the serving cell to the SC), this drop is much slower than that of

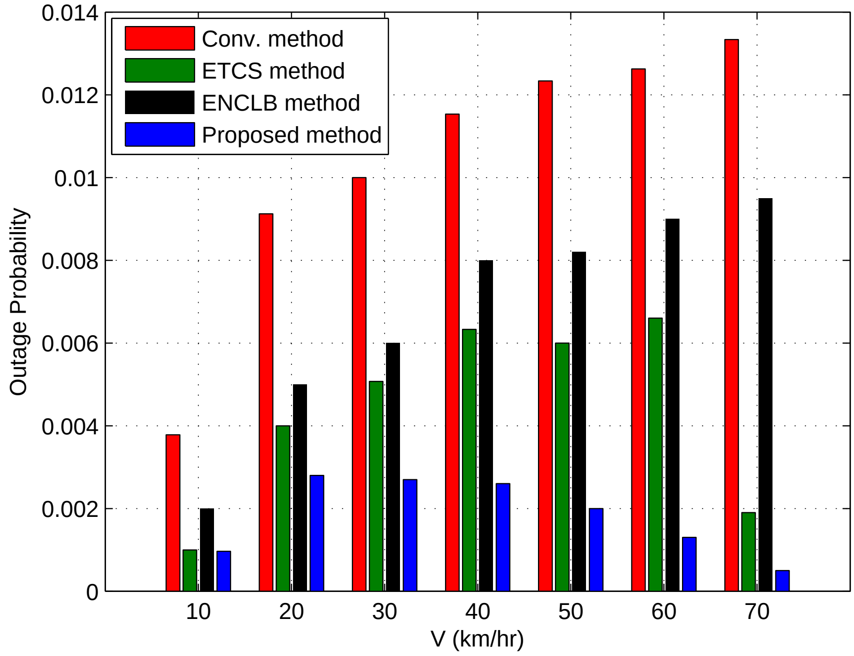

Figure 5.13: Outage Probability

the other competitive methods. Fig. 5.16 depicts the system throughput when the density of the UEs in the MC is varied. We assume that the density of the other cells in the network is fixed except for the MC, which is varied between 0 to 120 UEs. It is clear that the system throughput of the conventional method is always less than that of the other methods. Below 60 UEs in the network, the throughput of the conventional method keeps going up since the capacity of the MC is still sufficient to deliver resources to the incoming UEs, but a sudden drop in the throughput happens after that owing to the fact that the MC will be overloaded and its capacity will be limited. The same reason applies to the drop in the ENCLB method when the number of UEs exceeds 75. When the number of UEs is 60, we can notice that the proposed method has 15%, 12% and 2.5% enhancement in the throughput compared to the conventional, the ENCLB and the ETCS methods, respectively, and these percentages increase as the number of UEs increases. On the other hand, at 30 UEs and below, the performance of the proposed method is closer to that of the ETCS in terms of system throughput. However, above 30 UEs the proposed method's throughput is significantly higher than that of the ETCS due to the load-dependent margin incorporation which

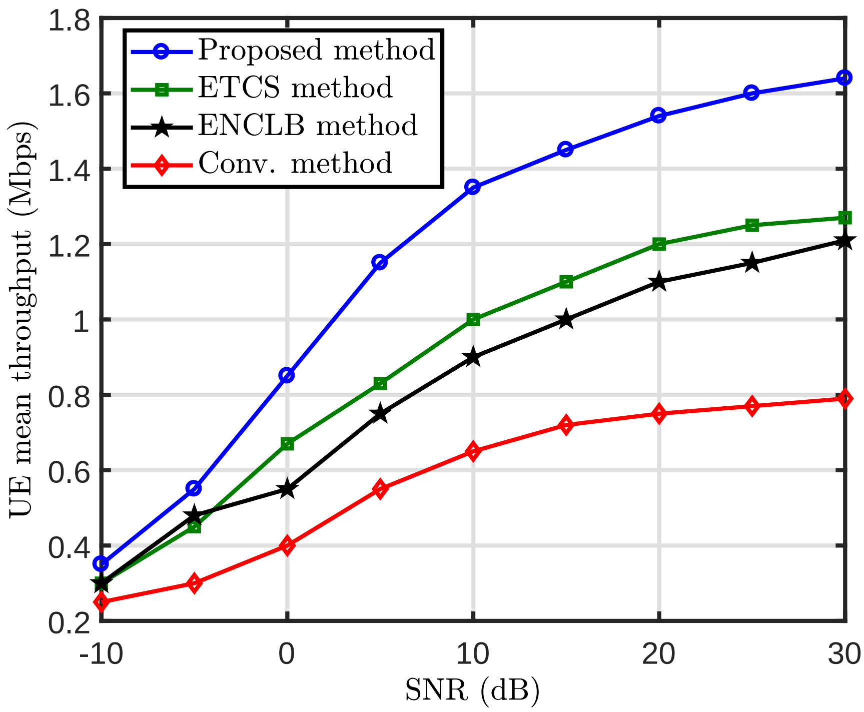

Figure 5.14: UE mean throughput vs SNR

proves the proper distribution of the load between MC and SC tiers. Generally, for the proposed method, the average system throughput increases with the increase in the density of UEs. The reason behind this increase is that the HO point of UEs is moving closer to the overloaded cell, hence forcing the UEs to HO to a light load target SC. This means that the overloaded cell will not accept new HO requests, hence, reducing the load on this cell and eventually increasing its throughput.

5.6 Summary

In this chapter, we addressed the problems of inbound and inter-SC HO scenarios in dense SC HetNets. We proposed a novel HO method that takes into account the two HO scenarios. The effects of interference and short ToS are used to reduce the number of SCs in the final candidate NCL so that the UE is forced to perform the HO to the tier that gives a sufficient data rate and has enough resources from a reduced NCL that contains a few and appropriate HO target SCs, in this way,

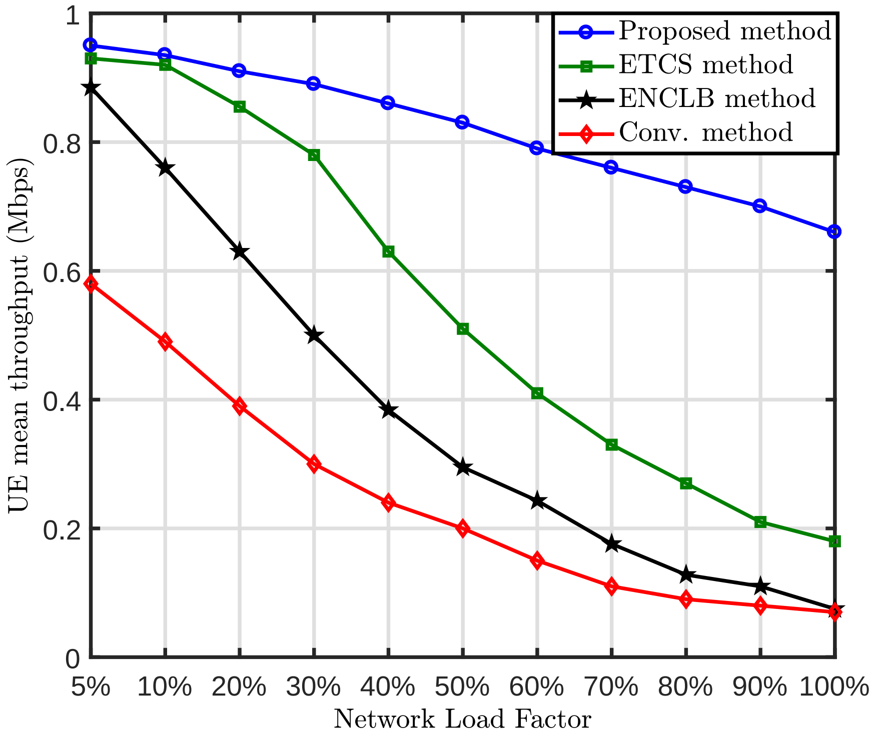

Figure 5.15: UE mean throughput vs load factor

traffic offloading from the MC tier to SC tier is accomplished. We proposed a modified A3 HO triggering condition considering the interference and cell load. Results show that our proposed method minimizes the unnecessary HO and outage probability compared to the other existing methods. The proposed method also outperformed the competitive methods by delivering higher throughput as the density of UEs increased in the network. Under different network conditions, including SNR and load factor, we tested and compared the proposed method against the ETCS, the ENCLB and the conventional methods. Under all network conditions our proposed method outperformed the other three methods by providing a higher system throughput.

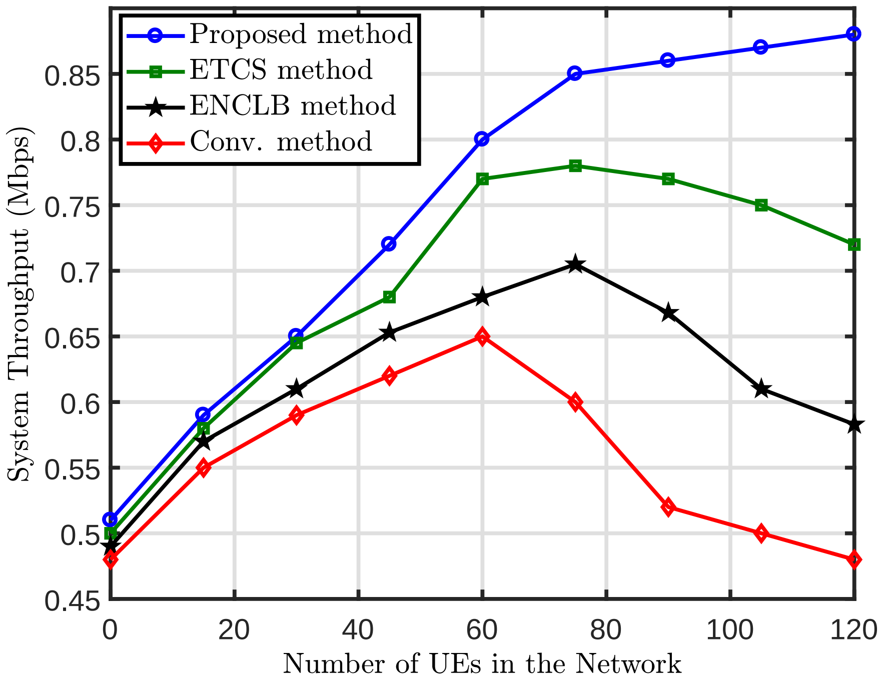

Figure 5.16: System throughput vs Number of UEs

Chapter 6

MADM-based Handover Methods for Dense Small Cell HetNets

The multiple attribute decision making (MADM) methods have been widely adopted to develop and solve many decision making problems. The MADM deals with the selection of the best alternatives which are characterised based on multiple attributes. Basically, all of the MADM methods have the following characteristics:

Alternatives: also called options or candidates. All of the alternatives are ranked based on certain criteria and the best one is nominated as candidate.

Attributes: also named metrics or criteria. Multiple attributes are taken into account when selecting the alternative.

Decision matrix: the MADM problem is formulated as a matrix whose rows represent the alternatives and columns represent the attributes of each alternative.

Weighting of attributes: every attribute must be weighted to measure the importance of them.

Normalization: because different attributes have different unit of measurement, the normalization is applied so that the attributes have same scale.

The HO problem can be dealt with by taking into account different criteria [20]. Therefore, the MADM techniques can be a proper solution to model and tackle the HO decision.

This chapter consists of two parts. The first part (6.1) uses the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to model and solve the HO decision problem. On the other hand, the second part (6.2) utilizes the Grey Rational Analysis method (GRA) to model the HO problem.

6.1 Modified Weighted TOPSIS Handover for Dense Small Cell HetNets

6.1.1 Introduction

The problems of frequent HOs and radio link failures (which causes the HO failure) are the main reasons for a degraded QoS delivered to the UE in a dense SCs environment due to the increased level of interference and the UE mobility management. A proper mechanism that can deal with these issues became a necessity. Therefore, in this work we jointly consider the interference and UE movement information to reduce the frequent HOs and radio link failure, and hence, enhancing the QoS delivered to the UE in terms of mean throughput.

In this part of this chapter, we model the HO decision based on TOPSIS. The base stations are considered as alternatives, and the HO metrics are considered as attributes to select the proper base station for HO. Most of the current TOPSIS literature works are dealing with base station selection for static UEs [101] and do not consider the HO due to the UE mobility which is a big challenge in future 5G networks. To the best of our knowledge, the exploitation of entropy and standard deviation weighting techniques (for HO metrics weighting), which are considered as an objective weighting techniques that assign very small weights to the attributes with small influence on decision making, in TOPSIS method is also not considered in the literature. In other words, the entropy and standard deviation techniques estimate the weights for HO metrics based on the actual values of these metrics for all base stations. If the value of a certain HO metric is similar for all base stations, this means that this metric will obtain very small weight as it has no influence on HO decision. The selection of the attributes (HO metrics) is a crucial factor for making the HO decision, especially in ultra-dense SCs environment. The SCs are usually deployed in an unplanned manner which results in severe interference levels in the HetNet. Therefore, we consider the SINR as one of the attributes for building the decision matrix. Moreover, fast-moving UEs pass the coverage area of SC and stay for a very short time causing an unnecessary HOs which leads to a signalling overhead and degraded QoS. The proposed methods incorporate the estimated time of stay for the UE in the target cell as one of the decision matrix attributes to minimize the probability of HO to the cell with a short time of stay and hence, reducing the unnecessary HOs. Furthermore, the UE angle of movement with respect to the target cell is a very important parameter to consider in HO decision making because it will help in reducing the number of target cells for HO (i.e., only cell within the direction of UE movement will be included in the decision matrix). Therefore, we consider this metric as another attribute for the decision matrix. On the other hand, giving fixed weights for the attributes is inefficient strategy because this may lead to improper cell selection and can result in either unnecessary HO or HO failure which eventually will reduce the throughput and increase the signalling overhead. Therefore, we deploy two weighting techniques that compute the attribute weight based on the actual values of these attributes and for all alternatives. The first technique is the entropy weighting and the second one is the standard deviation weighting technique in which the HO metric with the higher deviation variation, compared to the mean value, will obtain larger weight value. In other words, this HO metric will have a higher impact in HO decision making compared to other HO metrics.

Upper-case boldface letters are used to represent matrices and lower-case boldface are used to represent vectors.

The major contributions of this part of this chapter can be summarized as follows:

- The well-known MADM technique, TOPSIS, is used to model the HO problem. Two methods are proposed and both use the UE angle of movement, ToS and SINR as the selection criteria to form the HO decision matrix.
- The first method weights the attributes via entropy weighting technique, and hence named as Proposed Entropy Technique for Order Preference by Similarity to an Ideal Solution (PE-TOPSIS).
- The second proposed method uses the standard deviation weighting technique to assign weights to the attributes (HO metrics) and hence, named as Proposed Standard Deviation Technique for Order Preference by Similarity to an Ideal Solution (PSD-TOPSIS).
- The PSD-TOPSIS shows better performance but higher computational complexity. On the other hand, PE-TOPSIS shows lower complexity but worse

performance. As we know, there are different SCs with different sizes and transmit power, and hence, different capabilities. For example, low power SCs (e.g. residential femtocells) have small capabilities in terms of size and transmit power compared to other types of SCs (e.g. picocells). We draw a conclusion that when the complexity is not an issue in the application, then the PSD-TOPSIS method would be a good solution i.e., it can be used in picocell base stations. On the other hand, the PE-TOPSIS method can be used for femtocells.

The rest of this part is organized as follows. Section 6.1.2 presents the related works. The network system model is given in Section 6.1.3. The proposed TOPSIS methods' procedures are illustrated in Section 6.1.4. Section 6.1.5 gives the proposed weighting techniques. The performance and results analysis are given in Section 6.1.6. Finally, the conclusion is drawn in Section 6.1.7.

6.1.2 Related Works

TOPSIS method's principle, in wireless network field, is to select the target which is closest to the positive ideal solution and farthest from the negative ideal solution. Positive ideal solution is based on the best value for the attributes used in decision making. While negative ideal solution is based on the worst attributes values [102]. In the field of network selection, many researches in the literature have been accomplished by using TOPSIS method to solve the HO decision making. Authors in [103] proposed a TOPSIS method taking into account cost, total bandwidth, network utilization, delay and jitter in the HO decision matrix. Another research paper in [104], a TOPSIS method is proposed to rank the available networks. Different parameters are used when forming the decision matrix, such as the available bandwidth, cost and security level. The authors in [105] proposed a TOPSIS based method to reduce the connection failure in HetNets. The UE performs HO to the target cell when one of the following happens. First, when the received power is very low, even before the time to trigger expires so as to avoid radio link failure. Second, when the received signal from the serving cell is high enough but the downlink SINR drops below a predefined threshold. Results show that this method reduces the number of HOs, packet loss and increase UE mean throughput. However, the use of predefined value for weighting the HO metrics could lead to deficiency in HO decision due to the large variation in signal power because of UE mobility specially for fast moving ones in dense SCs scenarios.

6.1.3 Network System Model

In this work, as shown in Fig.6.1, we consider a two-tier downlink HetNet scenario consisting of a single MC of $500m$ radius and N_{sc} number of SCs with a radius of $100m$ each. Thus, we have a total number of N_{bs} base stations in the network. SCs are deployed randomly following uniform distribution. Both tiers are deployed with the same carrier frequency. The minimum distance between MC site and SC sites is set to $75m$ and the SC to SC site distance is set to $40m$ [10], which ensures an overlapping between SCs. Users are distributed uniformly in the MC coverage area and they move in a random direction with a constant speed. In this mobility model, the UE moves in straight line with a constant speed. It goes to a selected direction $[0, 2\pi]$ to the boundary. Upon completing the movement by reaching the boundary, the UE pauses and decides to move to another direction and travels to complete a second movement. This process is independently repeated until the simulation is finished. Which means that the UE has different angle of movement during the simulation. In this case, the UE angle of movement is measured with regards to the coordinates of the base stations at each period of time, so it is not constant. This movement direction, i.e., angle θ, is used to compute the time of stay and it is different with respect to different base stations.

A large scale channel is considered using the path loss model and shadowing effects. The path loss between the MC and the UE is defined as in [87] by

$$\delta_{m \to ue_k} = 128.1 + 37.6 \ \log_{10}(d_{m \to ue_k}), \tag{6.1}$$

where $d_{m \to ue_k}$ is the distance between the UE and the MC base station in kilometres. The path loss between the SC and the UE is defined as in [22] by

$$\delta_{sc_i \to ue_k} = 38 + 30 \ \log_{10}(d_{sc_i \to ue_k}), \tag{6.2}$$

where $d_{sc_i \to ue_k}$ is the distance between the UE and SC i in metres.

The SINR from SC i and MC received at UE k can respectively be expressed as

$$\gamma^r_{sc_i \to ue_k} = \frac{P^r_{sc_i \to ue_k}}{\sum_{j=1, j \neq i}^{N_{bs}} P^r_{bs_j \to ue_k} + \sigma^2}, \tag{6.3}$$

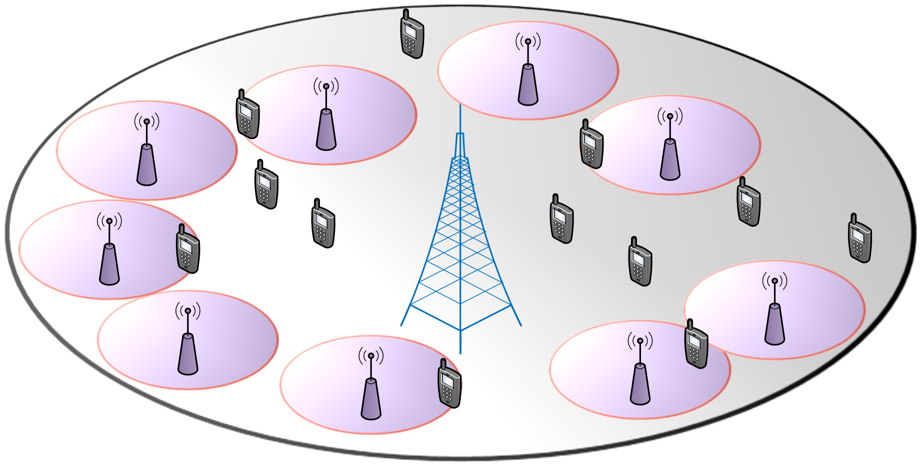

Figure 6.1: HetNet System Model

$$\gamma^{r}_{m \to ue_k} = \frac{P^{r}_{m \to ue_k}}{\sum_{j=1, j \neq m}^{N_{bs}} P^{r}_{bs_j \to ue_k} + \sigma^2}, \tag{6.4}$$

where $P^{r}_{sc_i \to ue_k}$ and $P^{r}_{m \to ue_k}$ are respectively the RSRP received from SC i and MC, $P^{r}_{bs_j \to ue_k}$ is the RSRP from the interfering MC/SCs, $\gamma^{r}_{m \to ue_k}$ is the SINR received from MC at UE k, $\gamma^{r}_{sc_i \to ue_k}$ is the SINR received from SC i at UE k, σ^2 is the noise power and N_{bs} is the total number of MC and SCs in the network.

As depicted in Fig.6.2, the real ToS, $ToS^{real}_{ue_k}$, and the angle θ, can be measured as

$$ToS^{real}_{ue_k} = \frac{2R_i \sqrt{1 - \frac{\left(|\overrightarrow{A_1 A_0}| \cdot \sin(\theta)\right)^2}{R_i^2}}}{V_k}. \tag{6.5}$$

The angle between the UE trajectory and the base station i, θ, can also be calculated as

$$\theta = \arccos\left(\frac{\overrightarrow{A_1 A_0} \cdot \overrightarrow{A_1 A_2}}{| \overrightarrow{A_1 A_0} | \times | \overrightarrow{A_1 A_2} |}\right), \tag{6.6}$$

where A_0, A_1 and A_2 are respectively the location of base station i, and the previous location of the UE and the current location of the UE, R_i is the base station radius and V_k is the velocity of UE k.

