



Study on Handover Decision Algorithms for 5G Heterogeneous Networks

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博士論文

Study on Handover Decision Algorithms for 5G Heterogeneous Networks

(5G 異種ネットワークのための
ハンドオーバー決定アルゴリズムに関する研究)

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Keep calm and carry on.

Abstract

In fifth-generation mobile communications (5G), heterogeneous networks (HetNets) are a pivotal technology for augmenting network capacity through dense deployment. Nevertheless, these devices also introduce complications to the handover process of user equipment (UE), resulting in significant challenges, including deterioration in communication quality. This thesis posits that these challenges emanate from inherent flaws in the three critical phases of the handover decision-making algorithm (HDMA): In the measurement phase, the widely used reference signal received power (RSRP) fluctuates significantly due to channel fading, leading to inaccurate handover trigger timing within the HDMA. This, in turn, is the fundamental cause of frequent handovers and handover failures. In the decision phase, traditional algorithms cannot identify the target cell type, often causing high-speed UE to handover to an inappropriate small cell. Additionally, these algorithms lack consideration of the handover direction between two different type cells. In the resource acquisition phase, the frequent handover triggered by the first two defects ultimately leads to resource congestion and handover blocking in the target cell.

To address these, the objective of this thesis is to construct a comprehensive handover decision-making algorithm. This will be achieved by conducting systematic theoretical analysis and algorithm optimization of the measurement, decision, and resource acquisition phases. The primary contributions of this study are as follows: In the measurement phase, a HDMA is proposed that is based on a more stable channel quality indicator (CQI). The purpose of this HDMA is to enhance the robustness of handover triggering. In the decision phase, a theoretical framework was developed that integrated stochastic Petri nets (SPN) and Poisson point processes (PPP) analytical model (Do-SPN-PPP) is constructed. This model is capable of analyzing different handover directions in HetNets. In addition, a decision algorithm is designed. This HDMA is based on NR cell identifier (NCI). The purpose of this HDMA is to identify the target cell type. In the context of the resource acquisition phase, the theoretical framework of integrated SPN and PPP is used to quantitatively elucidate the resource blocking that is precipitated by handover.

In summary, this thesis proposes a multi-stage solution for enhancing the handover performance and communication reliability of 5G HetNets through theoretical modeling

and simulation verification.

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Chapter 1

Introduction

1.1 Background on the technology of handover in 5G heterogeneous networks

Mobile communication networks play an integral role in our daily lives, including the facilitation of cellular voice calls, high-definition video calls, and mobile office applications. These applications are inherently dependent on the mobile communication networks.

The number of user equipment (UE) in mobile communication network is increasing exponentially in our daily lives, as shown in Fig. 1.1.

Fig. 1.1 illustrate the impact of mobile device technology on the market, both in the past and in the future. It is clear that wireless technology research plays a pivotal role in today's world and it is apparent that there has been a notable increase in the demand for mobile devices and the consumption of associated content. For the mobile communication market to be successful, the services it offers must be connected to the outside world (i.e., the Internet).

Over the years, a variety of radio access technologies (RATs) have been developed in order to achieve this objective. Examples include cellular networks, and satellite networks, to name a few. Nowadays, UEs are equipped with multiple network interfaces, including Fifth Generation Mobile Communication System (5G), Long-term evolution (LTE), Bluetooth, and Wi-Fi. These technologies facilitate internet connectivity, obviating the need to resolve connectivity issues through a single network. UEs anticipate uninterrupted connectivity across these network technologies, irrespective of the specific technology in use or the device's movement between them.

Mobile communication networks have evolved from the first generation mobile communication system at 10-year intervals to the current widespread commercialization of the 5G.

The fifth generation communication system are required,

- Higher data rate

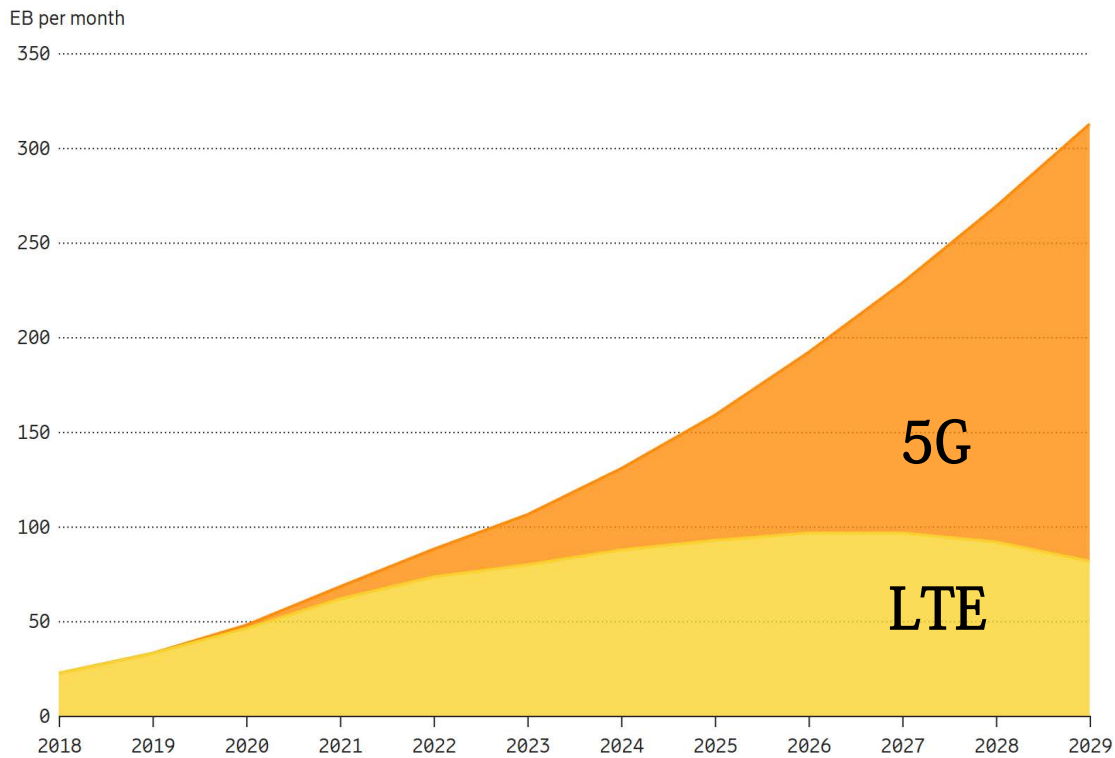


Figure 1.1: Global mobile network data traffic

- Latency in the order of 1ms
- High reliability
- Low-cost UEs with very long battery life
- Network energy efficiency

Therefore, 5G deploys more small cellular base stations (SBS) in a macro cellular base station (MBS), e.g. micro cell, pico cell, femto cell with low output power base station, such as on street light poles and building walls, and while having a large capacity that can accommodate more UE compare with long term evolution (LTE) to fulfill the requirements. Such a mobile communication networks including different output powers base stations is called a heterogeneous networks (HetNet), as shown in Fig. 1.2.

Since the coverage area of each cellular base station is limited. As a result, the UE is accompanied by the occurrence of a communication switching, also known as handover at some time point when the UE is continuously moving in a direction away from the currently connected cellular base station.

Handover refers to the wireless link between a UE and one cellular base station being switched to another cellular base station, as shown in Fig. 1.2. Usually, handover is considered as a positive approach that the UE can take to improve their communication environment quality during mobility [1].

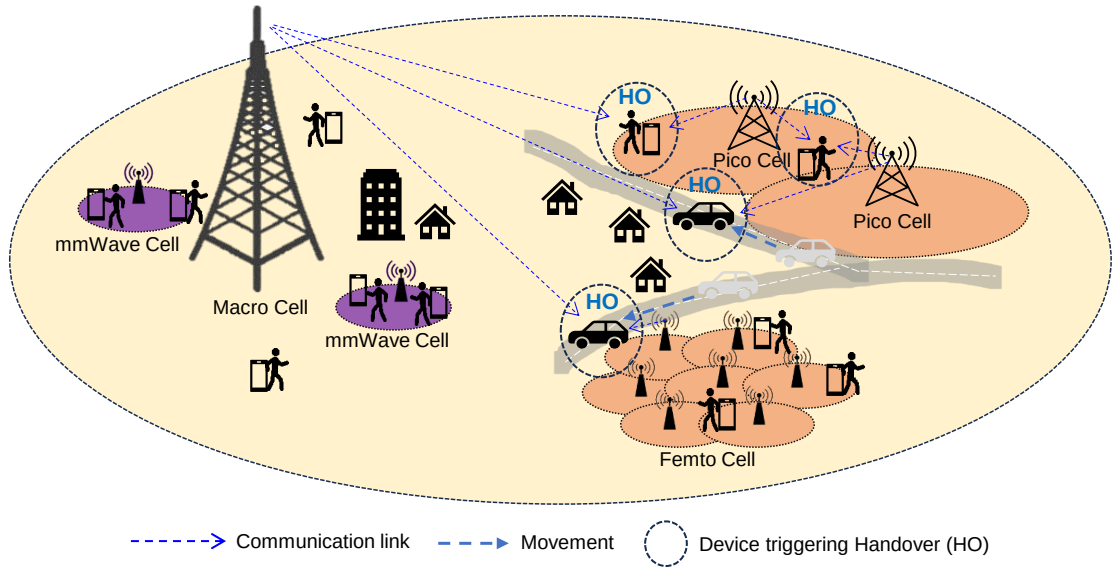


Figure 1.2: 5G heterogeneous networks

However, the problems such as load unbalancing, communication blocking, as well as dramatic fluctuations in the signal propagation within mobile communication networks, cause the handover performance of UEs to exhibit low reliability such as handover failure (HoF) and ping-pong handover (PPHO).

Therefore, it is important and necessary work to analyze and quantify the impact on the performance of handover due to communication blocking due to lack of resources, signal fluctuation, as well as improvement of handover to enhance the reliability of handover in 5G.

1.2 Research objectives and composition of the thesis

This study focuses on the development of a framework for evaluating handover decision algorithms based on the consideration of low time cost, as well as aiming to improve the performance of handover decision algorithms from the signal propagation level.

Chapter 1: An overview of the technical background of 5G heterogeneous networks and the topic of this thesis.

Chapter 2: Introduction to the topic of handover in 5G heterogeneous networks.

Chapter 3: Presentation of the network resource insufficiency situation and the theoretical modeling and analysis of handover.

Chapter 4: Presentation of the signal fluctuation situation and the theoretical modeling and analysis of handover.

Chapter 5: Presentation of an improvement approach for handover within signal fluctuation situation.

Chapter 6: Summarizes the results of this thesis.

Fig. 1.3 shows the guideline diagram of the research object corresponding to each chapter in this thesis.

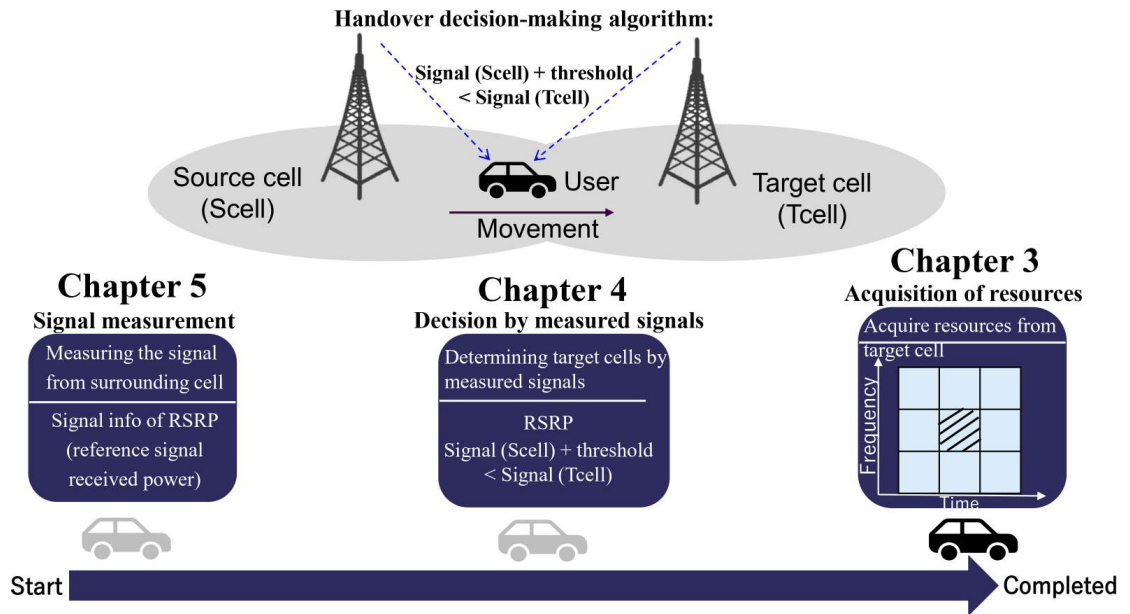


Figure 1.3: Organization of the thesis

Chapter 2

5G heterogeneous networks and challenges in handover

2.1 Characterization of 5G heterogeneous networks

5G has been driven by the increasing demand for data, the need for ultra-reliable low-latency communication (URLLC), and the requirement to support the connectivity of a large number of Internet of Things (IoT) devices [2] [3]. To achieve this objective, network architectures are evolving toward heterogeneous networks (HetNets) that integrate multiple low-power base stations (e.g., micro, pico, millimeter-wave, etc.) [4]. HetNets enhance system capacity and spectrum efficiency by overlaying small cells within the coverage area of macrocells, thereby providing users with higher data rates. However, the increased density and complexity of this network topology present challenges for mobility management, particularly handover management [5].

In HetNets, UE frequently traverses the boundaries of various cell types, each with distinct coverage ranges. A poorly designed handover mechanism can result in several issues, including the failure to ensure seamless service continuity and frequent degradation of communication quality, and even complete disconnection [6]. Conventional handover mechanisms principally depend on indicators of signal strength, which are insufficient for addressing the intricate interference environments and varied cell characteristics present in HetNets [7]. In order to achieve a fundamental enhancement in handover performance within HetNets, this paper utilizes an analysis of handover decision-making processes. The three core stages of this process—namely, “measurement”, “decision-making”, and “resource acquisition” are examined in order to systematically identify and address the challenges currently encountered by handover management. This chapter will detail the challenges faced by each of these three stages, which collectively form the research background and core issues addressed in this thesis.

2.1.1 Challenges in the resource acquisition phase: frequent handover request causes blocking

The final stage of the handover process involves the acquisition of communication resources from the target cell. The compounded effects of unstable measurements and uninformed decisions result in abnormally high handover frequency, particularly in HetNets with dense small cell deployments [8]. This high frequency of handovers significantly burdens the limited radio resources—such as physical resource blocks (PRBs) available at T-cells [9].

When numerous UEs simultaneously request access to the same T-cell within a short time frame, resource contention is likely to occur. This is especially problematic in small cells, where the resource pool is inherently limited. The consequence is handover blocking, where some handover requests are denied due to the unavailability of resources. This not only disrupts the continuity of user sessions but also undermines the network’s Quality of Service (QoS) [10].

Furthermore, in HetNet architectures modeled using stochastic geometry (e.g., Poisson Point Processes), accurately quantifying the blocking probability associated with frequent handovers remains a complex analytical challenge. Developing a tractable and realistic analytical framework to evaluate how handover behavior impacts network-level blocking performance is thus the third critical challenge, addressed in Chapter 3.

2.1.2 Challenges in the decision phase: traditional algorithms lack awareness of cell heterogeneity

Following the measurement phase, the handover process transitions into the decision phase. Conventional HDMA such as the A3-based RSRP algorithm typically compare the RSRP of the T-cell and S-cell. A handover is triggered once the RSRP of the T-cell exceeds that of the S-cell by a predefined handover margin (HOM) for a sustained time-to-trigger (TTT) duration.

However, this generalized, threshold-based approach performs poorly in heterogeneous network (HetNet) environments. Critically, it lacks the ability to discern the type of the target cell—whether it is a macrocell, a Sub-6GHz small cell, or a millimeter-wave (mmWave) cell [11]. As a result, the algorithm may mistakenly trigger a handover from a macrocell to a small or mmWave cell, despite the latter’s limited coverage and susceptibility to blockage. This often leads to frequent re-handover or handover failures, especially for high-mobility UEs such as those in vehicles or trains [12][13].

Moreover, the inherent asymmetry between macrocells and small cells—in terms of transmit power and coverage—means that handovers from macrocells to small cells (M2S) and from small cells to macrocells (S2M) exhibit fundamentally different dynamics. Traditional HDMA, which treat both directions identically, fail to capture this asymmetry, leading to low performance handover decisions. Hence, the ability to model

handover behavior accurately and to design decision logic that intelligently recognizes cell types is the second major challenge in handover optimization, discussed in detail in Chapter 4.

2.1.3 Challenges in the measurement phase: unstable indicator decrease reliable handover performance

The handover process in 5G networks begins with the measurement of radio link quality. Currently, most handover decision-making algorithms (HDMA) rely on the reference signal received power (RSRP) as the primary indicator. However, as a physical-layer metric, RSRP is highly susceptible to multi-path propagation, shadow fading, and other stochastic fluctuations inherent in mobile environments [14]. Even after applying filtering techniques, the RSRP signal exhibits persistent volatility, making it an unreliable basis for triggering handover decisions. This instability can lead to erroneous outcomes. On one hand, signal jitter may cause the source cell (S-cell) to prematurely initiate a handover based on inaccurate measurement reports, resulting in Too-Early Failure (TEF)—a condition where the target cell (T-cell) does not yet offer superior link quality, thereby degrading post-handover communication [15], [16].

On the other hand, fluctuations may also cause the UE to oscillate between the S-cell and T-cell in a phenomenon known as ping-pong handover, which increases signaling overhead and service interruptions [14]. This issue is particularly severe in low-mobility scenarios such as pedestrian users, where small-scale fading is more pronounced. Therefore, identifying a more stable and representative metric than RSRP—one that can reflect long-term link quality—is a critical challenge in improving handover reliability and constitutes a key research focus in Chapter 5.

Chapter 3

Quantitative analysis of blocking caused by handover request

3.1 Overview of insufficient resource block in 5G

As outlined in Chapter 2, frequent handovers—resulting from unstable signal measurements and limitations in traditional decision-making logic—intensify resource contention in the target cell, ultimately increasing the likelihood of UE blocking because it is necessary to acquire the PRBs within in the HDMA and the PRB is limited within a cell, as shown in Fig. 3.1.

Therefore, before proposing any advanced optimization algorithms aimed at mitigating unnecessary handovers, it is essential to conduct a rigorous theoretical and quantitative analysis of how frequent handovers degrade network resource availability. Such an analysis serves a key purpose: It provides a theoretical foundation to support network operators in designing more efficient resource allocation and admission control policies.

However, conventional blocking analyses often rely on simplified assumptions, such as fixed-grid network topology. In contrast, real-world HetNets exhibit highly irregular and stochastic spatial distributions of base stations, particularly in scenarios involving dense small-cell deployments. These irregularities must be captured to ensure realistic performance evaluation.

To address this limitation, this chapter focuses on the resource acquisition phase of the handover process and investigates the following core research question: How can we quantitatively assess the impact of frequent handovers on blocking probability in randomly deployed HetNets? To answer this, we introduce a novel model-based analytical framework that combines stochastic geometry with stochastic Petri Nets (SPNs). Specifically: A Poisson point process (PPP) is used to represent the spatial randomness of macro and small cells in HetNet deployments. SPNs are employed to model the dynamic behavior of UEs, including cell association, service request processing, resource occupation, and handover events. This integrated SPN-PPP framework allows us to

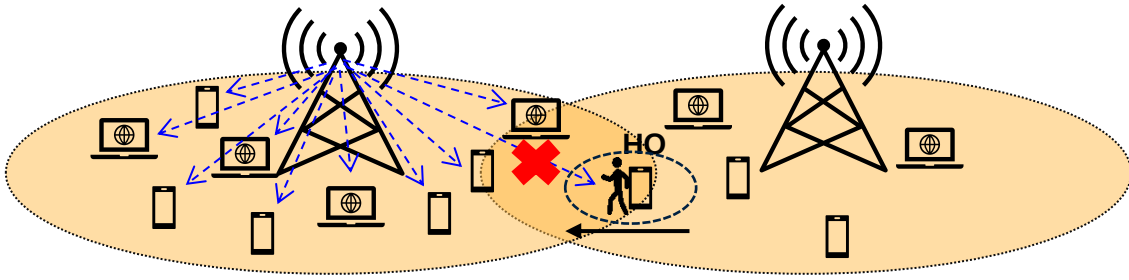


Figure 3.1: Insufficient resource within 5G.

simulate and analyze the impact of the presence or absence of handover request on the UE's blocking probability. The findings from this chapter provide quantitative insights into the interplay between handover dynamics and network resource constraints, offering a robust analytical basis for understanding and mitigating resource contention in next-generation heterogeneous networks.

3.1.1 Overview of A2A4RSRQ HDMA

Handover is primarily designed to maintain stable connectivity and good quality of service (QoS) while the user equipment (UE) is on the move. In 5G networks, the handover process determines whether to handover the UE's connection from one cell to another through specific trigger conditions. Due to the complex network environment of 5G HetNet, which introduces a higher cell density structure, the complexity of handover is greatly increased and the frequency of handover is significantly higher compared to previous mobile communication networks.

In the handover process, the commonly considered triggering conditions include reference signal received power (RSRP) and reference signal received quality (RSRQ) indicators. The A2A4RSRQ HDMA is one of handover policy based on the indicator of the RSRQ, which is usually used for handover when the RSRQ of the T-cell is sufficiently high than a threshold and the RSRQ of the S-cell is poor than a threshold, and these thresholds of RSRQs are certainly value, as shown in

- A2 event trigger: when the UE detects that the RSRQ of the current service cell is lower than the preset A2 threshold, it triggers the A2 event.
- A4 event trigger: when the RSRQ of a neighboring cell is found to be higher than the A4 threshold, the A4 event is triggered after the A2 event is triggered, the UE continues to monitor the signal quality of neighboring cells, which indicates that the signal quality of the neighboring cell is better than that of the current cell.

The specific process of A2A4RSRQ HDMA is that the UE firstly sends the measurement report of the A2 event to the S-cell when the RSRQ received by the UE from the S-cell is less than a certain threshold. After that, the UE device will send the measurement report of the A4 event to the S-cell when the RSRQ received by the UE from

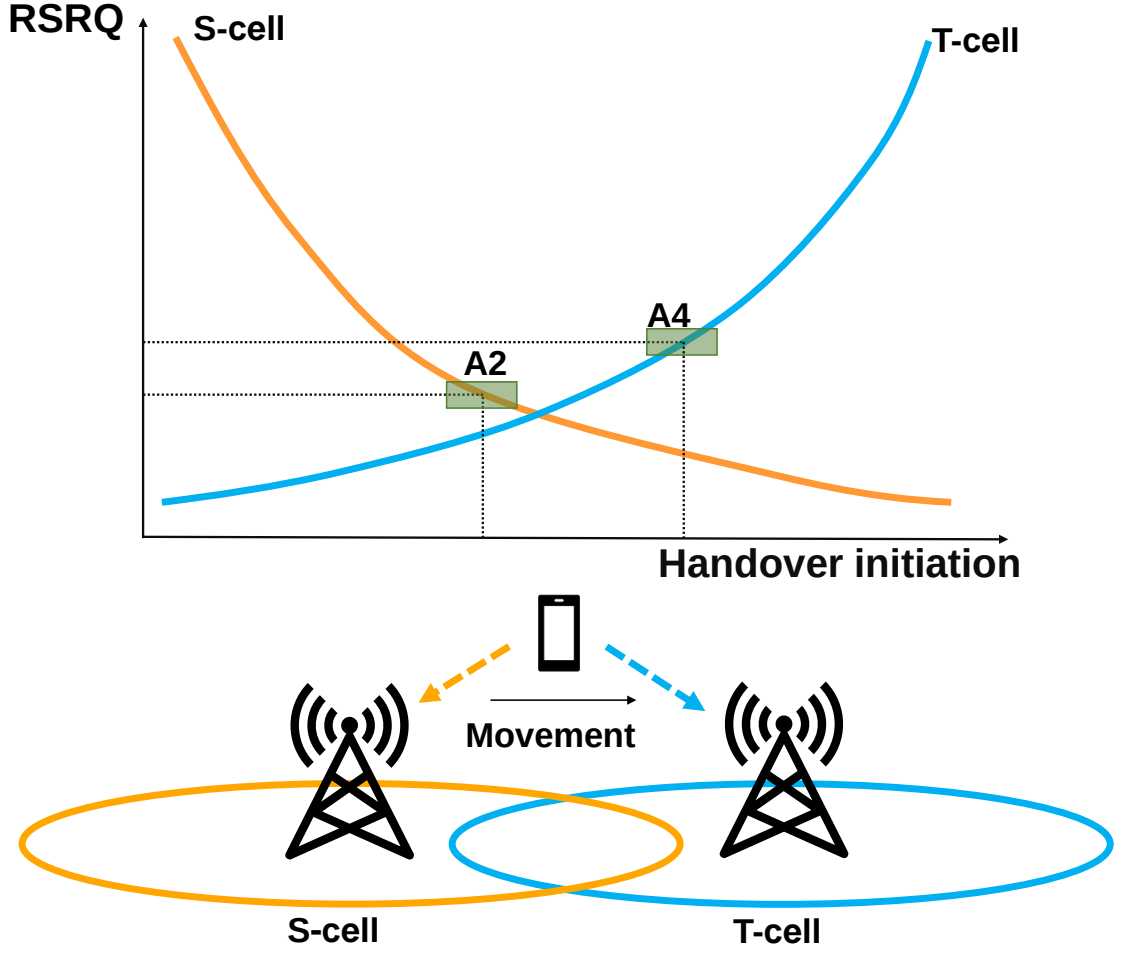


Figure 3.2: A2A4RSRQ handover decision-making algorithm

the T-cell is greater than a certain threshold. Finally, the S-cell will send a handover command to the UE based on the A2 and A4 measurement reports from the UE.

3.2 Design of handover and queue framework based on probabilistic modeling

In 5G networks, there are a large number of UEs, which can be existing UE, new UE trying to access the network, and handover UE switching from neighboring cells. Meanwhile, the behaviors of these different types of UEs in the network are concurrent, and they compete with each other for resources.

Therefore, it is necessary to establish a suitable mathematical model to describe this concurrency relationship and the accurate description of this concurrent UE behavior. This not only helps us to better understand the network load characteristics, but also provides an important theoretical basis for the subsequent resource scheduling and quality of service assurance.

PPP exhibits unique advantages when describing a large-scale network distribution.

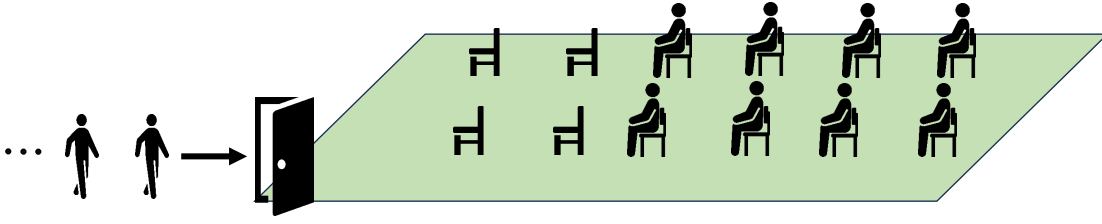


Figure 3.3: Arriving UEs and occupying resources (like a seat) in the network.

As a spatial stochastic process, it can effectively capture the random distribution characteristics of cells and UEs within a large-scale networks. Especially, it can capture the average characteristics of RSRQ and RSRP received by UEs in large-scale networks.

Furthermore, Petri Net provides a powerful modeling framework to characterize the concurrent behavior of user equipment. The most significant advantage of Petri Net as a graphical, mathematical modeling tool is its ability to intuitively and critically characterize state changes and resource competition in concurrent systems, including the arrival process of a new UE, the process of a UE receiving service from a cell, and the UE experiencing a handover, and these different types of UEs concurrently request network resources, service queues are often formed, as shown in Fig. 3.3

3.2.1 Theoretical foundations of probabilistic models

Propose the mathematical expressions used to model the switching failure probability and explain in detail the meaning of each variable and parameter. Explain how to integrate network conditions, resource block allocation, user mobility and other factors in the model to accurately assess the switching failure probability.

3.2.2 Poisson point process

In this section, we will first introduce the knowledge about Poisson distribution, which is discussed in the fundamentals of probability theory before introducing the PPP.

In probability theory and statistics, Poisson distribution represents a discrete probability distribution, in a certain period of time or space interval if the mean density of events occurring given then the probability of the number of events occurring in the certain interval can be found, and these events occurring independently of each other, the distribution of random events following this type of description is called the Poisson distribution. The Poisson distribution is expressed by the equation as follows,

$$Pr(N(t, t + \Delta t) = n) = \frac{(\lambda \Delta t)^n}{n!} e^{-\lambda \Delta t}, \quad n = 0, 1, 2, \dots, \quad (3.1)$$

where λ denotes the intensity of event occurrences, Δt denotes a fixed time interval, and n denotes the number of event occurrences. Meanwhile, the Poisson distribution as a kind of exponential distribution its time interval between each event occurrence is

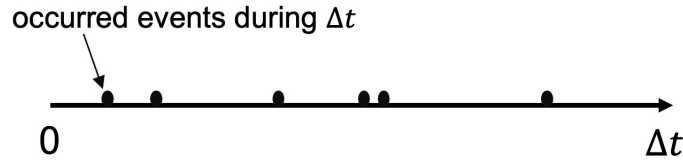


Figure 3.4: The Poisson distribution in the one-dimensional.

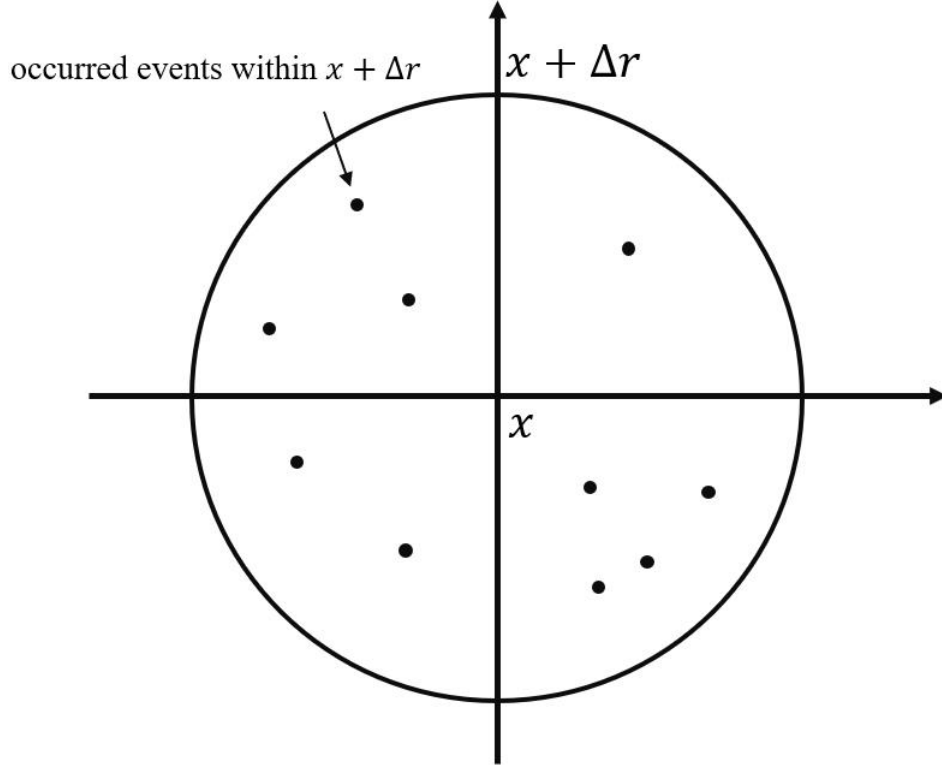


Figure 3.5: The Poisson distribution in the two-dimensional.

following the exponential distribution. If the occurrence of these events are visualized, the following figure can be obtained, where the points in Fig. 3.4 represent the occurrence of events, and the interval between points represents the time interval between the occurrence of each event, which is following the exponential distribution as we mentioned above. The Poisson and exponential distributions and the relationship between them can be studied through Eq. (3.1) and Fig. 3.4. However, at also, we know through Eq. (3.1) and Fig. 3.4 that they represent the probability of the occurrence of an event based on the length of a one-dimensional time line, so this is also understood as a one-dimensional interpretation of the Poisson point process.

In this thesis, what we need is to model and analyze the distribution of cell, but the distribution of realistic cells is based on a 3D spatial distribution and not necessarily just based on a straight line between cell for deployment. Therefore, the one-dimensional Poisson Point Process (Poisson distribution) only cannot satisfy our requirements. Al-



Figure 3.6: Before the system state change (left); after the system state change (right).

though the distribution of cell in realistic networks is 3D spatially based, in this thesis we only discuss the distribution of cells based on the 2D plane.

The 2D PPP is the explanation of the Poisson distribution in the 2D plane. It represents a probability distribution of the number of events occurring in a certainly area, and the mathematical expression can be obtained as follows,

$$Pr(\Phi(B_x(\Delta r)) = n) = \frac{(\Lambda B_x(\Delta r))^n}{n!} e^{-\Lambda B_x(\Delta r)}, \quad n = 0, 1, 2, \dots, \quad (3.2)$$

where $\Phi(\cdot)$ denotes the measure of the random point process, $B_x(\Delta r)$ denotes a circle centered at x and $x + \Delta r$ as the radius in the 2D plane, n denotes the number of points in the area of $B_x(\Delta r)$, and Λ denotes the density parameter of the point occurrence. It can be seen by Eq. (3.2) that, different from the 2D PPP from the one-dimensional one is that the random variable about the defined given interval changes from a measure of one-dimensional length to a measure of 2D area, and similarly, if also the 2D PPP can be represented graphically, the following figure can be obtained.

The PPP in Figure 1.5 indicates that if the intensity parameter of the event is Λ , then the probability of the event occurring k times randomly in the area of the circle with x as the center has $x + \Delta r$ as the radius is $\frac{(\Lambda B_x(\Delta r))^k}{k!} e^{-\Lambda B_x(\Delta r)}$, $k = (0, 1, 2, \dots)$. It can be seen that the Poisson point process based on the 2D plane can help us analyze and discuss the characteristics of cell based on random distribution in 2D space.

3.2.3 Stochastic Petri Net

In this section, we introduce the mathematical formal model, Petri Net, that was mainly used in this section, including transaction processing submodel, servicing submodel and capacity control submodel in the case of considering handover.

A Petri net is a mathematical formal model, which includes three components, *place*, *transition* and directed *arc*. Place and transition are represented by circles and rectangles, respectively. Petri nets represent the dynamics of a system or network by the dynamics of *token* distributed in places, as shown in Fig. 3.6.

Define the state of the token distribution in the left place as $(1, 0)$ before the system change in Fig. 3.6, and define the state of the token distribution in the right place as $(0, 1)$ after the system change in Fig. 3.6, and the time consumed from state $(1, 0)$ to state $(0, 1)$ follows exponential distribution, which the transition is represented by a white rectangle. Such the notation to represent the system state in Petri Net is called

marking. The marking of an Petri Net is given by a vector that represents the number of tokens for all the places, providing the state of a target system. In addition, there is the following form of describing the dynamics of the system in Petri Nets,

Therefore, in Petri Net, there can exist the following types of transitions [17][18],

- IMM transition (Immediate, i.e., they fire in zero time),
- EXP transition (Timed with exponentially distributed firing time),
- GEN transition (Timed with generally distributed firing time).