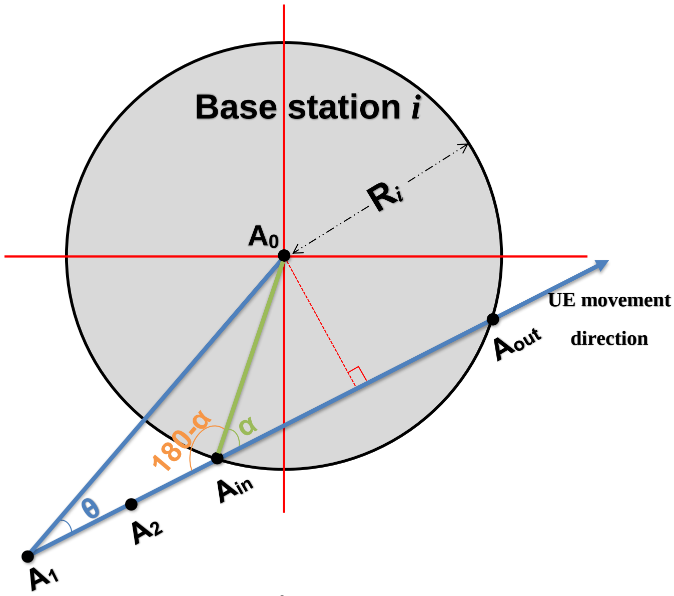

Figure 6.2: Time of stay measurement

6.1.4 Proposed Weighted Techniques for Order Preference by Similarity to an Ideal Solution

The proposed methods adopt one of the well known MADM techniques, Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS), to select the proper target cell for HO by ranking the available neighbouring candidate cells. The attributes (i.e. HO metrics) used to rank the target cells are: the time of stay ($ToS^{real}_{ue_k}$), the UE angle of movement (θ) and the SINR of the target cell.

The HO decision is based on choosing a proper alternative (i.e. base station) among the available set of alternatives. The proposed methods grant that the selected HO target cell is suboptimal solution i.e. near the positive ideal solution and far from the negative ideal solution. Henceforth the base station(s) will be called alternative(s) and the HO decision metric(s) will be called attribute(s). The UE has (m) target alternatives with (n) attributes and attributes weighting vector $\mathbf{w}$. Generally, the procedures of the proposed method can be listed as follows:

Procedure 1: *Decision Matrix*, the decision matrix, $\mathbf{D}$, is formed by mapping the alternatives against the attributes as shown

$$\mathbf{D} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ a_{31} & a_{32} & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}, \tag{6.7}$$

where each row represents one alternative, and the columns represent their correspondent attributes, $n = 1, \cdots, 3$, $m = 1, 2, \cdots, N_{bs}$, a_{ij} represents the value of the j^{th} attribute (HO metric) for the i^{th} alternative (base station). In our proposed methods, $a_{i1} = \theta$, $a_{i2} =$ ToS, and $a_{i3} =$ SINR.

Procedure 2: *Normalization*, the decision matrix is then normalized using a Square root normalization method as described in (6.8)

$$a_{ij}^{norm} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} a_{ij}^2}} \ , \quad a_{ij}^{norm} \in [0, 1], \tag{6.8}$$

where a_{ij}^{norm} is the j^{th} normalized attribute of the i^{th} alternative. Which means that each element in the decision matrix $\mathbf{D}$ is divided by its correspondent column squared-elements sum. Thus, we can write the normalized decision matrix, $\mathbf{D^n}$, as

$$\mathbf{D^n} = \begin{bmatrix} \frac{a_{11}}{\sqrt{\sum_{i=1}^{m} a_{i1}^2}} & \frac{a_{12}}{\sqrt{\sum_{i=1}^{m} a_{i2}^2}} & \frac{a_{13}}{\sqrt{\sum_{i=1}^{m} a_{i3}^2}} \\ \frac{a_{21}}{\sqrt{\sum_{i=1}^{m} a_{i1}^2}} & \frac{a_{22}}{\sqrt{\sum_{i=1}^{m} a_{i2}^2}} & \frac{a_{23}}{\sqrt{\sum_{i=1}^{m} a_{i3}^2}} \\ \frac{a_{31}}{\sqrt{\sum_{i=1}^{m} a_{i1}^2}} & \frac{a_{32}}{\sqrt{\sum_{i=1}^{m} a_{i2}^2}} & \frac{a_{33}}{\sqrt{\sum_{i=1}^{m} a_{i3}^2}} \\ \vdots & \vdots & \vdots \\ \frac{a_{m1}}{\sqrt{\sum_{i=1}^{m} a_{i1}^2}} & \frac{a_{m2}}{\sqrt{\sum_{i=1}^{m} a_{i2}^2}} & \frac{a_{m3}}{\sqrt{\sum_{i=1}^{m} a_{i3}^2}} \end{bmatrix}. \tag{6.9}$$

Procedure 3: *Attributes Weighting*, the normalized matrix is weighted in this step so as to take into account the importance of each attribute. The detailed weighting calculations are presented in Sections 6.1.5.1 and 6.1.5.2. Thus, the weighted normalized decision matrix can be expressed as

$$\begin{aligned}\mathbf{D^{n,w}} &= \begin{bmatrix} a_{11}^{norm}\cdot w_1 & a_{12}^{norm}\cdot w_2 & a_{13}^{norm}\cdot w_3 \\ \\ a_{21}^{norm}\cdot w_1 & a_{22}^{norm}\cdot w_2 & a_{23}^{norm}\cdot w_3 \\ \\ a_{31}^{norm}\cdot w_1 & a_{32}^{norm}\cdot w_2 & a_{33}^{norm}\cdot w_3 \\ \vdots & \vdots & \vdots \\ a_{m1}^{norm}\cdot w_1 & a_{m2}^{norm}\cdot w_2 & a_{m3}^{norm}\cdot w_3 \end{bmatrix} \\ &= \begin{bmatrix} d_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ d_{31} & d_{32} & d_{33} \\ \vdots & \vdots & \vdots \\ d_{m1} & d_{m2} & d_{m3} \end{bmatrix}\end{aligned} \tag{6.10}$$

$$\text{subject to} \sum_{j\in n} w_j = 1, \tag{6.11}$$

where d_{ij} is the j^{th} weighted normalized attribute of the i^{th} alternative i.e., $d_{11} = a_{11}^{norm}\cdot w_1$, $d_{12} = a_{12}^{norm}\cdot w_2$ and so on.

Procedure 4: *Ideal Positive and Negative Solutions*, the weighted normalized decision matrix is used to find the ideal positive solution (best alternative which has the best attribute values, denoted as $\mathbf{a}^+$) and the ideal negative solution (worst alternative which has the worst attribute values, denoted as $\mathbf{a}^-$) by

$$\begin{aligned}\mathbf{a}^+ &= \Big\{(\max_{i\in m} D_{ij}^{n,w} \mid j\in \mathbf{j}^+), (\min_{i\in m} D_{ij}^{n,w} \mid j\in \mathbf{j}^-)\Big\} \\ &= \Big\{d_1^+, d_2^+, d_3^+\Big\},\end{aligned} \tag{6.12}$$

$$\begin{aligned}\mathbf{a}^- &= \Big\{(\min_{i\in m} D_{ij}^{n,w} \mid j\in \mathbf{j}^+), (\max_{i\in m} D_{ij}^{n,w} \mid j\in \mathbf{j}^-)\Big\} \\ &= \Big\{d_1^-, d_2^-, d_3^-\Big\},\end{aligned} \tag{6.13}$$

where $D_{ij}^{n,w} = a_{ij}^{norm}\cdot w_j$, $\mathbf{j}^+$ is the set with the attributes having positive impact (i.e., the higher value the better) such as SINR and ToS, and $\mathbf{j}^-$ is the set with the attributes having negative impact (i.e., the lower value the better) such as θ. The best alternative value for the attributes θ, ToS and SINR are respectively $\min(\theta)$, $\max(ToS)$ and $\max(SINR)$. On the other hand, the worst alternative for the attributes are respectively $\max(\theta)$, $\min(ToS)$ and $\min(SINR)$. Hence, θ is considered as a cost attribute and both ToS and SINR are considered as benefit attributes.

Procedure 5: *Distance to Positive and Negative Solutions*, compute the Euclidean distance between each alternative and both the positive and negative ideal solutions as shown below

$$dist^{+} = \sqrt{\sum_{j=1}^{n}(D_{ij}^{n,w} - d_j^{+})^2}, \ \forall i = 1, \cdots, m \tag{6.14}$$

$$dist^{-} = \sqrt{\sum_{j=1}^{n}(D_{ij}^{n,w} - d_j^{-})^2}, \ \forall i = 1, \cdots, m \tag{6.15}$$

Procedure 6: *Obtain the Ranking Vector*, in this step, the ranking network vector, **r**, is obtained so as to measure the relative closeness of each candidate alternative to the ideal solution, as shown

$$r = \frac{dist^{-}}{dist^{+} + dist^{-}}, \ \forall i = 1, \cdots, m. \tag{6.16}$$

According to [106], it has been shown that in some situations the above equation in (6.16) cannot ensure that the optimal alternative is having the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution at the same time. Therefore, the formula in (6.16) can be replaced by the revised closeness as in (6.17), which computes the extent to which the optimal alternative closes to the positive ideal solution and far from the negative ideal solution, that is

$$r = \frac{dist^{-}}{\max(dist^{-})} - \frac{dist^{+}}{\min(dist^{+})}, \ \forall i = 1, \cdots, m. \tag{6.17}$$

Indeed, $\forall i = 1, \cdots, m$, $r(i) \leq 0$, bigger r means the better alternative. When an existing alternative satisfies both of the conditions $\Big(\max(dist^{-}) = dist^{-}\Big)$ and $\Big(\min(dist^{+}) = dist^{+}\Big)$, this means that this alternative is the best one which is close to the positive ideal solution and far away from the negative ideal solution. **Procedure 7: *Ranking***, the resulted vector from the previous step is then ranked in descending order and the best alternative (with the highest rank) from **r** vector is selected as a target (i.e., the HO target base station)

$$\mathrm{HO}_{\mathrm{target}} = \arg\max \ r(i). \tag{6.18}$$

6.1.5 Attribute Weighting Measurements

Attributes weighting represents a very significant role in HO decision making. Thus, the way of determining the weights is a crucial factor for the proposed methods. Some HO metrics have significant impact on HO decision making. On the other hand, some metrics have less impact or sometimes have no impact at all on the HO decision. Therefore, it is very important to deploy a weighting technique that is capable of assigning proper weights for each HO metric based on the actual values of these metrics. We present two weighting techniques in this section, namely the entropy and standard deviation weighting techniques. We also validate and compare the differences between the two techniques using a numerical example in subsection 6.1.5.3.

6.1.5.1 Entropy Attributes Weighting

The entropy weighting technique measures the uncertainty in the data by using the probability theory. This means that if the data distribution is broader then the uncertainty is higher. On the other hand, if the data distribution is sharply peaked then the uncertainty is lower. The entropy weighting technique precisely calculates the amount of decision information that each attribute has in the decision matrix [107]. The entropy technique is a type of objective weighting techniques which measures the attribute weight based on the relative difference between them. The resulted weight of the attribute is then normalized to obtain the entropy weight of that attribute [108]. The j^{th} entropy coefficients divergence degree, denoted e_j, can be measured using the normalized decision matrix as follows

$$e_j = 1 - c_j, \tag{6.19}$$

$$\text{where} \quad c_j = \left[\frac{1}{\ln(n)} \sum_{i=1}^{n} a_{ij}^{norm} \ \ln(a_{ij}^{norm}) \right], \tag{6.20}$$

and the term $\frac{1}{\ln(n)}$ is a constant which ensures that the value of the coefficient $c_j \in$ [0,1] i.e., $0 \leq c_j \leq 1$.

The entropy coefficient divergence degree e_j represents the inherent contrast intensity of the attributes (i.e., HO metrics). The more divergent the values of a_{ij}^{norm} for attribute j, the higher its corresponding entropy coefficient divergence degree e_j, and the more important the attribute j for HO decision. In other words, this means that if the alternatives have similar performance ratings for a certain attribute (e.g. ToS for all base stations), then this attribute has less influence in HO decision making. On the other hand, if an attribute j for all alternatives in the decision matrix is identical, then this attribute is not useful in HO decision making because it has absolutely no useful information for the decision maker [109]. For example, for a given attribute j, when all elements a_{ij}^{norm} are the same, then the coefficient $c_j \approx 1$ means that $e_j \approx 0$ and hence, the weight of this attribute becomes zero as well. This means that this attribute has no influence on the HO decision.

Finally, the entropy weighting of the j^{th} attribute is expressed as

$$w_j^e = \frac{e_j}{\sum_{j=1}^{n} e_j}, \tag{6.21}$$

where w_j^e is the final weight of the j^{th} attribute using the entropy weighting technique.

6.1.5.2 Standard Deviation Attributes Weighting

The proposed method also deploys the standard deviation (SD) weighting technique [110] so as to rate the importance of the attributes for each cell in the network. The SD weighting technique measures the weights of each attribute in terms of the standard deviation.

The SD weighting technique gives a small weight for an attribute if the value of this attribute is identical for all available alternatives. For example, if an attribute has an equal values on all available alternatives, then it has no significant impact on HO decision making and hence, its weight is null. In other words, attributes with small standard deviation are given smaller weights and vice versa. The weights can be calculated using SD technique as shown below

$$w_j^{sd} = \frac{\sigma_j}{\sum_{k=1}^{3} \sigma_k}, \tag{6.22}$$

$$\sigma_j = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(a_{ij}^{norm} - \mu_j)^2}, \tag{6.23}$$

$$\mu_j = \frac{1}{m}\sum_{i=1}^{m} a_{ij}^{norm}, \tag{6.24}$$

where σ_j and μ_j are respectively the standard deviation and the mean value of the j^{th} normalized attribute.

6.1.5.3 Numerical Example

To validate and compare the differences between the two weighting techniques, we examine a numerical example, whose decision matrix is randomly generated and is given as

$$\mathbf{D} = \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ A_4 \end{array} \begin{array}{c} \begin{array}{ccc} \theta & ToS & SINR \end{array} \\ \begin{bmatrix} 80 & 100 & -109 \\ 45 & 20 & -106 \\ 20 & 50 & -81 \\ 5 & 90 & -45 \end{bmatrix} \end{array}$$

where A_i is the i^{th} alternative $\forall i = 1, \cdots, 4$.

First, the decision matrix is normalized by Square root normalization method as

$$\mathbf{D^n} = \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ A_4 \end{array} \begin{array}{c} \begin{array}{ccc} \theta & ToS & SINR \end{array} \\ \begin{bmatrix} 0.8504 & 0.6901 & -0.6149 \\ 0.4783 & 0.1380 & -0.5937 \\ 0.2126 & 0.3450 & -0.4537 \\ 0.0531 & 0.6211 & -0.2521 \end{bmatrix} \end{array}$$

Then, we can obtain the weighting vector for the entropy and SD techniques respectively as

$$\mathbf{w^e} = \begin{bmatrix} 0.0189 & 0.0144 & 0.9667 \end{bmatrix}.$$

$$\mathbf{w^{sd}} = \begin{bmatrix} 0.4522 & 0.3310 & 0.2168 \end{bmatrix}.$$

It is clear that the entropy and SD techniques evaluate the three attributes with different ranking, i.e., $w_3 > w_1 > w_2$ for entropy and $w_1 > w_2 > w_3$ for SD, where w_1, w_2 and w_3 are respectively the weights of θ, ToS and SINR.

The entropy technique gives very high weight for the SINR, about 97%, and less for θ and ToS, about 1.8% and 1.4% respectively. Unlike the entropy technique, the SD technique assigns more moderate and accurate weights for the attributes 45%, 33% and 21% for θ, ToS and SINR respectively.

The entropy technique nearly gives the whole weight to one attribute (i.e., SINR) which may be an undesirable feature for this technique because the ToS and θ attributes are also significant factors for HO decision. The UE may receive high SINR from a certain cell but its ToS is very short and its moving direction is away from the cell (i.e., θ is very large) and hence, assigning a higher weight for only SINR is considered as a drawback of this technique which will result in a HO to a wrong cell leading to an increase in the number of unnecessary HOs and eventually results in a throughput reduction. These problems could be avoided by the SD technique which has a better distribution for the weights for all attributes.

Thus, we now have two proposed methods. The first method utilizes the entropy weighting technique to find the weighting vector $\mathbf{w}$ and is named as PE-TOPSIS. The second one uses the SD weighting technique for measuring the weighting vector $\mathbf{w}$ and is named as PSD-TOPSIS.

The procedures of the proposed methods PE-TOPSIS and PSD-TOPSIS are illustrated in Fig.6.3. The procedures begin by first obtaining the cells that have a downlink RSRP greater than or equal to the threshold ($RSRP_{th}$). This step is essential to reduce the number of alternatives in the decision matrix and hence, reducing the computational complexity. For each of the obtained cells, the parameters θ, ToS, and SINR are measured to build the decision matrix. Then, the normalization of the decision matrix is applied. After that, the weighting vector $\mathbf{w}$ is calculated using the entropy weighting technique for PE-TOPSIS method and standard deviation weighting technique for PSD-TOPSIS method. The resulted cells from the previous steps are combined in vector $\mathbf{r}$. Finally, the HO target is the cell with highest order in vector $\mathbf{r}$.

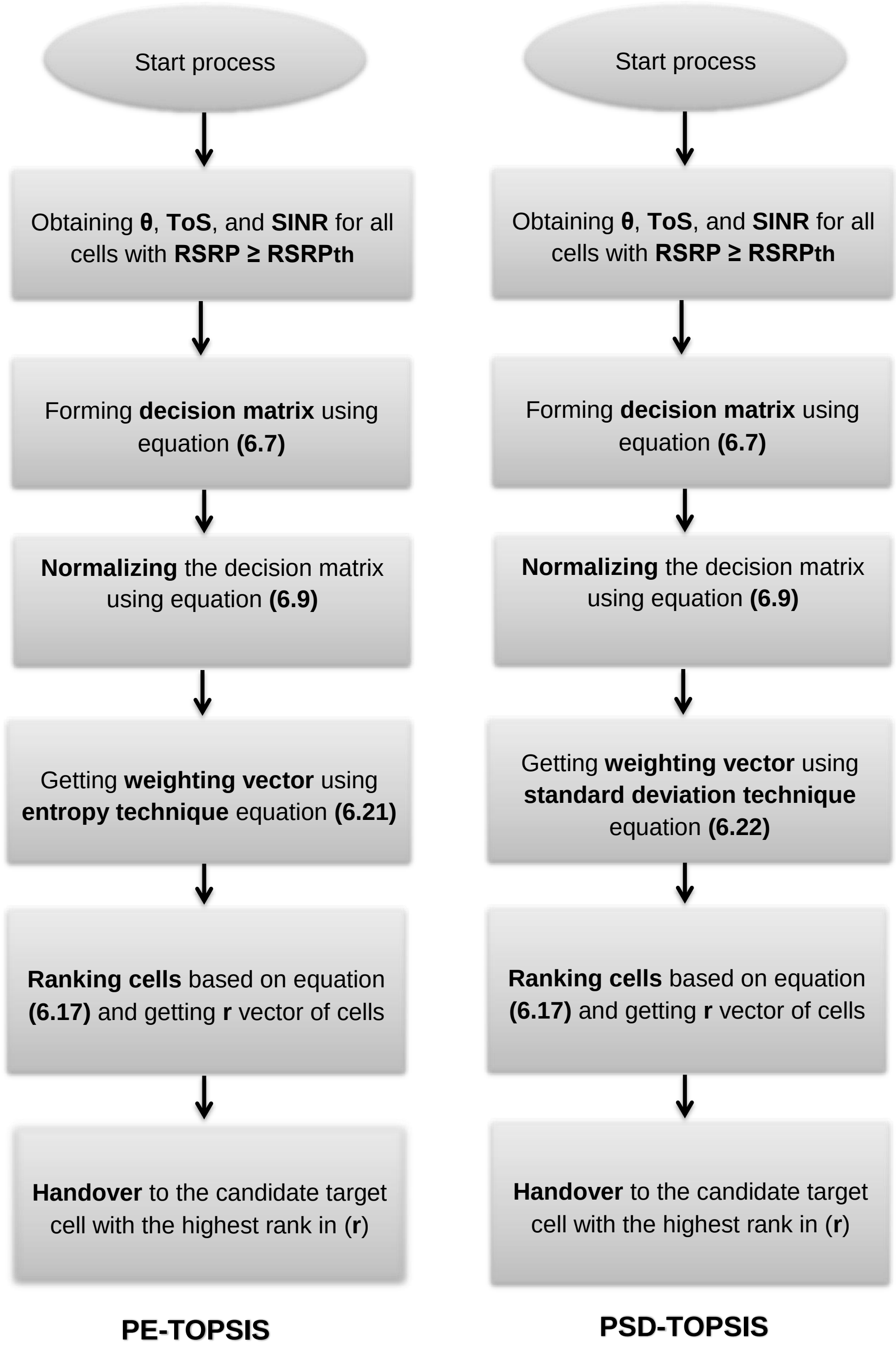

Figure 6.3: Procedures of PE-TOPSIS and PSD-TOPSIS

6.1.6 Performance and Results Analysis

The performance of the PE-TOPSIS and PSD-TOPSIS methods is evaluated in terms of number of HOs, radio link failure and UE mean throughput and compared against other three methods, the conventional method, the network controlled HO method (NCH) in [111] and the method in [105] denoted as TOPSIS, which uses a predefined weighting vector with fixed values. Users are distributed uniformly in the simulation area and move in a straight line with constant speed. Simulations parameters are listed in table 7.1 [98].

Table 6.1: Simulation Parameters

Parameter	Value
MC radius	500 meters
SC radius	100 meters
Number of SCs	50
Bandwidth	20 MHz
MC transmission power	46 dBm
SC transmission power	30 dBm
MC Shadowing standard deviation	8 dB
SC Shadowing standard deviation	10 dB
UE velocity	{1, 20, 40, 60, 80, 100} km/h
$RSRP_{th}$	-70 dBm
γ_{th}	-8 dB
T310	1 sec

Recall the density definition defined in (5.34). We set up the number of SCs to 50, which means that density metric $D_{sc} \approx 2$ and hence, the dense SCs scenario is achieved.

First, we only compare the PE-TOPSIS with the conventional, NCH and TOPSIS methods.

6.1.6.1 Number of Handovers

Fig.6.4 depicts the total number of HOs. Fig.6.4 validates the proposed method performance. For example, when there is one user with a velocity of 20 km/h, the number of HOs for the proposed PE-TOPSIS method is identical to that of TOPSIS [105] method and slightly lower than that of the NCH [111] and the conventional [17] methods. After that we can notice the enhancement in number of HOs reduction for the PE-TOPSIS compared to the other methods. It is clear that the conventional and NCH methods have higher number of HOs compared to TOPSIS and PE-TOPSIS. This is because that both methods do not predict the target cell for HOs and they respectively perform the HO when the downlink received power from the neighbour cell is offset greater than that of the serving cell for TTT period of time and if the SINR is below the SINR threshold for NCH method. On the other hand, the TOPSIS and PE-TOPSIS have less number of HOs compared to the other two methods. The PE-TOPSIS has also outperformed the TOPSIS method by reducing the number of HOs due to the modified entropy weighting calculations which leads to proper assigning of importance to the HO metrics θ, ToS and SINR. Unlike the TOPSIS method which gives a predefined fixed weights for the HO metrics.

6.1.6.2 Radio Link Failure Probability

A radio link failure is declared if the HO is initiated to the target cell from vector $\mathbf{r}$ but the SINR of that cell drops below the threshold γ_{th} for a period of time window T310, which is 1 second, as defined in [65]. The radio link failure is depicted in Fig.6.5. The higher the speed the higher the radio link failure for all methods. The conventional method yields higher failure due to the frequent HOs as the velocity increases, hence, the HO will be initiated but interrupted before completion due to the sudden drop in the target cell received power at the UE side. The NCH method has lower failure compared to the conventional method because it performs the HO when the SINR of the serving cell drops below a predefined threshold. Both the TOPSIS and PE-TOPSIS methods have the lowest radio link failure with the PE-TOPSIS outperforming specially at high speeds due to the early HO to the correctly predicted HO target cell. The low radio link failure in the PE-TOPSIS method emphasizes the accuracy of weighting

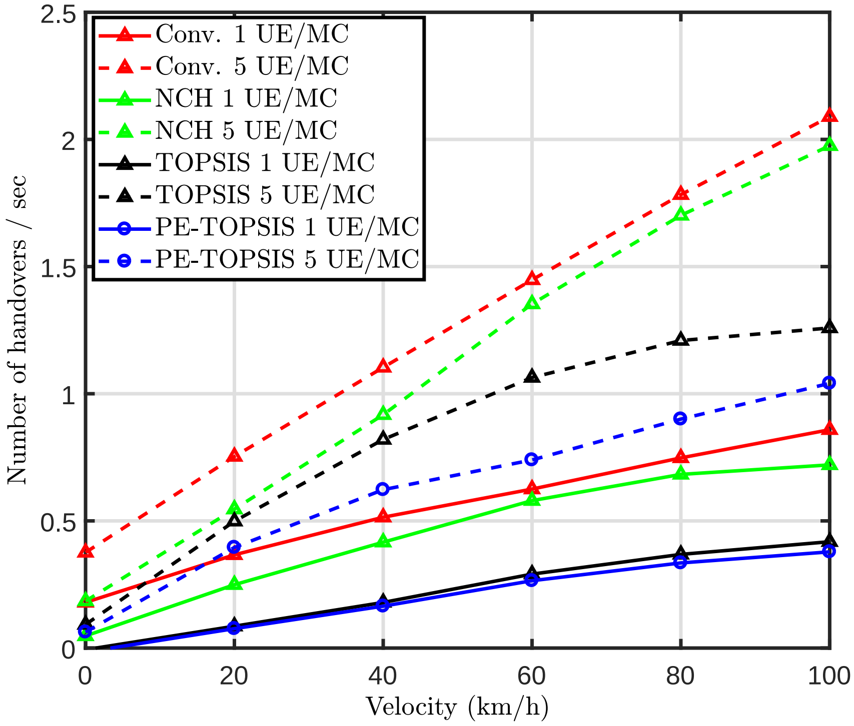

Figure 6.4: Number of handovers

assignment to the HO metrics which leads to an accurate cell selection compared to the other methods.

6.1.6.3 User Mean Throughput

Fig.6.6 shows the UE mean throughput for the four methods. All methods have dropped in the mean UE throughput as the velocity increase. The conventional and NCH methods have the lowest throughput compared to the other two methods because of their higher number of unnecessary HOs which results in producing a lower throughput for the UE (since the high speed UEs will result in radio link failure which leads to poor throughput gain). The TOPSIS and PE-TOPSIS methods produce higher throughput because they perform the HO upon the proper target prediction with the PE-TOPSIS outperforming the TOPSIS method.

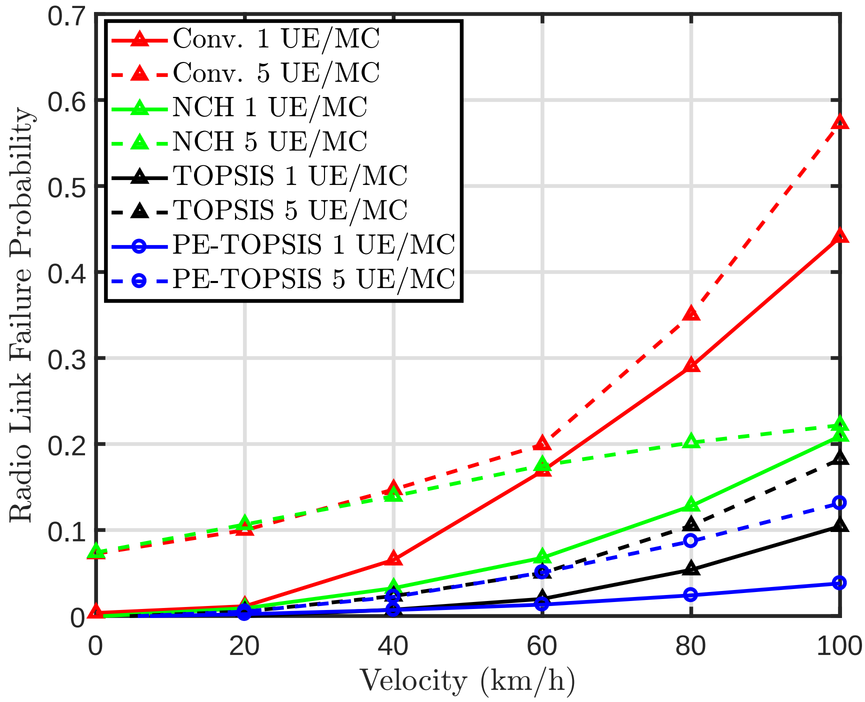

Figure 6.5: Radio link failure probability

6.1.6.4 Comparing PE-TOPSIS and PSD-TOPSIS

In this subsection we compare the performance of PE-TOPSIS with that of the PSD-TOPSIS methods in terms of the number of HOs, radio link failure, UE mean throughput and complexity of calculations.

Fig.6.7 shows that the number of HOs has been reduced in PSD-TOPSIS method compared to PE-TOPSIS. For all velocities, the PSD-TOPSIS method produces less number of HOs. The SD weighting technique provides more stable weights to the attributes which in turn leads to an efficient alternative selection among the available options.

The radio link failure is depicted in Fig.6.8. The PSD-TOPSIS method reduces the radio link failure, which may cause HO failure. The level of increase in the link failure increases with the increase in UE velocity according to the common sense because the fast moving UEs may leave the coverage area of the cell before completing the HO process, hence the failure increases.

In Fig.6.9, the mean UE throughput is illustrated. As expected the PSD-TOPSIS method produces higher achieved throughput for the UE.

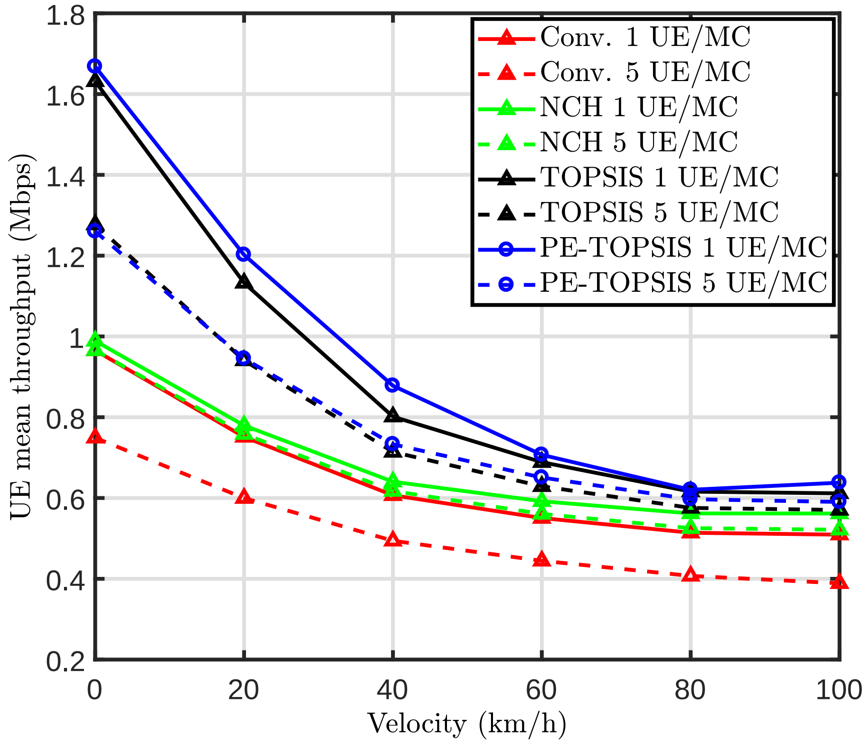

Figure 6.6: User mean throughput

For the sake of clarity, we did not compare the proposed PSD-TOPSIS method with the conventional, NCH or TOPSIS because it has been shown that our proposed method PE-TOPSIS outperformed those methods.

To further conclude the impact of the weighting techniques on the proposed methods, we compare the performance in a form of tables. Tables 6.2, 6.3 and 6.4 give the numerical results of the PE-TOPSIS and PSD-TOPSIS methods when the velocity is 20km/h, 40km/h and 80km/h respectively.

We can see from the tables that the PSD-TOPSIS method has outperformed PE-TOPSIS at all velocities. For instance, when the velocity is 20km/h, the number of HOs is reduced by 9%. Furthermore, the radio link failure is reduced by 30.7% in the same case. At a velocity of 80km/h, the number of HOs is reduced by approximately 5.2% for PSD-TOPSIS compared to PE-TOPSIS. Furthermore, the radio link failure is minimized by 8% in the same case and the UE mean throughput is enhanced by 78.8%. When using the entropy weighting technique the overall performance is getting worse (but still better than that of the TOPSIS,

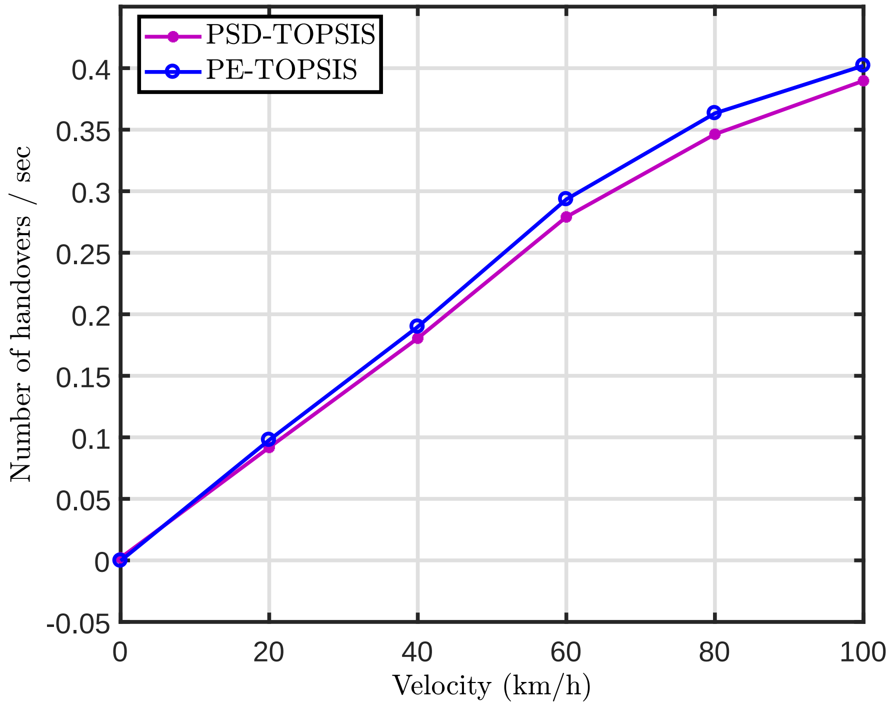

Figure 6.7: Number of handovers

Table 6.2: Performance analysis at 20 km/h

Method	HOs/sec	RLF	UE throughput(Mbps)
PE-TOPSIS	0.100	0.0038	1.20
PSD-TOPSIS	0.0917	0.00263	1.28

Table 6.3: Performance analysis at 40 km/h

Method	HOs/sec	RLF	UE throughput(Mbps)
PE-TOPSIS	0.19	0.0085	0.86
PSD-TOPSIS	0.17	0.0078	0.97

NCH and the conventional methods) compared to that when using SD weighting technique. This proves the advantage of the SD over the entropy weighting technique in distributing the weights between the attributes and hence, gives a better

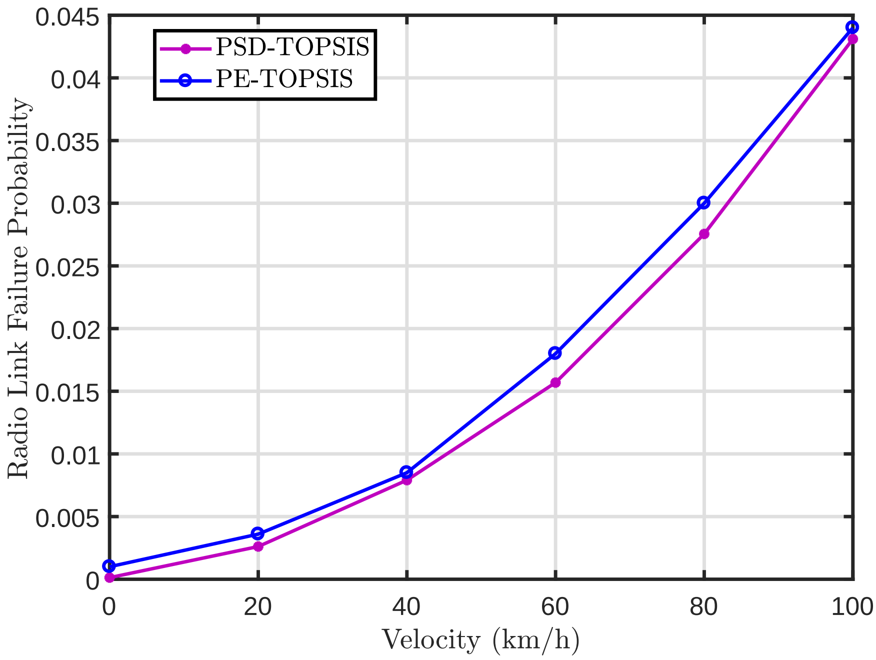

Figure 6.8: Radio link failure probability

Table 6.4: Performance analysis at 80 km/h

Method	HOs/sec	RLF	UE throughput(Mbps)
PE-TOPSIS	0.365	0.030	0.15
PSD-TOPSIS	0.346	0.0276	0.71

performance in terms of reducing the number of HOs and radio link failures in addition to enhancing the UE mean throughput.

To further analyse the benefits of the proposed methods, PE-TOPSIS and PSD-TOPSIS, we evaluate the complexity of both methods. Fig.6.10 depicts the computational complexity of the proposed methods. This is done by evaluating the two methods in terms of the total number of floating point operations (flops) with different sizes of the decision matrix (i.e., different number of SCs). We used the Matlab function defined in [112] which scans and parses each line of the simulation code and counts the number of flops. As can be noticed from Fig.6.10, the computational complexity increases linearly with the increase in the number of SCs for both methods. The PSD-TOPSIS method has slightly higher

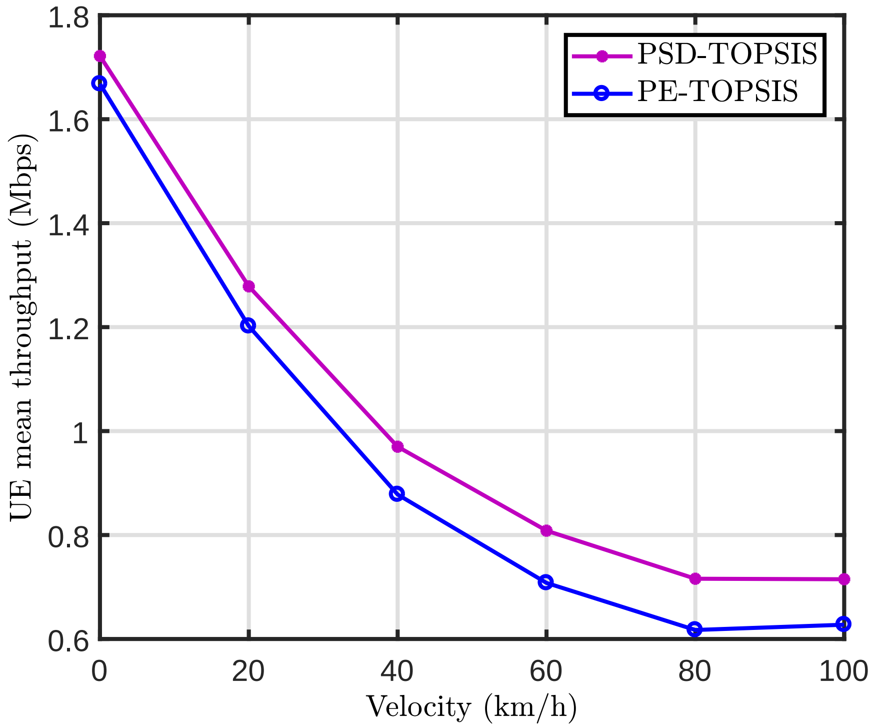

Figure 6.9: User mean throughput

complexity operations compared to the PE-TOPSIS. In fact, as the number of SCs increases the difference between the two methods in terms of complexity increases. We conclude that, when the complexity is not an issue in the application, then the PSD-TOPSIS method would be a good solution. Otherwise, the PE-TOPSIS method is an alternative at the expense of less accuracy on attributes weight assignment. Furthermore, higher complexity means higher energy consumption. Therefore, deploying PE-TOPSIS or PSD-TOPSIS also depends on the capability of the SCs. For example, when residential SCs are deployed (e.g. femtocells), then the PE-TOPSIS is more preferred due to the limited calculation capabilities of the femtocell. On the other hand, when other SC types are used (e.g. picocell), then the PSD-TOPSIS could be the best option.

6.1.7 Summary

In this part of this chapter, we jointly consider the interference and UE movement information to control the number of HOs and radio link failure so as to

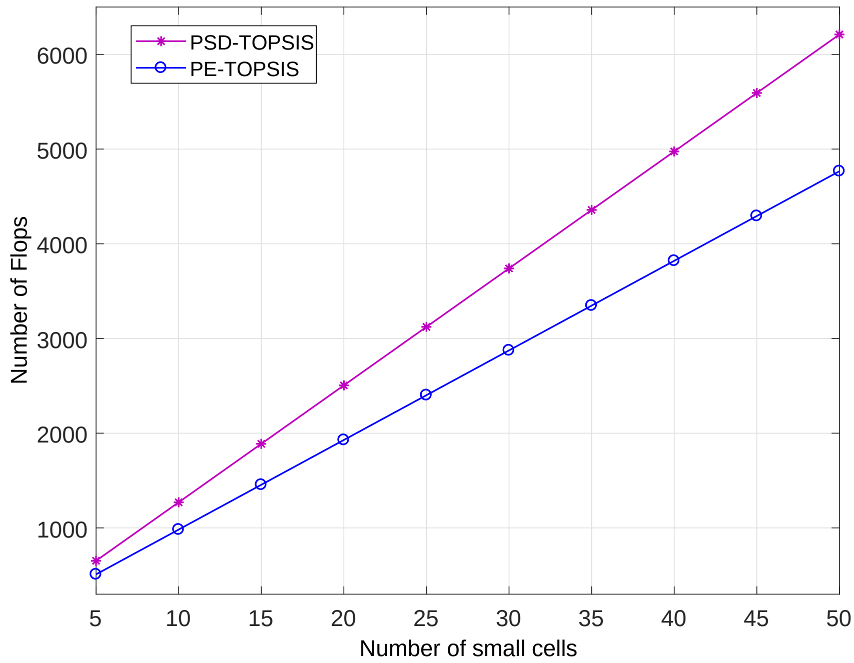

Figure 6.10: Complexity analysis

improve the UE mean throughput. The proposed methods exploit the TOPSIS principle of ranking the HO candidate cells based on their attributes and the weights of each attribute. The final HO destination cell is selected when it is close to positive ideal solution and far from the negative ideal solution. In the first method, PE-TOPSIS, we deploy the entropy weighting technique to weight the attributes. This method shows a good performance in reducing the number of HOs and radio link failures and enhancing the achieved UE throughput compared to the NCH, TOPSIS and conventional methods. The second proposed method, PSD-TOPSIS, deploys the standard deviation weighting technique to scale the importance of each attribute for all HO candidate cells. As the results show, our proposed PSD-TOPSIS method reached low number of HOs and low radio link failure, while higher mean UE throughput is achieved compared to the existing methods. This method shows even better results in enhancing the network performance by reducing the number of HOs and radio link failure, in addition to increasing the mean UE throughput owing to the accurate weight distribution between the attributes. Furthermore, we compare the performance of

PE-TOPSIS and PSD-TOPSIS in terms of complexity and suggest to choose the method based on the size and capability of calculations of the SCs. For smaller size SCs, the PE-TOPSIS is more suitable, otherwise, the PSD-TOPSIS is an alternative solution.