In general, the IMM transition, EXP transition and GEN transition are often expressed by a thin black bar, a white rectangle, a white rectangle, respectively. The IMM transitions have priority to fire over timed transitions. There is at most one transition which is enabled in a marking. When two or more transitions are enabled at the same time, the enabling functions, also called guard functions (GFs), are added to these transitions to control the firing sequence. GFs determine the enabled timing and are given by the interrelationships between the transition and the corresponding places. A transition with a guard function occurs when the value of the guard function is evaluated to be true. For a stochastic Petri Net (SPN) is defined as a Petri net with exponential distribution of firing times for transitions.

3.3 SINR and RSRQ assumption by Poisson point process

3.3.1 SINR-based cell association

In this section, we describe how the UE associates cells based on the SINR within two-tier HetNet, indicating that the UE associates with the cell that has a better SINR by comparing the SINR of two-tier cells, instead of associating cells by comparing a given threshold with the SINR of each cell tier, because if the condition is not satisfied, the UE cannot associate cells. The SINR model we considered is given below,

$$SINR_S = \frac{P_S G_{a_i} D_{a_i}^{-\eta}}{I_1 + I_2 + \sigma^2}, \quad SINR_M = \frac{P_M G_{b_i} D_{b_i}^{-\eta}}{I_3 + I_4 + \sigma^2}, \quad (3.3)$$

where $SINR_M$ and $SINR_S$ are the SINR when the UE is associated with macro and small cells, respectively; P_S and P_M are the reference power of small and macro cell, respectively; G_{a_i} is the channel gain of the UE associated with small cells, which follows an exponential $G \sim (\mu_{a_i})$ distribution; G_{b_i} is the channel gain of a UE associated with macro cells, which also follows an exponential $G \sim (\mu_{b_i})$ distribution; D_{a_i} and D_{b_i} are the random variables of UE distance from small and macro cell, respectively, while satisfying the exponential distribution property, the parameter η is the path loss with

value as 4 in this paper; the expressions of interference I_1 and I_2 in $SINR_S$ are as follows,

$$I_1 + I_2 = \sum_{b_i \in \Phi_2} P_M G_{b_i} D_{b_i}^{-\eta} + \sum_{a_i \in \Phi_1 \setminus RHO_a} P_S G_{a_i} D_{a_i}^{-\eta} + \sigma^2. \quad (3.4)$$

Since we assumed that macro cells and small cells were in the same frequency, I_1 implied that if the UE was associated with a small cell, it will be subject to interference from other surrounding macro cells, and the UE will also be subject to interference from other surrounding small cells that use the same frequency. In addition, we considered interference cancellation in intra servicing cell, so the UE would suffer from the interference I_2 from other small cells in the same frequency outside the interference cancellation range RHO_a . Similarly, if the UE was associated with a macro cell after measuring two-tier, the interference received will be in the form of I_3 and I_4 , as follows,

$$I_3 + I_4 = \sum_{a_i \in \Phi_1} P_S G_{a_i} D_{a_i}^{-\eta} + \sum_{b_i \in \Phi_2 \setminus RHO_b} P_M G_{b_i} D_{b_i}^{-\eta} + \sigma^2. \quad (3.5)$$

By allowing the UE to compare the SINR of two-tier cells to be associated with the better cell for transmission, we considered the association model as in Eq. (3.6) at the bottom of this page, where $T2$ denotes the threshold of $SINR_M$, and its detailed derivation procedures we give in the Appendix.

$$\begin{aligned} \zeta_s &= \Pr \{ SINR_S > SINR_M \} \\ &= 1 - \left(\int_0^\infty 2\pi \lambda_a D_a \exp \left\{ -\lambda_a \pi D_a^2 - \lambda_b \pi D_a^2 \sqrt{\frac{\mu_a P_M T2}{\mu_b P_S}} \arctan \left(\frac{D_a^2 \sqrt{\frac{\mu_a P_M T2}{\mu_b P_S}}}{RHO_a^2} \right) \right. \right. \\ &\quad \left. \left. - \lambda_a \pi D_a \sqrt{T2} \arctan \left(\frac{D_a^2 \sqrt{\frac{\mu_a P_M T2}{\mu_b P_S}}}{RHO_a^2} \right) \right\} dD_a \right) \cdot \frac{\sqrt{T2} + (1 + T2) \arctan(\sqrt{T2})}{2\sqrt{T2} (1 + T2) \left[1 + \sqrt{T2} \arctan(\sqrt{T2}) \right]^2}. \end{aligned} \quad (3.6)$$

3.3.2 A2-A4RSRQ-based handover

A2-A4RSRQ handover is one of the many handover algorithms, based on the handover algorithm we described in Fig. 3.2. It is an HDMA by combining the A2 events and A4 of the handover events published by 3GPP, with the purpose of reducing the UE frequent occurrence of handover in Het-Net. The signal indicator used in the A2-A4RSRQ handover algorithm is RSRQ, which is an indicator of the signal quality received by the UE from the cell. Different from the signal strength indicator RSRP, RSRQ includes the investigation of the number of available resource blocks (RBs) from the cell in the sig-

nal strength indicator RSRP, the relationship between them was given in the following equation,

$$RSRQ = \frac{N \cdot RSRP}{RSS} \quad (3.7)$$

where N denotes the number of resource blocks available in the cell, and RSS in here denotes the signal strength in the full frequency band, which includes the signal strength of the source cell and also includes the interference signal from other cells. In addition, in A2-A4RSRQ algorithm, the steps of UE from triggering handover to completing handover can be divided into three phases: handover preparation, handover execution judgment and handover completion, where in this paper we called handover preparation as handover enable and handover execution judgment as celloffset. The specific process is shown in the Fig. 3.2,

3.3.3 Handover enable

We consider the first condition branch in Fig. 3.2, *source cell RSRQ* < *threshold*, as handover enable. In the composite event A2-A4RSRQ handover algorithm, as the UE gradually moves away from the source cell, the received signal strength from the source cell will gradually weaken, and the event A2 will be triggered when the signal strength of the source cell is lower than a threshold. However, the UE will not immediately trigger handover after event A2, but will change the handover status to enable, and then perform the judgment of event A4 or repeat this step again, as shown in Fig. 3.2. In addition, the UE trigger event A2 is not instantaneous but cumulative in time, therefore, we assume that the time of small cell UE trigger event A2 is following exponential distribution with the intensity parameter $T_{sserv_HOoccur}$, the time of macro cell UE trigger event A2 also following exponential distribution with the intensity parameter $T_{mserv_HOoccur}$, as equation in the below,

$$F(x) = 1 - e^{-T_{sserv_HOoccur}x}, \quad F(x) = 1 - e^{-T_{mserv_HOoccur}x}. \quad (3.8)$$

3.3.4 Cell offset

The second condition branch we considered *target cell RSRQ* - *source cell RSRQ* < *celloffset*. The UE that has triggered event A2 will continue to judge event A4, whether the RSRQ of the target cell is greater than the RSRQ of the source cell, and if the condition is satisfied then the process of handover of the UE will succeed. Conversely, it will be failed and return to the initial step again. In this paper we consider that the triggering of event A4 was immediate and a probability event.

The assumed RSRQ model were shown in Eq. (3.9) and Eq. (3.10) as follow,

$$RSRQ_S = \frac{N_S P_{S_k} G_{a_i} D_{a_i}^{-\eta}}{\sum_{a_i \in \Phi_1} N_S P_{S_k} G_{a_i} D_{a_i}^{-\eta} + \sum_{b_i \in \Phi_2} N_M P_{M_k} G_{b_i} D_{b_i}^{-\eta} + \sigma_{\text{noise}}^2}, \quad (3.9)$$

$$RSRQ_M = \frac{N_M P_{M_k} G_{b_i} D_{b_i}^{-\eta}}{\sum_{a_i \in \Phi_1} N_S P_{S_k} G_{a_i} D_{a_i}^{-\eta} + \sum_{b_i \in \Phi_2} N_M P_{M_k} G_{b_i} D_{b_i}^{-\eta} + \sigma_{\text{noise}}^2}, \quad (3.10)$$

where P_{S_k} and P_{M_k} are the output power of the small and macro cells, respectively, at the k th RB, the other parameter is same as Eq. (3.6). Eq. (3.9) denotes the RSRQ of UE in small cell and Eq. (3.10) denotes the RSRQ of UE in large cell. Eq. (3.9) and Eq. (3.10) were assumed based on Eq. (3.7) of the definition of RSRQ. Therefore, the definition of event A4 we given the following Eq. (3.11),

$$\begin{aligned} \zeta_{\text{offset}_{\text{sm}}} &= \Pr \{RSRQ_M - RSRQ_S > C_0\} \\ &= \frac{\lambda_a \pi \sqrt{p_1 (C_0 + T3)} + \lambda_b \pi \sqrt{C_0 + T3}}{2\lambda_a + \lambda_a \pi \sqrt{C_0 + T3} + \lambda_b \pi \sqrt{p_1 (C_0 + T3)}} \cdot \frac{\lambda_a \pi (\lambda_a \sqrt{T3} + \lambda_b \sqrt{T3})}{\left[(2 + \pi \sqrt{T3}) + \lambda_b \pi \sqrt{p_1 T3} \right]^2 (T3)}. \end{aligned} \quad (3.11)$$

where $\zeta_{\text{offset}_{\text{sm}}}$ denotes the successful probability of UE handover from a small to macro cell, $T3$ denotes the threshold value for triggering the A2 event during handover from a small to a macro cell, $p_1 = \frac{N_S P_{S_k}}{N_M P_{M_k}}$, $p_2 = \frac{N_M P_{M_k}}{N_S P_{S_k}}$, C_0 is the assumed the cell offset value. It denotes the model of celloffset when UE is handover from small cell to macro cell, meaning that the probability of successful handover when UE is handover from small cell to macro cell was $\zeta_{\text{offset}_{\text{sm}}}$. The same applies during handover from macro to small cell. The equation when UE handover from macro to small cell can be derived as Eq. (3.12).

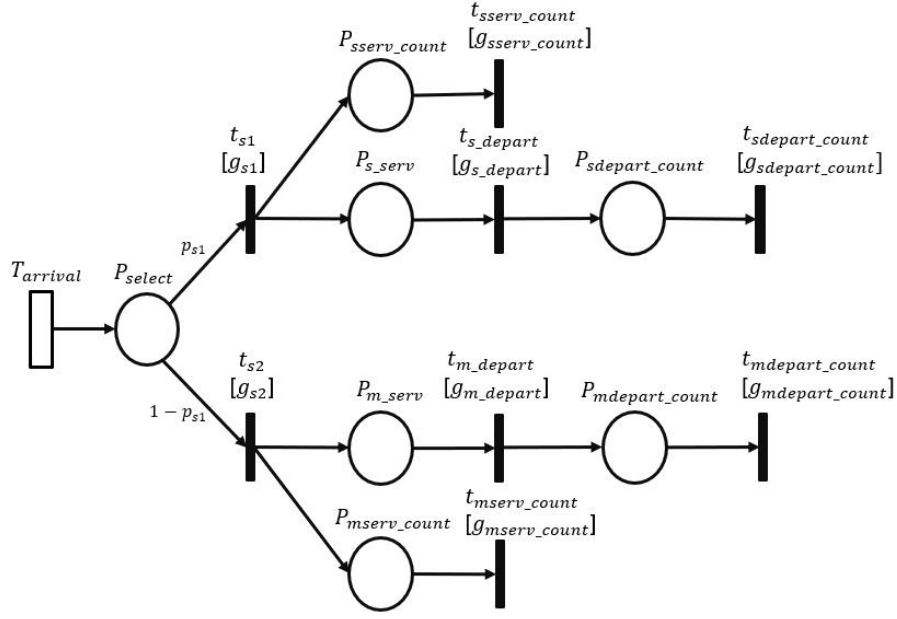


Figure 3.7: SPN for transaction processing submodel without handover.

$$\begin{aligned}
 \zeta_{\text{offset}_{\text{ms}}} &= \Pr \{ RSRQ_S - RSRQ_M > C_1 \} \\
 &= \frac{\lambda_a \pi \sqrt{p_1 (C_0 + T3)} + \lambda_b \pi \sqrt{C_0 + T3}}{2\lambda_a + \lambda_a \pi \sqrt{C_0 + T3} + \lambda_b \pi \sqrt{p_1 (C_0 + T3)}} \cdot \frac{\lambda_a \pi (\lambda_a \sqrt{T3} + \lambda_b \sqrt{T3})}{\left[(2 + \pi \sqrt{T3}) + \lambda_b \pi \sqrt{p_1 T3} \right]^2 (T3)}. \quad (3.12)
 \end{aligned}$$

Eq. (3.12) denotes the model of celloffset when the UE handover from macro cell to small cell, which means the probability of successful handover when the UE handover from macro cell to small cell was $\zeta_{\text{offset}_{\text{ms}}}$. The detailed derivation process was given in the Appendix.

3.4 Proposed composite stochastic Petri Nets

3.4.1 Composite SPN without handover

In this section, we first introduce the model for SPN without considering UE handover, which includes transaction processing submodel, servicing submodel and capacity control submodel.

3.4.1.1 Transaction processing submodel

This subsection describes the Transaction processing submodel without handover. As shown in Figure 3.7, the white rectangle T_{arrival} represents the arrival of UEs, and the arrival time distribution of UEs follows an exponential distribution. UEs arriving at

Table 3.1: The description of places in transaction processing submodel.

Place	Description
P_{select}	Associated cell
$P_{\text{s_serv}}$	Waiting for service in small cell
$P_{\text{m_serv}}$	Waiting for service in macro cell
$P_{\text{sdepart_count}}$	Complete the service and depart small cell
$P_{\text{mdepart_count}}$	Complete the service and depart macro cell
$P_{\text{sserv_count}}$	Pass signals to $t_{\text{serv1_in}}$ and t_{sconsume} , no meaning
$P_{\text{mserv_count}}$	Pass signals to $t_{\text{serv2_in}}$ and t_{mconsume} , no meaning

Table 3.2: The description of transitions in transaction processing submodel.

Transition	Description	Attribute
T_{arrival}	UEs arrivals based on exponential distribution	EXP
t_{s1}	Fires whenever a UE associates small cell with probability p_1 .	IMM
t_{s2}	Fires whenever a UE associates macro cell with probability $1 - p_1$	IMM
$t_{\text{s_depart}}$	Complete the service and depart small cell	IMM
$t_{\text{m_depart}}$	Complete the service and depart small cell	IMM
$t_{\text{sdepart_count}}$	Receive signals from $P_{\text{sserv_depart}}$	IMM
$t_{\text{mdepart_count}}$	Receive signals from $P_{\text{mserv_depart}}$	IMM
$t_{\text{sserv_count}}$	Receive signals from $P_{\text{scons_count}}$ and $P_{\text{strans_count}}$	IMM
$t_{\text{mserv_count}}$	Receive signals from $P_{\text{mcons_count}}$ and $P_{\text{mtrans_count}}$	IMM

Het-Net enter the state of cell association, which is represented by place P_{select} . The probabilities of UE associating with small and macro cell, p_{s1} and $1 - p_{\text{s1}}$, respectively, are derived from Eq. (3.6).

Let t_{s1} and t_{s2} denote control UEs associating with small and macro cell, respectively. t_{s1} fires with probability p_{s1} when there is capacity available for allocation to UE in small cell, and t_{s2} fires with probability $1 - p_{\text{s1}}$ when there is capacity available for allocation to UE in macro cell. When UE enters the small cells $P_{\text{s_serv}}$ or the macro cell $P_{\text{m_serv}}$, the UE begins to receive the service from cell, and UE departs the cell when finishes the service. t_{sdepart} fires when the UE finishes the service in the small cell, and t_{mdepart} fires when the UE finishes the service in the macro cell.

Let $P_{\text{sserv_count}}$ and $P_{\text{mserv_count}}$ used to pass signals to $t_{\text{serv1_in}}$ in Figure 3.8 and t_{sconsume} in Figure 3.10, respectively; $P_{\text{sdepart_count}}$ and $P_{\text{mdepart_count}}$ were used to pass signals to $t_{\text{sserv_depart}}$ in Figure 3.8 and $t_{\text{mserv_depart}}$ in Figure 3.13, respectively.

On the other hand, $t_{\text{sserv_count}}$ and $t_{\text{mserv_count}}$ were to fire by receiving signals from $P_{\text{scons_count}}$ in Figure 3.8 and $P_{\text{mcons_count}}$ in Figure 3.13, respectively, $t_{\text{sdepart_count}}$ and $t_{\text{mdepart_count}}$ were to fire by receiving signals from $P_{\text{sserv_count}}$ in Figure 3.8 and $P_{\text{mserv_count}}$ in Figure 3.13, respectively, and both of them were immediate fire. We summarize the relevant places and transitions in Figure 3.7 as Table 3.1 and Table 3.2, respectively.

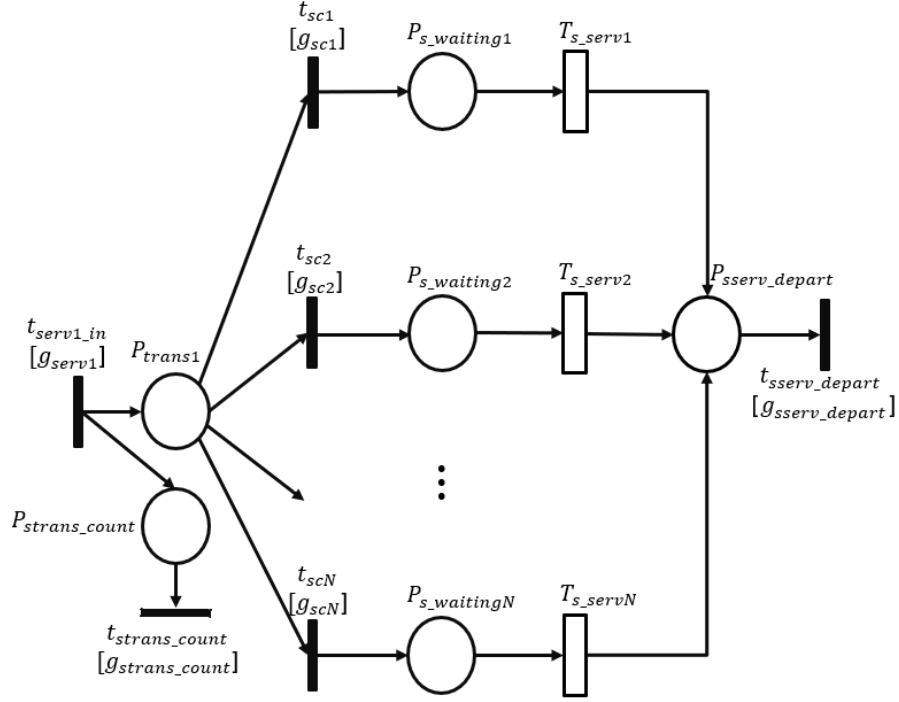


Figure 3.8: SPN for small cell servicing submodel without handover.

3.4.1.2 Servicing submodel

This section describes the Servicing submodel when without handover. As shown in Figure 3.8, t_{serv1_in} is briefly described in the previous subsection. When t_{serv1_in} receives a signal from P_{sserv_count} , it fires, indicating that a UE enters the queue to wait for service from the cell, denoted by place P_{trans1} . $P_{s_waiting1}$, $P_{s_waiting2}$, and $P_{s_waitingN}$ denote the N queues that the small cell can provide to the UE, and the waiting UE who receives service enters the corresponding queue to receive service through the firing of t_{sc1} , t_{sc2} and t_{scN} . The firing probabilities of t_{sc1} , t_{sc2} and t_{scN} are equal and sum to 1. In this paper, we assumed that the time that a UE receives service in a cell follows an exponential distribution, and that the UE departs the cell after receiving service.

Therefore, the firing times of T_{s_serv1} , T_{s_serv2} and T_{s_servN} were based on exponential distribution. P_{strans_count} was used to pass signals to t_{sserv_count} in Fig. 3.7. Let P_{sserv_depart} was used to pass signals to t_{s_depart} in Fig. 3.7 and $t_{increase1}$ in Fig. 3.10, both of them have no meaning in describing UEs behavior. t_{strans_count} fires by receiving signals from P_{sserv_count} in Fig. 3.7, t_{sserv_depart} fires by receiving signals from $P_{sdepart_count}$ in Fig. 3.7 and P_{sincr_count} in Fig. 3.10, and both t_{strans_count} and t_{sserv_depart} were immediate fires.

Similarly, the process of UE receiving service in a macro cell is the same as in a small cell as shown in Fig. 3.9, but since the communication environments of small and macro cells are completely different, which means that the time consumed by UE receiving service in a macro cell is different from that in a small cell. Therefore, the cumulative

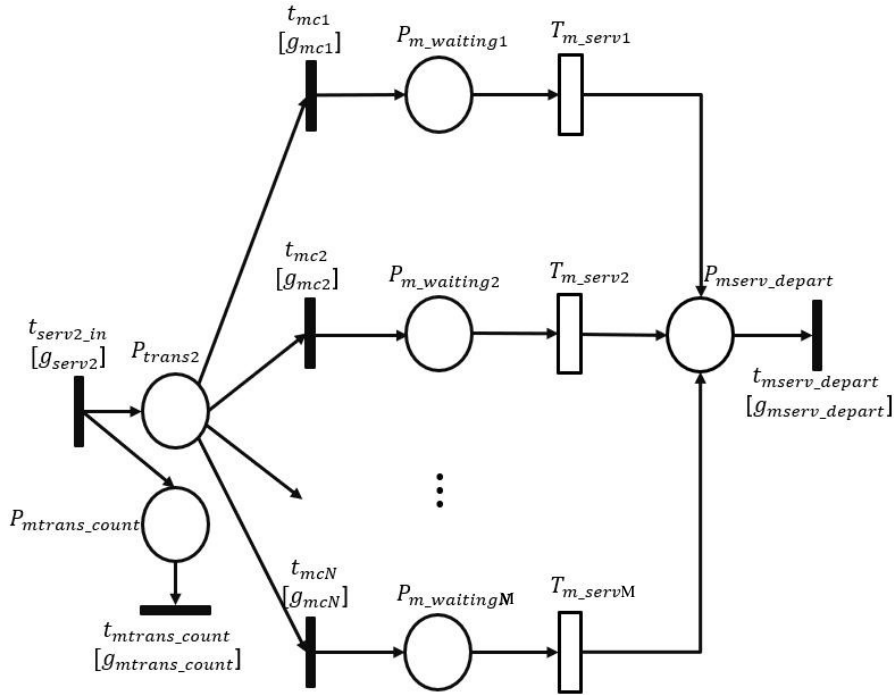


Figure 3.9: SPN for macro cell servicing submodel without handover.

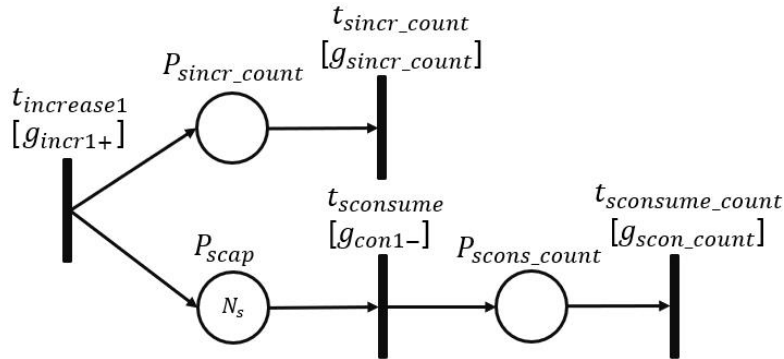


Figure 3.10: SPN for macro cell capacity control submodel without handover.

firing times of T_{m_serv1} , T_{m_serv2} and T_{m_servM} are different from those of T_{s_serv1} , T_{s_serv2} and T_{m_servN} in Fig. 3.8, but they also followed the exponential distribution of firing time. We summarize the relevant places and transitions in Fig. 3.8 and Fig. 3.9 as Table 3.3 and Table 3.4, respectively.

3.4.1.3 Capacity control submodel

This section describes the capacity control submodel when without handover. As shown in Fig. 3.10. Let P_{scap} denotes the number of available capacity of the small cell N_s . Whenever a UE enters the small cell, $t_{sconsume}$ receives a signal from place P_{sserv_count} in Fig. 3.7 to decrease the available capacity by one time, while $t_{increase1}$ receives a signal from place P_{sserv_depart} in Fig. 3.8 to increase the available capacity by one time

Table 3.3: The description of places in small and macro cell servicing submodel.

Place	Description
P_{trans1}	Receive the signals from P_{sserv_count} , no meaning
P_{strans_count}	Restrict repeated firing of t_{serv1_in}
$P_{s_waiting1}$	Waiting for service in the 1 queue of small cell
$P_{s_waiting2}$	Waiting for service in the 2 queue of small cell
$P_{s_waitingN}$	Waiting for service in the N queue of small cell
P_{sserv_depart}	Complete the service and depart small cell
P_{trans2}	Receive the signals from P_{mserv_count} , no meaning
P_{mtrans_count}	Restrict repeated firing of t_{serv2_in}
$P_{m_waiting1}$	Waiting for service in the 1 queue of macro cell
$P_{m_waiting2}$	Waiting for service in the 2 queue of macro cell
$P_{m_waitingM}$	Waiting for service in the M queue of macro cell
P_{mserv_depart}	Complete the service and depart macro cell

Table 3.4: The description of transitions in small and macro cell servicing submodel.

Transition	Description	Attribute
t_{serv1_in}	Fires when a UE is associated with small cell	IMM
t_{strans_count}	Receive the signals from P_{sserv_count}	IMM
t_{sc1}	Fires when the queue $P_{s_waiting1}$ has available capacity	IMM
t_{sc2}	Fires when the queue $P_{s_waiting2}$ has available capacity	IMM
t_{scN}	Fires when the queue $P_{s_waitingN}$ has available capacity	IMM
T_{s_serv1}	Fires whenever a UE completes service in the queue $P_{s_waiting1}$	EXP
T_{s_serv2}	Fires whenever a UE completes service in the queue $P_{s_waiting2}$	EXP
T_{s_servN}	Fires whenever a UE completes service in the queue $P_{s_waitingN}$	EXP
t_{sserv_depart}	Receive signals from P_{sincr_count} and $P_{sdepart_count}$	EXP
t_{serv2_in}	Fires when a UE is associated with macro cell	IMM
t_{mtrans_count}	Receive the signals from P_{mserv_count}	IMM
t_{mc1}	Fires when the queue $P_{m_waiting1}$ has available capacity	IMM
t_{mc2}	Fires when the queue $P_{m_waiting2}$ has available capacity	IMM
t_{mcN}	Fires when the queue $P_{m_waitingM}$ has available capacity	IMM
T_{m_serv1}	Fires whenever a UE completes service in the queue $P_{m_waiting1}$	EXP
T_{m_serv2}	Fires whenever a UE completes service in the queue $P_{m_waiting2}$	EXP
T_{m_servM}	Fires whenever a UE completes service in the queue $P_{m_waitingM}$	EXP
t_{mserv_depart}	Receive signals from P_{mincr_count} and $P_{mddepart_count}$	EXP

whenever a UE departs the small cell after receiving the service, achieving dynamic control of the dynamic increase or decrease of the available capacity in the small cell.

Let P_{sincr_count} and P_{scons_count} used to restrict the repeated firings of $t_{increase1}$ and $t_{sconsume}$, respectively, and have no meaning in describing UE behavior. Besides, t_{sincr_count} fires by receiving signals from P_{sserv_depart} , t_{scons_count} fires by receiving signals from P_{sserv_count} .

Similarly, the dynamic capacity model of macro cell was shown in Fig. 3.11, and its capacity dynamic control process was exactly the same as that of the small cell model, but the capacity of macro cell was N_m . We summarize the relevant places and transitions in Fig. 3.10 as Table 3.5 and Table 3.6, respectively. Finally, we also summarize the definitions of GF of all places and all transitions for models transaction processing submodel, servicing submodel and capacity control submodel in Table 3.7.

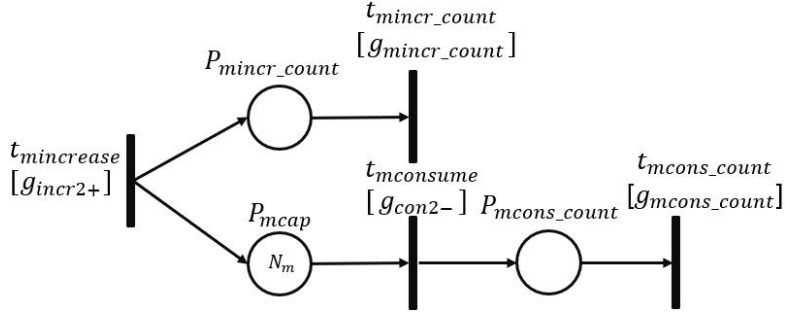


Figure 3.11: SPN for small cell capacity control submodel without handover.

Table 3.5: The places description of capacity control SPN in this section.

Place	Description
P_{sincr_count}	Restrict the repeated firings of $t_{increase1}$, no meaning
P_{scap}	Available capacity N_s of small cell
P_{scons_count}	Restrict the repeated firings of $t_{sconsume}$
P_{mincr_count}	Restrict the repeated firings of $t_{increase2}$, no meaning
P_{mcap}	Available capacity N_m of macro cell
P_{mcons_count}	Restrict the repeated firings of $t_{mconsume}$

Table 3.6: The transitions description of capacity control SPN in this section.

Transition	Description	Attribute
$t_{increase1}$	Control the increase of small cell capacity	IMM
t_{sincr_count}	Receives the signals from P_{sserv_depart}	IMM
$t_{sconsume}$	Control the decrease of small cell capacity	IMM
$t_{sconsume_count}$	Receives the signals from P_{sserv_count}	IMM
$t_{increase2}$	Control the increase of macro cell capacity	IMM
t_{mincr_count}	Receives the signals from P_{mserv_depart}	IMM
$t_{mconsume}$	Control the decrease of macro cell capacity	IMM
$t_{mconsume_count}$	Receives the signals from P_{mserv_count}	IMM

Table 3.7: Guard functions of SPN without handover.

Guard	Guar function
g_{s1}	$\#(P_{scap}) > 0$
g_{s2}	$\#(P_{mcap}) > 0$
g_{s_depart}	$\#(P_{sserv_depart}) == 1 \& \& \#(P_{sdepart_count}) == 0$
g_{m_depart}	$\#(P_{mserv_depart}) == 1 \& \& \#(P_{mdepart_count}) == 0$
g_{sserv_count}	$\#(P_{scons_count}) == 1 \& \& \#(P_{strans_count}) == 0$
g_{mserv_count}	$\#(P_{mcons_count}) == 1 \& \& \#(P_{mtrans_count}) == 0$
$g_{sdepart_count}$	$\#(P_{sserv_depart}) == 0$
$g_{mdepart_count}$	$\#(P_{mserv_depart}) == 0$
g_{serv1}	$\#(P_{sserv_count}) == 1 \& \& \#(P_{strans_count}) == 0$
g_{serv2}	$\#(P_{mserv_count}) == 1 \& \& \#(P_{mtrans_count}) == 0$
g_{sserv_depart}	$\#(P_{sincr_count}) == 1 \& \& \#(P_{sdepart_count}) == 1$
g_{mserv_depart}	$\#(P_{mincr_count}) == 1 \& \& \#(P_{mdepart_count}) == 1$
g_{strans_count}	$\#(P_{sserv_count}) == 0$
g_{mtrans_count}	$\#(P_{mserv_count}) == 0$
g_{sc1}	$\#(P_{s_waiting1} < scap/N$
g_{sc2}	$\#(P_{s_waiting1} < scap/N$
g_{sc3}	$\#(P_{s_waiting1} < scap/N$
g_{mc1}	$\#(P_{m_waiting1} < mcap/M$
g_{mc2}	$\#(P_{m_waiting1} < mcap/M$
g_{mc3}	$\#(P_{m_waiting1} < mcap/M$
g_{incr1}	$\#(P_{sserv_depart}) == 1 \& \& \#(P_{sincr_count}) == 0$
g_{incr2}	$\#(P_{mserv_depart}) == 1 \& \& \#(P_{mincr_count}) == 0$
g_{con1}	$\#(P_{sserv_count}) == 1 \& \& \#(P_{scons_count}) == 0$
g_{con2}	$\#(P_{mserv_count}) == 1 \& \& \#(P_{mcons_count}) == 0$
g_{sincr_count}	$\#(P_{sserv_depart}) == 0$
g_{mincr_count}	$\#(P_{mserv_depart}) == 0$
g_{scons_count}	$\#(P_{sserv_count}) == 0$
g_{mcons_count}	$\#(P_{mserv_count}) == 0$

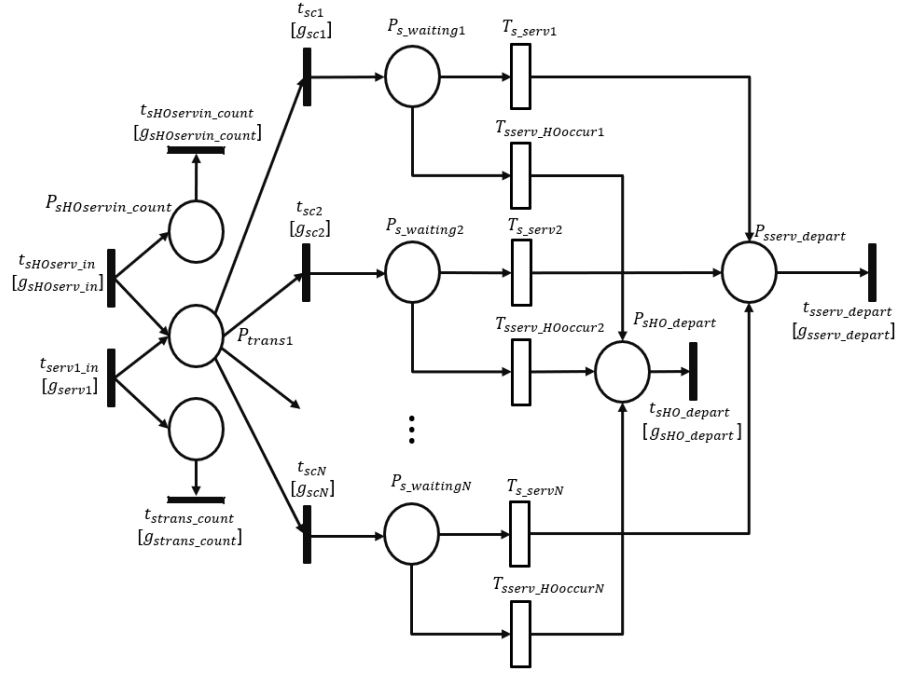


Figure 3.13: SPN for small cell servicing submodel with handover.

state changes to enable does not necessarily complete the handover successfully, but has to determine the RSRQ of the target cell first.

Therefore, a UE handover from a small cell P_{s_serv} to a macro cell P_{m_serv} will complete the handover successfully with probability p_{smHO} , enter the handover success state $P_{sHOsucc_count}$, failed with probability $1 - p_{smHO}$, and return to the P_{select} state. Similarly, a UE handover from a macro cell P_{m_serv} to a small cell P_{s_serv} will complete the handover successfully with probability p_{msHO} , enter the handover success state $P_{mHOsucc_count}$, failed with probability $1 - p_{msHO}$, and return to the P_{select} state.

3.4.2.2 Servicing submodel

This section introduces the model when considering UE handover, as shown in Fig. 3.13. Similarly, t_{serv1_in} fires when it receives a signal from P_{sserv_count} , indicating that the UE enters the queue to receive the service and can enter any of the queues, denoted by $P_{s_waiting1}$, $P_{s_waiting2}$ and $P_{s_waitingN}$ for the different queues. t_{sc1} , t_{sc2} and t_{scN} , which control the entering queues, also fire with equal probability and sum to 1. The UE that has received the service also departs the cell, denoted by P_{sserv_depart} . Different from the model in Fig. 3.8, we consider UE handover in this Servicing submodel, which may occur in any of the queues $P_{s_waiting1}$, $P_{s_waiting2}$ and $P_{s_waitingN}$ while receiving service due to the change in signal quality RSRQ.