6.2 Energy Efficient GRA-based Handover for Dense Small Cell HetNets

6.2.1 Introduction

In fact, energy saving for UE due to its transmission power consumption is a crucial factor to mitigate the interference in dense SCs environment, in addition to enhancing the power saving of the UE battery. In this work, we jointly consider the reduction of unnecessary HOs and the UE energy efficiency. The proposed method considers the UE transmit power with respect to the target cell as a HO metric. This will make sure that the UE performs HO to the cell that requires less power in uplink, which in turn will reduce the power consumption and eventually enhance the energy efficiency. Moreover, the cell capacity is also used in HO decision so as to reduce the link failure (HO failure due to lack of resources) and also manage the load balance among cells in the network. The highly dense deployment of SCs leads to severe interference in the network. Therefore, we incorporate the downlink SINR as one of the HO metrics. High-speed UEs pass the coverage area of a SC and stay for a short time causing an unnecessary HOs which causes a signalling overhead. For this reason the proposed method also incorporates the predicted time of stay for the UE in the target cell as one of the HO attributes to reduce the probability of unnecessary HOs.

The proposed method, named as GRA-HO, adopts the combination of the Analytical Hierarchy Process (AHP) technique to obtain the weight of the HO metrics and GRA method to rank the available cells for the best HO target. The AHP technique first assigns the weights for all HO metrics then the GRA selects the target HO cell by ranking the available neighbouring candidate cells. In order to ensure fair comparison and dimensional attributes, the normalization is considered as a main process in all MADM techniques. There are many normalization techniques that can be used to achieve the attributes normalization such as square-root, sum, max-min and enhanced max-min techniques [108]. Ranking abnormality is the phenomena of reversal ranking which means that the ranking of the alternatives changes when omitting any of the lowest ranked alternative [113]. This phenomena can lead to high number of unnecessary HOs.

To limit this problem, the enhanced max-min normalization technique is used in our proposed GRA-HO method.

Many research studies have been conducted by using MADM techniques in network selection. However, most of them do not consider proper weighting assignment and energy efficiency. Also, most of these works do not consider the UE mobility, which means that the HO metrics values are not really the actual values measured during the UE movement, when using MADM techniques in network selection with dense SC deployment. To this extent, our contributions can be drawn as:

- The selection of multiple HO metrics including SINR, UE transmit power, cell capacity and UE ToS in the target cell.
- Using the AHP technique to obtain the weights of the HO metrics prior to cell selection.
- Deploying the GRA method to rank the available cells for HO purpose and select the cell with the highest rank as HO target.
- Adopting the enhanced max-min normalization technique in which the benefit and cost attributes are dealt with differently so as to minimize the effect of the probability of ranking abnormality on the proposed method, and hence, reducing the unnecessary HOs.
- Integrating the AHP and GRA in a (GRA-HO) method for dense SCs HetNet scenario.
- Implement, evaluate and compare the proposed GRA-HO method with the traditional MADM methods including SAW and VIKOR where the results show that the proposed GRA-HO method outperformed the other two methods in terms of reducing the unnecessary HO and link failure, in addition to enhancing the energy efficiency.

The reminder of this part of this chapter is organized as follows. Section 6.2.2 presents the related works. The network system model is given in Section 6.2.3. The proposed GRA-HO method procedures are illustrated in Section 6.2.4. The performance and results analysis are given in Section 6.2.5. Finally, the conclusion is drawn in Section 6.2.6.

6.2.2 Related Works

One of the simplest MADM methods is the simple additive weighting (SAW). In [114], authors proposed a SAW method for HO decision. The serving cell is in charge of performing the process of alternative selection aiming to extend the lifetime of the UE battery. The HO metrics used in their work are bandwidth and cost. However, one of the disadvantages of SAW method is that a low value of one HO metric can negatively be affected by high value metric, e.g., when an alternative has low throughput with an affordable cost, it can be chosen over a slightly costly alternative with a much better throughput gain.

In [115], the authors used TOPSIS with AHP in alternative ranking for HO method. The AHP is used to obtain the attribute weights and TOPSIS is then applied to rank the alternatives. Multiple attributes used in their work include packet delay, bandwidth, jitter, packet loss, cost and security.

Authors in [116] compared the performance of four MADM methods for a network selection. TOPSIS, SAW, GRA and multiplicative exponential weighted (MEW) methods are adopted. The attributes used in their comparison include delay, jitter, bit error rate and bandwidth. They also used four traffic classes in their comparison including conversational, streaming, interactive and background traffic class. The authors concluded that all of the methods have identical performance for conversational and streaming classes. While for interactive and background traffic classes, the performances of SAW, MEW and TOPSIS are the same. On the other hand, the GRA method produces higher bandwidth and less delay for the interactive and background traffic.

6.2.3 Network System Model

The network system model is identical to that in (6.1.3) except for the UE mobility model which follows a Gauss distribution model as described in Section 4.3.

Let N_{bs} be the set of all cells in the network, $N_{bs} = \{0, 1, 2, \cdots, N_{sc}\}$, where 0 represents the MC base station, N_{sc} is the number of SCs and U_i is the set of UEs served by cell i.

In order to maintain service continuity for UE k, it should receive a minimum signal strength of $RSRP_{th}$ and to maintain the ongoing service quality, it should have a minimum SINR of γ_{th}^{up}.

In the following we illustrate the HO metrics used in the proposed method including the downlink SINR of target cell, the UE transmit power with respect to the target cell, the capacity of target cell and the ToS.

The downlink RSRP of cell i can be expressed as

$$P_{bs_i \to ue_k}^r = P_{bs_i}^t \cdot h_{bs_i \to ue_k}, \tag{6.25}$$

where $P_{bs_i \to ue_k}^r$ is the downlink RSRP of cell i received at UE k, $P_{bs_i}^t$ is the transmission power of cell i and $h_{bs_i \to ue_k}$ is the channel gain between the UE k and cell i considering the path loss and shadowing effects [87].

The downlink SINR for cell i received at UE k can be computed as

$$\gamma_{bs_i \to ue_k}^r = \frac{P_{bs_i \to ue_k}^r}{\sum_{bs \in N_{bs}, bs \neq bs_i} P_{bs}^t \cdot h_{bs \to ue_k} + \sigma^2}, \tag{6.26}$$

where σ^2 is the noise power and the term $\left(\sum_{bs \in N_{bs}, bs \neq bs_i} P_{bs}^t \cdot h_{bs \to ue_k}\right)$ represents the summation of the downlink power from the neighbouring cells except cell i i.e., the interfering cells.

The mean UE transmit power can be estimated for a candidate cell by performing the standard measurement. Assuming that the channel gain is symmetric, i.e., $h_{bs_i \to ue_k} = h_{ue_k \to bs_i}$, and using (6.25), the uplink RSRP of UE k for the target cell i, $P_{ue_k \to bs_i}^r$, can be given as

$$P_{ue_k \to bs_i}^r = \frac{P_{ue_k}^t P_{bs_i \to ue_k}^r}{P_{bs_i}^t}, \tag{6.27}$$

where $P_{ue_k}^t$ is the UE mean transmit power for cell i. Thus, the uplink SINR can be written as

$$\gamma_{ue_k \to bs_i}^r = \frac{P_{ue_k \to bs_i}^r}{I_{ue_k \to bs_i}}, \tag{6.28}$$

where $I_{ue_k \to bs_i}$ is the interference caused by UEs in the same cell i and the interference caused by UEs in the neighbouring cells plus noise,

$$\begin{aligned} I_{ue_k \to bs_i} = & \sum_{ue \in U_i, ue \neq ue_k} P_{ue}^t \cdot h_{ue \to bs_i} + \\ & \sum_{bs \in N_{bs}, bs \neq bs_i} \sum_{ue \in U_i} P_{ue}^t \cdot h_{ue \to bs} + \sigma^2, \end{aligned} \tag{6.29}$$

where the first line of (6.29) represents the interference from the UEs in the same cell and the second line represents the interference from the UEs in the neighbouring cells plus noise power.

Given the minimum requirement for maintaining quality performance γ_{th}^{up} and based on (6.27) and (6.28), we can measure an estimate of the UE transmit power with respect to cell i as shown in (6.30)

$$P_{ue_k}^{t} = \frac{I_{ue_k \to bs_i} \cdot P_{bs_i}^{t} \cdot \gamma_{th}^{up}}{P_{bs_i \to ue_k}^{r}}. \tag{6.30}$$

Equation (6.30) can be utilized to predict the power consumption of UE k, if we consider the UE transmit power as a main source of the UE power consumption. Therefore, we can use this criterion to minimize the UE transmit power by performing the HO to the cell that requires a lower power requirement.

The cell capacity plays an important role in HO decision making as it can limit the HO failure, and hence, improving the QoS delivered to the UE in terms of throughput satisfaction. The cell capacity can be defined as [117]

$$CP_i = BW \cdot R_{ue}^{i} \cdot \log_2(1 + \gamma_{bs_i \to ue_k}^{r}), \tag{6.31}$$

where BW is the system bandwidth and R_{ue}^{i} is the total ratio of resources assigned to all active UEs in cell i compared to the cell's total resources, R_{total}^{i}, which can be expressed as

$$R_{ue}^{i} = \frac{\sum\limits_{\forall j} R_{uej}}{R_{total}^{i}} \tag{6.32}$$

The ToS is taken from equation (6.5).

6.2.4 Proposed Grey Relational Analysis Based Handover (GRA-HO) Method

The proposed GRA-HO method combines the AHP and GRA principles in a HO decision method for dense SC HetNets. The attributes (i.e. HO metrics) used for cell ranking are: the downlink SINR ($\gamma_{bs_i \to ue_k}^{r}$) from (6.26), the UE transmit power ($P_{ue_k}^{t}$) from (6.30), cell capacity (CP_i) from (6.31) and ToS from (6.5). The whole procedures of the proposed method can be divided into three parts. In the first part, the attributes of all cells that satisfy the condition of sustaining service continuity (i.e., cells with $RSRP \geq RSRP_{th}$), are obtained. The second part is to obtain the weighting vector $\mathbf{w}$ which will be detailed in Section 6.2.4.1. While the third part involves applying the GRA to rank the available alternatives so as to obtain the best alternative for HO as explained in Section 6.2.4.2.

6.2.4.1 Analytical Hierarchy Process Handover Metrics Weighting

We deploy the Analytical Hierarchy Process (AHP) technique [118] to obtain the weights of the attributes prior to the process of GRA-HO. The AHP is a beneficial tool that deals with complex decision making. It can be used to check the consistency of the priorities that a decision maker gives to each attribute, and hence, minimizing the bias in the HO decision making. The AHP builds a weight for each attribute based on a pairwise comparisons of the attributes. The AHP uses the Saaty scale table 6.5 [118] to grant the importance of each attribute in a range of 1 to 9 to construct the pairwise comparison matrix. Note that the intermediate values in table 6.5 are used for uncertainty states e.g. when the decision maker is not sure whether to choose "strong importance 5" or "very strong importance 7", the alternative solution is to choose the intermediate value 6.

Generally, the importance of each attribute is different from others. Therefore, the first step is to derive a comparison matrix for the relative importance of each attributes according to the numerical importance scale in table 6.5. The pairwise comparison matrix is a square matrix with size (n x n). In our proposed method, we have n=4, i.e. 4 attributes, therefore the size of the pairwise comparison matrix is (4 x 4).

Let the pairwise comparison matrix, denoted as $\mathbf{P}$, defined as

$$\mathbf{P} = \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \\ p_{41} & p_{42} & p_{43} & p_{44} \end{bmatrix}, \tag{6.33}$$

$$\text{where } p_{ii} = 1, \text{ and } p_{ij} = \frac{1}{p_{ji}}, \tag{6.34}$$

where p_{ij} is constructed from table 6.5. The elements in $\mathbf{P}$ are weighted against each other e.g., SINR versus ToS. Therefore, the values of the diagonal of matrix

Table 6.5: Saaty Scale Table [118]

Importance Intensity	Definition
1	Equal Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Extreme Importance
2,4,6,8	Intermediate Values

P is equal to 1 because the relative importance of a certain attribute with respect to itself produces a value of 1.

After obtaining the pairwise comparison matrix, we need to construct the normalized Eigen vector of the matrix **P**. First, each element in the matrix is normalized by dividing it by the correspondent column sum producing the normalized matrix $\mathbf{P^n}$ with p^n_{ij} elements as given in (6.35), where the sum of each column must yield 1.

$$\mathbf{P^n} = \begin{bmatrix} \frac{p_{11}}{\sum_{i=1}^{n} p_{i1}} & \frac{p_{12}}{\sum_{i=1}^{n} p_{i2}} & \frac{p_{13}}{\sum_{i=1}^{n} p_{i3}} & \frac{p_{14}}{\sum_{i=1}^{n} p_{i4}} \\ \frac{p_{21}}{\sum_{i=1}^{n} p_{i1}} & \frac{p_{22}}{\sum_{i=1}^{n} p_{i2}} & \frac{p_{23}}{\sum_{i=1}^{n} p_{i3}} & \frac{p_{24}}{\sum_{i=1}^{n} p_{i4}} \\ \frac{p_{31}}{\sum_{i=1}^{n} p_{i1}} & \frac{p_{32}}{\sum_{i=1}^{n} p_{i2}} & \frac{p_{33}}{\sum_{i=1}^{n} p_{i3}} & \frac{p_{34}}{\sum_{i=1}^{n} p_{i4}} \\ \frac{p_{41}}{\sum_{i=1}^{n} p_{i1}} & \frac{p_{42}}{\sum_{i=1}^{n} p_{i2}} & \frac{p_{43}}{\sum_{i=1}^{n} p_{i3}} & \frac{p_{44}}{\sum_{i=1}^{n} p_{i4}} \end{bmatrix}. \tag{6.35}$$

The normalized Eigen vector **w**, of size (n x 1), is then obtained by averaging across the rows, that is

$$w_j = \frac{\sum\limits_{j=1}^{n} p^n_{ij}}{n} \tag{6.36}$$

where the sum of **w** vector is 1 because it is a normalized vector.

The Eigen vector is considered as the weighing vector providing that it is consistent. Consistency means to check whether the pairwise matrix **P** entries are consistent or not. Generally, inconsistency is allowed in AHP for some extent. A maximum of 10% inconsistency is tolerable by the AHP technique [107] [119]. The measure of consistency is called the consistency ratio (CR) where the smaller the CR the better the consistency and 10% is the highest acceptable ratio for CR. The procedures of finding CR can be summarized as:

- First step is to define the random index (RI) according to Saaty table 6.6 [118]. It has been proven that RI depends on the number of attributes. In our proposed GRA-HO method, we have 4 attributes, hence, RI = 0.9.

Table 6.6: Random Index [118]

Number of Attributes	1	2	3	4	5
RI	0	0	0.58	0.9	1.12

- Second step is to find the consistency index (CI) based on

$$CI = \frac{\lambda_{max} - n}{n - 1}, \tag{6.37}$$

  where λ_{max} is the largest principle value that can be obtained from the summation of products between each element of vector **w** and the sum of each column in the pairwise matrix **P**.

$$\lambda_{max} = \sum_{j=1}^{n} \Big(\sum_{i=1}^{n} p_{ij} \Big) \cdot w_j \tag{6.38}$$

- Finally, the CR is computed as

$$CR = \frac{CI}{RI}. \tag{6.39}$$

When CR is 10% or less, the judgement is proper and the weighing vector **w** is acceptable to be used in GRA-HO. Otherwise the AHP procedures must be repeated to attain the consistency [107].

6.2.4.2 Cell Ranking Using Grey Relational Analysis (GRA)

The GRA is an essential part of the grey system theory. Basically, the grey system theory deals with uncertainty in information. If the system information are all known, then the system is named as white system. On the other hand, if no information is available about the system, then it called a black system. With partially known information, the system is named as grey system [113]. Due to the multiple criteria that can be used in modelling the HO problem in dense SC environment, the GRA is a suitable MADM method that can be deployed to solve the cell selection problem. In order to obtain the grey relationship between HO metrics (attributes), the grey relational coefficients (GRC) need to be computed. Then, the GRC are ranked and the cell index with the highest rank is elected as a possible HO target cell. The benefits of deploying the GRA in dense SC HetNet are: the results depend on the original value of the HO metrics obtained during the measurement report by the UE, processing of the calculations is simple and straightforward and it is suitable for multiple complicated relationships between alternatives [120].

The UE has m target alternatives, n attributes for each alternative and attributes weighting vector $\mathbf{w}$. We can present the procedures of GRA method as follows:

Procedure 1: *Decision Matrix*, the decision matrix, $\mathbf{D}$, is built by mapping the alternatives against the attributes as given below

$$\mathbf{D} = \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} \\ x_{21} & x_{22} & x_{23} & x_{24} \\ x_{31} & x_{32} & x_{33} & x_{34} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & x_{m3} & x_{m4} \end{bmatrix}, \tag{6.40}$$

where the rows correspond to the alternatives, and the columns represent their correspondent attributes, $n = 1, \cdots, 4$, $m = 0, 1, \cdots, N_{sc}$, x_{ij} represents the value of the j^{th} attribute for the i^{th} alternative. Thus, $x_{i1} =$ SINR, $x_{i2} = P^t_{ue_k}$, $x_{i3} = CP_i$ and $x_{i4} =$ ToS.

Procedure 2: *Normalization*, the decision matrix is then normalized so as to make the attributes dimensionless in the range of [0,1] for comparability. We used the enhanced max-min normalization technique which accounts for both cost attributes (the smaller the better) and the benefit attributes (the larger the better). In our proposed method, we have four attributes, one of which is a cost attribute ($P_{ue_k}^t$) and the other three are benefit attributes (SINR, CP_i and ToS). For cost attribute, the normalization of the j^{th} attribute for the i^{th} alternative is computed as

$$x_{ij}^n = \frac{\max\limits_{\forall i}\{x_{ij}\} - x_{ij}}{\max\limits_{\forall i}\{x_{ij}\} - \min\limits_{\forall i}\{x_{ij}\}} \tag{6.41}$$

While for the benefit attributes, the normalization is expressed as

$$x_{ij}^n = \frac{x_{ij} - \min\limits_{\forall i}\{x_{ij}\}}{\max\limits_{\forall i}\{x_{ij}\} - \min\limits_{\forall i}\{x_{ij}\}} \tag{6.42}$$

Procedure 3: *Ideal Reference Sequence*, in this step, the definition of the ideal reference sequence is obtained, whose sequence is close to the best alternative. Generally, for an attribute j^{th} of an alternative i^{th}, if the value of x_{ij}^n is equal or close to 1, then the performance of this alternative for this attribute is the best one compared to others. Therefore, preferred value of the j^{th} attribute for the i^{th} alternative is 1, hence, we define the ideal reference sequence as x_j^*=1 $\forall j = 1, 2, 3, 4$, i.e., the ideal alternative vector can be defined as [1 1 1 1].

Procedure 4: *Grey Relational Coefficient*, this step calculates the Grey Relational Coefficient (GRC) which is used as a measure of how much is the j^{th} attribute for the i^{th} alternative, i.e., x_{ij}^n, close to the ideal sequence x_j^*. The formula for calculating the GRC is given as

$$GRC(x_{ij}^n, x_j^*) = \frac{\min\limits_{\forall i,\forall j}\{\delta ij\} + \Psi \max\limits_{\forall i,\forall j}\{\delta ij\}}{\delta_{ij} + \Psi \max\limits_{\forall i,\forall j}\{\delta ij\}}, \tag{6.43}$$

where $\delta_{ij} = \mid x_j^* - x_{ij} \mid$ and Ψ is the distinguishing coefficient $\in$ [0,1].

Procedure 5: *Obtaining Ranking Vector*, the ranking of the grey relational coefficients, denoted as GRA_i, is finally obtained as

$$GRA_i = \sum_{j=1}^{n} w_j \; GRC(x_{ij}^n, x_j^*), \tag{6.44}$$

$$\text{subject to} \sum w_j = 1, \tag{6.45}$$

where w_j is the j^{th} attribute weight.

Procedure 6: *Ranking*, the largest grey relational coefficient grade is the HO target cell.

$$\text{HO}_{\text{target}} = \arg\max \; GRA_i. \tag{6.46}$$

The procedures of the GRA-HO method is depicted in Algorithm (4).

Algorithm 4 Proposed GRA-HO Method

1: **Start procedures**
2: **Obtain HO metrics**, $\gamma^{r}_{bs_i \to ue_k}$, $P^{t}_{ue_k}$, CP_i and ToS for all cells with $RSRP \geq RSRP_{th}$
3: **Built the pairwise comparison matrix P**
4: Obtain the **weighting vector w** using AHP
5: Check the **consistency**
6: **if** **CR** $\leq 10\%$ **then**
7:     **Go** to step 10
8: **else**
9:     **Go** to step 3
10: **end if**
11: **Generate the decision matrix D** according to the values obtained in step 2
12: Apply the **GRA** steps on the decision matrix **D**
13: **Rank** the alternatives obtained from step 12
14: **Perform HO** to the alternative with the **highest rank**
15: **End procedures**

6.2.5 Performance and Results Analysis

The performance of the proposed GRA-HO method is evaluated in terms of computational complexity, number of HOs, radio link failure and mean UE energy efficiency and compared against other two methods, the conventional SAW method and the conventional VIKOR method. Simulation parameters are listed in table 6.7.

SAW scores the alternatives by adding the contributions of each attribute p^{n}_{ij} times the weight of it [108]. The alternative with the highest rank is selected as

Table 6.7: Simulation Parameters

Parameter	Value
Bandwidth	20 MHz
MC Transmit power	43 dBm
MC Radius	500 m
SC Radius	100 m
Number of SC	50
Number of UEs	100
Maximum SC Transmit power	30 dBm
$RSRP_{th}$	-70 dBm
Uplink SINR threshold (γ_{th}^{up})	3 dB
UE transmit power	23 dBm
Mean velocity of the UE	$\{1,20,40, 60,80,100\}$ km/h
Distinguishing coefficient (Ψ)	0.5

the best one as given in (6.47).

$$SAW^{*} = \arg\max \sum_{j=1}^{n} w_j x_{ij}^{n} \tag{6.47}$$

In VIKOR [121], the alternatives are ranked according to their closeness to the ideal positive solution (ideal solution is the solution that has the best values for all attributes compared to the other solutions, i.e., alternatives).

6.2.5.1 Complexity Analysis

Fig.6.11 depicts the computational complexity of the proposed GRA-HO method compared to SAW and VIKOR methods. This is done by evaluating the three algorithms in terms of the number of floating point operations (flops) with different sizes of the decision matrix (i.e., different densities of SCs) using Matlab

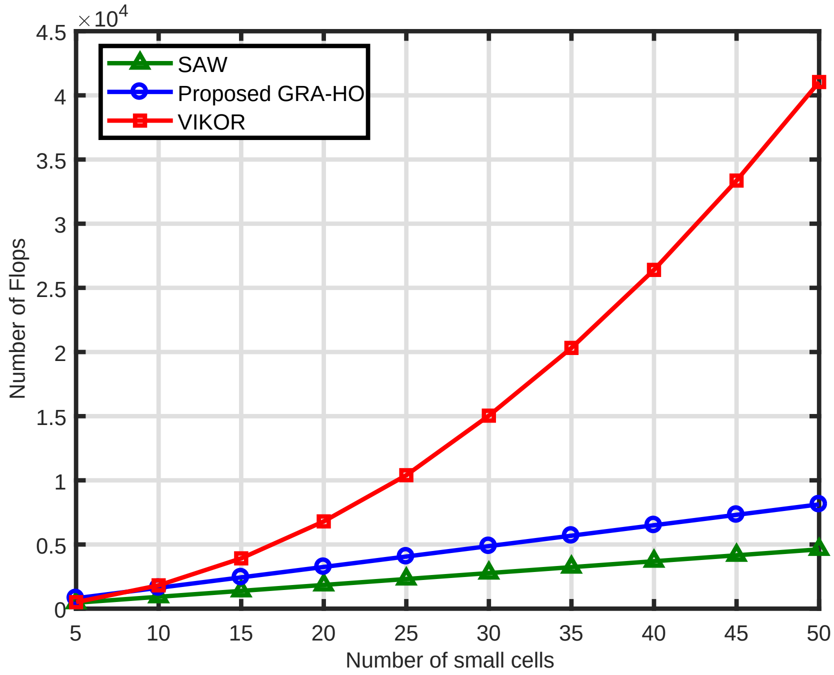

Figure 6.11: Complexity Analysis

function defined in [112]. When the number of SCs is around 10, the complexity performance of the proposed GRA-HO is very close to that of SAW [108] and VIKOR [121] methods which validates the performance of GRA-HO. As can be noticed from Fig.6.11, the computational complexity increases with the increase in the number of SCs for all method. The VIKOR method has extremely high complexity operations compared to SAW and GRA-HO. The proposed GRA-HO has slightly higher number of flops compared to SAW method owing to the operations of the AHP for consistent weight calculations. However, this slight difference well justified the accurate cell selection of the proposed GRA-HO method.

6.2.5.2 Number of Handovers

The number of HOs is depicted in Fig.6.12. The SAW method has the higher increase in the number of HOs compared to VIKOR and GRA-HO. The proposed GRA-HO method has the lowest number of HOs especially for low and medium speed UEs. This reduction can be owed to the use of ToS metric and the enhanced max-min in attribute normalization which helps in unnecessary HO reduction.

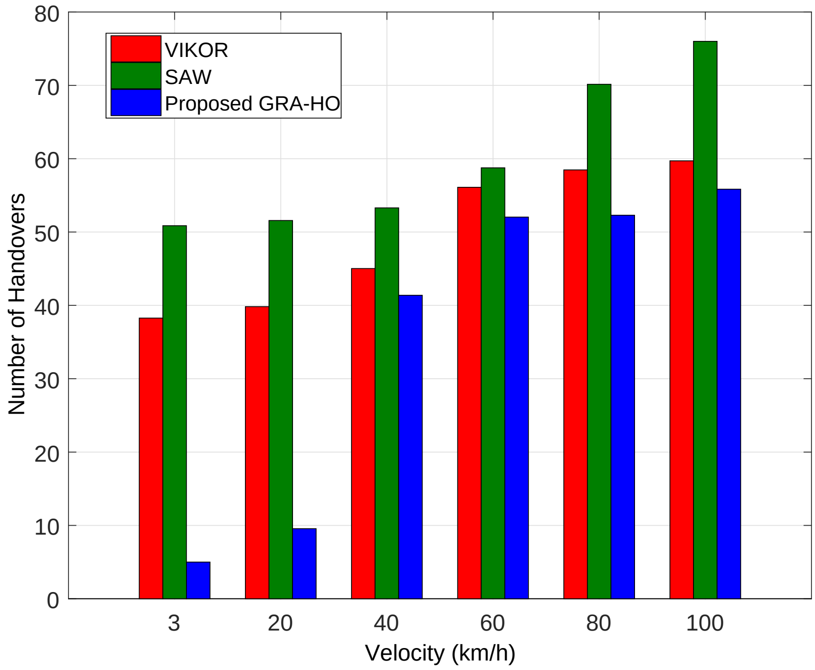

Figure 6.12: Number of handovers

Unlike the SAW and VIKOR method, which give a fixed weight for the attributes leading to a higher number of HOs, the GRA-HO method assigns consistent weights to the attributes leading to the minimization of unnecessary HOs.

6.2.5.3 Radio Link Failure

A radio link failure is declared if the HO is initiated to the target cell but the downlink SINR of that cell drops below a predefined threshold γ_{th} for a period of time window T310, which is 1 second, as defined in [65]. Fig.6.13 illustrates the radio link failure. The higher the velocity the higher the radio link failure for all methods. The SAW method yields higher failure compared to VIKOR due to its straight forward computational prior to HO, and hence, higher link failure. On the other hand, the proposed GRA-HO method has the lowest radio link failure due to the early HO to the correct target cell with a sufficient available capacity. For instance, when the velocity is 40km/h, the proposed GRA-HO method has 56% and 61% reduction in radio link failure compared to VIKOR and SAW methods respectively. The low radio link failure in the GRA-HO method emphasizes the

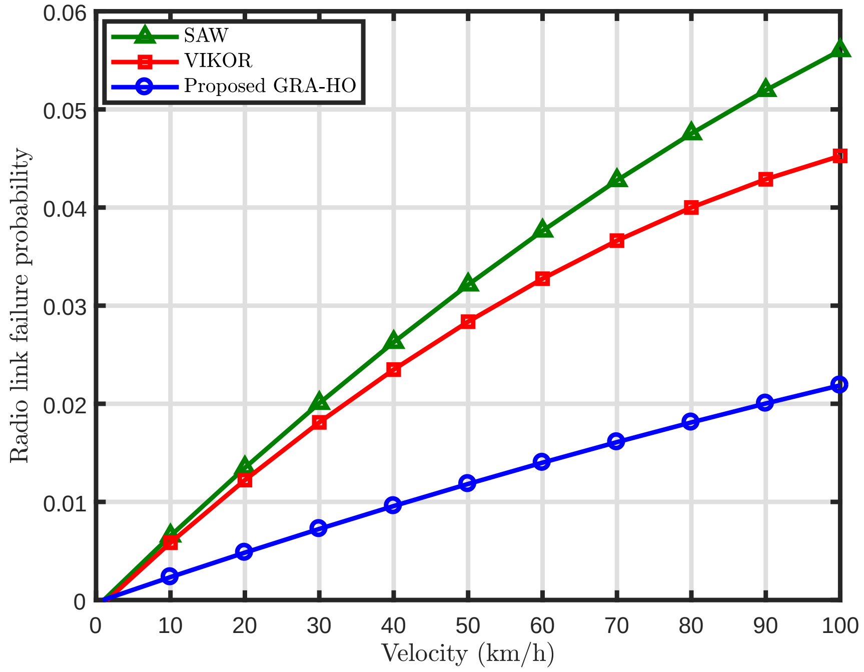

Figure 6.13: Radio link failure

consistency of weighting calculation of the attributes which leads to an accurate cell selection compared to the other two methods.

6.2.5.4 Energy Efficiency

In this subsection, we evaluate the performance of the three algorithms in terms of mean UE energy efficiency taking into account the UE transmit power consumption needed to associate to the target cells. We make use of the energy metric defined in [122] to measure the energy efficiency (EE)

$$EE = \frac{Channel\ capacity\ (bits/sec)}{Transmit\ power\ (watt)} \tag{6.48}$$

Which means how many bits is carried per joule energy i.e., how much energy is utilized to transmit that amount of bits. The mean UE energy efficiency is depicted in Fig.6.14. The energy efficiency is inversely proportional to the velocity in all methods because the higher the velocity the lower the ToS, and hence, the lower throughput which yields a lower energy efficiency. Generally, the VIKOR

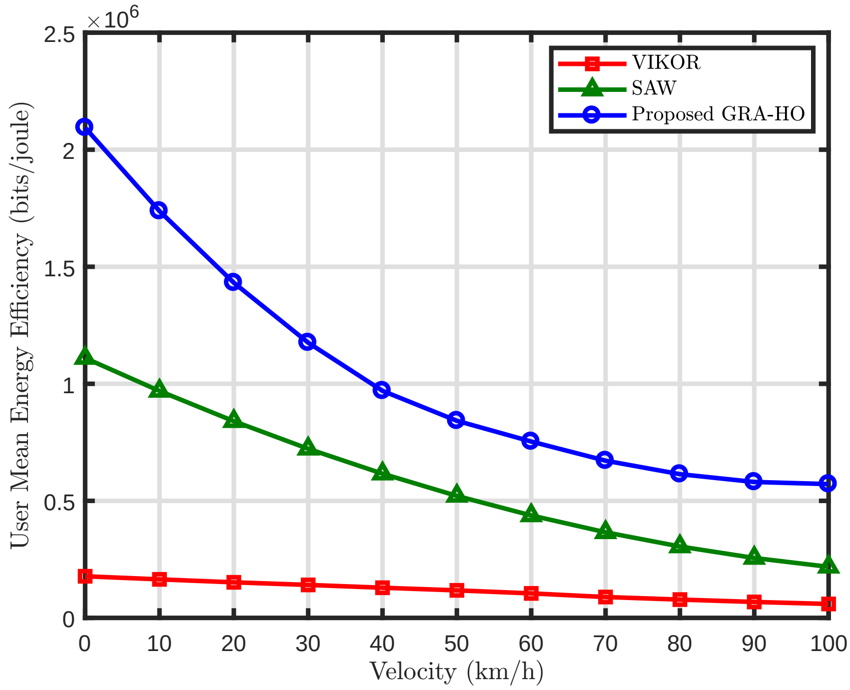

Figure 6.14: User energy efficiency vs. velocity

has the lowest energy efficiency compared to SAW and GRA-HO method due to its complicated computational complexity.

Fig. 6.15 shows the energy efficiency against variable densities of SCs when the mean velocity of the UE is fixed at 3km/h. Basically, the higher the number of SCs the better the performance in terms of mean UE energy efficiency. This is because the traffic load generated by the UEs will be distributed among the SCs, and hence, reduce the interference caused by other UEs. Which means that the UE mean throughput will be enhanced resulting in an improved energy efficiency. The proposed GRA-HO method has outperformed the other two methods owing to the AHP consistent weight assignment to the UE transmit power criterion.

6.2.6 Summary

In this part of this chapter, we proposed a GRA-HO HO method for dense SCs HetNet which jointly accounts for the influence of interference, cell capacity, energy consumption and predicted time of stay. The proposed method uses the AHP technique to assign weights to the attributes then the GRA MADM method is

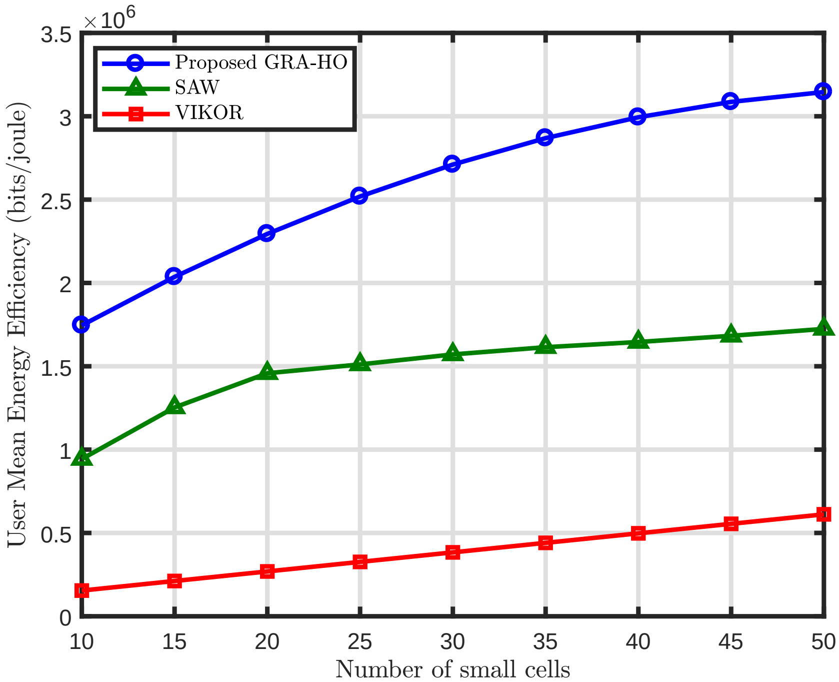

Figure 6.15: User energy efficiency vs. number of small cells

applied to rank the alternative and select the best one for HO. Enhanced max-min normalization is used to normalize the attributes during GRA process to reduce the ranking abnormality of the GRA and hence reduce the unnecessary HO. Simulation results show a good performance for the GRA-HO method in terms of computational complexity. Results also show that the proposed GRA-HO method can minimize the frequency of HOs and reduce the radio link failure in addition to enhance the energy efficiency compared to the classical SAW and VIKOR methods.

Chapter 7

Game Theoretical Handover Optimization

Game theory is linked to the strategies of a decision makers who are aware that their strategies influence each other [108]. Generally, the game consists of three components: players, strategy set and payoff function. The players represent the decision makers in which each player aims to maximize its payoff function by selecting a certain strategy. The strategy set represent the set of all possible actions that a player can choose from. On the other hand, the payoff function represent the utility that a player can obtain by choosing a certain strategy from the set of strategies. The game is usually solved by finding the optimum strategy for each player, named as the equilibrium of the game [108]. The energy efficiency is considered as one of the most challenging problems in dense SC HetNets. Therefore, a proper solution is needed to address it. Basically, if the base station is not activated on the right time, a connection failure will happen causing UE's dissatisfaction. Moreover, most literature works did not consider the UE mobility in dense small cell environment. When switching the base stations between on and off modes there will be an additional increase in the signal overhead due to handing over the UEs, which were associated with idle mode cell, to a new cell. To this end, we utilize the game theory as a tool to optimize the power transmission of base stations in the HetNet aiming to manage the issue of interference and hence achieve an efficient handover decision.

This chapter is divided into two parts. In part one, Section 7.1, we propose an energy efficient game theoretical method to reduce the energy consumption in HetNets. A non-cooperative game is formulated among the cells in the network to solve the cost function which considers the power mode of the cell, in addition to its load. The game is solved using the regret matching-based learning approach in which each cell chooses its optimal transmit power strategy to reach the equilibrium. While in the second part, Section 7.2, we propose a game theoretical solution, named Efficient Handover Game Theoretic (EHO-GT), using a dynamic transmission power for the base stations to enhance the performance in terms of throughput and energy efficiency. This is done by deploying a mathematical game where each base station compete to transmit power. In order to solve the game, we proved the existence of at least one Nash equilibrium. We then propose a novel EHO-GT game approach and evaluate the network performance in terms of energy consumption, average SC load, unnecessary handover and throughput.

7.1 A Non-Cooperative Game Theoretic Energy Efficient Handover

7.1.1 Introduction

Placing SCs into idle mode, without causing degradation to the QoS, is a good strategy to reduce the energy consumption in the network. In this part of this chapter, we propose an energy efficient game theoretical method to reduce the energy consumption in dense SCs network. The proposed method enables the SCs to adjust their transmitting power while considering to balance the load among themselves. A non-cooperative game is formulated among the cells in the network to solve the cost function which considers the power mode of the cell, in addition to its load. The game is solved using the regret matching-based learning distribution approach in which each cell chooses its optimal transmit power strategy to reach the equilibrium. The cell selection for HO is then made using a multiple attribute TOPSIS technique. Results show that the proposed method significantly reduces the energy consumption and unnecessary HOs, in addition to improving the average SC throughput compared to the conventional method.

The main contributions in this work can be explained as follows:

- The proposed method enables the SCs to update their transmitting power dynamically while considering the load among themselves.
- The problem is formulated as a non-cooperative game among the cells in the network. The game is solved using the regret matching-based learning distribution approach in which each cell learns its optimal transmit power strategy to reach the equilibrium.
- The main idea of this work is that each cell learns the regret of its played strategy at every instant of time targeting to reduce the average regret over time. The player's regret is defined as the difference between its average utility function when taking the same strategy in all previous rounds of the game and its average utility function gained by changing its strategies. Using the proposed game theoretical method, the cells will either reduce their

transmission power or switched off dynamically to minimize the power consumption. Then, the cell selection for HO takes place by using our proposed PSD-TOPSIS presented in 6.1.4.

- The proposed method is implemented and evaluated against the conventional method where the results show that the proposed method significantly minimizes the energy consumption and unnecessary HO, in addition to enhancing the average SC throughput.

The rest of this part of the chapter is organized as follows. Section 7.1.2 presents the related works. The network system model and problem formulation are given in Section 7.1.3. The proposed game theoretic method and cell selection are illustrated in Section 7.1.4. The performance and results analysis are given in Section 7.1.5. Finally, the conclusion is drawn in Section 7.1.6.

7.1.2 Related Works

In [123], authors proposed a power consumption reduction method which considers the trade-off between traffic load and energy efficiency. This method enhanced the energy efficiency by using a greedy algorithm to switch the cell between on and off modes. In [124]- [125] centralized switching methods are proposed to put base stations into on/off mode and transfer the UEs to the neighbouring base stations aiming to reduce the energy consumption. In [126], a mechanism that allows the base station to adjust its transmission power based on the traffic load is proposed. The base stations can reduce their transmission power instead of going into off mode.

Most works in the literature rely on a centralized controller to obtain the network information that are needed to make the decision of turning on/off the base station. Unfortunately, this mechanism will incur a huge signalling overhead in addition to the costs of over-utilizing the backhaul. Thus, it is important to give an effective solution which enables the base stations to dynamically adjust their power mode. In case of not activating the base station on the right time, a connection failure will happen causing UE's dissatisfaction. When switching the base stations between active and idle modes there will be an additional increase in the signalling overhead due to handing over the UEs, which were associated with idle mode cell, to a new cell. Therefore, in this work we consider a game theoretical solution to dynamically allow the base stations to switch between active and idle mode depending on load.

7.1.3 Network System Model and Problem Formulation

The system model in this work consists of two-tier HetNets which is formed by a single MC and dense SCs base stations deployed under the umbrella MC coverage area. The set of all base stations in the network $S = \{0, 1, 2, \cdots, N_{sc}\}$. Where 0 represents the MC, which covers a radius of $500m$, and N_{sc} is the total number of SCs, where each is deployed randomly according to a uniform distribution and covers a radius of $100m$. Both MC and SCs tiers utilize the same frequency band. The minimum distance constraint is also taken into account to make sure that the overlapping between SCs exists. The minimum distance between MC site and SC sites is set to $75m$ and the SC to SC site distance is set to $40m$ [10]. Users are uniformly distributed and their mobility follow a Gauss distribution model described in Section 4.3.

Let δ_i be the coverage area of cell $i \in S$ such that any UE at k location is served by cell i if and only if $k \in \delta_i$.

The downlink RSRP of cell i measured by the UE at location k can be written as

$$P^r_{bs_i \to ue_k} = P^t_{bs_i} \cdot h_{bs_i \to ue_k}, \tag{7.1}$$

where $P^r_{bs_i \to ue_k}$ is the downlink RSRP of cell i received by the UE at location k, $P^t_{bs_i}$ is the power transmitted by cell i and $h_{bs_i \to ue_k}$ is the channel gain between the UE and cell i considering the path loss and shadowing effects [87]. The downlink SINR for cell i received at UE k can be expressed as

$$\begin{aligned} \gamma^r_{bs_i \to ue_k} &= \frac{P^r_{bs_i \to ue_k}}{\sum_{bs \in S, bs \neq bs_i} P^t_{bs} \cdot h_{bs \to ue_k} + \sigma^2} \\ &= \frac{P^t_{bs_i} \cdot h_{bs_i \to ue_k}}{\sum_{bs \in S, bs \neq bs_i} P^t_{bs} \cdot h_{bs \to ue_k} + \sigma^2}, \end{aligned} \tag{7.2}$$

where σ^2 is the noise power and the term $\left(\sum_{bs \in S, bs \neq bs_i} P^t_{bs} \cdot h_{bs \to ue_k}\right)$ represents the summation of the downlink power from the neighbouring cells except cell i, i.e. the interfering cells. The throughput at UE location k received from cell i is given by Shannon capacity formula as

$$T^r_{bs_i \to ue_k} = BW \log_2(1 + \gamma^r_{bs_i \to ue_k}). \tag{7.3}$$

In order to account for the power consumption due to the power transmission and power needed for a base station in an active mode, we utilized the power formula defined by [127]. The total power needed for cell i in an active mode to generate an RF output power is defined as

$$P^i_{active} = \frac{P_{PA} + P_{RF} + P_{BB}}{(1 - \sigma_{DC})(1 - \sigma_{MS})(1 - \sigma_{cool})}, \tag{7.4}$$

where P_{BB} is the power consumed by the base band component, P_{RF} is the power consumed by the RF component, and metrics σ_{DC}, σ_{MS} and σ_{cool} are respectively the losses fraction of DC power supply, main supply and active cooling. It is worth noting that the loss fraction of the active cooling supply, σ_{cool}, is only applicable to MC and not used for SCs.