Therefore, each queue has a transition that controls UE handover, denoted by $T_{sserv_HOoccur1}$, $T_{sserv_HOoccur2}$ and $T_{sserv_HOoccurN}$, and their firing time follows the exponential distribution as well as the state of UE handover becomes enable after firing.

Table 3.9: The description of transitions in small and macro cell Servicing submodel.

Transition	Description	Attribute
$t_{sHOserv_in}$	Receive the signals from $P_{mHOsucc_count}$	IMM
$t_{sHOservin_count}$	Receive the signals from $P_{mHOsucc_count}$	IMM
t_{sHO_depart}	Receive the signals from P_{sm_init}	IMM
$T_{sserv_HOoccur1}$	Trigger event A2 in the small cell	EXP
$T_{sserv_HOoccur2}$	Trigger event A2 in the small cell	EXP
$T_{sserv_HOoccur3}$	Trigger event A2 in the small cell	EXP
$t_{mHOserv_in}$	Receive the signals from $P_{sHOsucc_count}$	EXP
$t_{mHOservin_count}$	Receive the signals from $P_{sHOsucc_count}$	IMM
t_{mHO_depart}	Receive the signals from P_{ms_init}	IMM
$T_{mserv_HOoccur1}$	Trigger event A2 in the macro cell	EXP
$T_{mserv_HOoccur2}$	Trigger event A2 in the macro cell	EXP
$T_{mserv_HOoccur3}$	Trigger event A2 in the macro cell	EXP

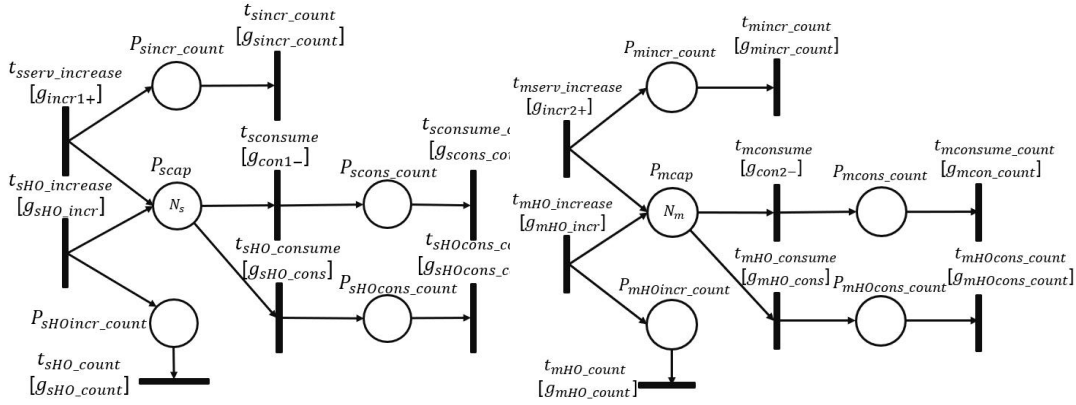


Figure 3.15: SPN for capacity control submodel with handover, small (left) and macro (right) cell.

3.4.2.3 Capacity control submodel

This section introduces the capacity control model with considering handover, as shown in Fig. 3.15 (left). Similarly, P_{scap} and P_{mcap} denote the small cell and macro cell capacity, respectively. $t_{sconsume}$ fires whenever a UE enters the small cell, which decreases the small cell capacity P_{scap} by one.

Different from Fig. 3.11 and Fig. 3.10, because UE handover is considered, the capacity increase or decrease of small cells is not only caused by arrived UEs and UEs completing service, but also by UEs that successfully complete handover. Therefore, $t_{sHO_increase}$ is the transition that controls the UEs that successfully handover from the small cell to a macro cell, and fires once to increase the small cell capacity by one if a UE successfully handovers, while $t_{mHO_consume}$ fires to decrease the macro cell capacity by one.

Similarly, $t_{sHO_consume}$ fires to decrease the small cell capacity by one and $t_{mHO_increase}$ fires to increase the macro cell capacity by one when a UE successfully handovers from the macro cell to a small cell. Let P_{scons_count} and $P_{sHOcons_count}$ pass signals to t_{sserv_count} and $t_{mHOsucc_count}$ in Fig. 3.15, respectively, and have no meaning. P_{sincr_count} and $P_{sHOincr_count}$ are used to restrict the repeated firing of $t_{sserv_increase}$ and $t_{sHO_increase}$. Besides, t_{sincr_count} , $t_{sconsume}$, $t_{sHO_consume}$, $t_{sconsume_count}$ and $t_{sHOcons_count}$ are to accept signals from P_{sserv_depart} , P_{sserv_count} , P_{sserv_count} , $P_{mHOsucc_count}$ and $P_{mHOsucc_count}$, respectively.

Similarly, the dynamic Capacity control for macro cell is the same as that for small cell, as shown in Fig. 3.15 (right), and the places and transitions in Fig. 3.15 are summarized in Table 3.10 and Table 3.11, respectively. Finally, the GFs of transaction processing submodel, servicing submodel, and capacity control submodel with handover are also summarized in Table 3.12.

Table 3.10: The description of places in Servicing submodel of small and macro cell.

Place	Description
$P_{sHOincr_count}$	Restrict repeated firing of $t_{sHO_increase}$
$P_{sHOcons_count}$	Restrict repeated firing of $t_{sHO_consume}$
$P_{mHOincr_count}$	Restrict repeated firing of $t_{mHO_increase}$
$P_{mHOcons_count}$	Restrict repeated firing of $t_{mHO_consume}$

Table 3.11: The description of transitions in small and macro cell Servicing submodel.

Transition	Description	Attribute
$t_{sHO_increase}$	Receive the signals from P_{sHO_depart}	IMM
$t_{sHOincr_count}$	Receive the signals from P_{sHO_depart}	IMM
$t_{sHO_consume}$	Receive the signals from $P_{mHOsucc_count}$	IMM
$t_{sHOcons_count}$	Receive the signals from $P_{mHOsucc_count}$	IMM
$t_{mHO_increase}$	Receive the signals from P_{mHO_depart}	IMM
$t_{mHOincr_count}$	Receive the signals from P_{mHO_depart}	IMM
$t_{mHO_consume}$	Receive the signals from $P_{sHOsucc_count}$	IMM
$t_{mHOcons_count}$	Receive the signals from $P_{sHOsucc_count}$	IMM

3.4.2.4 Underlying CTMC

Regarding the analysis of SPN models, there are marking-based analysis methods and Markov chain-based analysis methods. Since the marking-based analysis methods usually consume time. Therefore, in this paper, we used the Markov chain-based method to analyze the assumed SPN, and the transitions in the assumed SPN model all followed immediate or exponential distribution firing, so the assumed SPN could be analyzed by continuous-time Markov chain (CTMC) [19]. Based on basic methodology of the Markov chain, define $\mathbf{Q}$ be the infinitesimal generator matrix of the underlying CTMC. Then, the transaction loss rate, P_{loss} , is given by

$$P_{loss} = \frac{\lambda \boldsymbol{\tau} \mathbf{r}_{loss}}{\lambda \boldsymbol{\tau} \mathbf{1}}, \quad (3.13)$$

where $\boldsymbol{\tau}$ is the sojourn time in all states and $\boldsymbol{\tau} = (-1/q_{ii})$, with q_{ii} as the diagonal elements of $\mathbf{Q}$. Besides, λ denotes the arrival rate of UE, $\mathbf{r}_{loss}$ is the reward vector corresponding to the loss occurrence states, and $\mathbf{1}$ is a the column vector whose elements are all 1.

3.5 Numerical experiment

We assumed the following parameters in our model for performance analysis of the two-tier HetNet, as shown in Table 3.13. The intensity of small and macro cells was $3/\text{km}^2$ and $1/\text{km}^2$, respectively; the power of macro and small cells was 46 dBm and 30 dBm, respectively; the mean channel gain of both macro and small cell were $\frac{1}{\mu_a} = \frac{1}{\mu_b} = 1$; the SINR threshold of macro cell $T2$ was -7 dB, the threshold $T3$ for a handover was -10 dB; the number of available resource blocks both in macro and small cells were 6,

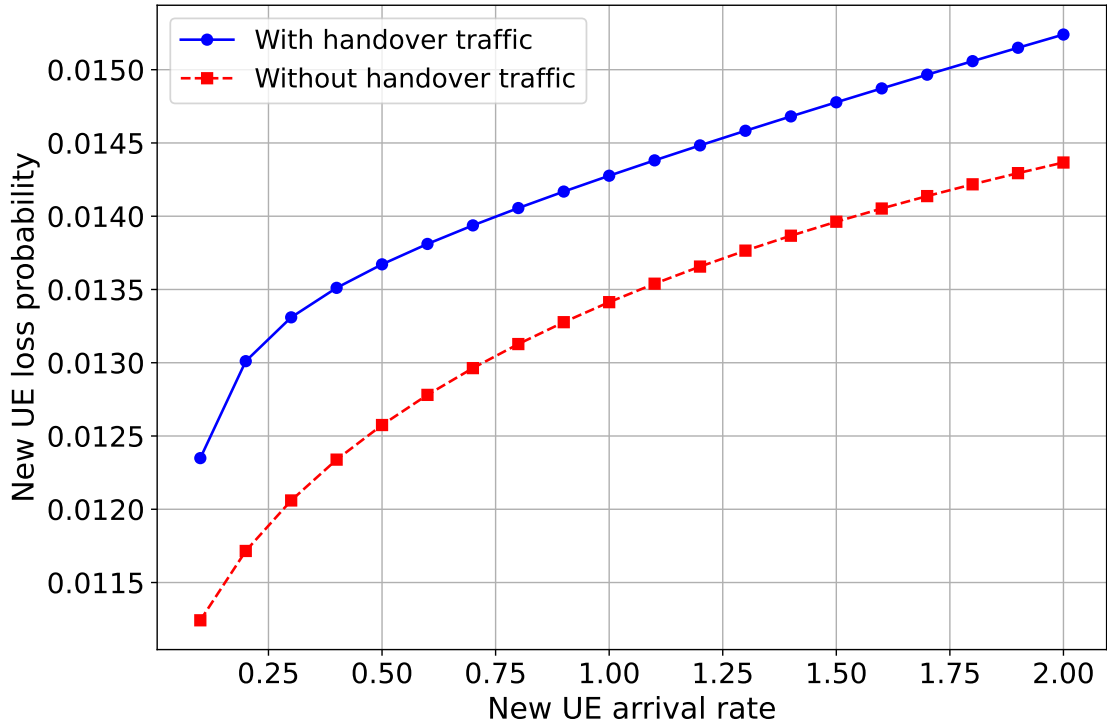
Table 3.12: Guard functions of SPN with handover.

Guard	Guar function
g_{s1}	$\#(P_{scap}) > 0$
g_{s2}	$\#(P_{mcap}) > 0$
g_{s_depart}	$\#(P_{sserv_depart}) == 1 \& \& \#(P_{sdepart_count}) == 0$
g_{m_depart}	$\#(P_{mserv_depart}) == 1 \& \& \#(P_{mdepart_count}) == 0$
g_{sserv_count}	$\#(P_{scons_count}) == 1 \& \& \#(P_{strans_count}) == 0$
g_{mserv_count}	$\#(P_{mcons_count}) == 1 \& \& \#(P_{mtrans_count}) == 0$
$g_{sdepart_count}$	$\#(P_{sserv_depart}) == 0$
$g_{mdepart_count}$	$\#(P_{mserv_depart}) == 0$
g_{sm_init}	$\#(P_{sHO_depart}) == 1 \& \& \#(P_{sm_init}) == 0$
g_{sm_exe}	$\#(P_{sHO_depart}) == 0 \& \& \#(P_{mcap}) > 0$
g_{sm_fail}	$\#(P_{sHO_depart}) == 0$
$g_{sHOsucc_count}$	$\#(P_{mHOservin_count}) == 1 \& \& \#(P_{mHOcons_count}) == 1$
g_{ms_init}	$\#(P_{mHO_depart}) == 1 \& \& \#(P_{ms_init}) == 0$
g_{ms_exe}	$\#(P_{mHO_depart}) == 0 \& \& \#(P_{scap}) > 0$
g_{ms_fail}	$\#(P_{mHO_depart}) == 0$
$g_{mHOsucc_count}$	$\#(P_{sHOservin_count}) == 1 \& \& \#(P_{sHOcons_count}) == 1$
g_{serv1}	$\#(P_{sserv_count}) == 1 \& \& \#(P_{strans_count}) == 0$
g_{serv2}	$\#(P_{mserv_count}) == 1 \& \& \#(P_{mtrans_count}) == 0$
g_{sserv_depart}	$\#(P_{sincr_count}) == 1 \& \& \#(P_{sdepart_count}) == 1$
g_{mserv_depart}	$\#(P_{mincr_count}) == 1 \& \& \#(P_{mdepart_count}) == 1$
g_{strans_count}	$\#(P_{sserv_count}) == 0$
g_{mtrans_count}	$\#(P_{mserv_count}) == 0$
g_{sc1}	$\#(P_{s_waiting1} < scap/N)$
g_{sc2}	$\#(P_{s_waiting1} < scap/N)$
g_{sc3}	$\#(P_{s_waiting1} < scap/N)$
g_{mc1}	$\#(P_{m_waiting1} < mcap/M)$
g_{mc2}	$\#(P_{m_waiting1} < mcap/M)$
g_{mc3}	$\#(P_{m_waiting1} < mcap/M)$
g_{sHO_depart}	$\#(P_{sm_init}) == 1 \& \& \#(P_{sHOincr_count}) == 1$
g_{mHO_depart}	$\#(P_{ms_init}) == 1 \& \& \#(P_{mHOincr_count}) == 1$
$g_{sHOserv_in}$	$\#(P_{mHOsucc_count}) == 1 \& \& \#(P_{sHOservin_count}) == 0$
$g_{sHOservin_count}$	$\#(P_{mHOsucc_count}) == 0$
$g_{mHOserv_in}$	$\#(P_{sHOsucc_count}) == 1 \& \& \#(P_{mHOservin_count}) == 0$
$g_{mHOservin_count}$	$\#(P_{sHOsucc_count}) == 0$
g_{incr1}	$\#(P_{sserv_depart}) == 1 \& \& \#(P_{sincr_count}) == 0$
g_{incr2}	$\#(P_{mserv_depart}) == 1 \& \& \#(P_{mincr_count}) == 0$
g_{con1}	$\#(P_{sserv_count}) == 1 \& \& \#(P_{scons_count}) == 0$
g_{con2}	$\#(P_{mserv_count}) == 1 \& \& \#(P_{mcons_count}) == 0$
g_{sincr_count}	$\#(P_{sserv_depart}) == 0$
g_{mincr_count}	$\#(P_{mserv_depart}) == 0$
g_{scons_count}	$\#(P_{sserv_count}) == 0$
g_{mcons_count}	$\#(P_{mserv_count}) == 0$
g_{sHO_incr}	$\#(P_{sHO_depart}) == 1 \& \& \#(P_{sHOincr_count}) == 0$
g_{sHO_count}	$\#(P_{sHO_depart}) == 0$
g_{sHO_cons}	$\#(P_{mHOsucc_count}) == 1 \& \& \#(P_{sHOcons_count}) == 0$
$g_{sHOcons_count}$	$\#(P_{mHOsucc_count}) == 0$
g_{mHO_incr}	$\#(P_{mHO_depart}) == 1 \& \& \#(P_{mHOincr_count}) == 0$
g_{mHO_count}	$\#(P_{mHO_depart}) == 0$
g_{mHO_cons}	$\#(P_{sHOsucc_count}) == 1 \& \& \#(P_{mHOcons_count}) == 0$
$g_{mHOcons_count}$	$\#(P_{sHOsucc_count}) == 0$

and the intra-cell interference cancellation parameter RHO was 0.5. The firing rate of T_{s_serv} and T_{m_serv} was 0.2 and 0.1, respectively; the firing rate of $T_{sserv_HOoccur}$ and $T_{mserv_HOoccur}$ was 0.2 and 0.2, respectively. The $p_1 = 0.025$, $p_2 = 40$. The number of queues N in Fig. 3.8 and Fig. 3.13 were both 3; the capacity $scap$ and $mcap$ were both 6.

Table 3.13: Parameter settings

Parameter	Description	Value
λ_a	the intensity of small cell in the plane	3 mc/km ²
λ_b	the intensity of macro cell in the plane	1 mc/km ²
P_a	the power of small cell	1 W
P_b	the power of macro cell	10 W
p	the probability of select small cell	0.5
μ_a	the channel gain of small cell	1
μ_b	the channel gain of macro cell	1
X	the paprameter of reservation channel	7
$\#T_{\text{arrival}}$	the arrival of UEs rate	1/4.5
$\#T_{\text{s_serv}}$	the small cell servicing rate	1/9
$\#T_{\text{m_serv}}$	the macro cell servicing rate	1/10
$\#T_{\text{sserv_HOoccur}}$	the small cell handover rate	1/3
$\#T_{\text{mserv_HOoccur}}$	the macro cell handover rate	1/4

**Figure 3.16:** New UE loss probability with and without handover traffic.

3.6 Summary

In this Chapter, Since the assumed UE service time distribution in the Het-Net and the A2 event trigger time distribution was based on the exponential distribution. However, the time cumulation based on the exponential distribution is often too desirable; thus, the service time based on the general distribution and the trigger time of events A2 and A4 may be modeled and analyzed to consider the specific movement of the UE in a cell, which will be considered in future work. Moreover, with the model, more comprehensive network performance metrics such as handover call drop probability, average users in

the network, average delay, and throughput of the network will be considered in the future. After this, simulation-based approach will be used to verify the accuracy of the model.

Chapter 4

Modeling analysis of handover properties and design of handover decision-making algorithms

In Chapter 3, we established a theoretical framework to analyze the impact of frequent handovers on resource blocking. However, that analysis treats all handovers as homogeneous events, without distinguishing between their directional characteristics. In reality, one of the core factors behind frequent and inefficient handovers lies in the decision-making phase, where flawed logic fails to consider the asymmetry between different handover directions.

As discussed in Chapter 2, conventional HDMA algorithms such as A3RSRP—apply direction-agnostic logic, triggering handovers based solely on RSRP comparisons without recognizing whether the transition is from a macrocell to a small cell (M2S) or from a small cell to a macrocell (S2M). This oversimplification becomes a critical flaw in HetNets, where macrocells and small cells differ significantly in terms of transmission power, coverage, and service stability.

This directional asymmetry results in fundamentally different behaviors in terms of handover trigger probability (HoT), handover failure probability (HoF), and user dwell time, especially for high-speed UEs. For instance, handing over a fast-moving UE to a small cell with a limited coverage area often leads to rapid handover reversals (ping-pong effects) and communication degradation. Therefore, a deep quantitative understanding of directional handover behaviors is essential before designing intelligent handover algorithms.

To address this, the first part of this chapter develops a direction-aware continuous-time analytical model to distinguish and analyze M2S and S2M handovers. Building on the SPN-PPP framework introduced in Chapter 3, we propose a novel extension named Do-SPN-PPP (Direction-Oriented SPN over Poisson Point Process). This framework incorporates continuous-time Markov chains (CTMCs) to model UE state transitions

between macro and small cells in a spatially random HetNet environment.

Through this model, we quantitatively analyze how M2S and S2M handovers differ in terms of HoT and HoF, and how key parameters such as the handover margin (HOM) affect direction-specific performance and user residence times. Our findings show that traditional discrete-time models often underestimate these effects, while the proposed continuous-time model achieves greater predictive accuracy.

In the second part of this chapter, we shift focus to designing an intelligent, direction-aware handover decision algorithm. While traditional HDMA lack the ability to identify the type of the target cell, each base station in a 5G network carries a unique NR Cell Identity (NCI), which includes the gNB ID. Inspired by this, we propose an NCI-aware handover mechanism that semantically extends the 22-bit gNB ID by reserving the top 2 bits to encode the gNB type—macrocell, Sub-6GHz small cell, or mmWave gNB.

By parsing this encoded gNB type, either the UE or the network can intelligently interpret the nature of the candidate target cell during the handover decision phase. This enables smarter strategies, such as preventing high-speed UEs from switching to cells with limited coverage (e.g., mmWave cells), thereby avoiding suboptimal decisions and improving mobility robustness in dynamic environments.

Collectively, the research in this chapter constructs a full-stack solution to the “direction-blindness” problem in handover logic, by integrating directional modeling, cell type identification, and intelligent decision-making into a coherent and theoretically grounded framework.

4.1 Overview of the A3RSRP HDMA

A3RSRP HDMA is another important handover algorithm for smooth switching of UE communication connections between different cell in mobile communication networks, which is more commonly used in LTE and 5G networks than A2A4RSRQ HDMA, and is the main HDMA in mobile communication networks.

Compared to A2A4RSRQ HDMA, which is mainly used in communication environments with strong interference, the A3RSRP HDMA is mainly used in scenarios dominated by signal strength, especially scenarios dominated by significant variations of received signal strength and path loss, and is able to effectively manage the handover of UE between different cells to ensure that the UE can always be connected to a cell with a stronger signal and ensure the quality of the communication environment.

Specifically, the UE measures the RSRP from different surrounding cells in real-time, and when the UE receives an RSRP from a T-cell that is greater than the RSRP of the S-cell by a certain value of handover margin (HOM) for the next period of time interval TimeToTrigger (TTT), and then triggers the handover execution process that from the S-cell to the T-cell [20], as shown in Fig. 5.3. These conditions within the A3RSRP HDMA that the difference between the RSRP of the T-cell and the S-cell is referred to

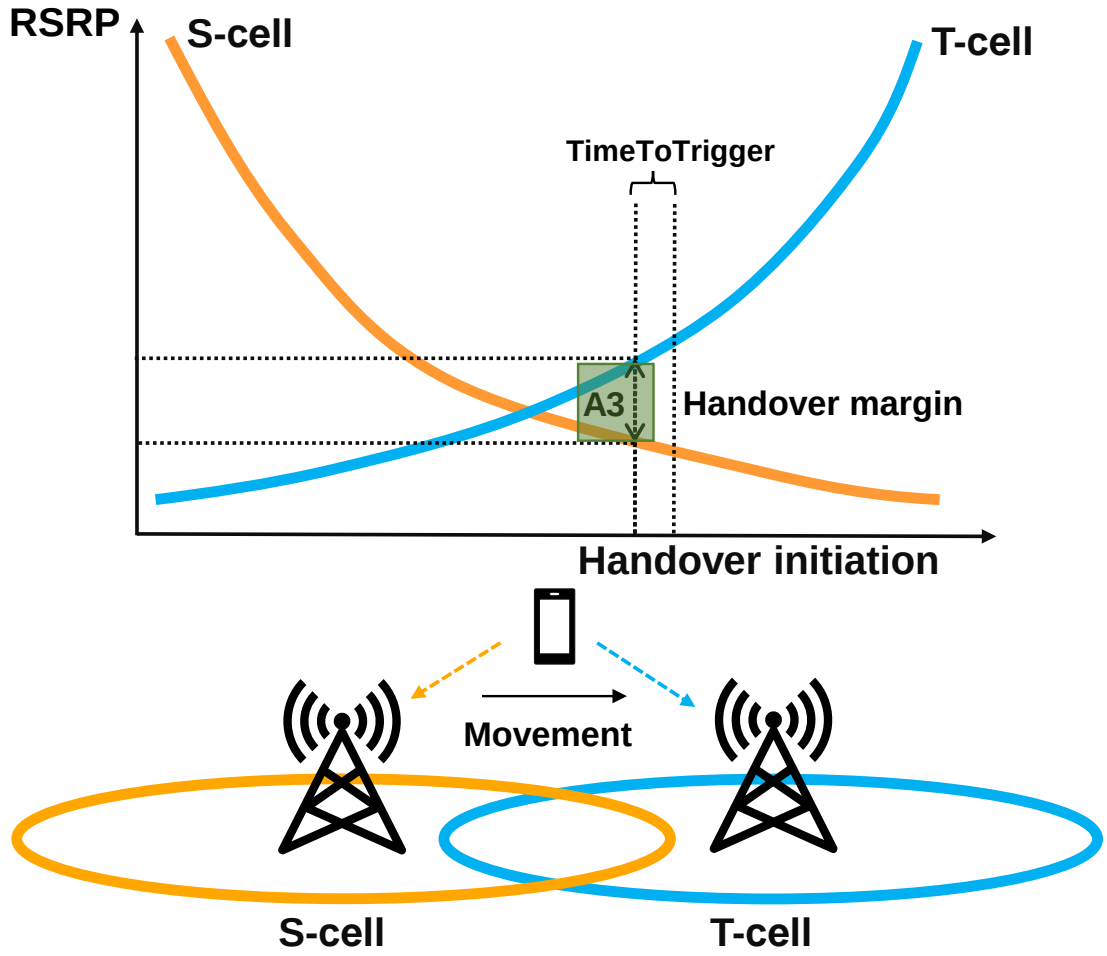


Figure 4.1: A3RSRP handover decision-making algorithm.

as an A3 event, and the trigger condition for event a3 can be written in the following form:

$$RSRP_t - RSRP_s > HOM, \quad (4.1)$$

- A3 event (HOM): refers to the measurement event that triggers the switching process when the signal strength of the neighboring area exceeds the signal strength of the serving cell plus a preset offset.
- TTT: refers to the time threshold at which this event condition needs to be continuously satisfied for a certain period of time before triggering the action.

The selection of parameters HOM and TTT has a great impact on the probability of the UE's handover triggering and the probability of the HoF occurring, as well as on the residence time in a cell.

However, A3RSRP HDMA exhibits high number of the HoF and ping-pong han-

dover performance problems due to inappropriate parameter setting [21], fading, and shadowing even though the A3RSRP HDMA is mainly used in scenarios with significant signal strength fluctuations.

Even though the UE is not moving, its received signals are affected by fading and shadowing, which also show obvious fluctuation, resulting in the A3RSRP HDMA not being able to distinguish perfectly whether the UE's handover is due to a genuine environmental change or due to the effects of fading and shadowing, and thus making wrong handover trigger judgment. Therefore, researchers have conducted a lot of optimization studies on HOM and TTT to make up for the design deficiencies of A3RSRP HDMA.

However, researchers have ignored an important problem when performing optimization; the HetNet communication environment is different from homogeneous networks, and the difference in output power between macro cell and small cell is huge, which leads to different communication conditions for UEs when triggering a handover based on the judgment of formula (4.1).

In other words, macro-to-small (M2S) and small-to-macro (S2M) handover are two different handovers in HetNet.

Therefore, it is necessary to analyze the impact of A3 events on different handover directions when qualitative and quantitative analyses of handovers, because it can reveal the characteristics of the different handover directions in HetNet and provide more specific and accurate policies or suggestions for the subsequent optimization of handover within HetNet.

4.2 Related research on optimization and analysis of A3RSRP HDMA topics

The literature related to qualitative and quantitative analysis in evaluating handover performance can be categorized according to the approach used, which is as follows:

- Measurement-based,
- Simulation-based,
- Theoretical analysis modeling-based,
- Formal modeling-based,

where simulation and modeling-based approaches are widely accepted in handover research. Hence, researchers prioritize the performance evaluation of handover based on the simulation and modeling as a low-cost approach compared with the measurement-based. This paper focuses on the literature related to modeling and simulation-based approaches.

4.2.1 Theoretical analysis based

The literature on analytical modeling techniques focuses on the use of the Poisson point process (PPP) because the modeling based on the PPP is tractable and spatially averaged, which provides direction and methodology for researchers to analyze large and stochastic networks quantitatively [22].

ElSawy and Hossain [23] proposed a closed expression for increasing small-cell coverage by enabling the small-cell to be cognizant of macro-cell interference in a two-tier HetNet. However, the authors have not discussed the handover properties of the UE in the HetNet.

Vasudeva et al [24] presented a geometric model and analyzed the impact of velocity and TTT on the handover probability and HoF in fading and no-fading environments. However, the authors have not considered the impact of the A3 event on the handover and HoF probabilities.

Suarez Rodriguez et al [25] proposed a base station association analysis model based on environment maps and evaluated the handover overhead. In addition, the optimal radius of the associated base stations is determined by defining throughput optimization. Then, the rationality of the proposed model is verified using the Monte Carlo simulation. However, the authors only focus on the UE throughput.

Arshad et al [5] proposed an analytical model considering the antenna height of UE, then analyzed the effect of antenna height on the performance of associated base station probability and handover frequency, and finally verified the reasonableness of the model through Monte Carlo simulation.

Soltani et al [26] proposed an analytical model for handover in indoor-based optical attocell networks, which considers the variation in handover performance due to the rotation angle of the user device and evaluates the performance of the handover probability of the UEs in this network, and finally validates the model through Monte Carlo simulations.

4.2.2 Formal modeling-based

Researchers primarily use Petri Net and Markov chain-based modeling approaches to characterize and analyze handover behavior within the formal modeling-based approaches.

Lee et al [30] assumed the vehicle's handover as a discrete-time Markov chain (DTMC) and proposed a method to determine the T-cell. The result shows the effectiveness of the proposed model in improving the vehicle throughput.

He et al [27] used a combination of the PPP and DTMC to model handover in a homogeneous network and evaluated the impact of HOM and TTT parameters on the performance of the HoF and ping-pong handover probabilities. However, the authors considered a homogeneous network environment. Hence, the assumptions and conclusions can not apply to the HetNet environment. Guidolin et al [31] proposed a DTMC

Table 4.1: Comparison of different approaches in handover analysis

Research work	Approach	Analysis metrics	Handover direction analysis based on A3 event	A3 event impact on UE residence time	Computational efficiency analysis
Vasudeva et al. [24]	Geometric model	HoF & HoT	✗	✗	✗
He et al. [27]	PPP + DTMC	HoF & ping-pong handover in homogeneous networks	✗	✗	✗
Zhang et al. [28]	DTMC	HoT & throughput	✗	✗	✗
Balakrishnan et al. [29]	DTMC	handover cost & interruption time	✗	✗	✗
Do-SPN-PPP (proposed)	SPN + PPP	HoF & HoT within HetNet	✓	✓	✓

framework that evaluated the average capacity of UEs at different speeds and the impact of TTT parameters on the average capacity and determined the optimal TTT parameters at different speed scenarios. Zhang et al [28] modeled a network with only one macro-cell and one small-cell using DTMC and evaluated the performance impact of the HOM on the handover probability and throughput. However, the authors considered an oversimplified network environment and did not consider the direction of handover or the impact of HOM on HoF probability.

Balakrishnan and Akyildiz [29] proposed a local anchor-based handover mechanism and an evaluation framework based on DTMC, through which closed-form expressions for handover cost and handover interruption time can be derived, and the results of Monte Carlo simulation show that although the proposed framework has a gap between the numerical and the simulation results, the trend of the both of the results is the same.

Moreover, several works use the formal modeling-based approach to evaluate the probability of handover packet loss (HPL) due to a lack of network resources under the assumption of a fully loaded state in queueing theory.

Yang et al [9] modeled the handover behavior of users between 3G and WLAN and evaluated the new UE packet loss and the HPL probability based on the assumption of link capacity limit for 3G and WLAN. Gautam and Dharmaraja [32] modeled the call admission control (CAC) protocol using SPN and evaluated the HPL and the packet loss for the new UE due to the full load. Alioua et al [33] also modeled the handover under the CAC protocol using SPN by assuming handover as a queueing model and evaluated

the HPL probability and repeated handover probability by assuming the general number of channels and the number of channels dedicated to handover.

In our previous work [34], we modeled a two-tier HetNet using SPN and evaluated the HPL probability performance of the A2A4RSRQ HDM under the full load of the network based on the assumptions of the upper capacity limit of the network channel and the UEs reaching the network following a Poisson distribution. In [35], the authors modeled vertical handover between Wi-Fi and cellular using an SPN and discussed the HoF probability at the state of the full-capacity network. Nevertheless, the probability of HoF based on the state of the full-capacity network was considered in both cases, whereas the probabilities of HoF and HoT due to inappropriate HOM or TTT parameter settings were not considered.

In our latest work [36], we modeled the A3 event using a PPP and a stochastic Petri Net and investigated the probability of HoT and HoF. Consequently, this paper differs from our latest work in that we improved the model and included a quantitative analysis of the impact of the A3 event on the UE's different handover directions and the residence time of the UE in a cell, as well as validated the reasonableness of the proposed model through Monte Carlo simulation.

In a recent paper [37], the authors have modeled a highway scenario using CTMC for vehicular mobility that contains an overtaking model and evaluated the impact of vehicle overtaking on communication delays and travel times. However, the authors did not consider the vehicle's handover scenario. In addition, the authors mention the limitations of the formal modeling approach based on DTMC when evaluating highways.

Due to the short time granularity and very high randomness of the signal changes under the influence of fading in mobile communication networks, the HDM process is strongly influenced by the signal variations, resulting in the UE's handover behavior not being discrete.

However, they have not used continuous time-based modeling approaches to analyze the handover behavior in different directions, and no one considered the impact of A3 events on M2S and S2M handover, neither in analytical and formal modeling-based works nor simulation-based works. Therefore, it is necessary to consider and practice the handover behavior of UEs through continuous time modeling to qualitatively and quantitatively analyze the impact of the A3 event on handovers in different directions and explore the limitations of discrete time in analyzing handovers compared to continuous time.

4.2.3 Improvement of the handover decision-making

On the other hand, Recently, there has been a lot of research on high-speed mobility management and handover optimization. Some of the work focuses on using user mobility information to optimize handover decisions. In [38], fuzzy logic control is used to dynamically optimize the handover trigger timing based on UE speed and the cell

size of a gNB, thereby reducing handover failures and ping-pong handovers. In [39], a HDMA is proposed for UE speed and service type that prevents the UE speed between 15 km/h and 30 km/h from handover to small cells by considering the UE service type and speed to maintain the downlink throughput. In [40], an adaptive handover scheme is proposed to adjust the threshold of the absolute value of RSRP to adjust the handover trigger conditions according to the UE speed. In [41], a HDMA based on multiple parameters, including received signal strength (RSS), equivalent RSS, handover margin (HOM), UE speed, quality of service (distinguishing between real-time services), and available bandwidth, is proposed. This HDMA aims to encourage high-speed users to either stay within or hand over to the macro base station to prevent frequent handovers.

Additionally, machine learning and reinforcement learning techniques have been widely applied to optimize 5G handovers. In [42], a data-driven approach is employed, utilizing a multi-layer perceptron model to adaptively adjust handover control parameters such as HOM and Time-to-Trigger (TTT), while considering numerous factors, including UE speed, RSRP, SINR, and load. This approach has proven effective in achieving a significant reduction in handover failure rates, handover times, and ping-pong handover rates. In [43], a convolutional neural network (CNN)-long short-term memory (LSTM) deep learning model is employed to predict UE trajectories, enabling the selection of the target gNB in advance. This approach significantly reduces the number of unnecessary handovers and enhances service continuity. In [44], it proposes an adaptive user-centric virtual cell handover decision oriented towards connectivity, which uses reinforcement learning with indicators such as RSRP and SINR to ensure the seamless connection of the UE to the virtual cell, thereby maintaining the stability of the communication channel for high-speed UEs. In [45], it proposes a deep reinforcement learning algorithm based on deep deterministic policy gradient (DDPG) to optimize the handover parameters autonomously. The thresholds, such as HOME, can be dynamically adjusted according to the environment, thereby enhancing the robustness of mobility at different speeds while maintaining high throughput and low latency. However, these learning-based solutions are predicated on a large amount of training data and offline optimization and are still insufficient for real-time response to network changes. Furthermore, these approaches do not use cell-level information.