The power consumed by the power amplifier, P_{PA}, is given as

$$P_{PA} = \frac{P^t_{bs_i}}{\eta \cdot (1 - \sigma_{feed})}, \tag{7.5}$$

where η is the power efficiency of transmitting $P^t_{bs_i}$ and σ_{feed} is the feeder loss fraction which is set to -3 dB.

On the other hand, the power needed for cell i in an idle mode is expressed as

$$P^i_{idle} = \frac{P_{RF} + P_{BB}}{(1 - \sigma_{DC})(1 - \sigma_{MS})(1 - \sigma_{cool})}. \tag{7.6}$$

In the active mode, the base station will serve all UEs in its vicinity. It is worth noting that in an idle operation mode, the power consumption of the base station is not zero to allow the base station to discover the incoming UEs into its coverage area.

It is assumed that the UEs in cell i are homogeneous, i.e., all of the UEs in cell i have the same QoS requirement in terms of packet arrival size. Let λ_k be the packet arrival rate for UE at location $k \in \delta_i$ and $1/\mu_k$ is the mean size of that packet. The load density of cell i, denoted as $\zeta_{i\to k}$, can be expressed as

$$\zeta_{i\to k} = \frac{\lambda_{i\to k}}{1/\mu_{i\to k} \cdot T^r_{bs_i \to ue_k}}, \tag{7.7}$$

Which eventually makes the load of cell i is

$$L_i = \sum_{k \in \delta_i} \zeta_{i \to k}. \tag{7.8}$$

Each cell $i \in S$ can minimize its load by increasing the offered data rate $T^r_{bs_i \to ue_k}$, which means to increases its transmission power so that the SINR will improve. This can also cause higher power consumption which makes it necessary to compromise between reducing the load (maximizing throughput) and reducing the power consumption at the same time. Basically, if the base station is capable of dynamically adjusting its transmitted power $P^t_{bs_i}$ according to its traffic load then the energy efficiency could be enhanced. Hence, the cost function for cell i that captures the power consumption and base station load, denoted as Θ_i, can be expressed as

$$\Theta_i = \alpha P^t_{bs_i} + \beta L_i. \tag{7.9}$$

where α and β are respectively predefined weighting factors for transmission power $P^t_{bs_i}$ and cell load L_i.

Therefore, the overall objective function to reduce the cost in (7.9) can be written as

$$\begin{aligned} \underset{P^t_{bs_i}}{\text{minimize}} \quad & \sum_{\forall i \in S} \Theta_i, \\ \text{subject to} \quad & 0 \leq L_i \leq 1, \forall i \in S \\ & 0 \leq P^t_{bs_i} \leq P_i^{max}, \forall i \in S, \end{aligned} \tag{7.10}$$

where P_i^{max} is the maximum power that can be transmitted by cell i and the condition $(0 \leq L_i \leq 1)$ is used to limit connection failures by delivering service to all UEs served by cell i and located in the coverage area δ_i. A dynamic self-organizing mechanism where each cell in the network can control its transmission power independently is sufficient of solving the problem in (7.10).

7.1.4 Energy Efficient Game Theoretic Approach

7.1.4.1 Energy Efficient Game Formulation

The proposed energy efficient method is formulated mathematically using game theoretical approach. A non-cooperative game is defined using the three components of the game, that is players, strategy (or action) and utility function, so the game is defined as $\Gamma = \Big\{S, \{A_i\}_{i \in S}, \{u_i\}_{i \in S}\Big\}$.

Each player $P_i \in S$ has $A_i = \left\{a_{i,1}, a_{i,2}, \cdots, a_{i,|A_i|}\right\}$ set of strategies where a strategy of cell i, i.e., a_i, is composed of its own transmit power $P^t_{bs_i} \in [0, \frac{P_i^{max}}{2}, \frac{2P_i^{max}}{3}, P_i^{max}]$. The strategy a_i of cell i and the strategies of other cells $\mathbf{a}_{-i}$ describe the power of the network and u_i is the utility of cell i where $u_i(a_i, \mathbf{a}_{-i}) = -\Theta_i$. The major aim of the game is that each player P_i chooses its best strategy that leads to the best utility function periodically.

1. **Players:** represent the base stations in the network, $(P_1, \cdots, P_i, \cdots, P_n)\ \forall P_i \in S$.

2. **Strategies:** $A_i; \forall i \in S$ represent the action space for player. Each cell in the network, i.e., P_i, can transmit a minimum power of 0 and a maximum power of P_i^{max}. Hence, $A_i = [0, \frac{P_i^{max}}{2}, \frac{2P_i^{max}}{3}, P_i^{max}]$

3. **Utility function:** the utility function u_i is the total cost of playing action a_i for player P_i. The utility function in this work includes two cost functions, the power function and load function.

   - **Power function:** represents the cost for player $P_i \in S$ of playing the strategy a_i. This function reflects the cost of adjusting the cell transmit power $P^t_{bs_i}$ as each cell aims to reduce its transmit power. The power function is defined as

   $$\hat{P}^t_{bs_i} = \alpha P^t_{bs_i}, \tag{7.11}$$

   For each player the aim is to reduce the transmit power so as to optimize the energy efficiency.

   - **Load function:** The load function represents the cost of the load of cell i which is taken from equation (7.8) and can be expressed as

   $$\hat{L}_i = \beta L_i, \tag{7.12}$$

   Finally, the utility function for each player $P_i\ \forall i \in S$, which considers the transmission power and load, is defined as

   $$\begin{aligned} u_i &= -\hat{P}^t_{bs_i} - \hat{L}_i \\ &= -\alpha P^t_{bs_i} - \beta L_i. \end{aligned} \tag{7.13}$$

In order to solve the game $\Gamma = \Big\{S, \{A_i\}_{i\in S}, \{u_i\}_{i\in S}\Big\}$, we have to prove the existence of at least an equilibrium which means that each player in the game can reach an optimal strategy $a_i^* = P_{bs_i}^{t*}$ where it has no gain to change its own action.

The strategy set A_i is finite and discrete, therefore the non-cooperative game Γ permits at least a single equilibrium [128]. Since the outcome of this non-cooperative game is a suboptimal mixed strategy of Nash equilibrium, then it is better to deploy another solution for the game that could result in an optimal expected utility for each player in the game. According to [129], if the players in a non-cooperative game can correlate their strategies, then the equilibrium can be obtained better than that of Nash equilibrium (every finite game has a mixed strategy Nash equilibrium). For example, if transmission power is generated according to a prior knowledge of the player's strategy, then the strategy of the player will lead to a generalized form of Nash equilibrium which is called correlated equilibrium (CE). A mixed Nash equilibrium, in which a player plays its available actions with certain probabilities, is a special case of CE. Therefore, the CE are more likely to happen than mixed Nash equilibrium [130]. A CE is a probability distribution on strategy profiles, which can be simply explained as the distribution of play instructions delivered to each player by some device. Indeed, the CE is a beneficial concept in dense SCs HetNets where some SCs can correlated their transmission power. In CE, the players are committed to play an action after they receive the recommendation. However, in coarse correlated equilibrium (CCE), the players decide to play the action before they receive the recommendation to play it. In other words, player P_i has to follow the recommendation because other players also select to commit. If it happens that a single player does not commit then it may experience a low expected utility [130]. In this work, we consider the concept of ε-coarse correlated equilibrium, where each player $P_i \in S$ has the best expected utility function for playing a certain strategy before seeing that strategy itself.

Assuming that $\Upsilon_i(t) = \big[\Upsilon_{i,1}(t), \Upsilon_{i,2}(t), \cdots, \Upsilon_{i,|A_i|}(t)\big]$ is the probability distribution in which each player $P_i \in S$ plays an action from A_i at time t. In other word, $\Upsilon_{i.j}(t) = \mathbb{P}\big(a_i(t) = a_{i,j}\big)$ is the mixed strategy of player $P_i \in S$, where $a_i(t)$ is the action of player P_i played at time instant t.

Theorem 7.1.1 *ε-coarse correlated equilibrium is defined as a probability distribution Υ_i over strategy vectors such that for every player $P_i \in S$ and every strategy $a_i^* \in A_i$ and $a_i \in A_i$ we have:*

$$\sum_{a_{-i}^* \in A_{-i}} \Big(u_i(a_i^*, \mathbf{a}_{-i}) \Upsilon_{-i}, \mathbf{a}_{-i} \Big) - \sum_{a \in A_i} \Big(u_i(a) \Upsilon_i \Big) \leq \varepsilon, \tag{7.14}$$

where $\Upsilon_{-i}, \mathbf{a}_{-i} = \sum_{a_i^* \in A_i} \Upsilon(a_i^*, \mathbf{a}_{-i})$ is the marginal probability distribution of player P_i and $u_i(a)$ is the utility of the player when strategy a is played from the distribution Υ_i, the strategy is measured using the joint distribution of its strategy a_i^* and the other players' strategies $a_{-i} \in A_{-i}$, where a_{-i} is an element of $\mathbf{a}_{-i}$. The distribution of the play in the regret matching-based learning procedure approaches to the correlated equilibrium distribution as the time goes to infinity. For a finite time interval, the empirical distribution converges to ε-coarse correlated equilibrium. In order to design a mechanism for the distribution to solve the game and reach the ε-coarse correlated equilibrium, in the next section, the regret matching-based learning process is explained so that a ε-coarse correlated equilibrium is achieved and eventually an optimal utility is ensured for every player in the game so that no player has incentive to deviate.

7.1.4.2 Regret Matching-based Learning Energy Efficient Game Solution: Equilibrium Learning

In order to have the best possible utility, each player in the game uses the principle of the regret matching-based learning approach to evaluate its regret of not playing a certain action targeting to reduce the regret over time and hence enhancing the utility by reaching the ε-coarse correlated equilibrium.

Assume that player $P_i \in S$ repeatedly changes its action following strategy distribution Υ_i and monitors its utility u_i while the other players playing their actions following their strategy distribution vector Υ_{-i}. Based on the monitored utility, player P_i may regret playing the action $a_i(t)$. In order to evaluate the regret, it is necessary to have the utility u_i and this also needs to know the actions of the remaining players due to the load L_i in equation (7.13). Because of the random cell distribution, it is not possible to practically have the required information. Thus, player P_i needs to estimate its utility and regret for each action played [131]. At each instant of time t, player P_i adjusts its mixed strategy probability distribution Υ_i according to its estimated regret. The process of regret matching-based learning can therefore be based on the estimations procedures which are illustrated as follows:

First, by using the instantaneous utility $u_i(t-1)$, each player P_i estimates its expected utility function with each of its action as

$$u_i^{est}(t) = u_i^{est}(t-1) + \rho_i\Big(u_i(t-1) - u_i^{est}(t-1)\Big), \tag{7.15}$$

where $u_i^{est}(t)$ is the new estimated utility for player P_i, $u_i^{est}(t-1)$ is the previously estimated utility and ρ_i is the learning rate for the utility.

Then, each player estimates the new regret $r_i^{est}(t)$ of playing a certain action by utilizing the estimated utility in (7.15) as

$$r_i^{est}(t) = r_i^{est}(t-1) + \tau_i\Big(u_i^{est}(t-1) - u_i(t-1) - r_i^{est}(t-1)\Big), \tag{7.16}$$

where $r_i^{est}(t-1)$ is the previously estimated regret and τ_i is the regret learning rate.

Finally, the estimated regret is used to compute the new probability distribution of the mixed strategies $\Upsilon_i^{est}(t)$ as given below

$$\Upsilon_i^{est}(t) = \Upsilon_i^{est}(t-1) + \psi_i\left(G_i\Big(r_i^{est}(t)\Big) - \Upsilon_i^{est}(t-1)\right), \tag{7.17}$$

where $\Upsilon_i^{est}(t-1)$ is the previously estimated strategy and ψ_i is the learning rate for the mixed strategy probability. The learning rates (ρ_i, τ_i and ψ_i) take the scheme $1/t^e$, where e is the learning rate exponent.

Obviously, the probability distribution of changing to a different strategy is proportional to its regret relative to the current strategy. Which means that when the regret is high, then the probability of changing the action is also high. Boltzmann-Gibbs distribution (BG) [131], denoted as G_i, can be utilized to estimate the mixed strategy probability $\Upsilon_i(t)$ given in (7.17). BG distribution weighs the mixed strategy actions according to their regrets, which means that the cells with high regret values have the highest probability of adjusting their played actions. Generally, BG distribution can be expressed as

$$G_i\Big(r_i^{est}(t)\Big) = \frac{\exp\Big(\Omega_i r_i^{est}(t)\Big)}{\sum_{\forall i^* \in A_i} \exp\Big(\Omega_i r_{i^*}^{est}(t)\Big)}, \tag{7.18}$$

where Ω_i is a temperature parameter > 0 represents the interest of player P_i to select other actions instead of those maximizing the regret, and hence improving regret estimation.

Hence, each cell selects the best action (transmit power) over the time with which the mixed strategy $\Upsilon_i(t)$ approaches to the required ε-coarse correlated equilibrium where no player have the incentive to deviate from its played action.

7.1.4.3 Cell Ranking and Handover Decision

After optimizing the cell transmission power, we use multiple criteria for HO including SINR, UE velocity and cell load. The SINR is directly influenced by power optimization in the game part, therefore, it is taken as a measure metric in HO decision. We adopt our proposed TOPSIS method, the PSD-TOPSIS explained in 6.1.4, to select the proper target cell for HO by ranking the available neighbouring candidate cells.

7.1.5 Performance and Results Analysis

In this section, the proposed method is implemented, evaluated and compared against the conventional method, in which the cells are not able to transfer its power mode from active to idle mode, in terms of energy consumption, unnecessary HO probability and throughput. Each cell in the network dynamically adjusts its transmission power according to the solution of the game which is described in 7.1.4.2. The proposed method has two parts, the first part is power optimization using the game theory approach, then the second part is cell selection using PSD-TOPSIS explained in 6.1.4. In each time instance the two parts are repeated periodically because the load of each cell will change. Simulation parameters are listed in table 7.1.

7.1.5.1 Power Consumption

The average SC power consumption with respect to the number of UEs is depicted in Fig.7.1. The power consumption evaluation takes into account three samples of UE velocities, that is 30, 50 and 90 km/h. Generally, for all velocities the power consumption increases with the increase in the number of UEs. The conventional method has the highest power consumption because the transmit power of cells

Table 7.1: Simulation Parameters

Parameter	Value
MC radius	500 meters
SC radius	100 meters
Number of SCs	40
Bandwidth	20 MHz
MC maximum transmission power	46 dBm
SC maximum transmission power	30 dBm
UE velocity	{0, 10, 20, 40, 60, 80, 100} km/h
Mean offered traffic $(\frac{\lambda_{i \to k}}{1/\mu_{i \to k}})$	180 kbps
Boltzmann temperature Ω_i	10
(α, β)	(0.5, 0.5)
Learning rate exponents e for ρ_i, τ_i, ψ_i	(0.6, 0.7, 0.8)

is not optimized. The proportional increase of the power consumption with the increase in the number of UEs is because the increase of the load in the network makes most of the base stations on active mode. With high velocity, e.g. 90 km/h, the proposed method has the lowest level of power consumption because most of the UEs are kept associated with the MC leaving the SCs at idle mode. For low velocity, i.e., 30 km/h, the power consumption is higher compared to that at 90 km/h because low speed UEs are kept connected to the SCs, and hence the SCs switch to the power active mode. On the other hand, at all velocities, when the number of the UEs increases more SCs switch to active mode to deliver services to the UEs, therefore, the power consumption increases noticeably.

7.1.5.2 Unnecessary Handover

We defined the unnecessary HO when the UE starts a HO process to cell i and leaves the cell after the expiry of the time threshold which is set to one second. The probability of unnecessary HO with respect to the number of UEs for different

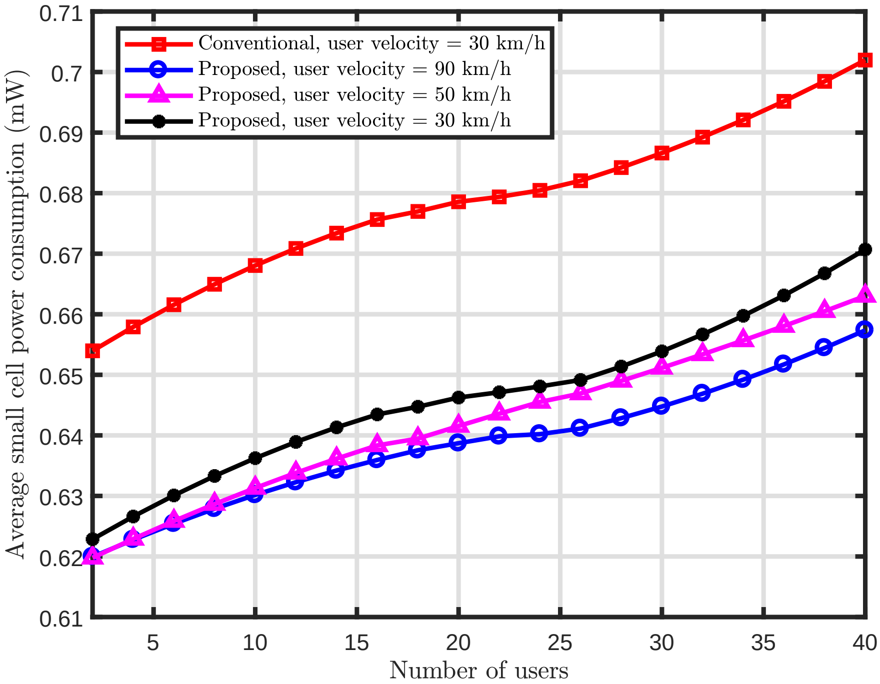

Figure 7.1: Average SC power consumption

velocities is shown in Fig.7.2. In general, the proposed method outperformed the conventional method at all UE velocities by producing the lowest unnecessary HO probability. For example, when the UE velocity is 30 km/h and the number of the UEs is 20, the proposed method shows 32.8% reduction in the probability of unnecessary HO compared to the conventional method. For the proposed method, for all velocities, unnecessary HO increases with the increase in the number of UEs.

7.1.5.3 Throughput

For different UE velocities, the average SC throughput with respect to the number of the UEs is presented in Fig.7.3. The results in Fig.7.3 validate the proposed method. For example, when the number of users is 10, the performance of the proposed method is slightly higher than that of the conventional method in terms of averages SC throughput. After that the proposed method starts to give higher throughput for different velocities. We notice that the proposed method has outperformed the conventional [17] method at all UE numbers. For instance, when

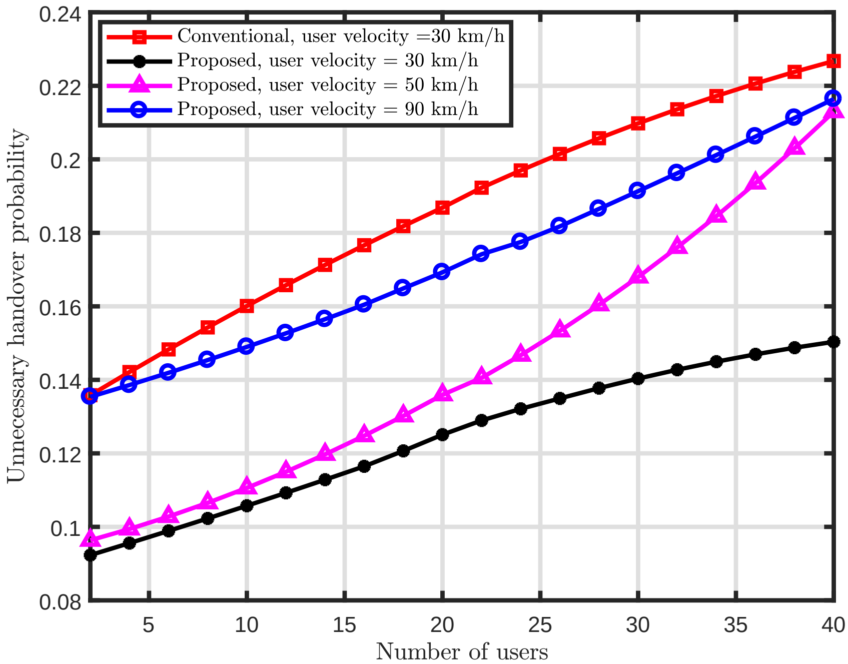

Figure 7.2: Unnecessary handover probability

the velocity of the UE is 30 km/h and the number of UEs is 20, the proposed method has 54.7% more SC throughput compared to the conventional method. Generally, the average SC throughput decreases with the increase in the UE velocity because the high speed UEs are connected to the MC. On the other hand, at lower UE speeds, e.g., 30 km/h, the throughput is improved due to the increased number of UEs connected to the SC. Fig.7.4 shows the average SC throughput with different UE velocities and number. Similar to the findings in Fig.7.3, the throughput in Fig.7.4 reduces with the increase in the velocity. However, the higher the number of UEs in the network gives the higher SC throughput.

7.1.6 Summary

In this work, an energy efficient HO method for HetNets is proposed. The proposed method exploits the principle of regret matching-based learning game theoretical approach where each base station tries to reduce its transmit power so as to reach the required ε-coarse correlated equilibrium. This is done by regretting to play the previous strategy and playing a new strategy that gives the

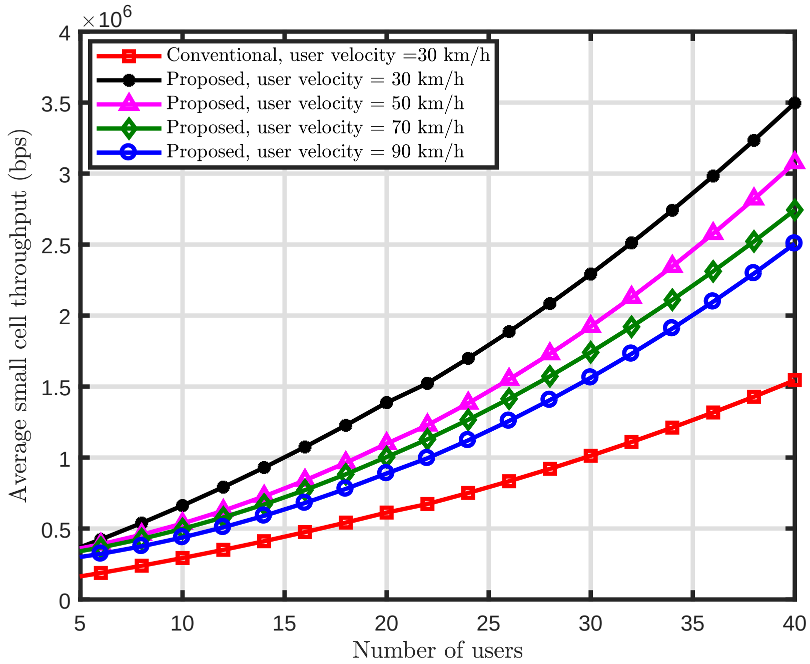

Figure 7.3: Average SC throughput

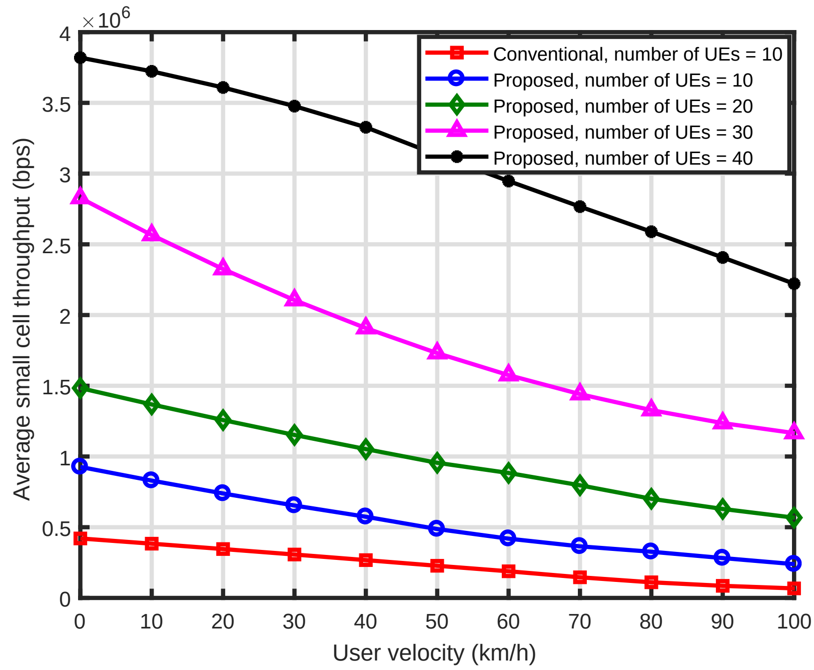

Figure 7.4: Average SC throughput vs. UE velocity

best expected utility for each player. The cell selection is then applied using the PSD-TOPSIS technique. Results show that the proposed method has enhanced the energy efficiency in the network by reducing the power consumption through putting the light loaded SC into idle mode. Moreover, the proposed method reduced the probability of unnecessary HO for different UE numbers and speeds. The average SC throughput is also improved.

7.2 Handover Optimization: A Game Theoretic Approach

7.2.1 Introduction

In this part of this chapter, a game theoretical solution, named Efficient Handover Game Theoretic (EHO-GT) is proposed, using a dynamic transmission power for the base stations to enhance the performance in terms of throughput and energy efficiency. This is done by deploying a mathematical game where each base station compete to transmit power. The payoff function is defined to consider the gain from increasing the base station transmission power (the utility function) against the cost resulted from energy consumption, base station load and unnecessary handovers performed to this base station. In order to solve the game, we proved the existence of at least one Nash equilibrium. We then propose a novel EHO-GT game approach and evaluate the network performance in terms of energy consumption, SC load, unnecessary handover and throughput. The cell selection for HO takes place by using our proposed PSD-TOPSIS presented in 6.1.4.

The main contribution of this part of this chapter can be illustrated as follows:

- We formulate a non-cooperative game approach in which all base stations compete in a selfish manner to transmit at higher power.
- The solution of the game is obtained by finding the optimal point, namely the Nash equilibrium (NE).
- Each player in the game optimizes its payoff by adjusting the transmission power so as to enhance the overall performance in terms of throughput, handover, energy consumption and load balancing. In order to choose the preferred transmission power for each player, the payoff function takes into account the gain of increasing the transmission power, energy consumption, base station load and unnecessary handover.
- The cell selection for handover is then takes place by using our proposed PSD-TOPSIS presented in 6.1.4.
- A game theoretical approach is implemented and evaluated for dense SC HetNets to validate the enhancement achieved in the proposed method.

Results show that the proposed game approach provides a throughput enhancement while reducing the energy consumption in addition to minimizing the unnecessary handover and balance the load between base stations.

The reminder of this part is organized as follows. Section 7.2.2 presents the system model used in this work. Section 7.2.3 illustrates the proposed game theoretic approach, game solution and TOPSIS cell selection. While Section 7.2.4 presents the results and their analysis. Finally, Section 7.2.5 draws the conclusions.

7.2.2 Network System Model

The system and mobility models in this part is similar to that of 7.1.3. The downlink SINR received from cell k at the UE is

$$SINR_{bs_k} = \frac{P^r_{bs_k \to ue}}{\sum_{bs \in S, bs \neq bs_k} P^r_{bs \to ue} + \sigma^2}, \tag{7.19}$$

where σ^2 is the noise power and the term $\left(\sum_{bs \in S, bs \neq bs_k} P^r_{bs \to ue}\right)$ represents the summation of the downlink power from the neighbouring cells except cell i i.e., the interfering cells.

The data rate at UE received from cell k is given by Shannon capacity formula as

$$T^r_{bs_k \to ue} = BW \log_2(1 + SINR_{bs_k}). \tag{7.20}$$

Let Y_k represents the set of all users served by cell k. Assuming that all the UEs in cell k have the same QoS requirement in terms of packet arrival size. Thus, the load on cell k can be written as

$$L_{bs,k} = \sum_{\forall \ ue \ \in \ Y_k} \frac{packet\ arrival\ rate \ \cdot \ mean\ packet\ size}{T^r_{bs_k \to ue}}. \tag{7.21}$$

7.2.3 Efficient Handover Game Theoretic Approach (EHO-GT)

7.2.3.1 Handover Game Formulation

The proposed EHO-GT method is formulated mathematically using game theory. Players in the game compete to increase their transmission power. Basically, the action played by one player in the game has an influence on the payoff of other players. The proposed game is governed by the following rules:

- All base stations in the game can transmit power at a range of $\left[0,\, P_{bs}^{t^{max}}\right]$.
- All base stations in the game share a density specific metric D_{bs}.
- Each base station in the game has a load metric, $L_{bs,k}$, which defines the current load on the base station.
- Each base station in the game has an unnecessary handover metric, N^{ho}, which defines the fraction of unnecessary handover compared to the total handovers in the base station.

The game is defined as $\Gamma = \left\{S, (A_k)_{k\in S}, (\phi_k)_{k\in S}\right\}$, where S is the number of players, A_k is the set of possible strategies for player S_k and ϕ_k is the payoff function for player S_k. Thus, the game components are listed below:

1. Players: represent the base stations in the network, $(S_1, \cdots, S_k, \cdots, S_n)$, $\forall k \in S$.
2. Strategies: each base station has a set of actions $A = (A_1, \cdots, A_k, \cdots, A_n)$, $\forall k \in S$, where $A_k = \left[0, P_{bs,k}^{t^{max}}\right]$ is the strategy set for player S_k, and hence, $A = \Pi_{k=1}^{n} A_k$.
3. Payoff function: it defines the cost for player S_k to transmit power at $P_{bs,k}^{t}$. In this part of the chapter, we define the payoff function using the gain (utility function) and the cost function, which includes the energy cost, load cost and unnecessary handover cost. All of which are defined below:
   - Utility function U_k: represents the gain of player S_k for playing the strategy a_k. The utility function here means the profits acquired by each base station by increasing its transmission power $P_{bs,k}^{t}$ aiming to maximize its gain. There are different types of utility functions, such as linear, logarithmic and exponential [132]. We used the exponential utility function where it has a strictly concave property and its second derivative is negative, that is
$$U_k(a_k) = \alpha\left(1 - e^{-P_{bs,k}^{t}}\right), \tag{7.22}$$

where α is a predefined weighting factor and $P^t_{bs,k}$ is the transmission power of player S_k. Each player aims to increase its transmission power so as to maximize its utility function.

- Energy cost function $E_k(a_k, a_{-k})$: energy consumption is one of the most critical issues in dense SCs HetNets. When a player increases its transmission power to maximize its utility, this will cause a negative impact by increasing the energy consumption in the network. Additionally, the dense SCs deployment also means more power needed for operating the network. Thus, we define the energy consumption cost function as

$$E_k(a_k, a_{-k}) = \beta \; D_{bs} \; P^t_{bs,k}, \tag{7.23}$$

where β is a predefined weighting factor for energy cost function and D_{bs} is the density metric of the network [100] in a given coverage area which can be obtained by using

$$D_{bs} = \frac{\mid S \mid \pi R_{sc}^2}{\pi R_m^2}, \tag{7.24}$$

where R_{sc} and R_m are respectively the SC and MC radius. The denominator represents the area of the umbrella base station i.e., the MC coverage area. We set up the number of SCs to 50, this means that $D_{bs} \approx 2$ and hence, the dense SCs scenario is obtained.

- Load cost function $L_k(a_k, a_{-k})$: represents the cost for player S_k of playing an action. Higher load means more consumption of power, thus, we define the load cost as follows

$$L_k(a_k, a_{-k}) = \lambda \; L_{bs,k} \; P^t_{bs,k}, \tag{7.25}$$

where λ represents a predefined weighting factor for load cost function and $L_{bs,k}$ is the load on base station k.

- Unnecessary handover cost function $N^{ho}_k(a_k, a_{-k})$: higher number of HOs means higher signalling overhead and hence higher energy consumption, in addition to uneven load distribution between cells. Therefore, we incorporate the transmission power on the cost function such that

$$N^{ho}_k(a_k, a_{-k}) = \delta \; N^{unho}_k \; P^t_{bs,k}, \tag{7.26}$$

where δ is a predefined weighting factor for unnecessary HO cost function and N_k^{unho} is the fraction of the number of unnecessary HO compared to the total number of HOs to base station k. We regard the HO as an unnecessary when an UE remains one second or less in the base station then performing another HO.

It is worth noting that the weighting parameters α, β, λ and δ can be adjusted by the network service provider reflecting the priority of each function on the network performance.

Now, the payoff function for player S_k $\forall k \in S$ can be written as

$$\phi_k(a_k, a_{-k}) = \alpha\big(1 - e^{-P^t_{bs,k}}\big) - \beta D_{bs}\ P^t_{bs,k} - \lambda L_{bs,k} P^t_{bs,k}\ - \delta N_k^{unho}\ P^t_{bs,k}, \quad (7.27)$$

where $\alpha > 0$, so that the second derivative of $\phi_k(a_k, a_{-k})$ will be negative at all times, i.e., concave function.

The solution of the non-cooperative game $\Gamma = \big\{S, (A_k)_{k\in S}, (\phi_k)_{k\in S}\big\}$ can be reached by finding the optimal transmission power for each player, that is the Nash equilibrium. This means that all players in the game reach optimal strategy $o_k^* = P^{t^*}_{bs,k}$ where no player can improve its payoff function by changing its current played strategy where $o_k^* = \big[P^{t^*}_{bs,1}, \cdots, P^{t^*}_{bs,k}, \cdots, P^{t^*}_{bs,n}\big]$.

Theorem 7.2.1 *The game $\Gamma = \big\{S, (A_k)_{k\in S}, (\phi_k)_{k\in S}\big\}$ is a concave n-person game which has at least one Nash equilibrium.*

Proof: The strategy set $A_k = \big[0, \cdots, P^{t^{max}}_{bs,k}\big]$ for player S_k is closed and bounded $\forall k \in S$ which means that A_k is a compact set for all players.

Let the two points x, $y \in A_k$ and $\zeta = [0, 1]$ where $A = \Pi_{k=1}^n A_k$. The strategy set A_k is convex $\forall k \in S$ if for any x, $y \in A_k$ and $\zeta = [0, 1]$, $\zeta x + (1 - \zeta)y \in A_k$.

Let the Hessian matrix H of the differentiable payoff function $\phi_k(a_k, a_{-k}) = \alpha\big(1 - e^{-P^t_{bs,k}}\big) - \beta\ D_{bs}\ P^t_{bs,k} - \lambda\ L_{bs,k}\ P^t_{bs,k} - \delta\ N_k^{unho}\ P^t_{bs,k}$ be as follows

$$H = \begin{bmatrix} \frac{\partial^2 \phi}{\partial P^{t2}_{bs,1}} & \frac{\partial^2 \phi}{\partial P^t_{bs,1} \partial P^t_{bs,2}} & \cdots & \frac{\partial^2 \phi}{\partial P^t_{bs,1} \partial P^t_{bs,n}} \\ \frac{\partial^2 \phi}{\partial P^t_{bs,2} \partial P^t_{bs,1}} & \frac{\partial^2 \phi}{\partial P^{t2}_{bs,2}} & \cdots & \frac{\partial^2 \phi}{\partial P^t_{bs,2} \partial P^t_{bs,n}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 \phi}{\partial P^t_{bs,n} \partial P^t_{bs,1}} & \frac{\partial^2 \phi}{\partial P^t_{bs,n} \partial P^t_{bs,2}} & \cdots & \frac{\partial^2 \phi}{\partial P^{t2}_{bs,n}} \end{bmatrix}. \quad (7.28)$$

By taking the second derivative of the payoff function ϕ_k, it is obvious that H is negative definite at $P^t_{bs,k}$ using the leading principle minor of H, which means that it reaches a local maximum at $P^t_{bs,k}$ [133] as depicted in (7.29). Therefore, the payoff function ϕ_k is strictly concave in A_k, $\forall k \in S$.

$$\phi_k^{''} = \begin{cases} -\alpha e^{-P^t_{bs,k}} & \text{for main diagonal elements} \\ 0 & \text{otherwise} \end{cases} \tag{7.29}$$

where ($\phi_k^{''} < 0$) to meet the strictly concave condition.

Theorem 7.2.2 *The non-negative weighted sum $\omega(P^t_{bs,k}, q)$ is diagonally strictly concave if the symmetric matrix $\left[\ G(P^t_{bs,k}, q)\ +\ G^{'}(P^t_{bs,k}, q)\right]$ is negative definite $\forall k \in S$, where q is positive vector $q = [q_1, q_2, \cdots, q_n]$ [134].*

Proof: We can express the non-negative weighted sum $\omega(P^t_{bs,k}, q)$ as the summation of ϕ_k, that is

$$\omega(P^t_{bs,k}, q) = \sum_{k=1}^{n} q_k \phi_k(P^t_{bs,k}),\ \forall k \in S,\ q_k \geq 0 \tag{7.30}$$

For each fixed q, a related mapping $g(P^t_{bs,k}, q)$ is defined as the gradients $\nabla_k \phi_k(P^t_{bs,k})$, that is

$$g(P^t_{bs,k}, q) = \begin{bmatrix} q_1 \nabla_1 \phi_1(P^t_{bs,1}) \\ q_2 \nabla_2 \phi_2(P^t_{bs,2}) \\ \vdots \\ q_n \nabla_n \phi_n(P^t_{bs,n}) \end{bmatrix}, \tag{7.31}$$

where $g(P^t_{bs,k}, q)$ is the pseudo-gradient of $\omega(P^t_{bs,k}, q)$ and $\nabla_k \phi_k(P^t_{bs,k}) = \alpha e^{-P^t_{bs,k}} - \beta\ D_{bs} - \lambda\ L_{bs,k} - \delta\ N_k^{unho}$, $\forall k \in S$.

As stated earlier, when the symmetric matrix $\left[\ G(P^t_{bs,k}, q)\ +\ G^{'}(P^t_{bs,k}, q)\right]$ is negative definite, the $\omega(P^t_{bs,k}, q)$ is diagonally strictly concave [134]. Therefore, we define the Jacobian matrix $G(P^t_{bs,k}, q)$ of $g(P^t_{bs,k}, q)$ with respect to $P^t_{bs,k}$ as follows

$$G(P^t_{bs,k}, q) = \begin{bmatrix} q_1 \frac{\partial^2 \phi}{\partial P^{t2}_{bs,1}} & q_1 \frac{\partial^2 \phi}{\partial P^t_{bs,1} \partial P^t_{bs,2}} & \cdots & q_1 \frac{\partial^2 \phi}{\partial P^t_{bs,1} \partial P^t_{bs,n}} \\ q_2 \frac{\partial^2 \phi}{\partial P^t_{bs,2} \partial P^t_{bs,1}} & q_2 \frac{\partial^2 \phi}{\partial P^{t2}_{bs,2}} & \cdots & q_2 \frac{\partial^2 \phi}{\partial P^t_{bs,2} \partial P^t_{bs,n}} \\ \vdots & \vdots & \ddots & \vdots \\ q_n \frac{\partial^2 \phi}{\partial P^t_{bs,n} \partial P^t_{bs,1}} & q_n \frac{\partial^2 \phi}{\partial P^t_{bs,n} \partial P^t_{bs,2}} & \cdots & q_n \frac{\partial^2 \phi}{\partial P^{t2}_{bs,n}} \end{bmatrix}. \tag{7.32}$$

Obviously, the symmetric matrix $\left[G(P^t_{bs,k}, q) + G^{'}(P^t_{bs,k}, q)\right]$ is negative definite $\forall P^t_{bs,k} \in S$, therefore, the non-negative weighted sum $\omega(P^t_{bs,k}, q)$ is diagonally strictly concave. This means that the game $\Gamma = \left\{S, (A_k)_{k\in S}, (\phi_k)_{k\in S}\right\}$ has a unique Nash equilibrium (Theorem 2 [134]).

7.2.3.2 Game Solution

In the previous section, we mathematically proved the existence of Nash equilibrium, we need to compute the optimal game solution for each player S_k. This is done by choosing a strategy that maximizes its payoff function $\phi_k(P^t_{bs,k})$. The optimal transmission power $P^{t^*}_{bs,k}$ $\forall k \in S$ is in the range $(0 \leq P^t_{bs,k} \leq P^{t^{max}}_{bs,k})$. Therefore, the optimization problem can be written as

$$\begin{aligned} \underset{P^t_{bs,k}\in A_k}{\text{maximize}} \quad & \phi_k(P^t_{bs,k}, P^t_{bs,-k}), \\ \text{subject to} \quad & P^t_{bs,k} \geq 0, \\ & P^t_{bs,k} \leq P^{t^{max}}_{bs,k}, \ \forall k \in S. \end{aligned} \tag{7.33}$$

To solve the above nonlinear optimization problem, we define the Lagrangian function $\mathcal{P}_k$ and the Lagrangian multipliers u_k and v_k for player S_k, $\forall k \in S$ as follows

$$\mathcal{P}_k = \phi_k\big(P^t_{bs,k}, P^t_{bs,-k}\big) + u_k P^t_{bs,k} + v_k\big(P^{t^{max}}_{bs,k} - P^t_{bs,k}\big), \tag{7.34}$$

The Karush-Kuhn-Tucker (KKT) conditions [135] of the maximization problem for player S_k are

$$\begin{gathered} u_k,\ v_k \geq 0, \\ P^t_{bs,k} \geq 0, \\ P^{t^{max}}_{bs,k} - P^t_{bs,k} \geq 0, \\ \nabla_{P^t_{bs,k}} \phi_k(P^t_{bs,k}, P^t_{bs,-k}) + u_k \nabla_{P^t_{bs,k}}(P^t_{bs,k}) \ + v_k \nabla_{P^t_{bs,k}}(P^{t^{max}}_{bs,k} - P^t_{bs,k}) = 0, \\ u_k(P^t_{bs,k}),\ v_k(P^{t^{max}}_{bs,k} - P^t_{bs,k}) = 0. \end{gathered}$$

The problem above can be solved as follows:

- When $P^t_{bs,k} = 0$ and $v_k = 0$

$$\alpha e^0 - \beta\ D_{bs} - \lambda\ L_{bs,k} - \delta\ N^{unho}_k + u_k = 0$$

$$u_k = \beta\ D_{bs} + \lambda\ L_{bs,k} + \delta\ N_k^{unho} - \alpha$$

The solution $P_{bs,k}^t = 0$ is feasible, if the condition $(u_k > 0)$ holds and it is as follows:

$$\beta\ D_{bs} + \lambda\ L_{bs,k} + \delta\ N_k^{unho} \geq \alpha$$

- When $P_{bs,k}^t = P_{bs,k}^{t^{max}}$ and $u_k = 0$

$$\alpha e^{-P_{bs,k}^t} - \beta\ D_{bs} - \lambda\ L_{bs,k} - \delta\ N_k^{unho} - v_k = 0$$

$$v_k = \alpha e^{-P_{bs,k}^t} - \beta\ D_{bs} - \lambda\ L_{bs,k} - \delta\ N_k^{unho}$$

The solution $P_{bs,k}^t = P_{bs,k}^{t^{max}}$ is feasible, if the condition $(v_k > 0)$ holds and it is as follows:

$$\beta\ D_{bs} + \lambda\ L_{bs,k} + \delta\ N_k^{unho} \leq \alpha e^{-P_{bs,k}^t}$$

- When $u_k = 0$, $v_k = 0$ and $(0 < P_{bs,k}^t < P_{bs,k}^{t^{max}})$

$$\alpha e^{-P_{bs,k}^t} - \beta\ D_{bs} - \lambda\ L_{bs,k} - \delta\ N_k^{unho} = 0$$

$$e^{-P_{bs,k}^t} = \frac{\beta\ D_{bs} + \lambda\ L_{bs,k} + \delta\ N_k^{unho}}{\alpha}$$

$$P_{bs,k}^t = \ln\left(\frac{\alpha}{\beta D_{bs} + \lambda L_{bs,k} + \delta N_k^{unho}}\right)$$

Therefore, the game solution for player S_k, $\forall k \in S$, is the optimum transmission power $P_{bs,k}^{t^*}$ which can be expressed as follows

$$P_{bs,k}^{t^*} = \begin{cases} 0 & \text{if condition } A \\ P_{bs,k}^{t^{max}} & \text{if condition } B \\ \ln\left(\dfrac{\alpha}{\beta D_{bs} + \lambda L_{bs,k} + \delta N_k^{unho}}\right) & \text{otherwise} \end{cases} \quad (7.35)$$

where condition A and condition B respectively are:

$$\beta D_{bs} + \lambda L_{bs,k} + \delta N_k^{unho} \geq \alpha, \quad (7.36)$$

$$\beta D_{bs} + \lambda L_{bs,k} + \delta N_k^{unho} \leq \alpha e^{-P^t_{bs,k}}. \tag{7.37}$$

The optimum transmission power $P^{t*}_{bs,k}$ is the Nash equilibrium and the solution of the game.