Moreover, the communication environment for high-speed UE handover to mmWave cells is unstable due to high loss for mmWave gNBs after blocking obstacles. In [46], an intelligent handover mechanism is proposed that can dynamically fine-tune parameters such as HOM and TTT based on the real-time SINR to achieve a fast response to the drastic fluctuations of mmWave channels. In [47], it is designed to minimize handover interruption time by incorporating backhaul delay considerations during handover signaling exchange. Additionally, it employs a transmission control protocol (TCP) proxy to ensure lossless data transmission following handover.

The existing research on optimizing handover decisions in 5G high-speed environ-

ments heavily relies on instantaneous channel measurement indicators and parameter tuning. However, existing research does not adequately address the gNB type information carried by the NR cell identity (NCI). As a result, the current handover decision mechanism lacks knowledge of the characteristics of the target cell when determining whether to trigger a handover. In other words, neither the gNB nor the UE knows whether the target base station is a macro cell, a sub-6GHz small gNB, or an mmWave gNB. This oversight can lead to frequent handovers, causing an unstable communication environment.

4.3 Improved the framework based on A3RSRP HDMA

4.3.1 Overview of framework improvements

The A2A4RSRQ and A3RSRP HDMA are two different HDMA because they use two completely different measurement indicators of the signal for the handover decision-making. Therefore, it is necessary to modify and optimize the previously proposed framework according to the characteristics of A3RSRP HDMA so that it can accurately analyze the performance of A3RSRP HDMA.

Firstly, in the PPP part, the RSRQ received by the user is defined in Chapter 3, while RSRQ and RSRP are two different measurements. Therefore, the same assumptions need to be performed additionally for RSRP.

Furthermore, we discussed and analyzed in Chapter 3 about the performance of handover in the insufficient resources scenario. To discuss the impact of inappropriate parameter setting on the handover performance, it is necessary to exhaust the impact due to insufficient resources in order to analyze and quantify the impact due to inappropriate parameters more accurately. Therefore, it is also necessary to design and optimize the proposed SPN within Chapter 3 for analysis of the inappropriate parameter.

4.3.2 Optimized framework for A3RSRP HDMA

For the PPP part, no changes to the topology of the network have been made and it remains a two-tier HetNet.

Specifically, the macro-cell is distributed according to PPP $\Phi_{m_i} = \{m_i \mid i = 1, 2, 3, \dots\}$ with the intensity λ_m , and the small-cell is distributed according to PPP $\Phi_{s_i} = \{s_i \mid i = 1, 2, 3, \dots\}$ with the intensity λ_s . Each PPP is independent and identical distribution and represented in $\mathbb{R}^2$ plane. The output power of the macro-cell and the small-cell are P_m and P_s , respectively.

Therefore, based on the above assumptions, a typical UE received RSRP from the macro-cell and small-cell in a HetNet can be described as follows,

$$RSRP_s = P_s G_{s_i} D_{s_i}^{-\eta}, RSRP_m = P_m G_{m_i} D_{m_i}^{-\eta}, \quad (4.2)$$

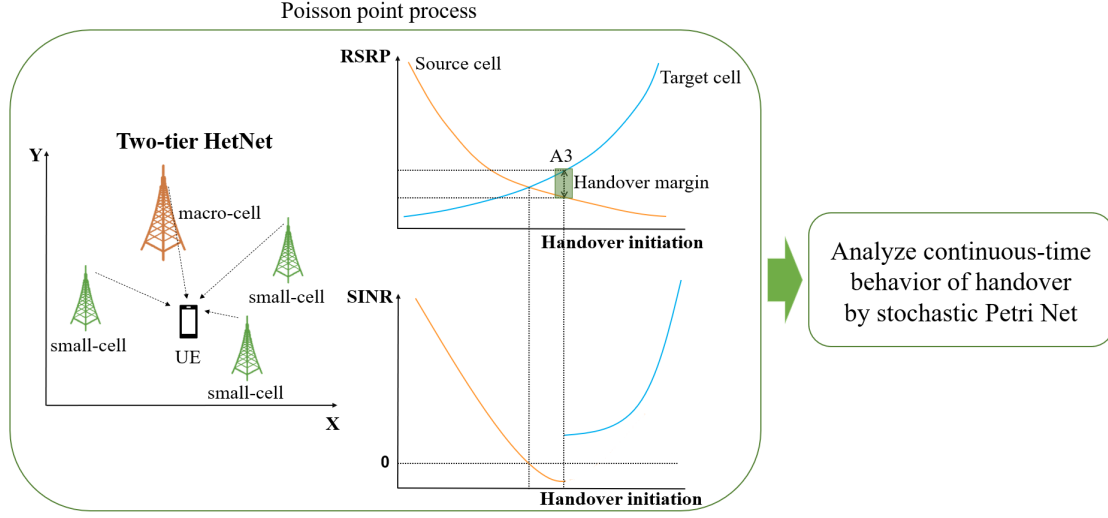


Figure 4.2: A framework based on the Poisson point process and stochastic Petri Net

where $RSRP_s$ and $RSRP_m$ denote the RSRP received by the UE from the small-cell and macro-cell, respectively; G_{s_i} with intensity μ_s and G_{m_i} with intensity μ_m denote the random variables of channels by Rayleigh distribution for the small-cell and macro-cell, respectively; D_{s_i} and D_{m_i} are denoted as the random variables of distance until the UE for the small-cell and macro-cell, respectively; η denotes the exponent of path-loss.

Consequently, we follow [23] and define the handover direction by the A3 event for the UE in the two-tier HetNet as the following lemma respectively:

Lemma 1. *In the two-tier HetNet, the cumulative distribution function (CDF) of the A3 event that is satisfied when the UE triggers the S2M handover is given by*

$$\zeta_{sm} = 1 - \int_0^\infty \frac{\lambda_s}{\lambda_m \left(\frac{P_m}{P_s \cdot T_{HOM}} g \right)^{\frac{2}{\eta}} + \lambda_s} \cdot \frac{\mu_s \mu_m}{(g \lambda_m + \mu_s)^2} dg. \quad (4.3)$$

The CDF of the A3 event that is satisfied when the UE triggers the M2S handover is given by

$$\zeta_{ms} = 1 - \int_0^\infty \frac{\lambda_m}{\lambda_s \left(\frac{P_s}{P_m \cdot T_{HOM}} g \right)^{\frac{2}{\eta}} + \lambda_m} \cdot \frac{\mu_s \mu_m}{(g \lambda_s + \mu_m)^2} dg, \quad (4.4)$$

where T_{HOM} denote the parameter HOM within the A3 event.

Proof: The detailed proof is provided in A.16.

Furthermore, as shown in Fig. 4.1, the A3 event occurs after the RSRP of the T-cell is larger than the RSRP of the S-cell. Therefore, the SINR of the UE is less than 0 dB. At the same time, the UE's HoF occurs due to poor SINR by the co-frequency after the A3 event is satisfied in the HetNet. Thus, we assume that the HoF occurs before the

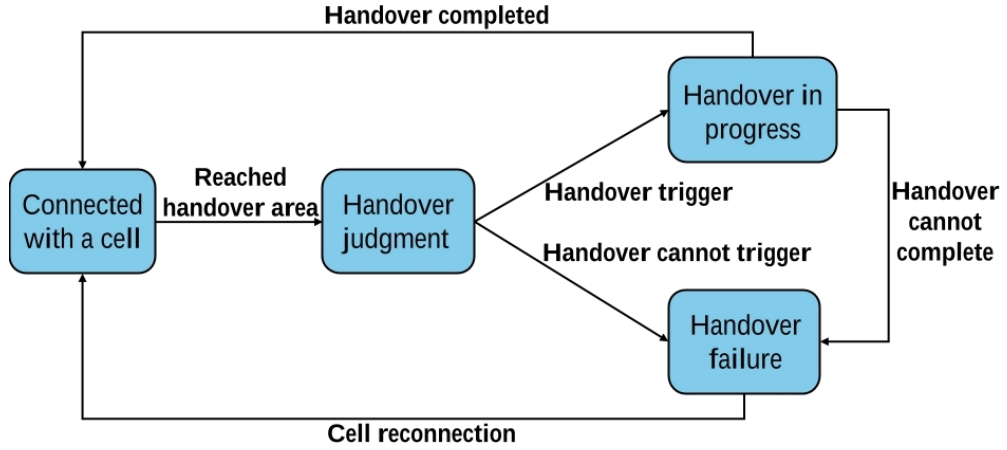


Figure 4.3: SPN modeling process

UE enters the HOE process after the A3 event is satisfied. On the other hand, even if the UE completed the HDM process and entered the HOE process before its SINR deterioration, there is a possibility that the UE may experience HoF during the HOE process due to the poor SINR of the T-Cell. Accordingly, the CDFs of the SINRs of the UE that in the small-cell and macro-cell when it is less than a certain threshold are $\tau_s = \mathbb{P}\{SINR_s < T_{out}\}$ and $\tau_m = \mathbb{P}\{SINR_m < T_{out}\}$ [23], respectively.

For the SPN part, in order to exclude the problem of insufficient resources described in Chapter 3, we remove the capacity model of Fig. 3.11 and Fig. 3.10, as well as the servicing process assumption part of the SPN in Fig. 3.13 and Fig. 3.14. Consider a more concise SPN and its modeling process as the description after.

The modeling process of the SPN is illustrated in Fig. 4.3. A UE is initially connected to a random cell in a HetNet, and we consider that the UE will connect with a macro cell because the coverage of a macro cell is significantly larger than that of a small cell. Moreover, the UE has mobility in the network, such as pedestrians, vehicles, and subways in the city. Therefore, the UE reaches the handover area and determines whether the handover can be triggered according to the A3 event after a period of time, the handover is triggered if the A3 event is satisfied; otherwise, handover failure occurs because the communication environment of the UE in the S-cell is not desirable by selecting an inappropriate HOM parameter. On the other hand, although the handover is triggered, there is a HoF due to the selection of inappropriate HOM parameters, resulting in an undesirable communication environment and poor SINR before the handover is completed; otherwise, the handover is completed.

The SPN with an initial token in P_{m_serv} is illustrated in Fig. 4.4, where P_{m_serv} and P_{s_serv} denote the exponential states that indicate the UE connected with a macro and small cell before a handover, respectively. Let $P_{sm_JugHoCond}$ and $P_{ms_JugHoCond}$ denote the immediate state that determines whether a UE can trigger handover. Let $P_{sm_ho_init}$ and $P_{ms_ho_init}$ denote the exponential state in which a UE successfully

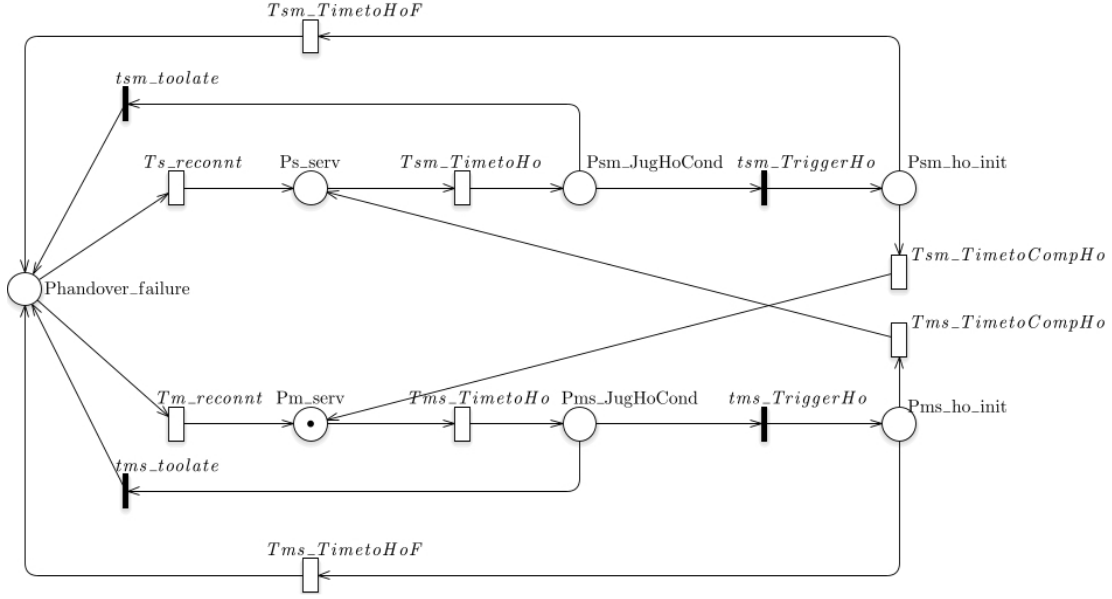


Figure 4.4: UE transaction behaviors before and after a handover by SPN

triggers handover in the small and macro cells, respectively. Because the coverage area of the macro cell is large, and the coverage area of a small cell is small within a macro cell, we only consider the handover between the macro and small cells. $P_{\text{handover_failure}}$ denotes the exponential state in which a UE fails to trigger or complete handover, resulting in HoF.

Let $T_{\text{sm_TimetoHo}}$ and $T_{\text{ms_TimetoHo}}$ denote the UE reaching the area where the handover should be triggered in a small and macro cell, respectively, and the firing rate of both of them follow an exponential distribution with an intensity of α_1 .

Let $t_{\text{sm_TriggerHo}}$ and $t_{\text{ms_TriggerHo}}$ denote the probabilities that a UE successfully triggers handover, which indicates the handover trigger condition is satisfied based on the CDFs, as expressed in Eq. (4.3) and Eq. (4.4).

Let $t_{\text{sm_toolate}}$ and $t_{\text{ms_toolate}}$ denote the probability that a UE fails to trigger handover in the small and macro cells after the firing of $T_{\text{sm_TimetoHo}}$ or $T_{\text{ms_TimetoHo}}$, respectively, which indicates the handover triggering condition is not satisfied resulting in HoF.

Let $T_{\text{sm_TimetoHoF}}$ and $T_{\text{ms_TimetoHoF}}$ denote a UE successfully triggering handover in the small and macro cells, respectively, but failing to complete the triggered handover process results in HoF. The firing rates of both of them follow an exponential distribution with an intensity α_2 .

Let $T_{\text{sm_TimetoCompHo}}$ and $T_{\text{ms_TimetoCompHo}}$ denote a UE that successfully triggers a handover and completes handover in the small and macro cells, respectively, and the firing rate of both of them follows an exponential distribution with an intensity α_2 .

Let $T_{\text{s_reconnt}}$ and $T_{\text{m_reconnt}}$ denote a UE randomly reconnects a cell after the HoF, and the firing rate follows an exponential distribution with an intensity α_2 .

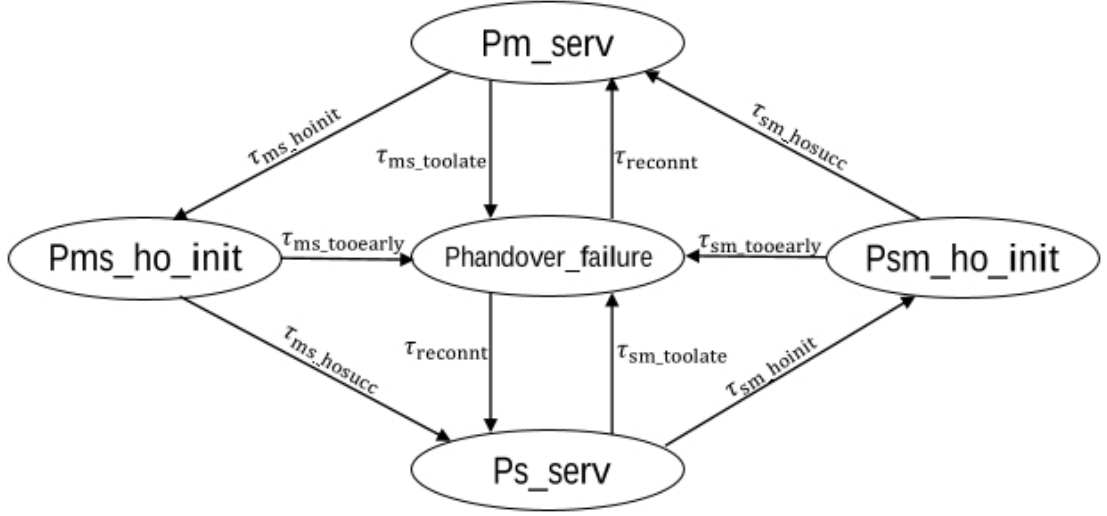


Figure 4.5: Underlying CTMC by the SPN

Fig. 4.4 illustrates an SPN that only includes the transition with the immediate and exponential firing. The SPN after the conversion to CTMC is illustrated in Fig. 4.5. For each transition rate, refer to Tab. 4.2

As described in Fig. 4.4, the P_{m_serv} and P_{s_serv} denote the states of a UE connected with a macro and the small cell, respectively.

Let $P_{sm_ho_init}$ and $P_{ms_ho_init}$ denote the states of a UE successfully triggering a handover in the small-cells and a macro-cell, respectively. $P_{handover_failure}$ denotes the state of a UE that fails to trigger handover.

Therefore, it is convenient to use the properties of the CTMC to derive the steady-state distribution of the CTMC in Fig. 4.5, as follows:

$$\pi_i \mathbf{1} = 1, \quad \pi_i \mathbf{Q} = \mathbf{0}, \quad (4.5)$$

where π_i is the steady-state distribution of the CTMC and i is $\{1, 2, 3, 4, 5\}$, corresponding to the five states P_{m_serv} , $P_{ms_ho_init}$, $P_{handover_failure}$, P_{s_serv} , and $P_{sm_ho_init}$ in the CTMC in Fig. 4.5. $\mathbf{Q}$ is the transition rate matrix of the CTMC.

Consequently, we can derive the steady-state distribution of states P_{m_serv} , P_{s_serv} , $P_{handover_failure}$, $P_{sm_ho_init}$, and $P_{ms_ho_init}$ in the CTMC by the two equations in Eq. (4.5).

4.4 Preliminary results based on improved framework SPN-PPP

The HOM parameter in the A3RSRP HDA can be selected from a range of $[-15, 15]$ dB in increments of 0.5 dB. However, the power outputs of a small cell are typically

Table 4.2: Numerical experiments parameter setting

Parameters	Value
P_b	46 dBm
P_a	32 dBm
HOM	[0.0, 10.0] dB
λ_a	10 km^{-2}
λ_b	1 km^{-2}
μ_a, μ_b	1
η	4
T_1	-10 dB
α_1	1/5
α_2	1/1
τ_{reconnt}	α_2
$\tau_{\text{ms_init}}$	$\alpha_1 \times \xi_{\text{ms_ho}}$
$\tau_{\text{sm_init}}$	$\alpha_1 \times \xi_{\text{sm_ho}}$
$\tau_{\text{ms_toolate}}$	$\alpha_1 \times (1 - \xi_{\text{ms_ho}})$
$\tau_{\text{sm_toolate}}$	$\alpha_1 \times (1 - \xi_{\text{sm_ho}})$
$\tau_{\text{ms_tooeearly}}$	$\alpha_2 \times \zeta_m$
$\tau_{\text{sm_tooeearly}}$	$\alpha_2 \times \zeta_s$
$\tau_{\text{ms_hosucc}}$	$\alpha_2 \times (1 - \zeta_m)$
$\tau_{\text{sm_hosucc}}$	$\alpha_2 \times (1 - \zeta_s)$

low. Thus, the RSRP received by the UE from a small cell is not expected to be 15 dB higher than the RSRP received from a macro cell. In addition, choosing a small HOM value as the handover parameter leads to FHOs, resulting in significantly unstable communication with the UE. Therefore, we considered the value of the HOM in [0.0, 10.0] dB for a reasonable parameter setting.

4.4.1 Handover failure and handover trigger probability

In this paper, the performance of the HoF and HoT probabilities is interesting: if these two handover performance measures of a network remain acceptable as its operation time tends to infinity, then the system design and parameter setting are considered reasonable.

Based on the CTMC steady-state distribution in Eq. (4.5), the expressions for the HoF and HoT measures considered in this paper can be derived as follows:

$$P_{\text{HoF}} = \pi_3, P_{\text{HoT}} = \pi_2 + \pi_5 \quad (4.6)$$

where P_{HoF} and P_{HoT} denote the HoF and HoT probabilities in the steady-state distribution in Eq. (4.5). π_3 , π_2 , and π_5 denote the probability distributions of $P_{\text{handover_failure}}$, $P_{\text{ms_ho_init}}$, and $P_{\text{sm_ho_init}}$ states in π_i , respectively. Consequently, the effect of HOM on the performance measures of the P_{HoF} and P_{HoT} probabilities can be observed by

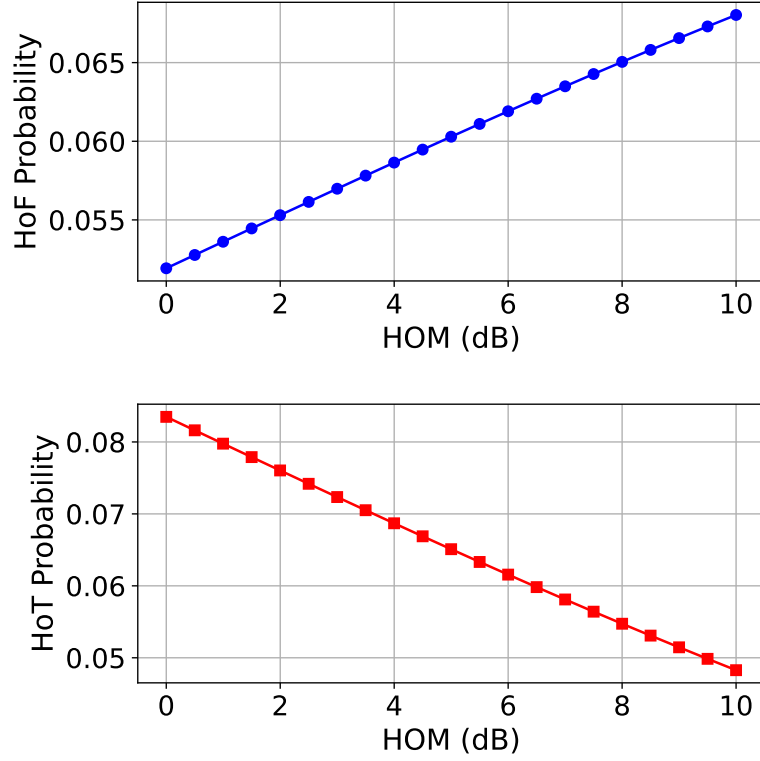


Figure 4.6: HoF and HoT probabilities

changing the handover parameter HOM in Eq. (4.3) and Eq. (4.4), and the results are presented in Fig. 4.6.

Fig. 4.6 consists of two sub-figures, where the upper sub-figure illustrates the HoF probability variation with HOM and the lower sub-figure illustrates the HoT probability variation with HOM . The results show that as the HOM increases, the HoF probability increases while the HoT probability decreases. These results are the same as those described in [16][48].

Specifically, the triggering conditions for handover become more difficult as HOM increases continuously, worsening the SINR of the UE before the triggering of handover and the occurrence of an HoF. Conversely, although the HoF probability increases when the HOM increases continuously, the HoT probability becomes lower because the probability of the UE triggering handover decreases by more difficult handover triggering condition, and the UE does not have to experience significant unstable communication due to excessive handovers, FHOs. Therefore, the trade-off between the two performance measures can be obtained from the results of the HoF and HoT probabilities, as shown in Fig. 4.7.

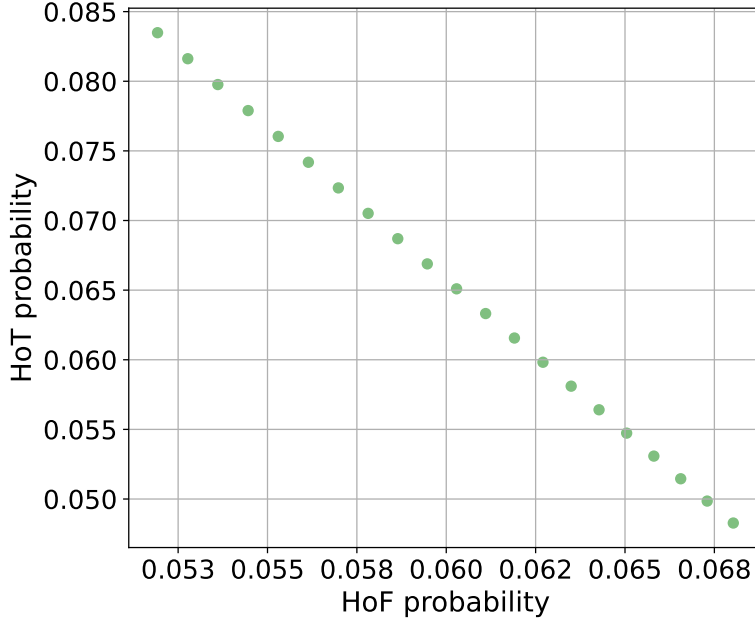


Figure 4.7: The trade-off between the HoF and HoT probabilities

Table 4.3: Optimal HOM parameter setting

HOM value	HoF probability	HoT probability
6 dB	0.06190705	0.06156111

4.4.2 Simple examination of optimal handover margin

The HoF and HoT probabilities are both lower and better for the UE because they indicate that the network communication is more reliable and stable. Simultaneously, the HoF and HoT probabilities variation with the HOM exhibit a trade-off relationship, as shown in Fig. 4.7.

Therefore, in this paper, we define the HOM, which minimizes the absolute value of the difference between the HoF and HoT probabilities, as the optimal handover performance parameter. The variation in the absolute value of the difference between the HoF and HoT probabilities for each value of HOM is illustrated in Fig. 4.8.

Fig. 4.8 presents the absolute value of the difference between the HoF and HoT probabilities, which shows a trend of an initial decrease followed by an increase as HOM increases. Moreover, when the parameter HOM is 6.0 dB, the absolute value of the difference between the HoF and HoT probabilities is minimized. Therefore, we conclude that the handover performance is optimal when the HOM is 6.0 dB. The corresponding values of the HoF and HoT probabilities are listed in Tab. 4.3.

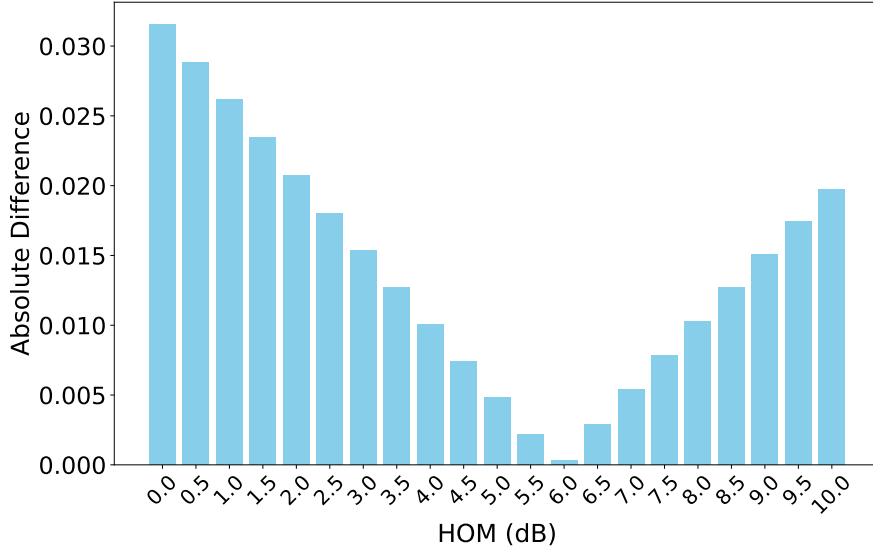


Figure 4.8: Absolute difference between HoF and HoT probability by each HOM parameter

4.5 Optimized framework based on the direction of A3 event triggering

Since the communication environment of HetNet is different from that of homogeneous networks, the output power of macro-cell and small-cell are quite different, which results in the attribute of triggering handover direction of UE from macro-cell to small-cells and from small-cell to macro-cell to be different during the HDM [49].

Although there are many research works on analyzing and optimizing HDM [22, 24, 25, 5, 26, 30, 27, 31, 28, 29, 9, 32, 33, 34, 36, 37]. However, in current studies, the authors have ignored the directional properties of the handover when analyzing and optimizing the handover. That can potentially result in an inaccurate analysis and optimization of the HDM, which prevents ping-pong handover and HoF issues from being correctly analyzed and resolved.

The attributes of macro-to-small (M2S) cell and small-to-macro (S2M) cell handover directions by the A3 event should be addressed when qualitatively and quantitatively analyzing the HDM process. It is necessary to analyze the impact of A3 events on the different directions of handover and reveal the characteristics of different handover directions in HetNet to provide more specific and accurate strategies or suggestions for subsequent network optimization based on the HDM process.

Let P_{m_serv} and P_{s_serv} denote the state of the UE when it is in a macro cell and a small cell, respectively, and the UE is in P_{m_serv} , indicating that the UE will be connected to the macro-cell at an initial time.

Let $P_{sm_JugSinr}$ and $P_{ms_JugSinr}$ denote the immediate state determining whether the UE can trigger a handover.

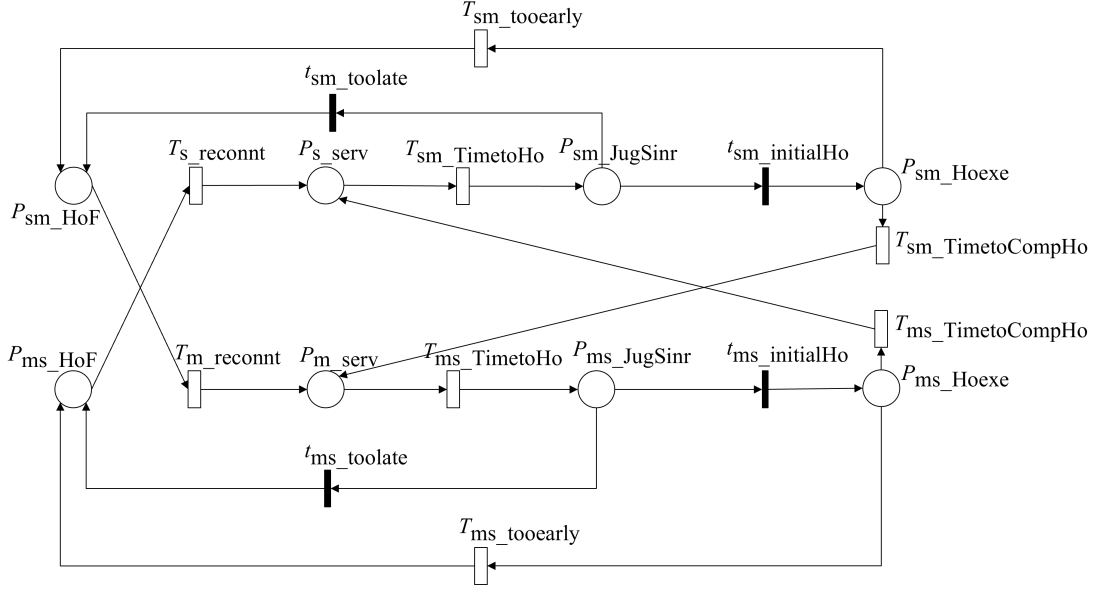


Figure 4.9: Handover directions modeling by SPN

Let P_{sm_Hoexe} and P_{ms_Hoexe} denote the states in which the UE completes HDM in the small cell and macro cell, respectively, and successfully enters the HOE process.

Let P_{sm_HoF} and P_{ms_HoF} denote the state of the HoF due to the UE failing to successfully enter into the handover execution process in the small-cell and macro-cell, respectively.

Let $T_{sm_TimetoHo}$ and $T_{ms_TimetoHo}$ denote the EXP transitions that the UE reaches the area where the handover should be triggered in a small and macro cell, respectively, as shown in Fig. 4.10

In general, no fixed distribution can fully describe the time that the UE is in the P_{m_serv} and P_{s_serv} states, as well as the movement of the UE in the cell, because it is highly random. However, the HOM parameter in the A3 event, the SINR performance of S-cell, and the cell density in a region may affect the time the UE resides in the cell until the HDM is triggered. Therefore, we consider that the A3 event trigger probability, cell density, and the SINR performance of S-cells are proportional to the firing rates of $T_{sm_TimetoHo}$ and $T_{ms_TimetoHo}$. The firing rates of $T_{sm_TimetoHo}$ and $T_{ms_TimetoHo}$ are defined as follows:

$$\begin{aligned}
 \theta_{sm_TimetoHo} &= \frac{1}{\sigma_{soj}} \times (\lambda_m + \lambda_s) \\
 &\quad \times \mathbb{P}(SINR_s < T_{out} \mid T_{out} = 0) \times \zeta_{sm}, \\
 \theta_{ms_TimetoHo} &= \alpha \cdot \frac{1}{\sigma_{soj}} \times (\lambda_m + \lambda_s) \\
 &\quad \times \mathbb{P}(SINR_m < T_{out} \mid T_{out} = 0) \times \zeta_{ms},
 \end{aligned} \tag{4.7}$$

where σ_{soj} is the time factor that affects the residence time of the UE in the cell, which is inversely proportional to the firing rates; λ_s and λ_m denote the densities of the small-cell and the macro-cell, respectively; ζ_{sm} and ζ_{ms} denote the CDFs of A3 events in HDM for S2M and M2S handover, respectively, as shown in Eq. 4.3 and Eq. 4.4; α denotes a multiplier, in which the residence time in the macro-cell is α times that in the small-cell.

Let $t_{\text{sm_InitialHo}}$ and $t_{\text{ms_InitialHo}}$ denote that after the UE satisfies the A3 event, it determines whether the SINR of the UE's current S-cell is not less than a certain threshold, and if it is not less than a certain threshold, then the UE completes the HDM and enters into the HOE process. Therefore, the firing probabilities are defined as follows:

$$\theta_{\text{sm_initHo}} = 1 - \tau_s, \quad \theta_{\text{ms_initHo}} = 1 - \tau_m. \quad (4.8)$$

Let $t_{\text{sm_toolate}}$ and $t_{\text{ms_toolate}}$ denote the probability that a UE fails to trigger HOE in the small and macro cells, respectively. Owing to the SINR is necessarily less than 0 dB after the UE satisfies the A3 event, as shown in Fig. 4.1. Therefore, the HoF occurs before triggering the HOE process if the UE receives the SINR from the S-cell is less than a threshold, and the firing probability of $t_{\text{sm_toolate}}$ and $t_{\text{ms_toolate}}$ are defined as follows:

$$\theta_{\text{sm_tlf}} = \tau_s, \quad \theta_{\text{ms_tlf}} = \tau_m. \quad (4.9)$$

Let $T_{\text{sm_TimetoCompHo}}$ and $T_{\text{ms_TimetoCompHo}}$ denote the EXP transitions that the UE that completes handover in the places of the $P_{\text{sm_Hoexe}}$ and $P_{\text{ms_Hoexe}}$, respectively, as shown in Fig. 4.10.

The UE in the HOE state tends to complete the handover process, including HDM and HoE processes, faster if the HOM is smaller [50, 51], which means that the time for the completion of the HOE process is directly proportional to the HOM scale and inversely proportional to the probability of triggering the A3 event because the HOM scale and the probability of triggering the A3 event are inversely proportional according to Eq. 4.3 and Eq. 4.4. Therefore, the probability of the A3 event trigger is proportional to the firing rates of the $T_{\text{sm_TimetoCompHo}}$ and $T_{\text{ms_TimetoCompHo}}$.