7.2.3.3 Cell Selection and HO Decision

After adjusting the transmission power for each cell, we use multiple criteria HO including data rate, UE velocity and cell load. We adopt our proposed method PSD-TOPSIS explained in 6.1.4, to select the proper target cell for HO by ranking the available neighbouring candidate cells.

7.2.4 Performance and Results Analysis

In this section, the proposed EHO-GT method is implemented, evaluated and compared against the conventional method, in which the cells are not able to optimize their transmission power, in terms of energy consumption, SC load, unnecessary HO probability and throughput. Each cell in the network dynamically adjusts its transmission power according to the solution of the EHO-GT method. Then, the cell selection is performed using PSD-TOPSIS technique. Simulation parameters are listed in table 7.2.

7.2.4.1 Power Consumption

For different velocities, the average SC power consumption with regards to the number of the users is depicted in Fig.7.5. Comparing the proposed EHO-GT method with the conventional method at 30km/h, at all user numbers the EHO-GT gives better performance. For example, when the number of users is 20, the EHO-GT has a 6.5% reduction in the average SC power consumption compared to the conventional method. It is observed for the proposed EHO-GT method, that the higher the velocity the lower consumption in power. This is because more SC will increase their transmission power when low speed users approach their coverage area. On the other hand, low power consumption for higher velocities owes to the association of the users to MC and reducing the transmission power of SCs.

Table 7.2: Simulation Parameters

Parameter	Value
MC radius	500 meters
SC radius	100 meters
Number of SCs	50
Bandwidth	20 MHz
MC maximum transmission power	46 dBm
SC maximum transmission power	30 dBm
UE velocity	{0, 10, 20, 40, 60, 80, 100} km/h
$(packet\ arrival\ rate\ \cdot\ mean\ packet\ size)$	180 kbps
$(\alpha, \beta, \lambda, \delta)$	(14, 7, 7, 7)

7.2.4.2 SC Load

The SC load versus the number of UEs with the considerations of different velocities is depicted in Fig.7.6. Fig. 7.6 also validates the performance of our proposed EHO-GT method compared to the conventional method [17]. When the number of users below 10, the performance of the EHO-GT method is slightly close to that of the conventional method in terms of SC load. It can be seen that for all velocities the proposed EHO-GT method has outperformed the conventional method as the latter do not optimize the transmission power prior to HO. For the proposed EHO-GT method, at high velocity (e.g., 90km/h), the SC load is the lowest because most high speed user will be connected to the MC due to reducing/deactivating the SC transmission power. The opposite is happening with low velocity of 30km/h because more users will be associated to the SC and the load increase with the increase of the number of users. Furthermore, in Fig.7.7, for a number of 40 UEs and variable numbers of SCs, the SC load is shown. The SC load decreases with the increase in the number of SCs for all UE velocities because the load will be distributed between the increased SCs. However, the load

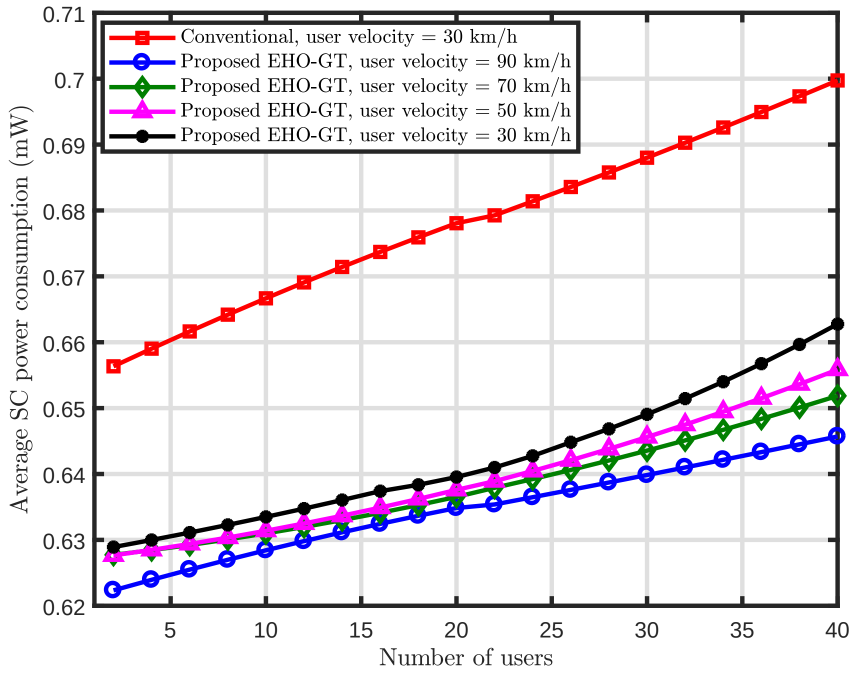

Figure 7.5: Average SC power consumption

starts to increase after that, e.g. at a number of 20 SCs, since some of the SCs are turned off for power optimization and this caused an increase in the load for other SCs. On the other hand, the load goes sharply down at a number of 40 SCs due to the load distribution among SCs.

7.2.4.3 Unnecessary Handover

Fig.7.8 shows the probability of unnecessary HO with respect to the number of the users and for different velocities. We can observe that our proposed EHO-GT method has outperformed the conventional method. For instance, comparing the two methods at 20 UEs and a velocity of 30km/h, the EHO-GT has about 51% reduction in the unnecessary HO and this percentage increases with the increase in the number of UEs. Generally, with the EHO-GT, the lower the velocity the lower the unnecessary HO since high speed UEs are likely to cause frequent HOs. The unnecessary HO increases with the increase in the number of UEs (i.e., load increases) affecting the load and unnecessary HO terms in the payoff function in (7.27), and hence, the increase occurs.

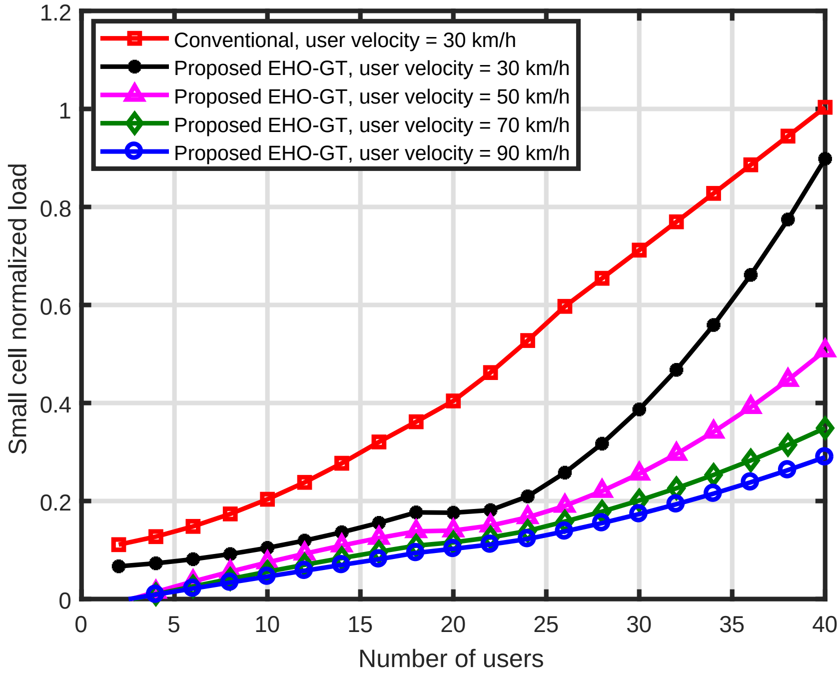

Figure 7.6: Small cell normalized load

7.2.4.4 Throughput

For different number of UEs, the averaged SC throughput is depicted in Fig.7.9. It is obvious that the EHO-GT method has outperformed the conventional method. For the EHO-GT, the average SC throughput for high speed UEs is the lowest compared to the lower speed UEs because the former tends to select the MC while the latter tends to select the SC in PSD-TOPSIS cell selection. Generally, the average SC throughput for all UE numbers reaches it is maximum point when the velocity of UEs is 40km/h, after that the throughput goes down because the high speed UEs connect to the MC and few number of UEs connect to the SC.

7.2.5 Summary

In this part of this chapter, we used the game theory approach to optimize the transmission power of the SC aiming to find the optimal power for all cells in the network. The payoff function for each player (each cell) is formulated mathematically using utility (gain) and cost functions where each cell selfishly aims

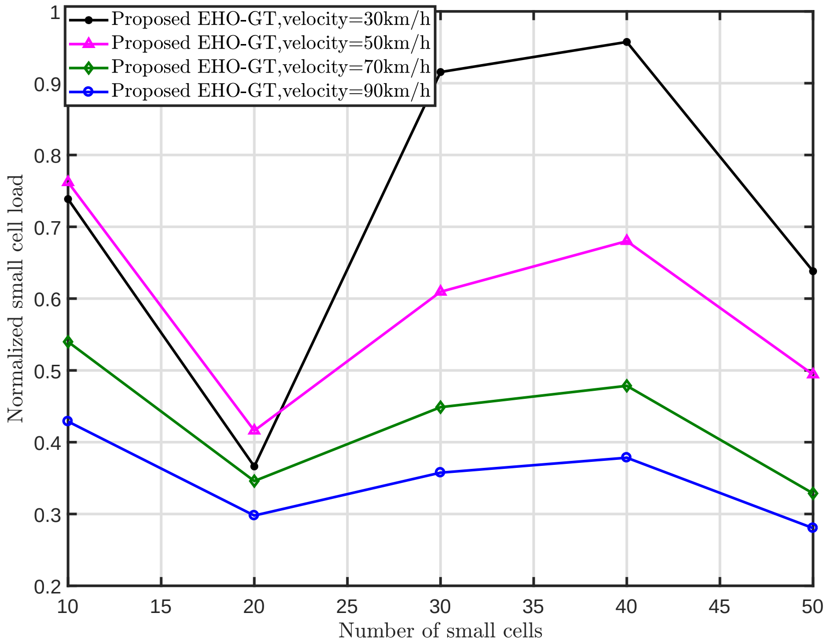

Figure 7.7: Small cell normalized load

to increase its transmission power to improve its utility. The cost function includes the influence of SC density, cell load and unnecessary HO. The proposed EHO-GT method is solved mathematically by finding the Nash equilibrium. The cell selection is then performed by deploying the multiple criteria PSD-TOPSIS technique to choose the best HO target cell. Furthermore, we have implemented, evaluated and compared the proposed EHO-GT method with the conventional method where the power optimization policy is not present. Simulation results reveal that the proposed EHO-GT method outperformed the conventional in terms of energy consumption, SC load, unnecessary HO and throughput. For example, with 30km/h velocity and 20 users, the proposed EHO-GT method has an improvement of 6.5%, 43%, 51% and 81% over the conventional method in terms of power consumption, SC load, unnecessary HO and average SC throughput respectively.

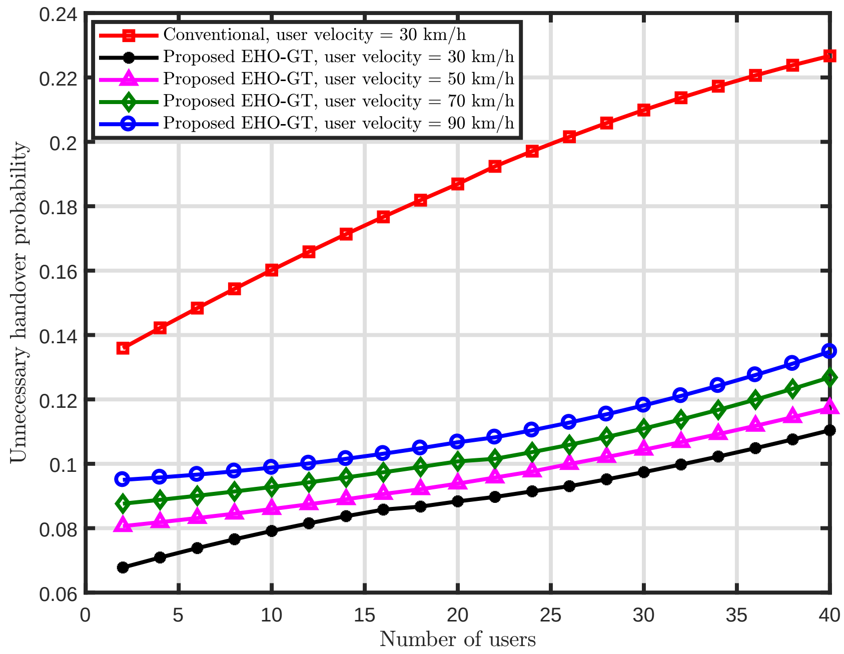

Figure 7.8: Unnecessary handover probability

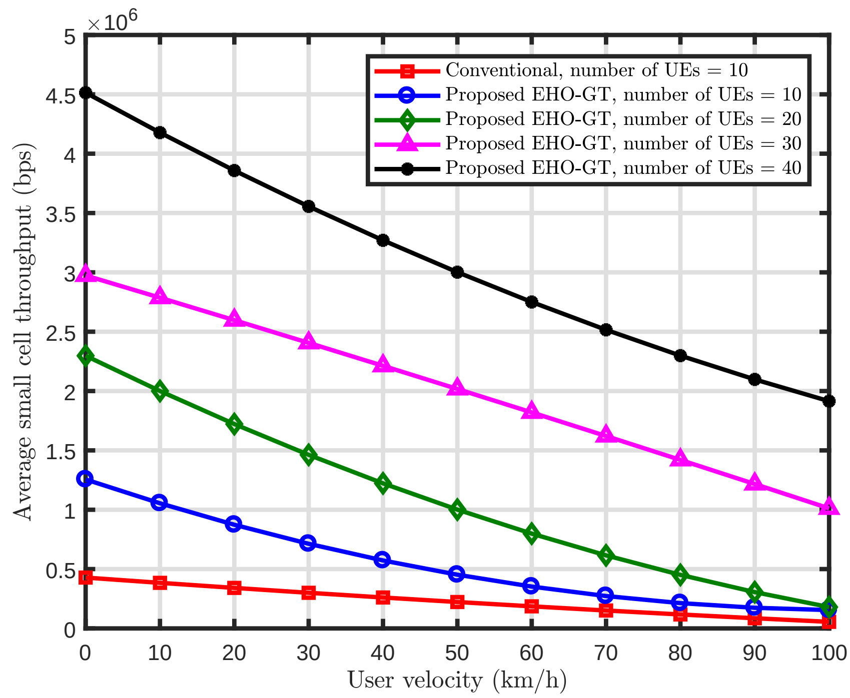

Figure 7.9: Average SC throughput vs. UE velocity

Chapter 8

Conclusion and Future Work

In this chapter, we summarize the research findings of this thesis and highlight the future directions of this work.

8.1 Conclusions

The work in this thesis has focuses on the management of handover in heterogeneous cellular networks with dense deployment of small cell base stations. Several conclusions have arisen from the study carried out in this thesis.

In Chapter 3, a HO method is proposed to minimize the unnecessary HO. First, the neighbour SC list is reduced by omitting all SCs that are located away from the users movement direction. This was done by using the velocity of the user, the distance and the angle between the user and the SC. A neighbour cell list is modelled as a circle whose center is the user location and its radius is a distance threshold. Then, any SC in the circle that is not in the moving trajectory of the user is removed from the neighbour cell list and the user can perform HO to the SCs with highest SNR. It was shown that the overall performance has improved compared to the conventional method in terms of reducing the number of target SCs, unnecessary HO and energy consumption of scanning, as well as improving the network throughput.

Further, in Chapter 4, a HO method which jointly considers the unnecessary HO and HO failure is proposed. First, the neighbour SC list is reduced by using a predicted time of stay in which a user may stay in the coverage area of a SC. Then, the user performs a HO to the SC with the highest SINR and has enough capacity. It was shown that the proposed method has outperformed the competitive literature works by reducing the unnecessary HO and HO failure.

In Chapter 5, we proposed a HO method to enhance the throughput and balance the load in HetNets. First, the proposed method optimizes the neighbour

SC list using predicted time of stay and SINR. Then, a HO margin is derived considering the load on the serving cell. After that, a modified A3 HO condition is applied using the derived HO margin and the interference from both serving and target cell so that the user can perform the HO aiming to offload the congestion on the serving cell. It was shown that the proposed method has outperformed the existing literature in terms of reducing the unnecessary HO and outage probability, in addition to improving the achieved throughput.

Then, we divided Chapter 6 into two parts. In part one of Chapter 6, we proposed two methods named, PE-TOPSIS and PSD-TOPSIS. In both methods the HO is performed to the cell with the highest rank according to the principles of TOPSIS technique. PE-TOPSIS uses the entropy weighting while PSD-TOPSIS uses the standard deviation weighting to weight the HO metrics. Results reveal that both methods outperformed the existing literature works by reducing the number of HOs and link failures, in addition to improving the throughput. It was also shown that the PE-TOPSIS could be more suitable for femtocell, while PSD-TOPSIS could be a good solution for picocells. In part two of Chapter 6, we proposed an energy efficient HO method called GRA-HO. The proposed GRA-HO method exploits the principles of GRA for HO decision making and the AHP principles of weight assignment to HO metrics. It was shown that the proposed GRA-HO method has outperformed the traditional MADM method in terms of reducing the number of HOs and link failure and enhancing the mean user energy efficiency.

Finally, Chapter 7 is also divided into two parts. In part one of Chapter 7, we proposed an energy efficient HO method using game theory. A non-cooperative game is formulated to solve the cost function which considers the power mode of the cell and its load. The solution of the game is obtained using the regret matching-based learning distribution approach in which each cell selects its optimal transmit power strategy to reach the equilibrium. Then, the cell selection for HO is made using a PSD-TOPSIS method. It was shown that the proposed method significantly reduces the energy consumption and unnecessary HOs, in addition to improving the average SC throughput compared with the conventional method. In part two of Chapter 7, we proposed HO optimization method called EHO-GT using game theoretical approach. The payoff function for each player is formulated mathematically using utility (gain) and cost functions where each cell selfishly aims to increase its transmission power to improve its utility. The cost function includes the influence of SC density, cell load and unnecessary HO. The EHO-GT method is solved mathematically by finding the Nash equilibrium. The cell selection is then performed by deploying the PSD-TOPSIS method. It was shown that the proposed EHO-GT method outperformed the conventional methods in terms of energy consumption, SC average load, unnecessary HO and throughput.

8.2 Future Works

This section outlines some of the potential future works based on the topics presented in this thesis.

1. Handover minimization in Multi-tier HetNets: the deployment of multiple sizes small cells, e.g. femtocell, picocell and microcell, can be considered as a one of the future challenges in HetNets. The interference in this case will be the major concern. In terms of handover management, this can be a big challenge because adjusting the handover parameters largely depends on the size of the small cell. Due to the interference caused by close access cells such as femtocells, it is very important to address such issue. The work of Chapter 3 can be extended so that different neighbour small cell list circle radius and angle threshold can be used. For example, in areas with heavy picocells deployment, the circle radius and angle threshold could be higher compared to the residential areas where the density is caused by femtocells deployment.

2. Small cell zooming for energy efficient handover: the cell zooming property has the advantage to increase/decrease the coverage area of a small cell to help offloading the traffic from macrocell. When small cell is zoomed in, there may be some coverage holes in which users may undergo handover failure. On the other hand, when small cell is zoomed out, there will be an increase in the interference. Therefore, a trade-off between zooming in and out is necessary. This can be jointly considered to achieve a smooth handover in dense small cells environment and offload the traffic from the congested macrocells.

3. Handover service interruption in HetNets: the service interruption resulted from processing the handover is also a big challenge for future 5G networks

due to the dense deployment of small cells which results in high number of handovers. Jointly considering the handover optimization and its service interruption is an efficient solution to cope with this issue. The handover optimization will reduce the number of handover which also help to mitigate the influence of service interruption. On the other hand, the service interruption could be dealt with according to the traffic type. For example, when the traffic is a voice call, which is intolerable to service interruption, the handover is performed quickly using few parameters or the user stays at macrocell for the duration of the call. On the other hand, when the traffic type is a web data session, which is tolerable to service interruption, the handover can be performed to the small cell considering multiple handover metrics.

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