Besides, we consider that the SINR performance and the density of the T-cell also affect the HOE process. The SINR performance of T-cells is proportional to the firing rate, and the density of the T-cell is inversely proportional to the firing rate. Accordingly, the firing rates of $T_{\text{sm_TimetoCompHo}}$ and $T_{\text{ms_TimetoCompHo}}$ are defined as follows:

$$\begin{aligned}\theta_{\text{sm_CompHo}} &= \zeta_{\text{sm}} \times \frac{1}{\lambda_{\text{m}}} \times (1 - \tau_{\text{m}}), \\ \theta_{\text{ms_CompHo}} &= \zeta_{\text{ms}} \times \frac{1}{\lambda_{\text{s}}} \times (1 - \tau_{\text{s}}).\end{aligned}\quad (4.10)$$

Let $T_{\text{sm_tooeary}}$ and $T_{\text{ms_tooeary}}$ denote the EXP transitions that the UE can not complete handover in the places of the $P_{\text{sm_Hoexe}}$ and $P_{\text{ms_Hoexe}}$, resulting in the HoF.

In contrast to $T_{\text{sm_TimetoCompHo}}$ and $T_{\text{ms_TimetoCompHo}}$, the UE that entered the HOE process faces a poor SINR in T-cell if the HOM in the A3 event takes a small value. Therefore, we assume that the triggering probability of the A3 event is inversely proportional to the firing rates of $T_{\text{sm_tooeary}}$ and $T_{\text{ms_tooeary}}$, and the relationship between the density of the T-cell and the firing rates is the same with $T_{\text{sm_TimetoCompHo}}$ and $T_{\text{ms_TimetoCompHo}}$. Accordingly, the firing rates are defined as follows:

$$\theta_{\text{sm_tef}} = \frac{1}{\zeta_{\text{sm}}} \times \frac{1}{\lambda_{\text{m}}} \times \tau_{\text{m}}, \quad \theta_{\text{ms_tef}} = \frac{1}{\zeta_{\text{ms}}} \times \frac{1}{\lambda_{\text{s}}} \times \tau_{\text{s}}. \quad (4.11)$$

Let $T_{\text{s_reconnt}}$ and $T_{\text{m_reconnt}}$ denote the EXP transitions that the UE reconnects the T-cell after a HoF.

As shown in Fig. 4.10, we consider that the movement direction of the UE is always away from the S-cell. Hence, when the UE reconnects the cell after the HoF occurs, the RSRP of the T-cell received by the UE is larger than the RSRP of the S-cell by a value, Furthermore, we assume that the higher the density of surrounding cells, the longer the time for UE to search the cell, which means that the density of surrounding cells is inversely proportional to the firing rate of $T_{\text{s_reconnt}}$ and $T_{\text{m_reconnt}}$, the firing rates are defined as follows:

$$\begin{aligned}\theta_{\text{s_reconnt}} &= k_{\text{outTime}} \times \zeta_{\text{ms}} \times \left(\frac{1}{\lambda_{\text{m}} + \lambda_{\text{s}}}\right), \\ \theta_{\text{m_reconnt}} &= k_{\text{outTime}} \times \zeta_{\text{sm}} \times \left(\frac{1}{\lambda_{\text{m}} + \lambda_{\text{s}}}\right),\end{aligned}\quad (4.12)$$

where k_{outTime} denotes a time factor that is proportional to the $T_{\text{s_reconnt}}$ and $T_{\text{m_reconnt}}$ firing rates and inversely proportional to the cell searching time of the UE.

4.5.1 Equivalent continuous-time Markov chain

Figure. 4.4 illustrates an SPN that contains only immediate and exponentially distributed transitions. Consequently, the equivalent model of the proposed SPN is a CTMC, as shown in Fig. 4.5.

In Fig. 6, the states of $M_{\text{m_serv}}$, $M_{\text{s_serv}}$, $M_{\text{ms_exe}}$, $M_{\text{sm_exe}}$, $M_{\text{ms_HoF}}$, and $M_{\text{sm_HoF}}$

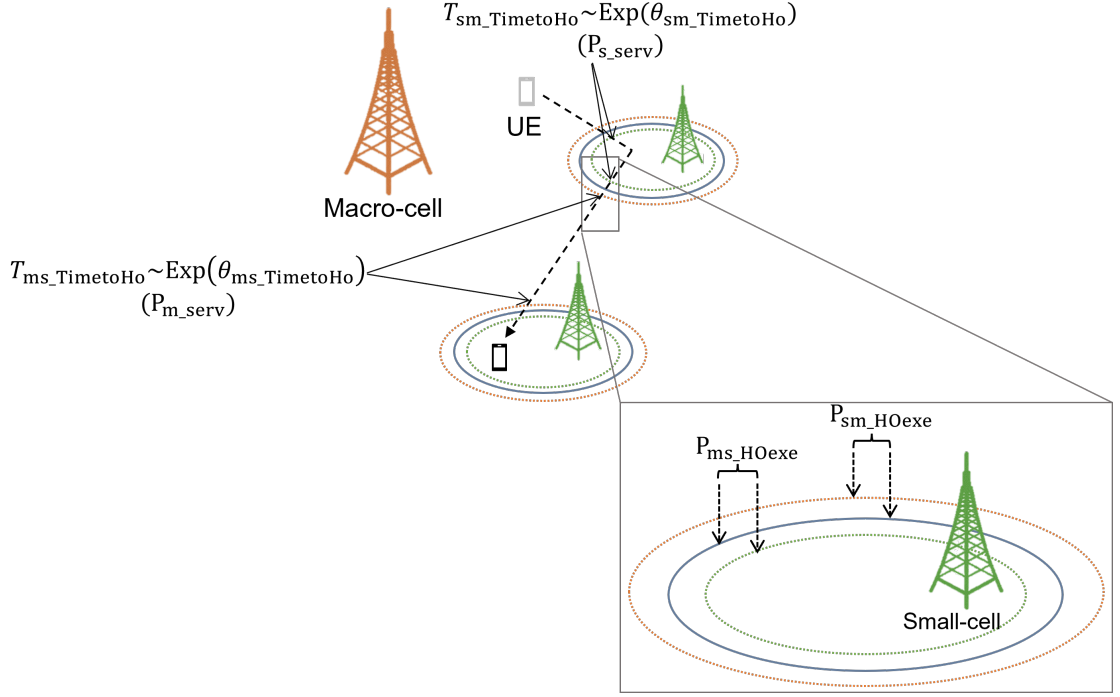


Figure 4.10: Monte Carlo simulation scenario

correspond to the states of P_{m_serv} , P_{s_serv} , P_{ms_Hoexe} , P_{sm_Hoexe} , P_{ms_HoF} , and P_{sm_HoF} in the SPN, respectively. In addition, since the places of $P_{sm_JugSinr}$ and $P_{ms_JugSinr}$ in SPN are connected with the IMM transitions, which are considered as vanishing states when transformed into a CTMC, they are not presented in the equivalent CTMC. Nevertheless, the probability of the IMM transitions of the vanishing states is multiplied by the EXP transition firing rate before it.

Therefore, we will quantitatively analyze the behavior of UE in continuous time based on the underlying CTMC to simplify the analysis of the proposed SPN. Moreover, we consider the handover behavior based on the CTMC transient solution to validate the results of the proposed model through simulation.

Generally, the expression of the transient solution of CTMC can be written in the following form,

$$\pi(t) = \pi_0 \exp(\mathbf{Q}t), \quad (4.13)$$

where $\pi(t)$ is the probability distribution of all states at any time point; π_0 is the initial vector of modeling objects; and $\mathbf{Q}$ is the transition rate matrix of the CTMC, which also denotes the state transition rate in the infinitesimal time interval. Therefore, according to Eq. 4.13, it is possible to calculate the probability distribution of all states in Fig. 4.11 at any time.

Regarding parsing the models in Fig. 4.9 and Fig. 4.11, we based on the software JSPetriNet [52], which is publicly available on GitHub for the parsing of Petri net, and

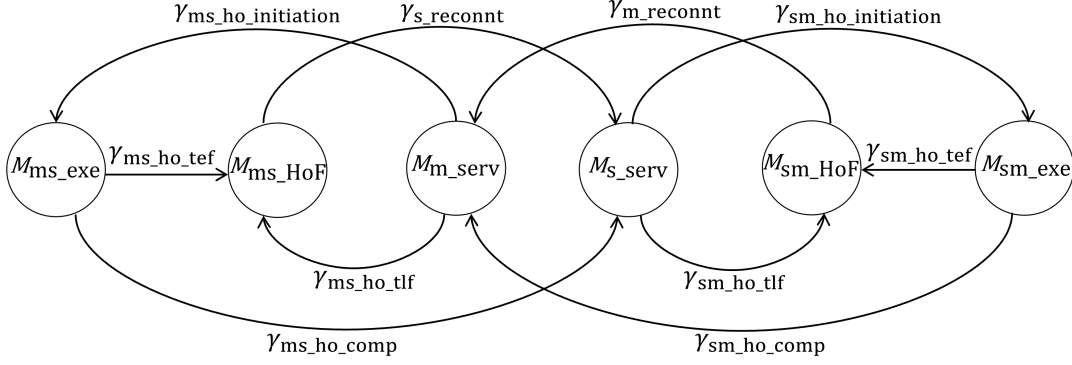


Figure 4.11: Equivalent continuous-time Markov chain of the SPN

the transition rate matrix $\mathbf{Q}$ with the initial state of the P_{m_serv} can be obtained.

4.6 Validation and parameter sensitivity analysis

4.6.1 Monte Carlo simulation design

To validate the results of our model, we design Monte Carlo simulations with a simulation time of 1000 seconds. We focus on considering and analyzing the performance impact of the A3 event on the handover direction. However, a HoF also occurs due to insufficient channel resources and communication congestion when there are many UEs in a network. Therefore, we do not consider a large number of UEs and only consider the behavior of one UE in the network to better analyze the impact of the A3 event.

Regarding the simulation environment, the number of macro-cells is not dense in an area. Consequently, we place one macro-cell in a $1 \text{ km} \times 1 \text{ km}$ region, and the location of the small-cell is randomly generated by PPP with a coverage area of 100 meters. Since we are considering a co-frequency HetNet environment, the location of the small-cell is not less than 400 meters away from the macro-cell. The channel model for the macro and small-cell is Rayleigh distribution.

At the beginning of the simulation, the UE randomly appears at a position close to the macro-cell and moves straight with an average speed of 20 m/s, where the average speed is calculated based on the total distance moved by the UE during the simulation time.

The UE in the macro-cell moves to the coverage area of the small-cell and determines the M2S handover according to the A3 event in the HDM. The UE in the small cell moves to the coverage area of the small cell and determines the S2M handover according to the A3 event. Moreover, the UE randomly selects a new direction of movement and moves directly to the small-cell when it completes the HOE. The specific simulation scenario is shown in Fig. 4.10.

By repeating the above process in each iteration through Monte Carlo simulation, the proportion of the total time occupied by each state during the movement of the UE

Table 4.4: Simulation parameters setting

Parameters	Value
Area range	1 km $\times$ 1 km
The number of macro-cell	1
Small cell coverage	100 m
P_m	46 dBm
P_s	32 dBm
T_{HOM}	[0.0, 10.0] dB
Channel model	Rayleigh distribution
Path-loss factor, η	4
Handover decision-making	A3RSRP-based
The number of UE	1
Average speed	20 m/s
Mobility model	Direction movement
λ_m	1 km ⁻²
μ_s, μ_m	1
T_{out}	-8 dB
k_{outTime}	20 (average 0.05 ms)
α	2
$\gamma_{\text{ms_ho_initiation}}$	$\theta_{\text{ms_TimetoHo}} \times \theta_{\text{ms_initHo}}$
$\gamma_{\text{sm_ho_initiation}}$	$\theta_{\text{sm_TimetoHo}} \times \theta_{\text{sm_initHo}}$
$\gamma_{\text{ms_ho_tlf}}$	$\theta_{\text{ms_TimetoHo}} \times \theta_{\text{ms_tlf}}$
$\gamma_{\text{sm_ho_tlf}}$	$\theta_{\text{sm_TimetoHo}} \times \theta_{\text{sm_tlf}}$
$\gamma_{\text{ms_ho_comp}}$	$\theta_{\text{ms_CompHo}}$
$\gamma_{\text{sm_ho_comp}}$	$\theta_{\text{sm_CompHo}}$
$\gamma_{\text{ms_ho_tef}}$	$\theta_{\text{ms_tef}}$
$\gamma_{\text{sm_ho_tef}}$	$\theta_{\text{sm_tef}}$
$\gamma_{\text{m_reconnt}}$	$\theta_{\text{m_reconnt}}$
$\gamma_{\text{s_reconnt}}$	$\theta_{\text{s_reconnt}}$

can be calculated. Therefore, different from the discrete-time model, the HoT and HoF evaluations here represent the probability distributions of the UE being in the states corresponding to $M_{\text{ms_exe}}$, $M_{\text{sm_exe}}$, $M_{\text{ms_HoF}}$, and $M_{\text{sm_HoF}}$, respectively, at a given time.

In addition, since we consider comparisons with simulation results based on larger time, the results can be considered as long-term averaged even if we consider the transient solution of CTMC, which has converged under the time parameter. Refer to Table 4.4 for detailed simulation parameter settings.

4.6.2 Evaluation of HoT and HoF probability

Fig. 4.12 and Fig. 4.13 show the impact of the HoT probabilities of M2S and S2M by the changes in the small-cell density and the T_{HOM} parameter, respectively.

The HoT probability of M2S and S2M decreases with increased T_{HOM} . This is because the difficulty of triggering HDM based on event A3 increases when the T_{HOM} is increased, resulting in inhibition of the process of the UE completing HDM and entering

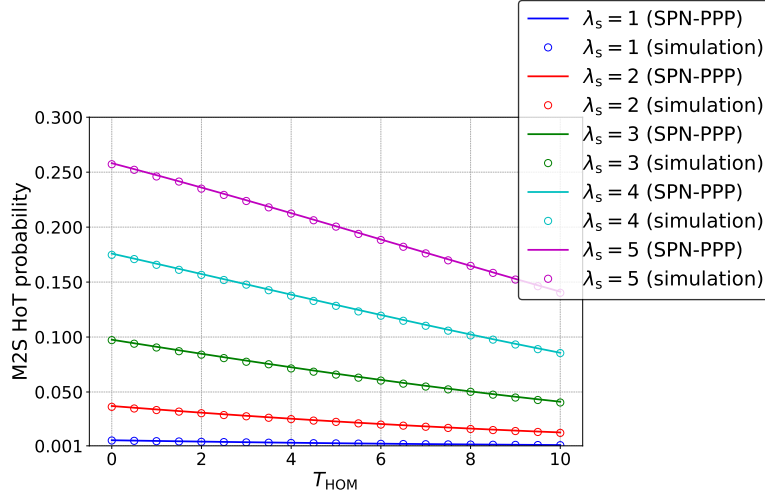


Figure 4.12: The T_{HOM} impact on M2S HoT probability (for $\sigma_{soj} = 5$)

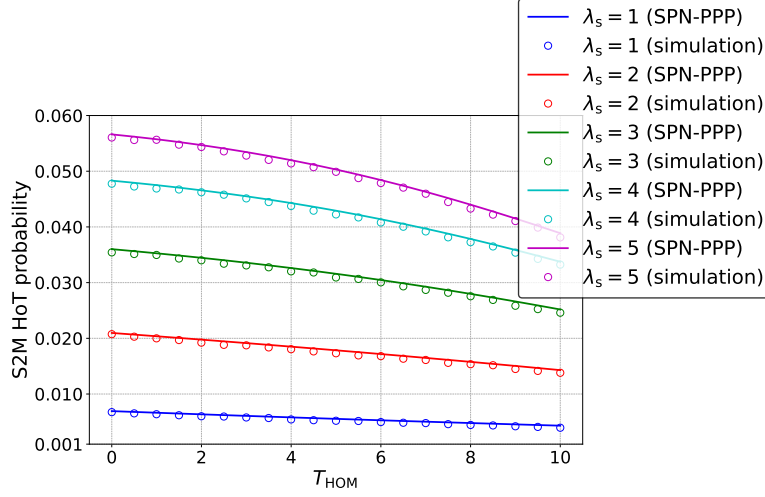


Figure 4.13: The T_{HOM} impact on S2M HoT probability (for $\sigma_{soj} = 5$)

the HOE.

Moreover, it shows that the effect of inhibiting M2S HoT probability is greater than that of S2M as the T_{HOM} increases. This is because the macro-cell coverage is much wider than that of the small-cell. The residence time of the UE in the macro-cell is increased significantly when the T_{HOM} is increased, and the transition rate of the UE at which from M_{m_serv} to the M_{ms_exe} for M2S handover decreases significantly, resulting in a greater impact on the M2S handover.

Besides, the S2M handover is triggered after the M2S handover has been completed or failed, which is one of the reasons why the HoT probability of the M2S handover is greater than that of the S2M handover.

On the other hand, the HoT probability of both M2S and S2M handover is almost close to 0 when the density of the small-cell is low, and the HoT probability of both M2S and S2M handover will increase when the density of the small-cell increases. This

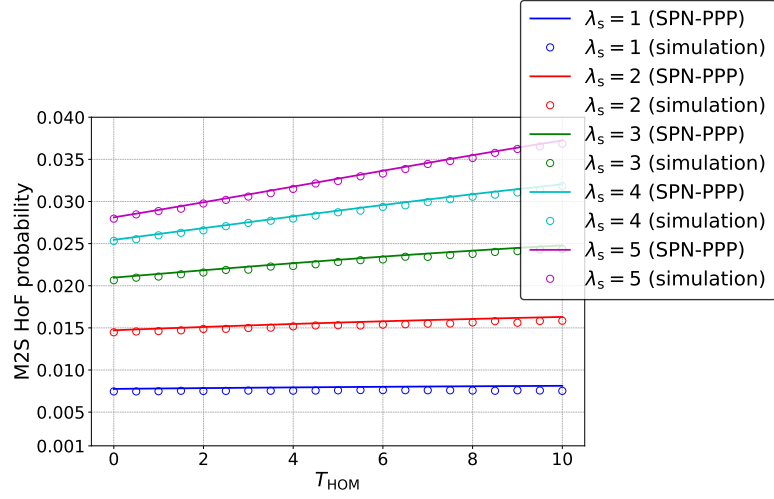


Figure 4.14: The T_{HOM} impact on M2S HoF probability (for $\sigma_{\text{soj}} = 5$)

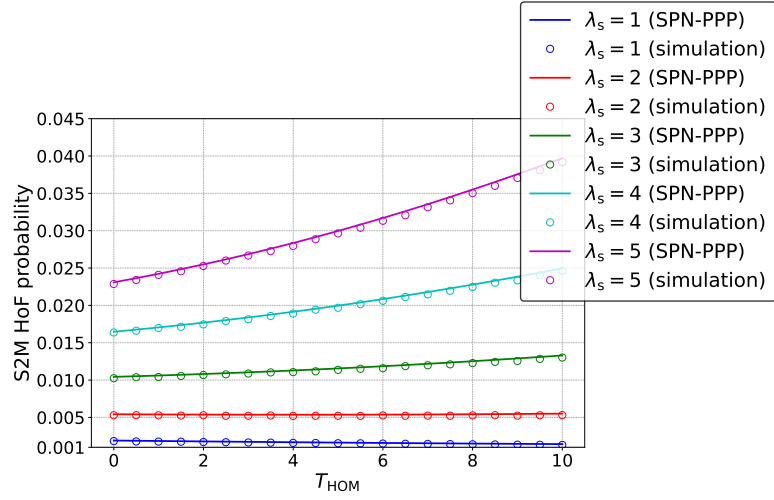


Figure 4.15: The T_{HOM} impact on S2M HoF probability (for $\sigma_{\text{soj}} = 5$)

is because of the deployment of the small-cell increases, which raises the chance of UE triggering handover. Moreover, the HoT probability of M2S increases significantly when the density of the small-cell increases. This is because the residence time of a moving UE in a macro-cell is longer than in a small-cell, which leads to the possibility of a UE in the macro-cell moving to any surrounding small-cell to trigger the M2S handover being much higher than the possibility of a UE triggering an S2M handover.

Fig. 4.14 and Fig. 4.15 show the impact of the HoF probabilities of M2S and S2M handover by the density of the small-cell and the T_{HOM} parameter, respectively. The HoF of M2S and S2M handover increases with the increase of T_{HOM} , while the HoT probability of M2S and S2M handover is close to 0 when the small-cell density is low. The HoF probability of the M2S handover is higher than the HoT probability of the M2S handover when the small-cell density is 1. This is because the density of the small-cell is too low, resulting in the UE more easily experiencing poor SINR when they are further

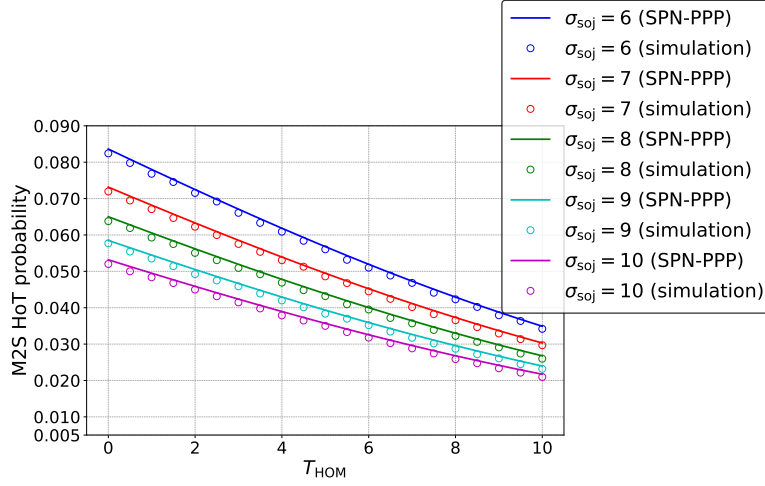


Figure 4.16: The T_{HOM} impact on M2S HoT probability (for $\lambda_s = 3$)

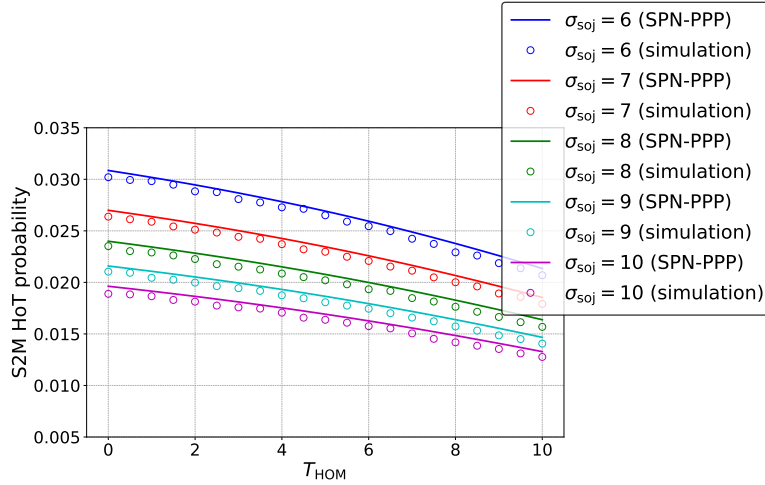


Figure 4.17: The T_{HOM} impact on S2M HoT probability (for $\lambda_s = 3$)

away from the macro-cell.

On the other hand, as the density of the small-cell increases, the probability of HoF for M2S and S2M handover also increases. In particular, the HoF probability of the S2M handover is higher than that of the M2S handover when the T_{HOM} is large, and the density of the small-cell is also high. This is because the S-cell is the small-cell in an S2M handover, and the A3 event is triggered later when the T_{HOM} is large, resulting in the UE easily experiencing poor SINR in the S-cell, where the RSRP variation is unstable.

In Eq. 4.7, we assumed the σ_{soj} , which is inversely proportional to the fire rate and proportional to the residence time of the user in the cell. By changing the value of the σ_{soj} , this equation can be used to describe changes in the residence time or the speed of the UE in the cell.

Fig. 4.16 and Fig. 4.17 show the impact of the HoT probability of M2S and S2M

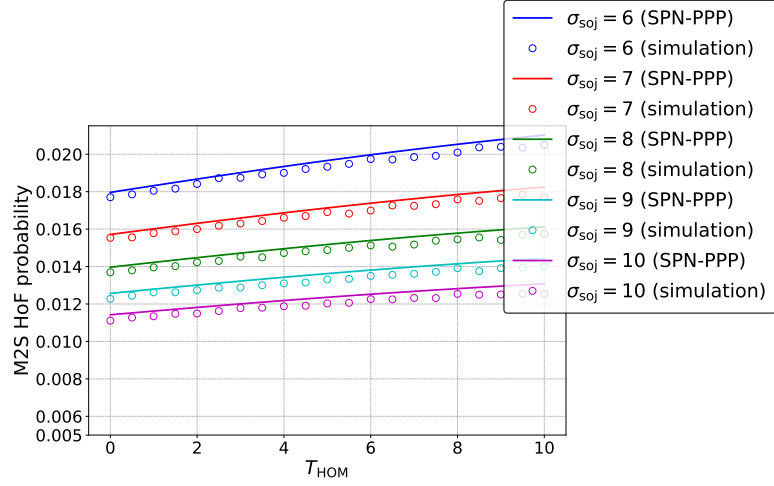


Figure 4.18: The T_{HOM} impact on M2S HoF probability (for $\lambda_s = 3$)

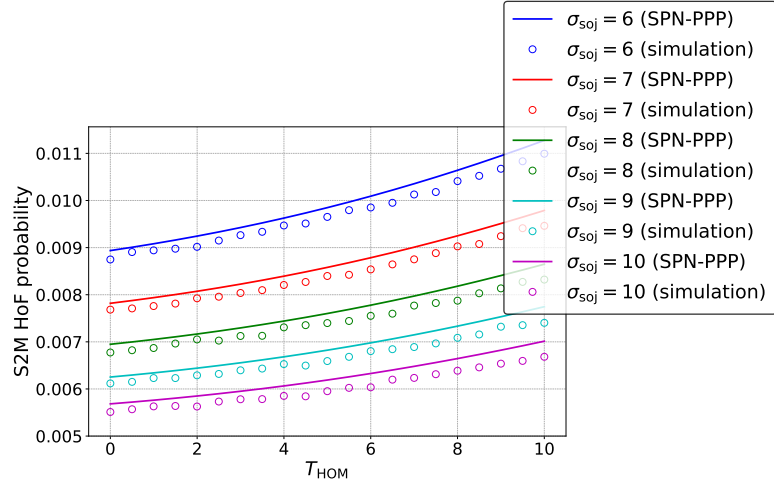


Figure 4.19: The T_{HOM} impact on S2M HoF probability (for $\lambda_s = 3$)

handover by the variation of the σ_{soj} and the T_{HOM} parameters.

The HoT probability of M2S and S2M handover decreases with increasing T_{HOM} and σ_{soj} parameters. This reason is the same as in Fig. 4.12 and Fig. 4.13.

Furthermore, an increase in σ_{soj} will increase the residence time in the cell, which represents a slowing down of the UE movement speed. Therefore, the HoT probability of M2S and S2M handovers decreases when σ_{soj} increases.

Fig. 4.18 and Fig. 4.19 show the impact of the HoF probability of M2S and S2M by the variation of the σ_{soj} and the T_{HOM} parameters. The HoF probability of both M2S and S2M decreases with the increase of the T_{HOM} , and the HoF probability of M2S is larger than the HoT probability of S2M. This is the same as in Fig. 4.14 and Fig. 4.15.

On the other hand, an increase in σ_{soj} will increase the residence time of the UE in the cell and slow down the UE movement speed. Therefore, the probability of the UE experiencing HoF decreases. Moreover, the HoF probability of the M2S and S2M

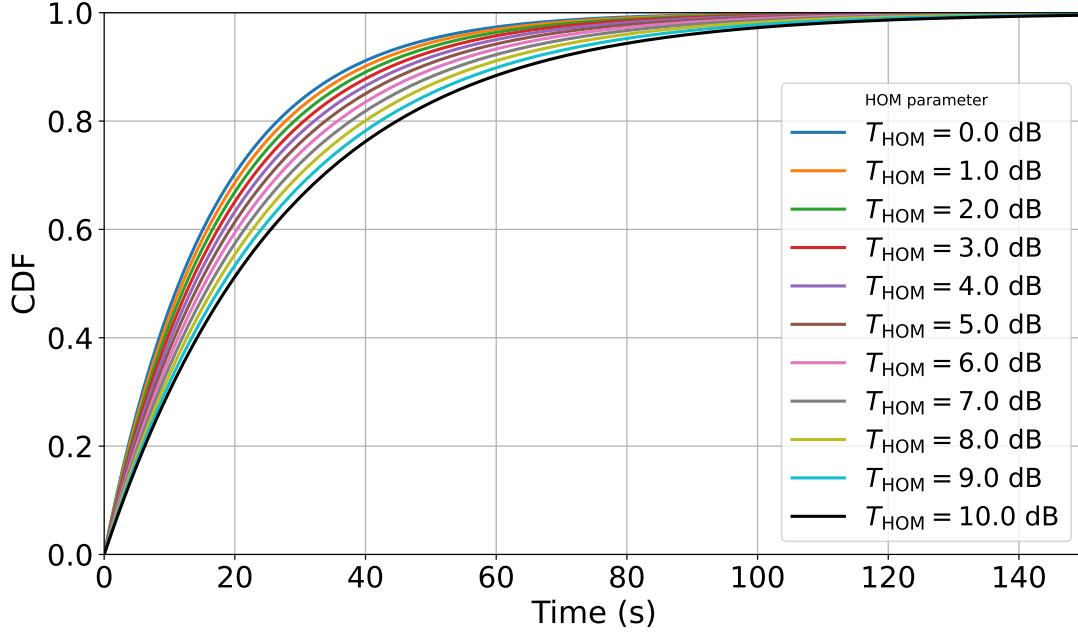


Figure 4.20: The CDF of the residence time of the UE in macro-cell (for $\sigma_{soj} = 5$ and $\lambda_s = 3$)

handover increases significantly with the increase of T_{HOM} when σ_{rmsoj} is small. This is because the UE with shorter residence time in the cell and faster speed require a smaller T_{HOM} to ensure a lower HoF probability.

4.7 Impact of handover margin on UE residence time

Besides the impact on the HoT and HoF probabilities, the T_{HOM} parameter can also significantly affect the UE residence time in the cell. Fig. 4.20 and Fig. 4.21 show the CDF variation of the UE residence time in the small-cell and macro-cell for the A3 event with the T_{HOM} parameter.

For the the UE residence time in the small-cell and macro-cell are based on the characteristics of CTMC, the CDF of residence time of UE in the macro-cell and the small-cell can be defined as follows:

$$F_{M_{m_serv}}(t) = 1 - \exp(-q_{ii} \cdot t), F_{M_{s_serv}}(t) = 1 - \exp(-q_{jj} \cdot t), \quad (4.14)$$

where $F_{M_{m_serv}}(t)$ and $F_{M_{s_serv}}(t)$ represent the probability that the UE has left the respective state by time t ; q_{ii} denote is the negative of the diagonal element in the i -th row of the $\mathbf{Q}$ of the CTMC, where i corresponds to the M_{m_serv} state; q_{jj} is the negative of the diagonal element in the j -th row of the $\mathbf{Q}$, where j corresponds to the M_{s_serv} state.

As shown in Fig. 4.20, the maximum residence time of the moving UE in the macro-

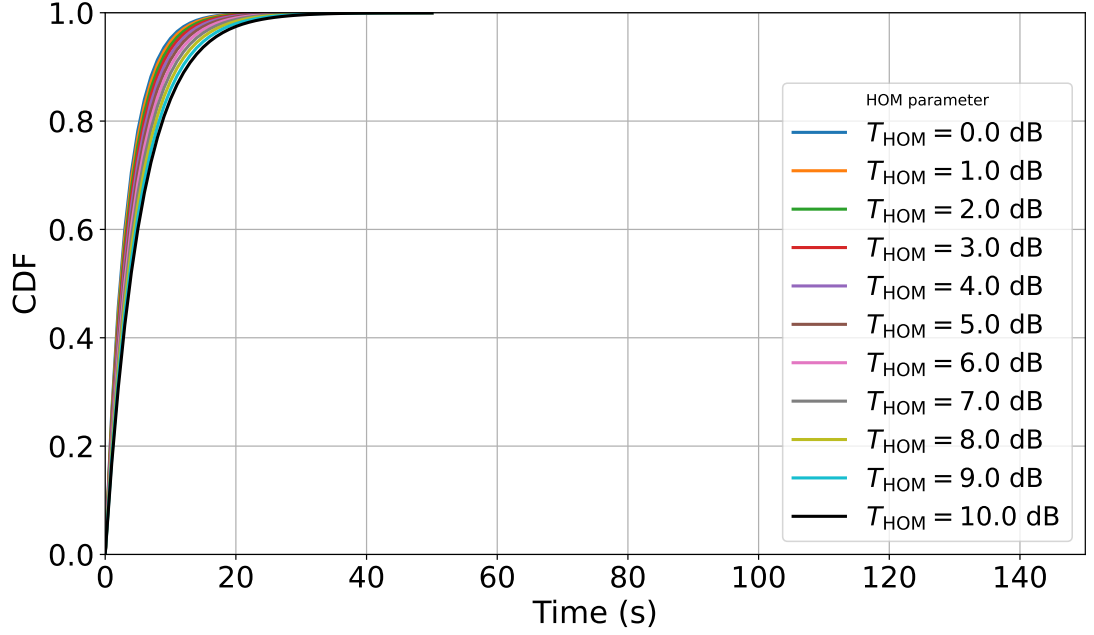


Figure 4.21: The CDF of the residence time of the UE in small-cell (for $\sigma_{soj} = 5$ and $\lambda_s = 3$)

cell is less than 150 seconds (for $\lambda_s = 3$, $\sigma_{soj} = 5$) according to all T_{HOM} , and the probability that the UE moves to the handover area and enters the HOE process of M2S handover or occurs HoF is more than 90% after more than 60 seconds.

Moreover, the residence time of the UE in the cell is significantly changed by the T_{HOM} parameter. As the T_{HOM} increases, the residence time of the UE significantly increases. This is because the difficulty of A3 event triggering increases when the T_{HOM} increases, which implies the UE prefers to stay on the current cell rather than choose a new one.

On the other hand, as shown in Fig. 4.21, the maximum residence time of a continuously moving UE in a HetNet in the small-cell does not exceed 30 seconds (for $\lambda_s = 3$, $\sigma_{soj} = 5$), and the probability of the UE moving to the handover area and enters the HOE process of S2M handover or occurs HoF is more than 90% after more than 10 seconds, and the change of T_{HOM} also significantly affects the residence time of the UE.

The potential factor to be noted through the CDF results is that the reduction of the residence time in the cell due to the change of the T_{HOM} increases the probability of handover, which results in an unstable communication environment for the UE. Meanwhile, the increased handover will also increase the load of resource allocation among cells.

Accordingly, it is worth noting that the CDF results obtained in Fig. 4.20 and Fig. 4.21 about the time that the UE resides in a cell can be used to predict the time when a UE triggers a handover from one cell to another in a scenario with a certain cell deployment and parameter configuration. This can provide a valuable reference for

efficient resource allocation in HetNet and enables the network to proactively prepare for an upcoming handover rather than responding to it.

4.7.1 Comparison of the Do-SPN-PPP and DTMC in predicting the UE residence time

This paper does not discuss user throughput and resource allocation between cells. However, accurate prediction of the residence time of the UE in a cell is helpful for efficiently allocating the resources for the handover process. Therefore, we compare the accuracy of DTMC and Do-SPN-PPP in predicting the residence time of the UE.

Specifically, we convert our CTMC to a DTMC using a discretization method, which allows for the approximation of continuous-time behavior through discrete time steps. The conversion is based on the principle that the CTMC can be approximated by a discrete-time process by introducing a time step Δt . This time step represents the interval at which the discretized model observes the system state.

The specific conversion to a DTMC is as follows:

$$\mathbf{P} = \mathbf{I} + \Delta t \cdot \mathbf{Q}, \quad (4.15)$$

where $\mathbf{P}$ is the transition probability matrix of the DTMC, $\mathbf{Q}$ is the rate matrix of the CTMC, and Δt is the discretization time step.

Next, we ensure non-negative transition probabilities by adjusting each element of $\mathbf{P}$ as follows:

$$\mathbf{P}_{ij} = \max(0, \delta_{ij} + \Delta t \cdot q_{ij}), \quad (4.16)$$

where δ_{ij} is the Kronecker delta function (which is 1 if $i = j$ and 0 otherwise), and q_{ij} is the transition rate from state i to state j in $\mathbf{Q}$.

Finally, we normalize each row of the matrix $\mathbf{P}$ to ensure it satisfies the properties of a stochastic matrix:

$$\mathbf{P}_{ij} = \frac{\mathbf{P}_{ij}}{\sum_k \mathbf{P}_{ik}}. \quad (4.17)$$

After obtaining the DTMC transition probability matrix $\mathbf{P}$, the cumulative distribution function (CDF) of the residence time of the UE in both the macro-cell and small-cell states can be computed. For a given state i in the macro-cell and j in the small-cell, the CDF of the residence time in those states can be calculated as follows:

$$F_{M_{\text{m_serv}}}(r) = 1 - (1 - p_i)^r, F_{M_{\text{s_serv}}}(r) = 1 - (1 - p_j)^r, \quad (4.18)$$

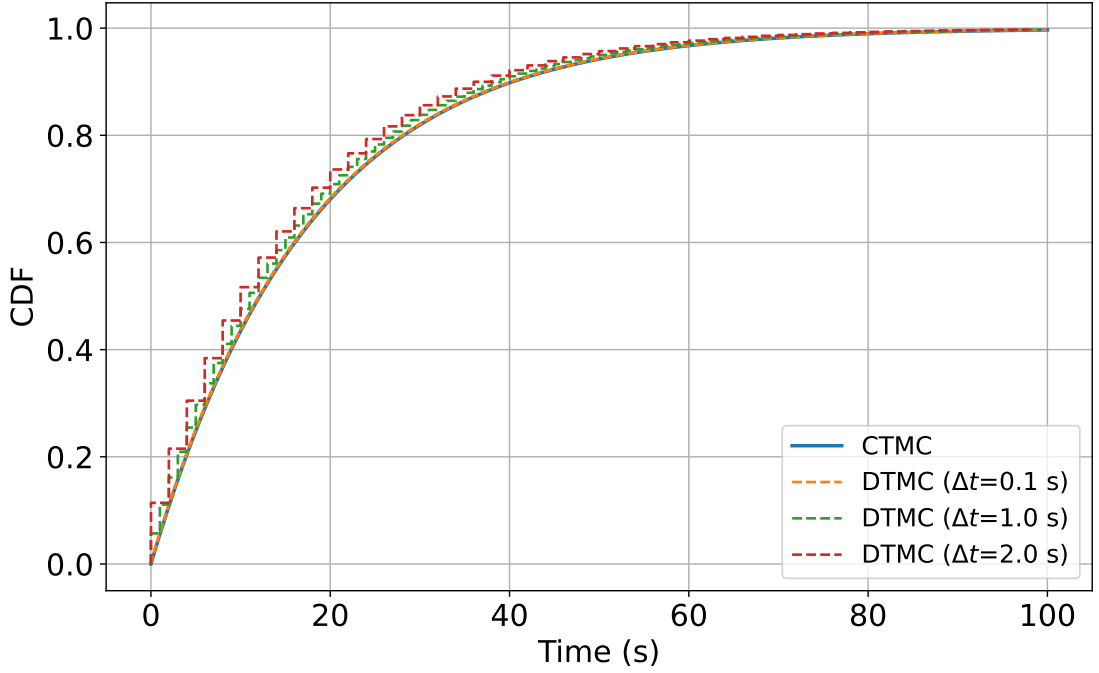


Figure 4.22: Differences between the Do-SPN-PPP and DTMC in predicting the residence time of the UE in the macro-cell

where p_i and p_j represent the probability of leaving states i and j , respectively, and r is the number of discrete time steps in the DTMC, with $r = \frac{t}{\Delta t}$, where t is the continuous time within the CTMC in Eq.4.14.

Therefore, the CDF of the residence time of the UE in the cell can be calculated based on Eq. 4.18. Moreover, we take the result of one T_{HOM} from Fig. 4.20 and Fig. 4.21 to do the comparison and the time steps of the DTMC is r of 0.1 s, 1.0 s, and 2.0 s, and the results are shown in Fig. 4.22 and Fig. 4.23.

From the comparison results, it is clear that the ability of the DTMC to capture the variation of the residence time of the UE in the cell is insufficient when the r is larger. In particular, the small-cell has a lower output power and a smaller coverage area. Thus, a lower prediction accuracy occurs compared with the Do-SPN-PPP if the DTMC is used to capture the variation of the UE residence time. This is because DTMC can only capture the behavioral changes of UE at specific discrete time points and cannot capture certain behavioral changes at short time granularity. Meanwhile, since the RSRP and SINR of the HDM process are affected by fading, which is based on continuous time variation, it would be inappropriate to analyze the handover trigger process with DTMC.

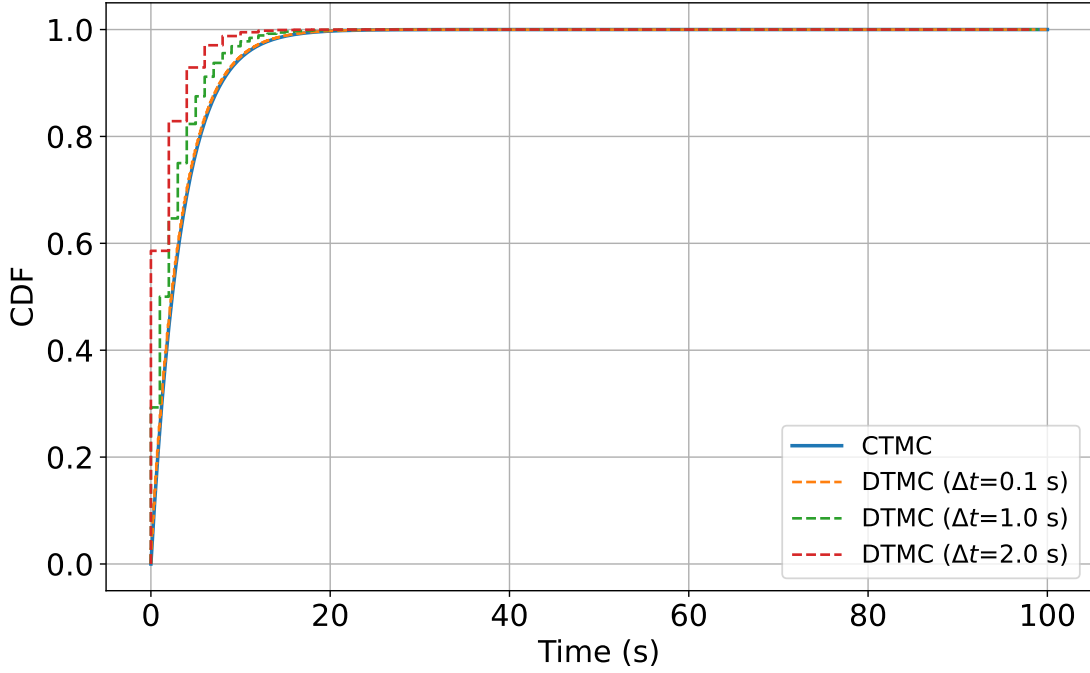


Figure 4.23: Differences between the Do-SPN-PPP and DTMC in predicting the residence time of the UE in the small-cell

4.7.2 Comparison of computation time between the Do-SPN-PPP and simulation

Generally, simulation is considered to be time-consuming, and if large-scale simulation is encountered, the time consumption of a simulation-based approach cannot be ignored [53]. Even though the simulation environments considered here are simple, we hope to provide a basic reference on the time consumption of simulation and the proposed approach (modeling-based) approaches in evaluation.

To compare the time consumption in the evaluation process between both the proposed approach and simulation-based approaches, we determined the appropriate sample size for the Monte Carlo simulation through a rigorous statistical analysis.

Initially, we conducted a preliminary simulation with 100 samples for a selected set of parameters. For each state i in the CTMC, we calculated the sample standard deviation using the following formula:

$$s_i = \sqrt{\frac{\sum_{j=1}^{100} (x_{ij} - \bar{x}_i)^2}{99}} \quad (4.19)$$

where x_{ij} represents the probability of state i in the j th simulation, and $\bar{x}_i$ denotes the average probability of state i across these 100 simulations.

Next, using the initial estimate of the standard deviation, we calculated the required sample size for each state to achieve a 95% confidence interval with a maximum error

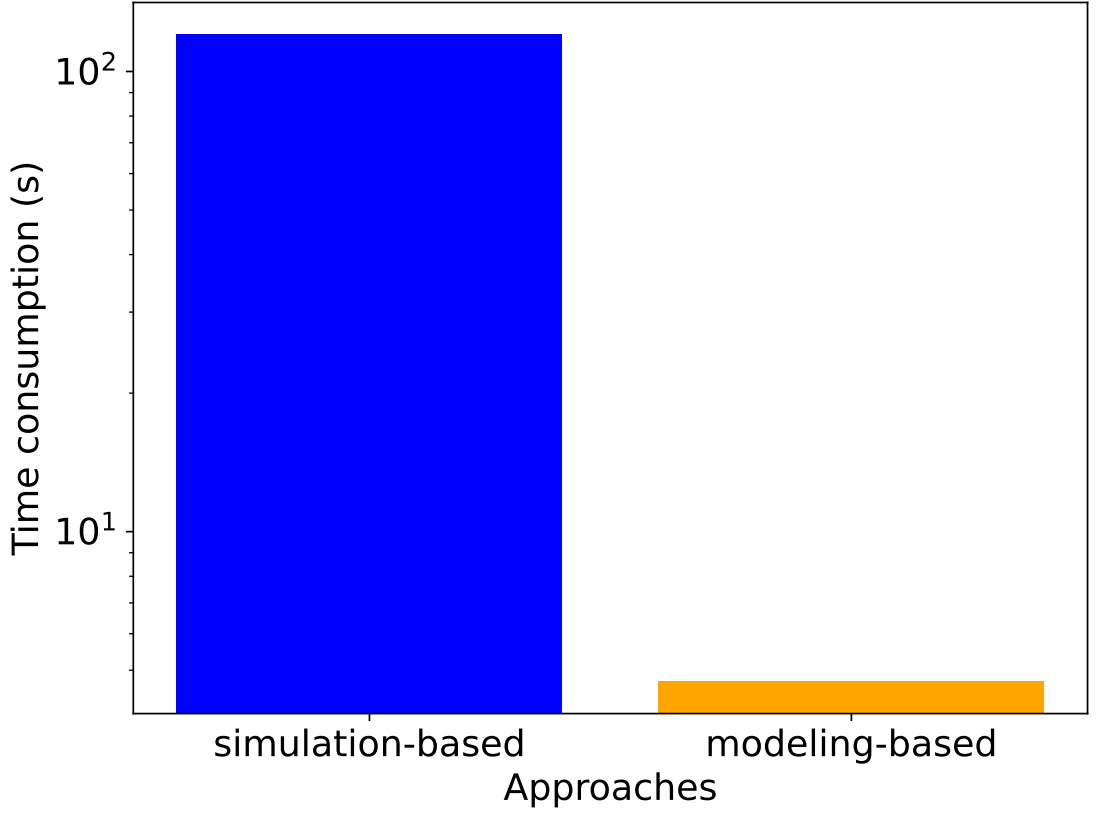


Figure 4.24: Comparison of the computation time based on the two approaches

of 0.5%, using the following equation:

$$n_i = \left(\frac{z \cdot s_i}{E} \right)^2 \quad (4.20)$$

where n_i is the required sample size for state i ; z is the z-value (1.96 for a 95% confidence interval from the standard normal distribution); s_i is the previously calculated sample standard deviation, and E represents the allowable absolute error (0.5%).

We used the sample standard deviation s_i from the preliminary simulation to directly determine the required sample size n_i . This approach enables us to estimate the variability of the result by s_i and calculate the number of samples necessary to achieve our desired precision level. After calculating n_i for all states, we selected the maximum value as the estimate for the required sample size:

$$n = \max_i(n_i) \quad (4.21)$$

Finally, to validate the applicability of this sample size across different parameter combinations of T_{HOM} , λ_s , and σ_{soj} , we conducted n simulations for each parameter combination to ensure robustness.

Therefore, we compare the time consumption of the two approaches based on n

sampling and based on the evaluation of $\lambda_s \in \{1, 2, 3, 4, 5\}$. We perform the simulation 10 times for each of the n samples and calculate the average time consumption. On the other hand, the numerical experiments by the Do-SPN-PPP with uniformization solution and time step 0.1 s are also performed 10 times, and the average time consumption is calculated. Consequently, the difference in time consumption between the two approaches is shown in Fig. 4.24.

According to Fig. 4.24, the difference in time consumption between the proposed approach and simulation-based approaches is significant even if the simulation scenario is simple, and the difference in time consumption between simulation and the proposed approach will be more significant if more factors and a longer simulation time are considered in the simulation scenario. Therefore, our proposed Do-SPN-PPP framework based on the modeling approach achieves about 96% improvement in computational efficiency while obtaining the same results as those based on the simulation approach.

4.8 Design a target cell aware decision-making for high-speed UE within HetNets

In Section 4.7, the distinct characteristics of handover for high-speed mobile UEs in heterogeneous networks were demonstrated. Furthermore, in the absence of distinction between UEs in heterogeneous networks during handover, UEs may handover to any available cell. This may result in frequent communication degradation, as the handover trigger condition is based on RSRP.

Consequently, the development of a handover decision algorithm capable of discerning diverse target cells is imperative to rectify the communication degradation that arises from frequent handovers in high-speed mobile user equipment (UE) within cells characterized by minimal coverage areas, such as mmWave cells.

5G, the fifth generation of cellular networks, faces the challenge of maintaining seamless connectivity and channel stability in high-speed scenarios [54] [55]. The current handover decision-making algorithm (HDMA) only considers channel measurement indicators, including reference signal received power (RSRP), reference signal received quality (RSRQ), or signal-to-interference-plus-noise (SINR) [56]. Consequently, the UE can trigger a handover to any gNB if these conditions are met. User equipment (UE) moving at high speeds will remain in a small gNodeB (gNB) for a short time, and frequent handovers by the current HDMA are inevitable, resulting in degraded or even interrupted communication quality, which has a significant impact on the UE experience [57] [58].

The dual connectivity (DC) scheme mitigates the problem of UE connection loss during hard handover to some extent by enabling the UE to connect to two base stations simultaneously and increase the throughput of the UE [45]. However, the presence of various types of gNBs in the heterogeneous ultra-dense network, including millimeter

waves (mmWave) and small gNBs within sub-6 GHz and due to the severe path loss of millimeter waves (mmWave), the high mobility of UEs, and the numerous obstacles present in urban environments, frequent intermittent interruptions of UE wireless links occur [11]. These problem of degraded communication quality caused by frequent handovers of highly mobile UEs still needs to be addressed and optimized [7] [59].

Recently, there has been a lot of research on high-speed mobility management and handover optimization. Some of the work focuses on using user mobility information to optimize handover decisions. In [38], fuzzy logic control is used to dynamically optimize the handover trigger timing based on UE speed and the cell size of a gNB, thereby reducing handover failures and ping-pong handovers. In [39], a HDMA is proposed for UE speed and service type that prevents the UE speed between 15 km/h and 30 km/h from handover to small cells by considering the UE service type and speed to maintain the downlink throughput. In [40], an adaptive handover scheme is proposed to adjust the threshold of the absolute value of RSRP to adjust the handover trigger conditions according to the UE speed. In [41], a HDMA based on multiple parameters, including received signal strength (RSS), equivalent RSS, handover margin (HOM), UE speed, quality of service (distinguishing between real-time services), and available bandwidth, is proposed. This HDMA aims to encourage high-speed users to either stay within or hand over to the macro base station to prevent frequent handovers.

In addition, machine learning and reinforcement learning techniques have also been widely used to optimize 5G handovers. In [42], it employs a data-driven approach, utilizing a multilayer perceptron model to adaptively adjust handover control parameters such as HOM and Time-to-Trigger (TTT), while considering numerous factors, including UE speed, RSRP, SINR, and load. This approach has proven effective in achieving a significant reduction in handover failure rates, handover times, and ping-pong handover rates. In [43], a convolutional neural network (CNN)-long short-term memory (LSTM) deep learning model is employed to predict UE trajectories, enabling the selection of the target gNB in advance. This approach significantly reduces the number of unnecessary handovers and enhances service continuity. In [44], it proposes an adaptive user-centric virtual cell handover decision oriented towards connectivity, which uses reinforcement learning with indicators such as RSRP and SINR to ensure the seamless connection of the UE to the virtual cell, thereby maintaining the stability of the communication channel for high-speed UEs. In [45], it proposes a deep reinforcement learning algorithm based on deep deterministic policy gradient (DDPG) to optimize the handover parameters autonomously. The thresholds, such as HOME, can be dynamically adjusted according to the environment, thereby enhancing the robustness of mobility at different speeds while maintaining high throughput and low latency. However, these learning-based solutions are predicated on a large amount of training data and offline optimization and are still insufficient for real-time response to network changes. Furthermore, these approaches do not use cell-level information.

Moreover, the communication environment for high-speed UE handover to mmWave cells is unstable due to high loss for mmWave gNBs after blocking obstacles. In [46], an intelligent handover mechanism is proposed that can dynamically fine-tune parameters such as HOM and TTT based on the real-time SINR to achieve a fast response to the drastic fluctuations of mmWave channels. In [47], it is designed to minimize handover interruption time by incorporating backhaul delay considerations during handover signaling exchange. Additionally, it employs a transmission control protocol (TCP) proxy to ensure lossless data transmission following handover.

The existing research on optimizing handover decisions in 5G high-speed environments heavily relies on instantaneous channel measurement indicators and parameter tuning. However, existing research does not adequately address the gNB type information carried by the NR cell identity (NCI). As a result, the current handover decision mechanism lacks knowledge of the characteristics of the target cell when determining whether to trigger a handover. In other words, neither the gNB nor the UE knows whether the target base station is a macro cell, a sub-6GHz small gNB, or an mmWave gNB. This oversight can lead to frequent handovers, causing an unstable communication environment.

To address this challenge, this study proposes, for the first time, a NCI-based mechanism for handover optimization in high-speed scenarios: NCI is used to determine the type of candidate gNB to avoid frequent handovers that lead to degraded communication quality.

4.9 System model

4.9.1 Dual connectivity

In 5G, dual connectivity refers to using multiple carriers supported by these gNBs for transmission and reception. This enables the UE to connect to both the master node (MN) and the secondary node (SN) simultaneously, thereby achieving broadband. The MN has a high output power and a low-frequency band. Thus, it has a large coverage area and can reliably exchange control signals with the UE; the SN has a low output power and a high-frequency band, so it has a short coverage area and can provide high data rates to the connected UE. Due to the MN's wide coverage, the UE always connects to the MN, and handover within the DC scenario is also referred to as a secondary node handover. In contrast to the hard handover scenario, in the DC scenario, when the UE experiences an SN handover, its data transmission is not completely interrupted, and the UE will communicate with the MN. Once the SN handover is complete, the UE will transmit data to the new SN. The MN channel is more stable than the SN channel, so if the UE's data transmission with the SN is interrupted due to handover or other reasons, the MN will immediately back up the data [47].

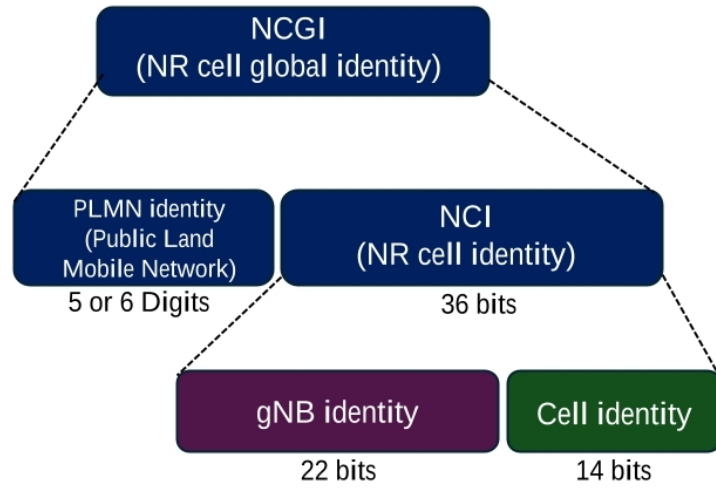


Figure 4.25: The composition of NR cell global identity

4.9.2 NR cell identity

The NR cell global identity (NCGI) is composed of two components: the Public land mobile network (PLMN) identity of the cell and the NCI of the gNB, as illustrated in Fig. 4.25.

Each gNB has a unique identity (gNB ID) that is used to distinguish different gNBs within the PLMN. Each gNB may have multiple cells, and each cell corresponds to a cell identity (cell ID). The gNB ID and the cell ID, when combined, form the 36 bits NCGI, with the gNB ID configurable from 22 to 32 bits, with a minimum of 22 bits and a maximum of 32 bits. The cell ID occupies 4 to 14 bits, with a minimum of 4 bits and a maximum of 14 bits. By default, the 22 bits gNB ID space is suitable for most operators' requirements.

According to the 3GPP standard, no bits or specific codes are reserved in the 36 bits of the NCI to identify the cell type [60]. Therefore, it is necessary to consider what coding characteristics correspond to a specific gNB type through the current NCI, such as macro base station, small gNB, or mmWave gNB .

In our semantic extension, we propose to split this 22 bits gNB ID into two subfields: the upper 2 bits, termed the 'gNB type ID', are reserved for encoding the gNB type (such as macro base station, sub-6GHz small, or mmWave gNBs), while the remaining 20 bits, termed the gNB ID, provide the unique identity for the gNB within its type. The detail is shown in Fig. 4.26. The 14 bits cell ID does not change. This semantic extension has the advantage that the upper 2 bits within the gNB ID are used to represent the cell type, allowing the gNB type to be identified by the gNB type ID without the need for additional signaling.

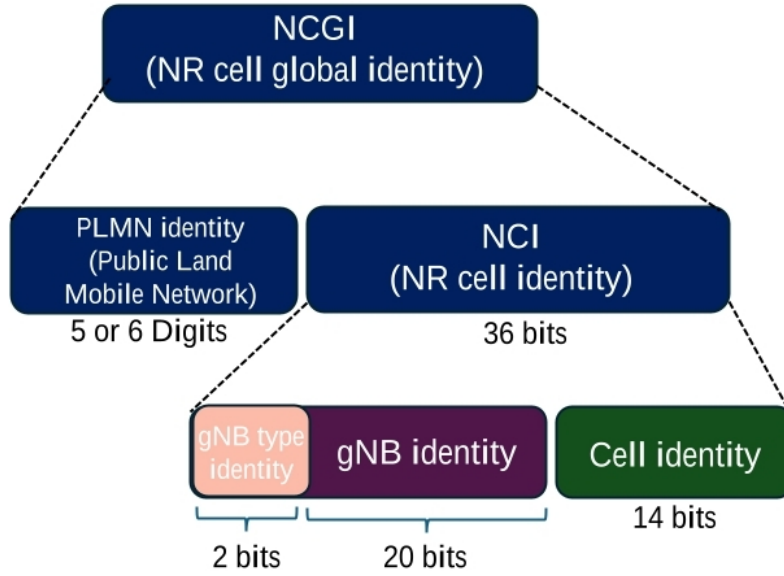


Figure 4.26: The proposed semantic extension of the NCI with gNB type identity

4.10 Proposed handover decision-making algorithm

UE moving at high speed on a macrocell may only be able to obtain a low throughput rate due to its long distance from the base station and high load. However, a small cell in the surrounding area can improve the instantaneous signal quality and throughput even if the service time is short. While frequent handovers of high-speed UEs can degrade UE communication quality, small gNBs in the Sub-6 GHz band have better coverage and anti-obstacle capabilities than mmWave gNBs, making their links more stable in high-speed scenarios and providing more reliable signal strength. However, in a 5G dense small gNBs scenario, if only instantaneous channel metrics such as RSRP, RSRQ, and SINR are used during HDMA, all potential gNBs will be included in the candidate target gNBs, resulting in frequent handovers, and communication degradation cannot be entirely avoided. Therefore, it is considered to introduce NCI into HDMA only so that the UE can recognize the target gNB type during HDMA execution and select the target base station that matches its characteristics. The proposed HDMA determination process is outlined in Algorithm 1.

Specifically, the UE in a DC scenario with the presence of macro base station, sub-6 GHz small gNBs, and mmWave gNBs identifies that the target gNB is a sub-6 GHz small cell by the high two-bit coding within the NCI and includes it in the target gNB; the UE identifies that the target base station is a mmWave gNB by the high two-bit coding within the NCI and does not include it in the target gNB, to achieve a more stable communication environment.

The details of the gNB ID semantic extension are shown in the following,

- Macro base station type ID $\leftarrow 00$

Algorithm 1 NCI-based handover decision algorithm

Require: UE i , speed v_i , speed threshold T_v , gNB list L with gNB type IDs, RSRP measurements, HOM H , TTT ttt

```

1: if  $v_i \geq T_v$  then
2:    $C \leftarrow \{\}$  ▷ Initialize target gNB candidate list
3:   for each gNB in  $L$  do
4:      $tb \leftarrow \text{Extract High Bits } b_i$  ▷  $b_i$  denotes the gNB type ID
5:     if  $tb = "01"$  or  $tb = "00"$  then
6:        $C \leftarrow C \cup \{\text{gNB with } tb\}$ 
7:     else if  $tb = "10"$  then
8:       continue ▷ Skip mmWave gNB
9:     end if
10:  end for
11:   $B \leftarrow \text{Find best RSRP } C$  ▷ Select the target gNB with the best RSRP
12:  if target gNB  $RSRP > \text{current gNB } RSRP + H$  within  $ttt$  then
13:    Execute UE  $i$  handover to  $B$ 
14:  else
15:    Cancel UE  $i$  handover
16:  end if
17: else
18:   Execute A3RSRP HDMA
19: end if

```

- Sub-6GHz gNB type ID $\leftarrow 01$
- mmWave gNB type ID $\leftarrow 10$

4.11 Evaluation

As shown in Fig. 4.27, we consider a 5G dual connectivity scenario that includes a macro base station within 2.1 GHz, two sub-6GHz small gNBs, and six mmWave gNBs, as a city scenario with multiple obstacles using MATLAB 5G Toolbox. This dual connectivity scenario is referenced from [47], and we added two sub-6 GHz small cells to that.

Specifically, the macro base station is the MN in the dual-link scenario, and the small base station and millimeter wave base station are the SN in the dual-link scenario. Initially, the UE travels in a straight line along the Y-axis from the position (100, 100, 1.5) at 60 km/h. The SN handover of the UE is triggered when the UE crosses the city. The detail of the simulation setting is shown in Table 4.5.

Additionally, to show the performance of the proposed HDMA, we compare it with the A3RSRP HDMA commonly used in 5G and the UE speed-based HDMA in reference [38] and [40]. The handover trigger condition based on A3RSRP HDMA is that the RSRP of the target gNB is greater than a threshold of the current base station RSRP within a short period of time; the handover trigger condition based on UE speed HDMA in reference [38] and [40] are that when the UE movement is greater than a threshold,

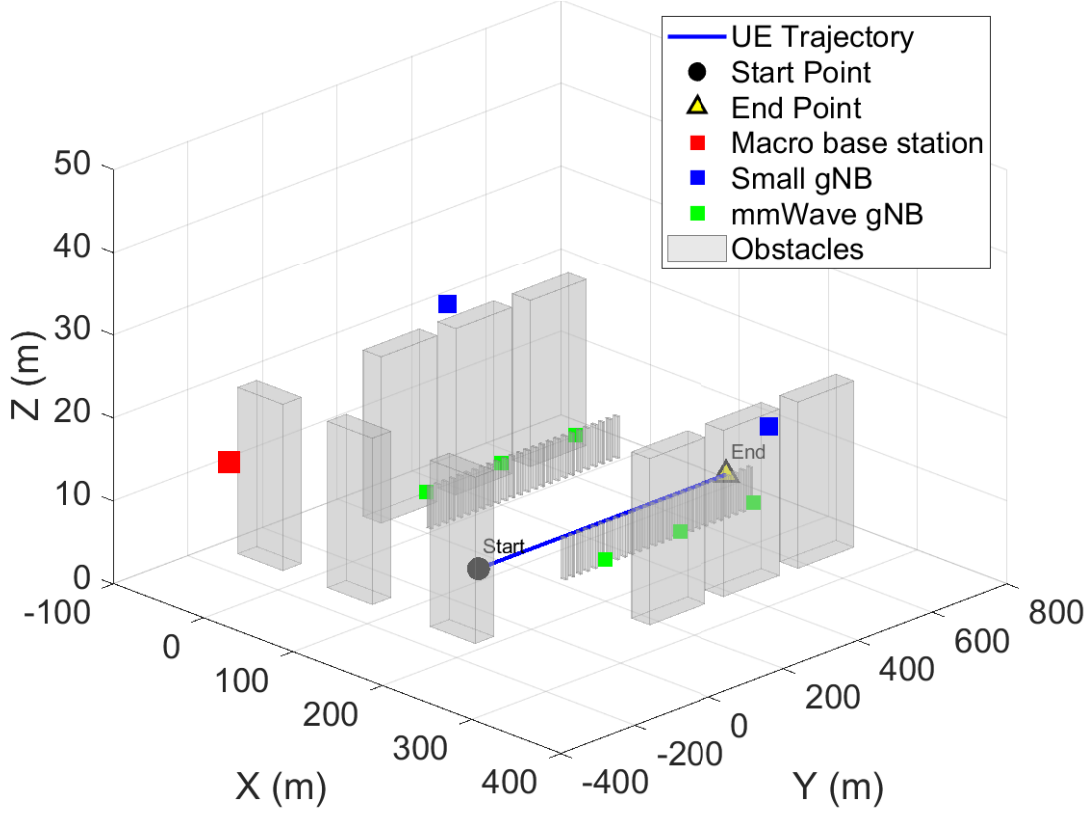


Figure 4.27: Simulation environment

the UE data transmission is fixed to the macro base station to ensure the seamless communication.

4.11.1 Handover numbers and throughput

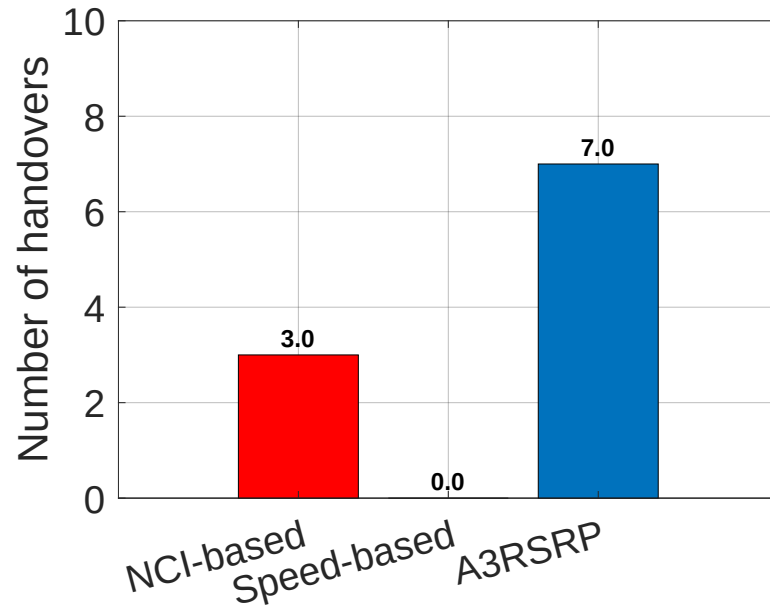
We first simulated and evaluated the number of handover triggers. As illustrated in Fig. 4.28, the number of handovers triggered by the three algorithms is shown. The results are NCI-based, Speed-based and A3RSRP HDMA from left to right, respectively.

As the results indicate, the number of handovers triggered by UE speed-based HDMA is 0 because the UE's movement speed exceeds the set speed threshold of 30 km/h. Consequently, the UE will not hand over to small cells or millimeter wave cells. The proposed NCI-based HDMA has a lower handover number than the A3RSRP HDMA. This is because the proposed NCI-based HDMA considers the NCI of the target gNB and UE movement speed, which enables avoidance of handover to the mmWave gNB and thereby reduces the number of handovers.

As illustrated in Fig. 4.29, although the handover number of HDMA based on UE movement speed is 0, the throughput is the lowest of the three, indicating that the communication environment in the macro cell is characterized by strong interference and high load, resulting in a low actual UE throughput. Conversely, although the number of handovers for the proposed HDMA and A3RSRP HDMA is notably higher than that

Table 4.5: Simulation parameters setting

Parameter	Value
Simulation time	40 s
Macrocell base station	2.1 GHz
Small gNB	3.5 GHz
mmWave gNB	28 GHz
UE speed	60 km/h
Speed threshold T_v	30 km/h
Handover margin	3 dB
Time-to-Trigger	200 ms
Packet sending interval	0.001 s

**Figure 4.28:** Number of handovers.

for UE-speed-based HDMA, the throughput performance of the former significantly surpasses that of the latter.

However, since A3RSRP HDMA does not identify the target gNB type, it hands over to the millimeter wave cell, resulting in an immediate increase in UE throughput and SINR, but also a significant degradation in communication due to obstruction.

4.11.2 Communication stability

Fig. 4.30 shows an evaluation of the stability of the three algorithms, where the three sub-figures represent the histograms of the SINR data distribution of the three algorithms during the simulation time. The top sub-figure in Fig. 4.30 shows the proposed NCI-based HDMA, the middle sub-figure shows the speed-based HDMA, and the bottom

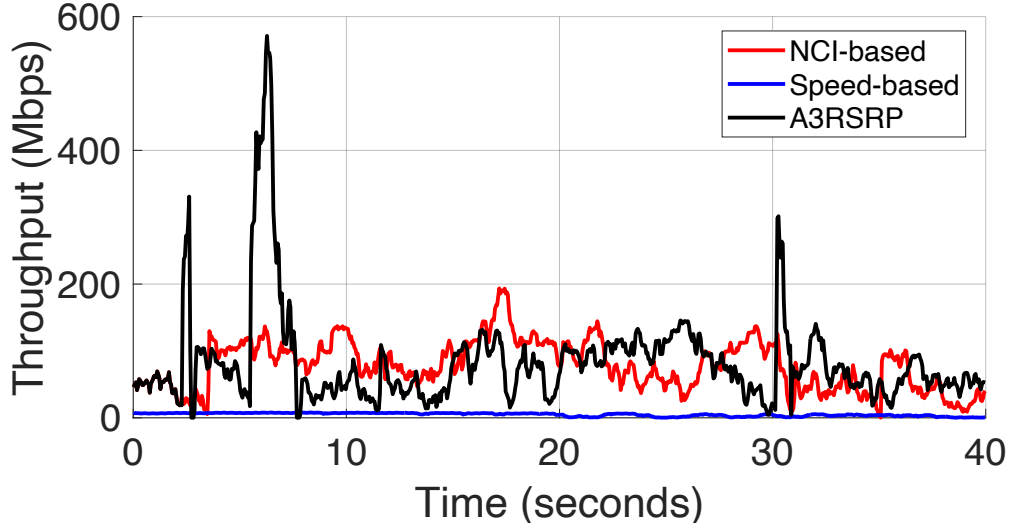


Figure 4.29: Throughput vs time.

sub-figure shows the A3RSRP HDMA.

The speed-based HDMA does not hand over to other small cells in this DC simulation scenario, and the UEs always communicate with the macro base station. Consequently, the SINR value remains consistent due to the lack of frequent handovers, and the average SINR is slightly higher than that of A3RSRP HDMA. Conversely, the proposed NCI-based HDMA uses the gNB type ID to filter out millimeter-wave cells by identifying the target cell for handover in advance, and only sub-6 GHz small cells are used as the target cells for handover. Consequently, the proposed NCI-based HDMA has a higher average SINR than the speed-based and A3RSRP HDMA, and the SINR values occur more frequently in the 0 to 5 dB range.

Fig. 4.31 shows the cumulative distribution function (CDF) of the SINR for the three HDMA. The proposed NCI-based HDMA prevents handovers to mmWave cells by identifying the target cell type in advance via the gNB type ID. Therefore, the SINR of the UE fluctuates more stably than with A3RSRP and speed-based HDMA. Fig. 4.30 and Fig. 4.31 demonstrate that the proposed NCI-based HDMA offers a more stable communication environment for the UE compared with speed-based and A3RSRP HDMA.

4.12 Summary

In this Chapter, a continuous-time framework, Do-SPN-PPP, is proposed based on the combination of the Poisson point process and stochastic Petri nets. The framework is used to qualitatively analyze the A3 event-based M2S and S2M handover in HetNet and quantitatively analyze the performance difference between M2S and S2M handover based on the direction of A3 events. According to the analysis results of HoT and HoF probabilities, there is a significant difference in the impact of HOM parameters on the

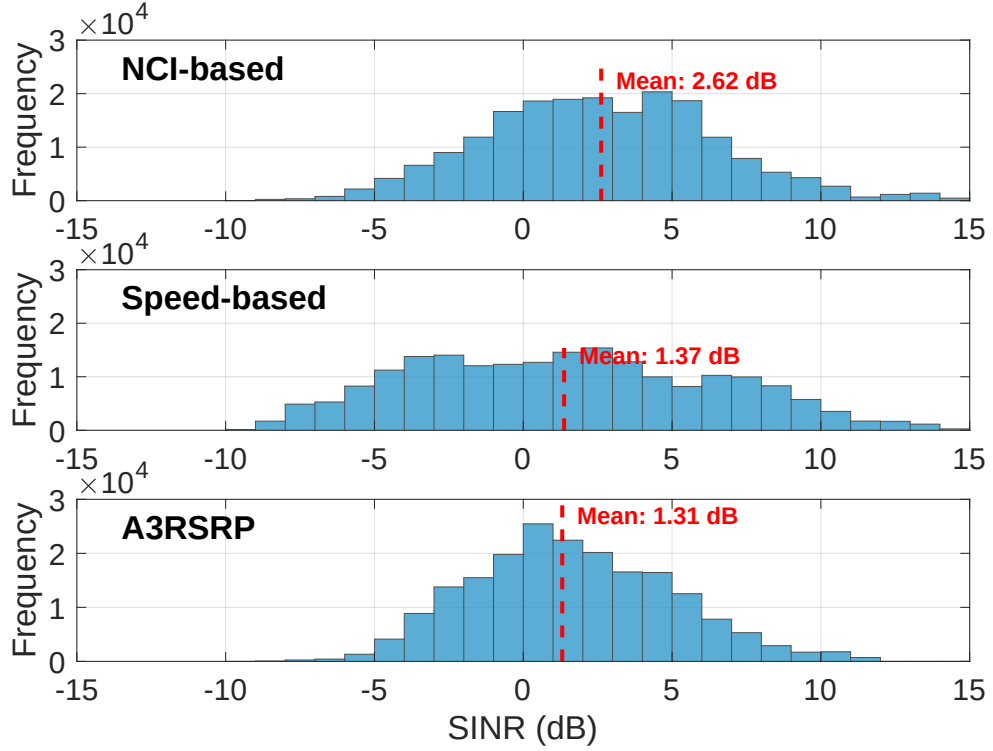


Figure 4.30: Comparison of the SINR data distribution

performance of M2S and S2M handover, and the reasonableness of the proposed model is verified by Monte Carlo simulation.

In addition, we quantitatively analyze the effect of HOM on the residence time of UEs in macrocells and small cells. The results show that different HOM parameters significantly increase or decrease the residence time of UEs in the cell.

Moreover, in order to show the advantages of our proposed framework over existing approaches, we compare it with discrete-time DTMC, which is widely used in other literature, and our proposed framework proved the advantages of the proposed framework in capturing and predicting the accuracy of UEs' residence time in the cell before handover, and the accuracy comparison results show that DTMC is significantly less capable of capturing UE S2M handover than the proposed framework when the UE's residence time in the cell is short. By comparing with widely used discrete-time models, the Do-SPN-PPP framework has significant potential value in capturing and predicting the UE's residence time in the cell, as well as analyzing the impact of different HOM parameters on the length of the UE's residence time in the cell, which is important for efficient channel resource allocation in the dense cell deployment scenarios of 5G.

Finally, the computation time of the simulation-based and the proposed framework in the evaluation process is compared. The results show a 96% reduction in computational time compared with the simulation-based approach.

On the other hand, we propose an extension of the NCI coding scheme based on the current NCI structure to help UEs identify the type of target base station during HDMA.

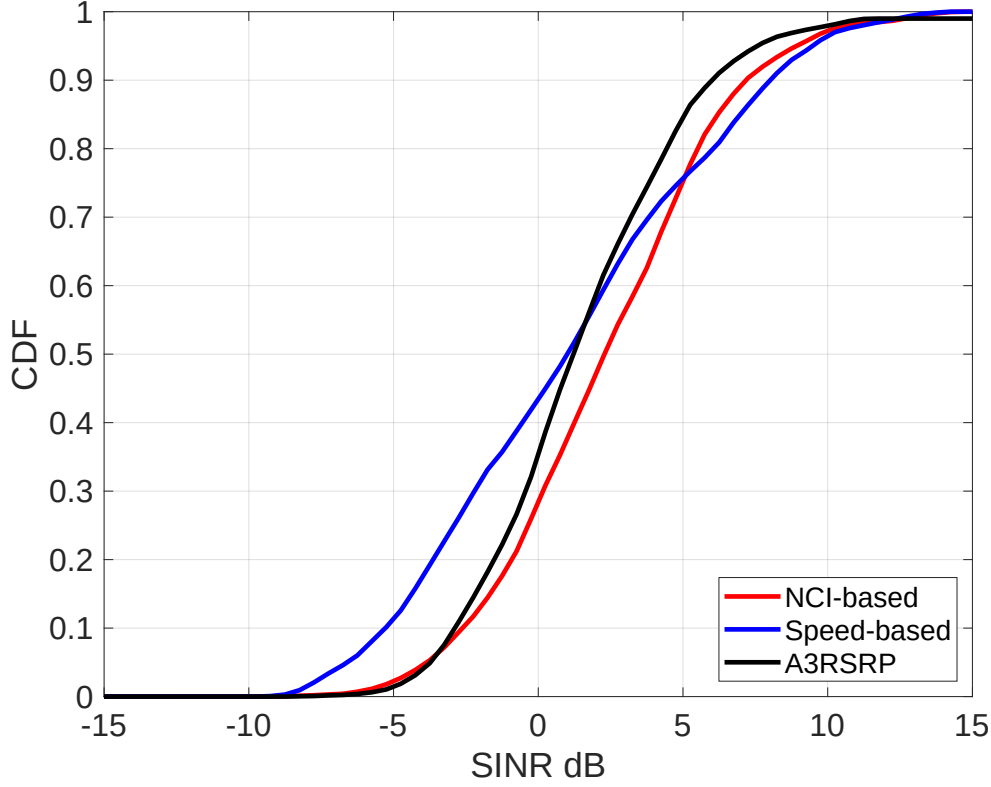


Figure 4.31: Comparison of the SINR CDF

This extension aims to provide a more stable communication environment for high-speed mobile UEs in dense 5G networks with multiple cellular types. Through a comparative analysis of the proposed NCI-based HDMA with A3RSRP-based HDMA and speed-based HDMA, it has been demonstrated that the former can ensure higher throughput while reducing the number of handovers and exhibiting improved performance in terms of communication stability.

In future work, firstly, since HoT and HoF are two important metrics for evaluating the switching performance and also two metrics that have trade-offs on HOM parameters, how to find the HOM parameters between these two metrics that can obtain the optimal handover performance is the direction to be considered. Secondly, the HOM parameters significantly increase or decrease the residence time of the UE in the cell. Therefore, how to provide proactively effective channel resource allocation schemes for M2S and S2M handover within the network side, respectively, may be another direction to consider.

On the other handover, we also consider the scenario where multiple cells exist in a gNB, to test and optimize the performance of our algorithm, and consider the scenario where there are a large number of UEs with different mobility speeds, and ways to improve the performance of the algorithm by combining machine learning approaches.

Chapter 5

Design of a handover decision algorithm based on channel quality indicators

While Chapter 4 focuses on optimizing handover decision logic through direction-aware modeling and target cell identification, the accuracy of any handover decision algorithm fundamentally depends on the reliability of its input—the channel measurement phase. As highlighted in Chapter 2, one of the most critical challenges facing current HDMA is the volatility of the RSRP, which is widely used as the primary metric for assessing signal quality.

In complex radio environments with multipath fading and shadowing, instantaneous RSRP values often fail to accurately represent long-term channel quality trends. Relying solely on RSRP as a handover trigger can result in frequent ping-pong handovers and handover failures—notably, too-early failures (TEFs). To fundamentally enhance handover reliability and robustness, it is therefore essential to address these deficiencies at the measurement stage. This chapter focuses on reforming the measurement phase of the handover process by addressing the shortcomings of RSRP. We propose a handover decision algorithm named CH-HDA (CQI and Hysteresis-based Handover Decision Algorithm), which replaces RSRP with the more stable and meaningful channel quality indicator (CQI) and incorporates an adaptive hysteresis control (HC) mechanism.

CQI is selected due to its inherent advantages over RSRP. As a link-layer metric, CQI guides the selection of modulation and coding schemes (MCS) based on average channel conditions over time, rather than instantaneous signal power. Quantized into discrete levels corresponding to SINR intervals, CQI exhibits significantly lower volatility and greater resistance to transient fading. Its slower variation makes it a more reliable reflection of sustained communication quality, especially in dynamic or fading-prone environments.

In summary, the contributions of this chapter lie in introducing a measurement-

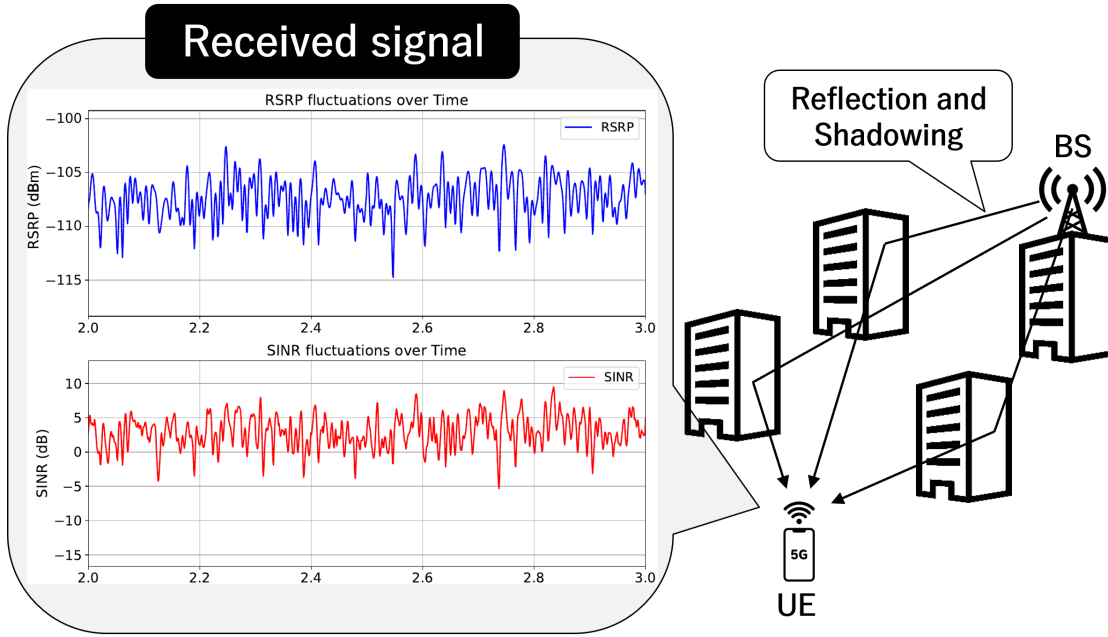


Figure 5.1: Propagation between the RSRP and CQI

aware and stability-driven approach to handover decisions. By shifting from a volatile, RSRP to a more stable, CQI, and by incorporating dynamic hysteresis control, CH-HDA significantly improves handover trigger accuracy, reduces unnecessary handovers, and enhances overall network performance in heterogeneous deployments. These insights provide a new perspective for resolving fundamental handover challenges in HetNets.

5.1 Propagation properties of RSRP, SINR

In wireless communications, radio signals are subject to various propagation phenomena that significantly affect their transmission characteristics. Two primary physical phenomena - multipath fading and shadowing - play crucial roles in signal propagation and directly impact the behavior of key wireless metrics including RSRP, RSRQ, and SINR.

Fading occurs when radio signals reach the receiving antenna through multiple paths due to reflection, diffraction, and scattering from various objects in the propagation environment. These multiple signal copies arrive at the receiver with different phases and amplitudes, leading to significant variations in the received signal strength due to multipath fading effects. This phenomenon leads to rapid and significant fluctuations in received signal strength over very short distances or time intervals, typically on the order of wavelengths.

Shadowing, also known as shadow fading or large-scale fading, results from the obstruction of radio waves by large objects such as buildings, hills, or other terrain features. Unlike multipath fading, shadowing causes slower variations in signal strength that occur over distances of several tens of wavelengths. These variations follow a log-normal

Table 5.1: SINR and CQI Mapping Table in LTE

SINR [dB]	CQI code	Modulation	Code rate	Spectral efficiency
-6.7	1	QPSK	0.076	0.15
-4.7	2	QPSK	0.12	0.23
-2.3	3	QPSK	0.19	0.38
0.2	4	QPSK	0.3	0.60
2.4	5	QPSK	0.44	0.88
4.3	6	QPSK	0.59	1.18
5.9	7	16QAM	0.37	1.48
8.1	8	16QAM	0.48	1.91
10.3	9	16QAM	0.6	2.41
11.7	10	64QAM	0.45	2.73
14.1	11	64QAM	0.55	3.32
16.3	12	64QAM	0.65	3.90
18.7	13	64QAM	0.75	4.52
21.0	14	64QAM	0.85	5.12
22.7	15	64QAM	0.93	5.55

distribution and can cause significant deviations from the mean path loss.

The combined effects of these propagation phenomena manifest as substantial fluctuations in RSRP, RSRQ, and SINR measurements. As shown in Fig. 5.1, RSRP and SINR exhibit considerable volatility even over short measurement periods. RSRP, which measures the average power of reference signals, shows direct susceptibility to both shadowing and multipath effects. For the RSRQ, it derived from RSRP and incorporating interference measurements, demonstrates even greater variability. SINR, which accounts for both signal strength and interference levels, exhibits particularly pronounced fluctuations due to the compound impact of fading effects on both desired and interfering signals.

5.1.1 CQI usage and propagation property in 5G

Channel quality indicator (CQI) is an important indicator reflecting the quality of the downlink channel, and its value ranges from 0 to 15, which is measured by the UE based on parameters such as SINR, RSRP, etc. and reported to the base station. A larger value of CQI indicates that the channel quality is better, and it can support higher-order modulation modes (e.g., QPSK, 16QAM, 64QAM) and higher coding rate.

In LTE and 5G systems, the mainly implement of the CQI is adaptation modulation and coding, resource scheduling, beam management and link adaptation. Base stations can dynamically select the best combination of transmission parameters by analyzing the CQI values reported by UEs, and realize high spectral efficiency while ensuring

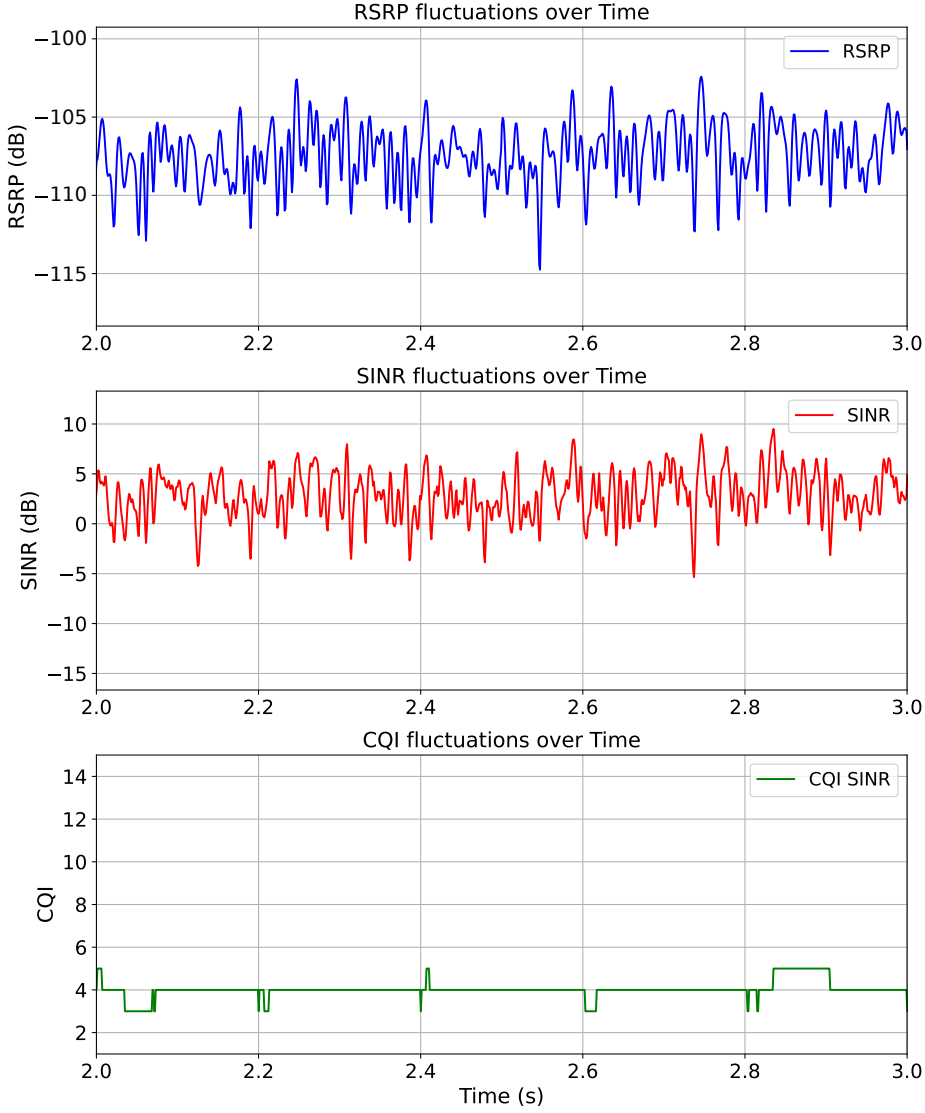


Figure 5.2: Propagation between the RSRP, SINR and CQI

transmission reliability [2].

In Table 5.1 the CQI and SINR are shown, along with the channel modulation, coding, and spectrum utilization corresponding to each of their values [61] [62]. In particular, the SINR in Table 5.1 indicates the lower limit value when corresponding to the CQI value, e.g., the CQI is always 1 when the SINR is below -6.7 dB, and the CQI is always 2 when the SINR is between -4.7 dB and -6.7 dB. It is worth noting that, according to the 3GPP standard specification, the correspondence table between CQI and SINR will be different in each version, but the interval in which a CQI value corresponds to a SINR is constant.

From Table 5.1, it is known that although SINR may fluctuate due to environmental effects such as fading and shadowing, CQI can be kept constant if the fluctuation of SINR is within a certain interval [62]. Similarly, in the fading environment, the correlation

between the fluctuation of RSRP and the fluctuation of SINR is consistent [63], both of which will fluctuate drastically by the influence of fading and shadowing. In other words, CQI fluctuates slower than SINR and RSRP, and the property of RSRP, SINR, and CQI as shown in Fig. 5.2.

Therefore, the property of CQI to remain constant and fluctuate slowly in severe fading environments is valuable in HDA, which aims to reduce the high HoF and ping-pong handover caused by severe fluctuations in RSRP due to fading.

In the design of CH HDA, the CQI was strategically chosen as a key metric over traditional RSRP and RSRQ measurements due to its distinct advantages in characterizing channel conditions. CQI employs a compact scale ranging from 0 to 15, offering a more concise value range compared to RSRP (-140 dBm to -44 dBm) and RSRQ (-19.5 dB to -3 dB).

This compact value range of CQI not only simplifies parameter optimization but also substantially reduces computational overhead. More importantly, the CQI scale exhibits inherent semantic significance: values above 5 indicate good communication conditions where handover operations may be unnecessary, while values below 5 serve as meaningful indicators for potential handover considerations, as shown in Table. 5.1. Furthermore, CQI demonstrates superior resilience to fading effects compared to RSRP, RSRQ, and Signal-to-Interference-plus-Noise Ratio (SINR) measurements. This reduced sensitivity to short-term channel fluctuations makes CQI a more stable metric for handover decisions-making, effectively filtering out transient variations that might otherwise trigger unnecessary handovers. The combination of these characteristics - compact value range, clear quality thresholds, and enhanced stability against fading, which makes CQI an ideal indicator for efficient and robust handover decision-making algorithm in HetNet.

5.2 Two type failures within the HDMA

In the handover decision-making algorithm, the UE measurement report includes the RSRP and RSRQ from surrounding cells, and the S-cell determines the necessity of a handover and to which cell it should be directed based on the received message of the measurement report in Fig. 5.3.

Generally, the entire handover process proceeds smoothly without handover failure (HoF). However, HoF often occurs when macro-cell and small-cells use the same frequency and are near each other because of the co-frequency interference [64]. According to the specific position of the UE where a radio link failure (RLF) occurs during the message exchange in the handover procedure in Fig. 5.3, RLF indicates that the UE loses the communication link with the S-cell owing to a poor signal-to-noise ratio (SINR) value [15] [16].

The HoF can be categorized into two main types [1], [65],

- Too-late failure (TLF),

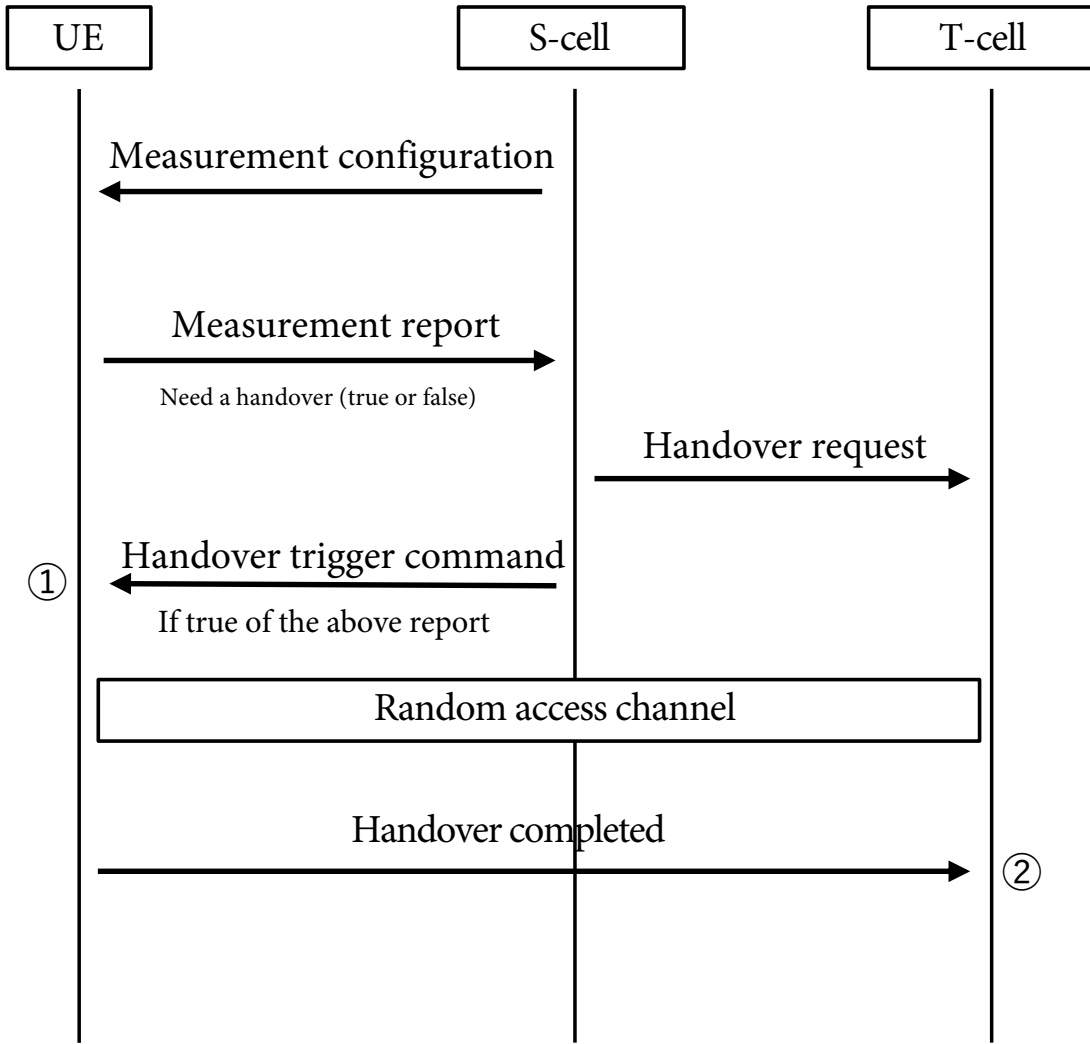


Figure 5.3: Two types of failures in the handover procedure

- Too-early failure (TEF).

In a communication environment using the same frequency, the downlink of the UE receives strong co-frequency interference. Consequently, the UE may experience RLF before receiving the handover trigger command [66], which refers to message 1 in Fig. 5.3. Additionally, because the output power of the small-cell is smaller than that of the macro-cell, sometimes the uplink SINR of the UE degrades to a level where the S-cell cannot receive its measurement report before the UE receives message 1 [64], [66]. As a result, the S-cell cannot receive the measurement report from the UE and cannot send a handover trigger command based on the measurement report, which eventually leads to an RLF of the UE. These two types of HoFs, where the RLF occurs before the UE receives the handover trigger command, are called TLF [16], [67].

Furthermore, the RSRP received by the UE from both the S-cell and T-cell can fluctuate significantly owing to fading, which is a physical phenomenon that occurs dur-

ing signal propagation. The fading causes the S-cell to receive inaccurate measurement reports from the UE, resulting in the S-cell prematurely determining the UE handover based on the inaccurate RSRP measurement reports from the UE [14]. The measurement report from the UE may not accurately reflect a communication environment, resulting in a poor RSRP of the T-cell [68]. This can cause the T-cell to not receive the handover completion message from the UE, and the message is shown as message 2 in Fig. 5.3. The HoF where the UE experiences RLF before the T-cell receives message 2 is called TEF [1].

5.3 Related work on the improvement of the A3RSRP HDAM

A3RSRP HDA involves two main parameters, HOM and TTT, which are crucial for selecting the cell with the best communication quality and resilience against fading. However, the HOM takes precedence over TTT as it determines the timing for a UE to trigger a handover [16], [69]. In addition, the two parameters, HOM and TTT, in the A3RSRP HDA do not dynamically change after a decision [70]. Selecting inappropriate HOM and TTT values because of insufficient knowledge can lead to increased HoF ratio incidents during the handover process. Recognizing the limitations of the A3RSRP HDA, 3GPP Release 8 introduces a self-organizing network entity into the mobile communication network, and this entity enhances handover performance by dynamically adjusting HDA parameters for UE [71]. This strategy, known as mobility robust optimization (MRO) [72], focuses on optimizing HDA.

Subsequent papers concentrated on dynamically adjusting and optimizing the A3RSRP HDA using different measurement indicators to reduce the HoF ratio and the number of frequent handovers. Research on handover can be divided into two main topics: HDA and handover execution. This paper is mainly concerned with HDA. Thus, it focuses on papers related to HDA management and optimization. Furthermore, based on the indicators used in the decision-making process of HDA, the related work is divided into the following two main aspects.

- RSRP/RSRQ based
- SINR based.

RSRP/RSRQ based

Reference [6], the author proposed an MRO algorithm to optimize the A3RSRP HDA. Specifically, HoF data were collected based on different failure types in the past time, and the HOM or TTT was dynamically adjusted based on the ratio of a single failure type in the collected HoF. Reference [73], the authors proposed an MRO algorithm to

optimize HOM and TTT parameters selection in A3RSRP HDA based on real-time feedback of HoF type, TLF, or TEF, to reduce the FHO. However, the algorithms require the analysis of historical data to adjust the handover parameters, the HOM or TTT. Therefore, the algorithm optimizes handover performance after a certain time by sacrificing historical handover performance.

Reference [74], the author proposed an MRO algorithm based on fuzzy logic control (FLC) to optimize the A3RSRP HDA. This approach considered RSRP, RSRQ, and speed to select better HOM and TTT parameters for the UE based on the changing environment. The results show significant suppression of both the HoF ratio and PPHO. Nevertheless, the authors considered the range of HOM to be insufficient. Furthermore, the HetNet environment was considered in the paper, and the proposed FLC-based approach is generally considered complex and difficult to apply.

Reference [75], the author used a combination of neural networks and FLC to predict the optimal HOM and T-cell prioritization in a 5G environment. The results demonstrated the effectiveness of the approach in optimizing handover success rate and PPHO. Reference [76], the authors used machine learning to optimize the A3RSRP HDA, aiming to determine the optimal HOM and TTT values under a specific network to reduce the HoF ratio and the number of PPHOs. Reference [77], the authors propose an MRO algorithm based on Q-learning to optimize the cell individual offset parameter setting in A3RSRP HDA to reduce the number of PPHOs and HoF ratio within the scenario of random deployment of small-cells. However, such approaches for predicting the optimal parameter setting within the A3RSRP HDA consume substantial computing time and resources, and the algorithm must be retrained after changing the environment, which is good for the specific environment but not for the real-world application.

SINR based

Reference [78], the authors proposed a heuristic algorithm to optimize the A3RSRP HDA by considering the SINR, RSRP, RSRQ, and speed. The numerical results showed that the weights of the four components were as follows: SINR (0.4215), RSRP (0.1054), RSRQ (0.0516), and speed (0.4215). Consequently, in networks with the same frequency, the influence of SINR, RSRP, and speed was high, while the proportion of RSRQ was low when considering measurement indicators. However, the algorithm did not consider the fading environment, potentially leading to an idealized result.

Reference [79], the authors proposed a handover trigger policy based on SINR and the trajectories of moving UE using Markov modeling to enhance the communication capacity of UE in HetNet. The results show that the proposed mathematical model improves the communication capacity by nearly 100% and was very close to the optimal solution. However, the SINR threshold of 1 dB for handover triggering is considered, which indicates that the direction of movement of the UE must have been away from the S-cell. Otherwise, it could result in a TEL.

Reference [80], the author proposed an algorithm based on the SINR and received signal strength to reduce FHO in vertical handover environments and showed that the proposed algorithm was effective.

Moreover, there are some other methods to optimize A3RSRP HDA. Reference [69], the authors propose an approach based on the dwell time of the UE in a cell to reduce FHO by forcing the UE with a short dwell time in a small-cell to hand over to a macro cell. Reference [81], the authors select the optimal small-cell to reduce the HoF ratio and FHO based on the dwell time of the UE in a cell.

Despite the previous works optimizing the performance of the A3RSRP HDA, they focus on the proposal of an MRO algorithm that dynamically adjusts the parameters of the HOM or TTT in A3RSRP HDA using an MRO algorithm for some particular scenarios to reduce the HoF ratio and FHO by using different measurement indicators, such as RSRP, RSRQ, and SINR.

However, all of these works are based on the existing A3RSRP HDA, which indicates the handover trigger conditions in these works are the same as the A3RSRP HDA. Furthermore, since RSRP, RSRQ, and SINR fluctuate drastically in fading environments, resulting in the optimization of A3RSRP HDA parameter settings using RSRP, SINR, and RSRQ usually requires the implementation of FLC, machine learning, or neural networks to accurately predict the optimal HOM or TTT parameter settings for a given environment. However, it is difficult to apply them in LTE and 5G real-world applications because these methods require significant computational time and resources for model learning and training.

5.4 Proposal of CQI-based HDMA

CQI is an indicator of the quality of UE communication used in mobile networks, and HC is a commonly used method for controlling the switching of equipment by environmental changes in the world of electrical and electronic engineering. With severe signal fading in the complex communication environments of mobile networks, both RSRP and RSRQ indicators, which are currently widely used in HDA, suffer from severe fading, resulting in poor handover performance. Therefore, in order to address this problem, we consider controlling the HDA process by using a combination of CQI and HC to shift the timing of handover triggering, as detailed in Algorithm 2.

Algorithm 2 shows the conditions and decision process of the proposed CH HDA, where CQI_{avg} denotes the average downlink CQI within 200 ms after rounding. This is because although the downlink CQI fluctuation is slower than SINR and RSRP, the resistance to fading is stronger. However, it is still subject to fading if the CQI is not pre-processed, resulting in the UE sending incorrect measurement reports to the S-cell, as with the RSRP and RSRQ, and we uniformly referred CQI_{avg} to as ‘CQI’ in the following for simplicity of description.

Algorithm 2 CQI+Hysteretic handover decision algorithm

```

1: if  $CQI_{avg} < T_{CQI_1}$  and  $CQI_{avg} \geq 1$  then
2:   if  $CQI_{avg} \leq T_{CQI_2}$  then
3:      $Offset_n = Offset_n - H^-$ 
4:   else
5:     if Ping-PongHo then
6:        $Offset_n = Offset_n + H^+$ 
7:     else
8:        $Offset_n = \text{initial } Offset_n$ 
9:     end if
10:  end if
11:  if  $Mn > Mp + Offset_n$  then
12:    Wait for TTT to do a handover of the cell
13:  else if  $Mn < Mp + Offset_n$  then
14:    Cancel the handover of the cell
15:  end if
16: else
17:   if  $CQI_{avg} \geq T_{CQI_1}$  then
18:    Cancel handover
19:   end if
20: end if

```

Specifically, T_{CQI_1} and T_{CQI_2} are thresholds used to determine UE handover and handover difficulty, respectively, where T_{CQI_1} is used to determine whether handover is necessary for the UE, and T_{CQI_2} is used to determine whether a reduction of the $Offset_n$ is necessary. This reduction is interpreted as a reduction in handover difficulty by the HDA based on the current quality of the communication of the UE.

In HC, there are two parameters, H^- and H^+ , which denote the specific value used to determine the decrease of $Offset_n$ according to the CQI and the specific value used to determine the increase of $Offset_n$ according to *Ping-PongHo*, respectively, as shown in Fig. 5.4. *Ping-PongHo* denotes whether a handover is performed between the same S-cell and T-cell within a short period of time, and if yes, the difficulty of handover is increased by H^+ .

Therefore, the whole idea and process of the CH HDA judgment is that it sends a measurement report to the S-cell when the UE needs to be handed over. The HDA determines that the current communication environment is degrading and allows the UE to prepare for trigger handover if the CQI of the UE is less than the T_{CQI_1} . Continuously, the HDA determines that the UE must start handover immediately and reduces the decrease the initial $Offset_n$ by H^- if the CQI of the UE is less than T_{CQI_2} before the UE triggers handover. Conversely, the initial $Offset_n$ is maintained if the CQI is not less than T_{CQI_2} . After the UE clears the CQI condition, the CH HDA checks the A3 event described in (4.1), and the UE will trigger a handover after the TTT time if the A3 event is satisfied while the UE does not trigger the handover and cancels the report

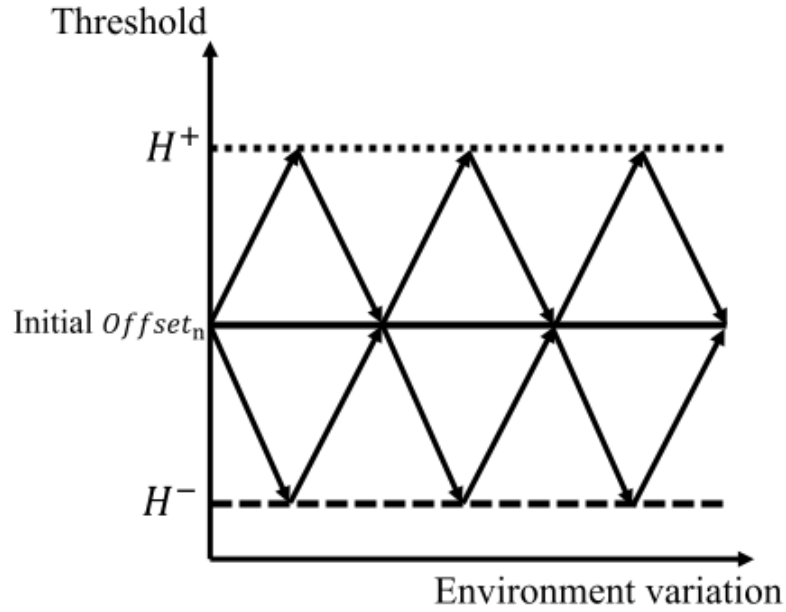


Figure 5.4: The HC scheme considered in the HDA

of the handover measurement to the S-cell if the A3 event is not satisfied.

Moreover, the handover request of the UE is canceled if the CQI is greater than the T_{CQI_1} before the handover is triggered, regardless of whether the A3 event is satisfied or not.

5.5 Simulation results of the proposed CQI HDAM

5.5.1 Simulation environment setting

We focus on the co-frequency HetNet environment, the variation in the number of cells results in the variation in the strength of interference. In addition, as the number of cells varies, the variation in the number of signals received by a UE results in a variation of the fading environment. Therefore, to evaluate the performance of both the proposed CH and the A3RSRP HDAs more comprehensively, we will evaluate the performance of the two HDAs through two simulation environments, which we refer to as small-scale and large-scale environments.

Furthermore, this paper focuses on the triggering conditions and timing of handover and considers ways to improve it. However, other factors often disrupt discussions due to the complex HetNet environment, leading to confusion and marginalization. For example, it is necessary to exclude the HoF owing to factors such as communication congestion or insufficient resource blocks when discussing the triggering conditions and handover timing of the A3RSRP HDA and how to improve it. Therefore, in this paper, we consider an environment with a small number of UEs to evaluate the performance of the proposed CH and A3RSRP HDAs.

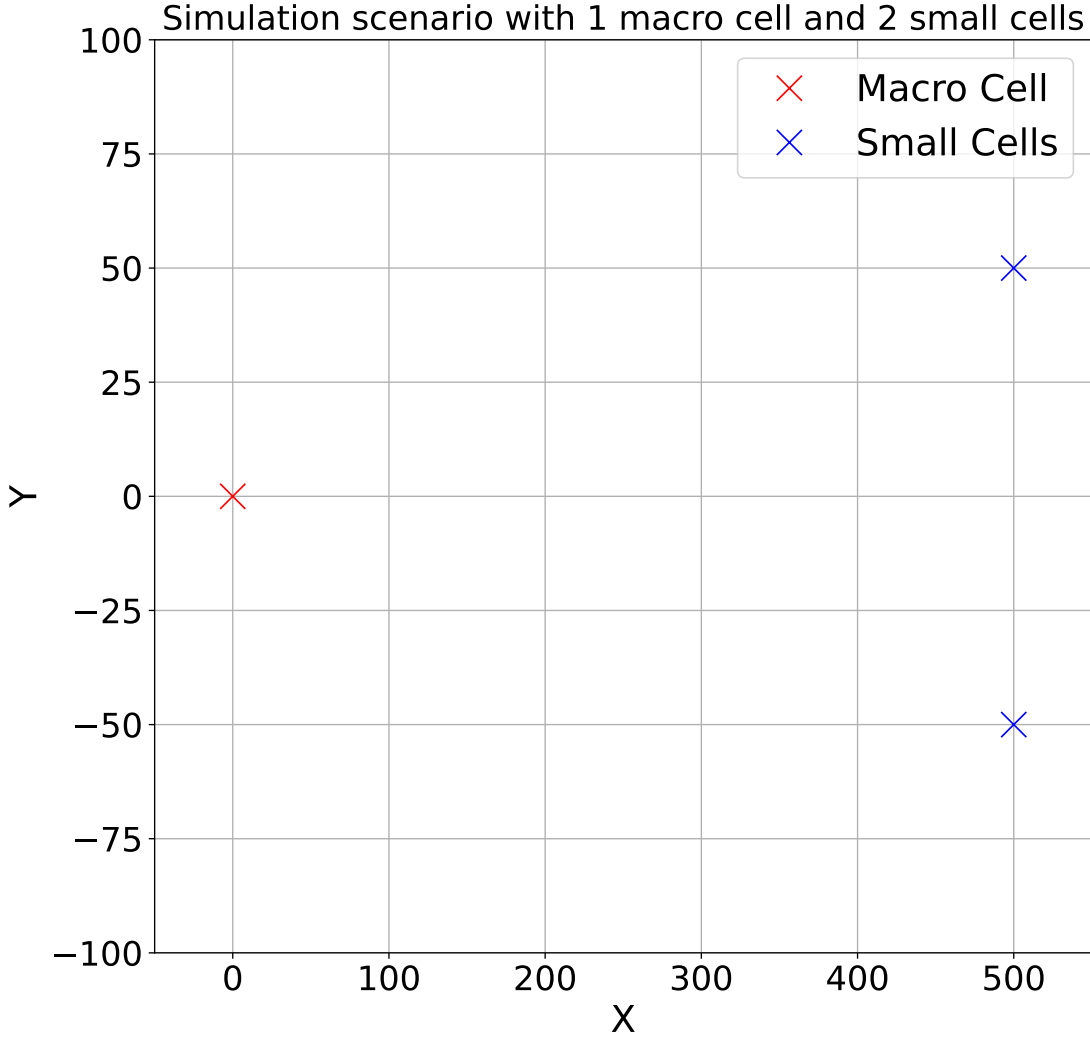


Figure 5.5: Simulation environment with small-scale

5.5.2 Small-scale environment simulation

The small-scale environment is illustrated in Fig.5.5. Specifically, the macro-cell is positioned at the origin $(0,0)$, and two small-cells using the same frequency with the macro-cell are positioned 500 m away from the macro-cell at $(500,50)$ and $(500,-50)$, respectively. The performance of the two HDAs is evaluated by the UE moves randomly with the RandomWalk2dMobility model. Furthermore, low-speed UE suffers more severely from fading and is more susceptible to TEF, especially in HetNet [82], [48]. Therefore, this paper considers the scenario of UEs moving at low speed, and the movement of UEs is limited to the range of $[200, 500]$ on the X -axis and the range of $[-100, 100]$ on the Y -axis to limit the UE travel to an irrelevant area with no handover.

Moreover, the parameter $Offset_n$ in the A3RSRP HDA can be selected in the range of $[-15, 15]$ dB. However, the received RSRP from a small-cell by the UE is not expected to be higher than the received RSRP from the macro-cell by the UE 15 dB because the

Table 5.2: Simulation parameter setting

Parameters	Value
Simulation time	1000 s
Frequency	2 GHz
Macro-cell power	46 dBm
Small-cell power	32 dBm
Bandwidth	50 resource blocks
Macro-cell path loss model [14]	$15.3 + 3.76 \times 10 \log(R)$, R in m
Small-cell path loss model [14]	$38.46 + 2.0 \times 10 \log(R)$, R in m
$Offset_n$	[0.5, 1.0, 1.5, 2.0, 2.5, 3.0] dB
T_{CQI_1}	2, 3, 4
T_{CQI_2}	1, 2
CQI generation interval	1 ms
Hysteretic control (H)	[-1.0, -0.5, 0, 0.5, 1.0] dB
Time interval to judge as a <i>Ping-PongHo</i>	1 s
TimeToTrigger	100 ms
Downlink out of synchronization	-5 dB
Timer 310	200 ms
Fading model [64]	Rayleigh fading
Number of UE	5
Low speed [6]	0.5 m/s, 1 m/s, 3 m/s
Mobility model	RandomWalk2dMobility
The number of seeds	5

power output of the small-cell is typically low. Similarly, selecting an $Offset_n$ that is too small will increase the number of FHO, owing to the HDA being susceptible to fading, leading to the TEF.

Therefore, we consider $Offset_n$ in the range of [0.5, 3.0] dB, the increment is 0.5 dB, to compare the performance of the CH HDA with the better performance of the A3RSRP HDA, and close to 0.5 dB is considered relatively small $Offset_n$, and close to 3.0 dB is considered relatively large $Offset_n$. Furthermore, only the effect of various $Offset_n$ values is discussed, the effect of different TTT is not discussed in this paper. Hence, a fixed TTT value of 100 ms is chosen. The specific parameter settings of the simulation environment are shown in Table 5.2.

5.5.3 Evaluation of handover failure ratio

The baseline for comparison is the $Offset_n$ present in the two HDAs, which have the same value because such a comparison provides a clear view of the effect of our proposed CH HDA on the handover.

Therefore, the two HDAs show the results on HoF ratio when the parameter of $Offset_n$ is set to $Offset_n$ dB in Table 5.2, for every 0.5 dB interval. Moreover, a handover is not possible with a large value of the CQI. At the same time, a successful

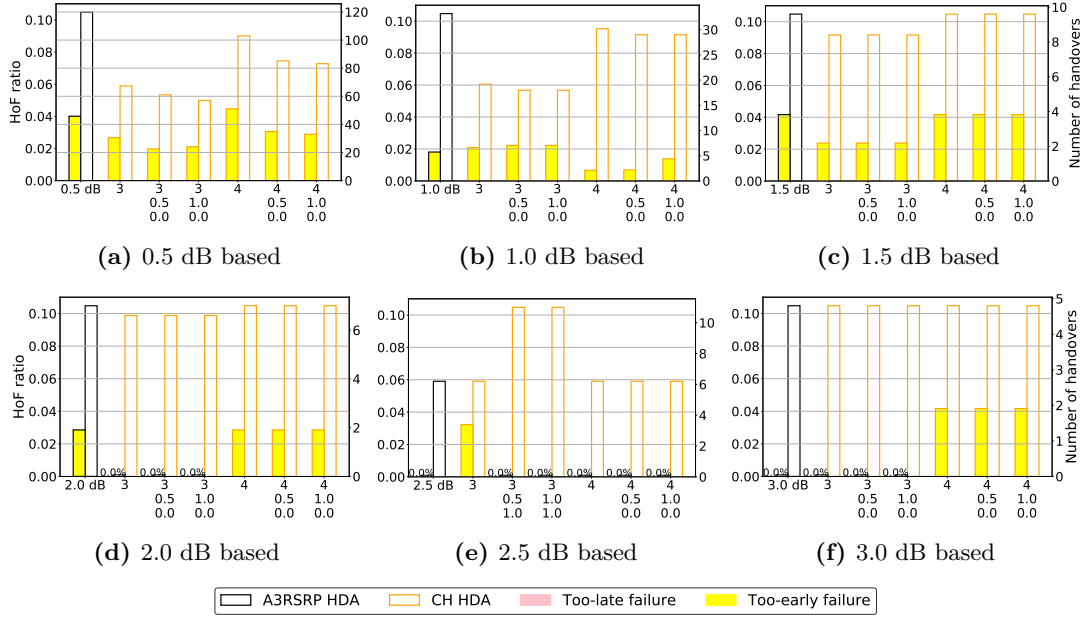


Figure 5.6: Comparison of the HoF ratio and number of handovers for the A3RSRP and CH HDAs at 0.5 m/s speed

handover has a lower probability with a value that is too small, such as the CQI equaling 1. Meanwhile, according to the mapping table of CQI and SINR in [62], a handover is most likely to occur when the SINR changes around 0 dB for the CQI values of 2, 3, and 4. Thus, we choose 2, 3, and 4 as the value of the T_{CQI} .

The equation concerning the calculation of HoF is shown as follows:

$$R_{\text{HoF}} = \frac{N_{\text{TEF}} + N_{\text{TLF}}}{N_{\text{SUCC_HO}} + N_{\text{TEF}} + N_{\text{TLF}}}, \quad (5.1)$$

where R_{HoF} , N_{TEF} , N_{TLF} , and $N_{\text{SUCC_HO}}$ denote the metric of HoF ratio, the number of TEFs, the number of TLFs, and the number of successful handovers, respectively. The number of handovers is defined as the sum of N_{TEF} , N_{TLF} , and $N_{\text{SUCC_HO}}$. The categorization criteria of N_{TEF} and N_{TLF} are based on Fig.5.3, which indicates that if message 1 is not received by a UE before an RLF occurs then the number of N_{TLF} is incremented by 1. Similarly, if message 2 is not received by T-cell before an RLF, then the number of N_{TEF} is incremented by 1.

Furthermore, the parameter H of the HC, including the H^+ and H^- , have both positive and negative effects at various UE speeds and combinations. For example, at low speeds of 0.5 m/s, the positive effect of HC is mainly on the H^+ , while at relatively higher speeds of 3 m/s, the positive effect of HC is mainly on the H^- . This is because, in the low-speed scenario, the UE's need for handover is extremely low. Hence, increasing the difficulty of handover by the H^+ is beneficial for avoiding the FHO and TEFs and maintaining a stable communication environment. On the other hand, in a higher-speed

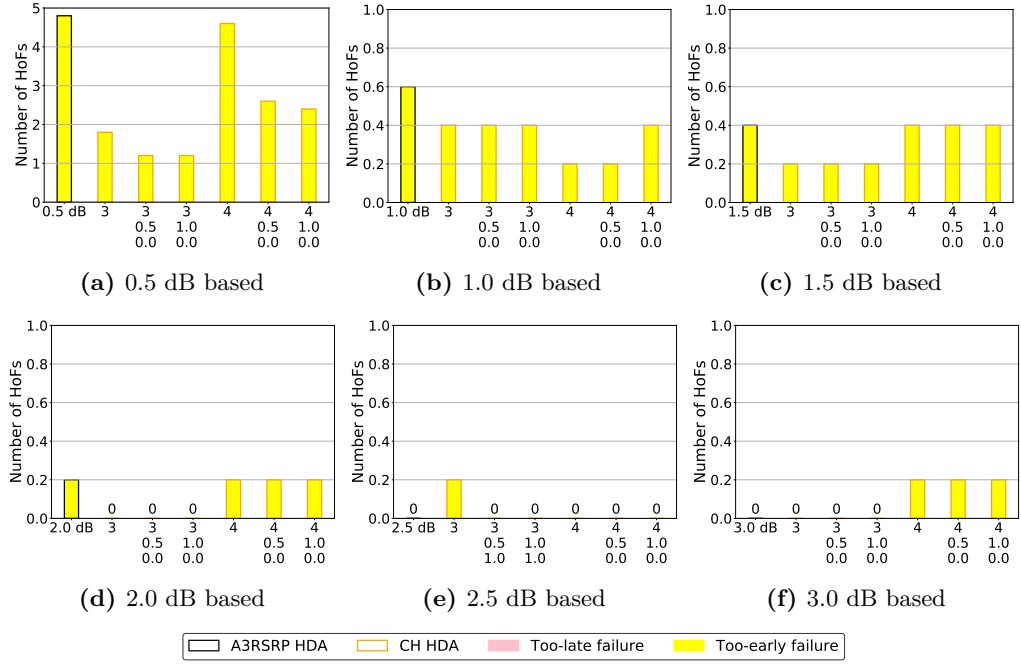


Figure 5.7: Comparison of the number of HoFs for the A3RSRP and CH HDAs at 0.5 m/s speed

scenario, the UE's need for handover increases substantially. Consequently, reducing the difficulty of handover by the H^- is beneficial to enable the UE to trigger handover early to reduce the risk of suffering from TLFs or a poor communication environment. Therefore, the parameter combinations for HC with positive effects are prioritized, and for the convenience of the description in the later paper, the parameter H including H^+ and H^- are described as a sum of H^+ and H^- , and the specific H^+ and H^- settings are exhibited in each result.

Regarding the presentation of the simulation results for the HoF ratio in Fig. 5.6, 5.8, 5.10, 5.13, 5.15, and 5.17. The X-axis shows parameter settings for the two HDAs, in which the A3RSRP HDA is $Offset_n$ setting, and the CH HDA is T_{CQI_1} threshold and two H parameters settings. For the CH HDA, the upper one is T_{CQI_1} , and below it is the setting of the two H parameters. Furthermore, a dual Y-axis illustrates the HoF ratio and the number of handovers. The left Y-axis represents the HoF ratio corresponding to the filled histogram on the left side, while the right Y-axis represents the number of handovers corresponding to the empty histogram on the right side. Moreover, Fig. 5.7, 5.9, 5.11, 5.14, 5.16, and 5.18 shows the performance comparison of the number of HoFs.

5.5.3.1 Evaluation of UE moving with 0.5 m/s

Fig. 5.6 shows the HoF ratio and number of handovers of both HDAs, and the results are evaluated when the threshold of the T_{CQI_2} is fixed to 1, and UE is moving at a speed

of 0.5 m/s.

Fig. 5.6a shows that the HoF ratio for the A3RSRP HDA is 4%. Since an initial offset threshold of 0.5 dB is selected, a smaller offset threshold results in all HoFs being TEF. Additionally, the results of the number of A3RSRP HDA handovers in Fig. 5.7a show that when $Offset_n$ is 0.5 dB, although the HoF ratio remains at 4%, resulting in a large number of handovers because a smaller $Offset_n$, which in turn results in a small HoF ratio.

In contrast, the CH HDA decreases the HoF ratio 2% by T_{CQI_1} 3 without HC compared to A3RSRP HDA. The results of the number of handovers for CH HDA in Fig. 5.7a show that the number of handovers is substantially suppressed by T_{CQI_1} 3 and without HC, and a 43% and 62% reduction in the number of handovers and number of TEFs, respectively, are observed compared to A3RSRP HDA. When T_{CQI_1} 3 with HC, the number of handovers is reduced by 52%, and the number of TEFs is reduced by 75% compared to A3RSRP HDA. When T_{CQI_1} 4 without HC, the suppression of TEFs by CQI is degraded due to the relaxed trigger condition for the CH HDA compared to T_{CQI_1} 3, while the number of handovers is reduced by 14% and the number of TEFs is reduced by 4% compared to A3RSRP HDA. When the T_{CQI_1} is 4 with HC, the number of handovers decreases by 28%, and the number of TEFs decreases by 50% compared to A3RSRP HDA.

Fig. 5.6b shows that the HoF ratio for A3RSRP HDA is 2%. In contrast, for the CH HDA, the HoF ratio when the T_{CQI_1} is 3 without and with HC is slightly higher than the A3RSRP HDA, while it does not mean that the performance of the CH HDA is worse than the A3RSRP HDA because it decreases the number of handovers and TEFs by 42% and 33%, respectively, when the T_{CQI_1} is 3 without HC compared with the A3RSRP HDA based on Fig. 5.7a. The number of handovers and TEFs decreases by 45% and 33%, respectively, when the T_{CQI_1} is 3 with HC. Meanwhile, the HoF ratio decreased by 1% when the T_{CQI_1} is 4 without HC, and the number of HoFs is almost negligible. The number of handovers and TEFs decreases by 9% and 66%, respectively, when the T_{CQI_1} is 4 without HC. The HoF ratio decreases by 1%, and the number of handovers and TEFs decreases by 12% and 66% compared with the A3RSRP HDA, respectively, when T_{CQI_1} is 4 with HC and the sum of the H parameter is 0.5 dB. The HoF ratio decreases less than 1%, and the number of handovers and TEFs decreases by 12% and 33%, respectively, when the sum of the H parameters is 1.0 dB. The performance when the sum of the H parameter is 1.0 dB is worse than the sum of the H parameter is 0.5 dB because the timing of the handover trigger is excessively shifted backward, resulting in a slightly increased number of TEFs. Thus, inhibiting a handover by shifting the trigger timing of the handover backward significantly may cause the UE to undergo uncertain fading after the handover is triggered, resulting in low SINR and a TEF. As we described in Fig. 5.3, the T-cell cannot receive message 2, leading to a TEF.

Fig. 5.6c shows that the HoF ratio is 4% when the initial $Offset_n$ is 1.5 dB. In

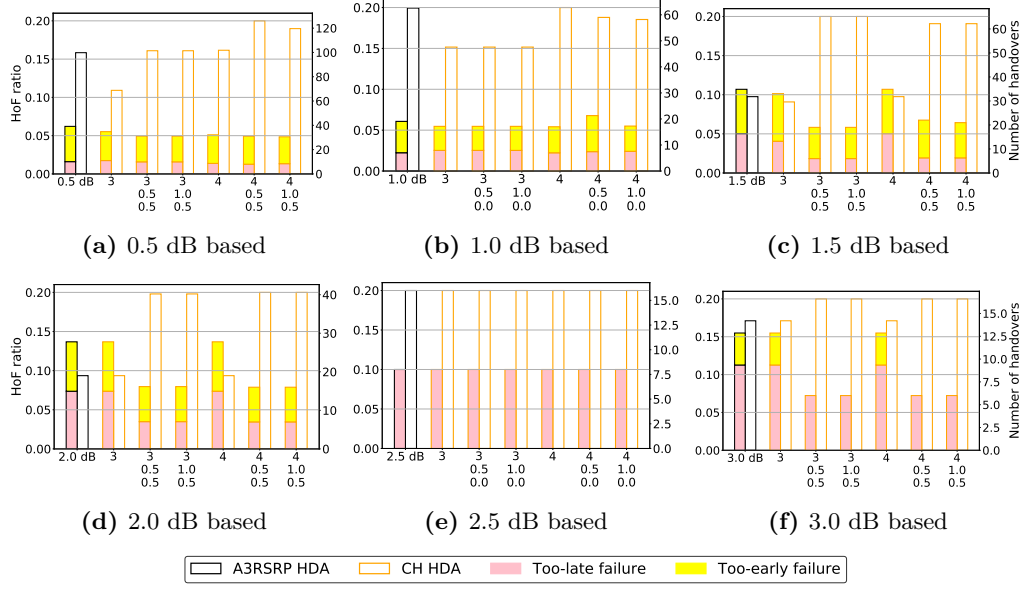


Figure 5.8: Comparison of the HoF ratio and number of handovers for the A3RSRP and CH HDAs at 1 m/s speed

contrast, the CH HDA reduces the HoF ratio by 2% when the T_{CQI_1} is 3 with HC. Moreover, the number of handovers and TEFs decreases by 12% and 50%, respectively, when the T_{CQI_1} is 3 with and without HC compared with the A3RSRP HDA based on the result in Fig. 5.7c, because the effect of suppressing handovers and TEFs mainly dominated by the T_{CQI_1} , and a T_{CQI_1} taking 3 shift the trigger timing of the handover backward as we described in Fig. 5.6b. In addition, the HoF ratio when the T_{CQI_1} is 4 with or without HC is the same as the A3RSRP HDA. This is because most FHO has been suppressed, and the remaining handovers are difficult to eliminate by a T_{CQI_1} of 4 based on the initial $Offset_n$ value at 1.5 dB.

Fig. 5.6d shows that the HoF ratio of the A3RSRP HDA is about 3%. In contrast, the CH HDA reaches zero HoF when the T_{CQI_1} is 3, which means no failure in all the handovers, and the same zero HoF is also achieved when HC is considered based on the result in Fig. 5.7d. Moreover, the number of handovers decreases by 5% based on the result in Fig. 5.7d. The number of TEFs reaches zero when the T_{CQI_1} is 3 with and without HC, which decreases the number of TEFs by 100% compared with the A3RSRP HDA. In addition, the results of the T_{CQI_1} 4 are almost the same with A3RSRP HDA, this is the same as the result in Fig. 5.6c.

Fig. 5.6e shows that zero HoF is also achieved for the A3RSRP HDA when the initial $Offset_n$ is 2.5 dB. This result shows that the initial $Offset_n$ should be at least 2.5 dB for the A3RSRP HDA to suppress most of the TEFs and handovers owing to the fading. In contrast, the HoF ratio of CH HDA is 3%, and while the number of handovers is the same with the A3RSRP HDA when the T_{CQI_1} is 3 without HC, the CH HDA causes slight TEFs. This worse result is because the triggering timing of the handover is shifted

backward too much owing to the T_{CQI_1} of 3 and a large value of the initial $Offset_n$, which may cause the UE to undergo uncertain fading after the handover is triggered and result in poor SINR even TEF. Meanwhile, zero HoF is achieved regardless of whether the sum of the H parameters is -0.5 dB or 0 dB when the T_{CQI_1} is 3 with HC while the number of handovers increases by 77% compared with the A3RSRP HDA based on the result in Fig. 5.7e. This is because when T_{CQI_1} 3 and large $Offset_n$, it is necessary to set the sum of the H to zero or negative in order to neutralize significantly shifted backward timing of the handover. However, the negative sum of the H will increase the number of handovers. In addition, the result of T_{CQI_1} 4 is the same with the A3RSRP HDA. This is because T_{CQI_1} 3 is not as effective as T_{CQI_1} 3 in suppressing handover and TEF, and A3RSRP HDA has the suppression effect on FHO and TEF for 0.5 m/s low-speed scenario when the initial $Offset_n$ at least 2.5 dB.

Fig. 5.6f shows that the A3RSRP HDA still achieves zero HoF when the initial $Offset_n$ is considered 3.0 dB. In contrast, the CH HDA also achieves zero HoF when the T_{CQI_1} is 3 with and without HC. Furthermore, the number of handovers by the T_{CQI_1} values of 3 and 4 is the same as the A3RSRP HDA, but some TEFs occur when the T_{CQI_1} is 4. This is because the handover trigger timing of shifted backward by the T_{CQI_1} 4 is worse compared to the T_{CQI_1} 3 for a scenario with a low-speed movement of 0.5 m/s and an initial $Offset_n$ of 3 dB. Therefore, it is suggested to choose the CH HDA with a combination of T_{CQI_1} 3 and HC in a low-speed scenario, and it is not suggested to choose the CH HDA with a combination of T_{CQI_1} 4 and HC in a low-speed scenario.

5.5.3.2 Evaluation of UE moving with 1 m/s

Fig. 5.8 shows the HoF ratio and number of handovers of the CH and A3RSRP HDAs at a speed of 1 m/s, and the threshold of the T_{CQI_2} is fixed to 2.

Regardless of how the parameters are adjusted by the two HDAs, zero HoF cannot be achieved, and TLFs occur. As the moving speed of UE increases, the received RSRP from the cells is subjected to more severe fading compared with those at 0.5 m/s moving speed in the same time period. These results are the same with [14], [81], [82], where a severe delay in handover triggering due to the setting of an unsuitable handover threshold will lead to severe degradation of the communication quality of UE, which results in a TLF.

Meanwhile, the co-frequency interference causes the downlink SINR of the UE to be low, leading to decoding failures and packet loss, which results in a TLF independent of speed. Therefore, with the increasing speed of movement, the UE exhibits more serious TLFs compared with the scenario of 0.5 m/s.

Fig. 5.8a shows that the HoF ratio for the A3RSRP HDA is 6% when the initial $Offset_n$ is 0.5 dB. More than half of the HoFs are TEFs, and the remainder are TLFs due to the selection of a small $Offset_n$. In contrast, the HoF ratio of CH HDA decreases by 1% when the T_{CQI_1} is 3 without HC compared with the A3RSRP HDA.

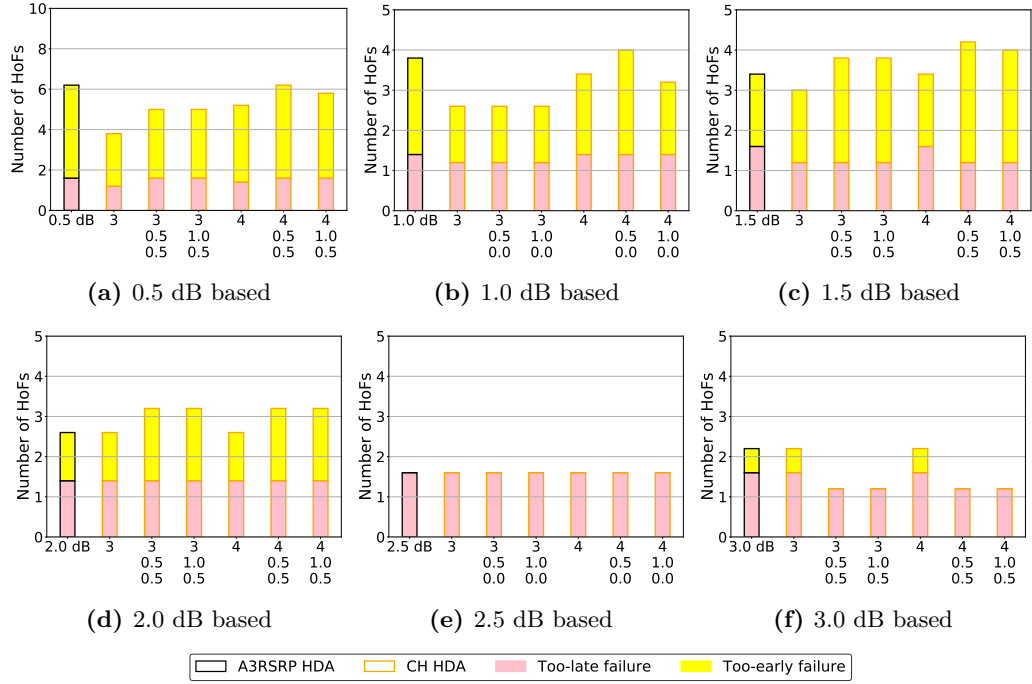


Figure 5.9: Comparison of the number of HoFs for the A3RSRP and CH HDAs at 1 m/s speed

Moreover, the CH HDA reduces the number of handovers, TLFs, and TEFs by 31%, 33%, and 40%, respectively, when T_{CQI_1} 3 without HC compared to the A3RSRP HDA based on Fig. 5.9a. This reason is the same as the result we described in Fig. 5.6. The CH HDA decreases the number of TLFs and TEFs by 11% and 22%, respectively, while increasing the number of handovers by 1% when the T_{CQI_1} is 3 with HC compared with the A3RSRP HDA. This is because after considering HC and the sum of H parameters is 0 dB and 0.5 dB, the CH HDA increases the $Offset_n$ to increase the difficulty of handover triggering to reduce TEFs and decreases the $Offset_n$ to decrease the difficulty of handover triggering to reduce TLFs by the HC. However, the decreased difficulty of the handover trigger by the H^- in the H has resulted in a slight increase in the number of handovers. Meanwhile, the CH HDA reduces the number of TLFs and TEFs by 11% and 18%, respectively, while the number of handovers increases by 2% compared with the A3RSRP HDA when T_{CQI_1} 4 without HC. When T_{CQI_1} is 4 with HC, the number of TLFs and TEFs are reduced by 0% and 9%, respectively, while the number of handovers increases by 26% and 19%, respectively. This is because the suppresses effect of the sum of H 0.5 dB on the TEFs is more than when the 0 dB, but both include H^- . Thus, the number of handovers increases in order to reduce the number of HoFs. From this result, it can be seen that the effectiveness of suppressing TEF with a T_{CQI_1} 4 can be enhanced by the HC.

Fig. 5.8b shows that the HoF ratio for A3RSRP HDA is 6%. In contrast, the HoF

ratio of the CH HDA reduces by 1% compared with A3RSRPHDA when T_{CQI_1} is 3 with or without HC. The HoF ratios of CH HDA decrease by 1% when T_{CQI_1} is 4 without HC compared with A3RSRP HDA, while the HoF ratios of CH HDA increase by 1% and decrease by 1% when the sum of the H is 0.5 dB and 1.0 dB, respectively.

Moreover, the number of handovers, TLFs, and TEFs are reduced by 24%, 25%, and 36%, respectively, compared with the A3RSRP HDA when T_{CQI_1} is 3 with or without HC based on the result in Fig. 5.9b. Meanwhile, the number of TEFs is reduced by 18% with almost the same number of handovers, while the number of TLFs is the same as A3RSRP HDA when T_{CQI_1} is 4 without HC compared with the A3RSRP HDA. Although the number of handovers decreases by 5%, the number of TLFs remains the same and the number of TEFs increases by 9% compared with the A3RSRP HDA when T_{CQI_1} is 4 with HC and the sum of H is 0.5 dB. When T_{CQI_1} is 4 with HC and the sum of H parameters is 1.0 dB, the number of handovers, TLFs, and TEFs decrease by 7%, 12%, and 18%, respectively, compared with A3RSRP HDA. This reason is the result in Fig. 5.6f.

Fig. 5.8c shows that the HoF ratio for the A3RSRP HDA is 11%. In contrast, the CH HDA reduces the HoF ratio by 1% when T_{CQI_1} is 3 without HC and by 5% when HC is considered, while the HoF ratio is the same when T_{CQI_1} is 4 without HC, and the HoF ratio reduces by 5% when HC is considered.

Moreover, the CH HDA reduces the number of handovers and TLFs by 7% and 25%, respectively, the number of TEFs remains unchanged when T_{CQI_1} is 3 without HC, reducing the number of TLFs by 25% when the T_{CQI_1} is 3 with HC, while increases the number of handovers and TEFs by 105% and 44% compared with the A3RSRP HDA when the sum of the H is 0 dB and 1.0 dB based on the result in Fig. 5.9c. Despite the CH HDA increasing the number of handovers when the T_{CQI_1} 3 with HC compared with the A3RSRP HDA, T_{CQI_1} can correctly determine the timing of the handover trigger and hence reduces the HoF ratio by 5% without increasing an excessive number of TEFs. Meanwhile, the number of handovers, TLFs, and TEFs does not change when the T_{CQI_1} is 4 without HC compared with the A3RSRP HDA because the effect of T_{CQI_1} 4 on suppressing handover and HoFs is still weaker than T_{CQI_1} 3. The CH HDA reduces the number of TLFs by 12% and increases the number of handovers by 95% when the T_{CQI_1} is 4 with HC, in which the number of TEFs increases 55% and 44% by the sum of H 0 dB and 0.5 dB, respectively. Regardless of the T_{CQI_1} 3 or 4, the H^- dominates in the HC to reduce the number of TLFs that stand the majority in the HoF ratio, which makes the handover easier to trigger, increasing the number of handovers and TEFs.

Fig. 5.8d shows that the HoF ratio for the A3RSRP HDA is 13%. In contrast, the CH HDA reduces the HoF ratio by 5% when T_{CQI_1} is 3 and 4 when HC is considered, while the HoF ratio of the CH HDA is the same as the A3RSRP HDA when HC is not considered. Moreover, the number of handovers, TLFs, and TEFs are the same as that of A3RSRP HDA when T_{CQI_1} is 3 and without HC based on the result in Fig. 5.9d.

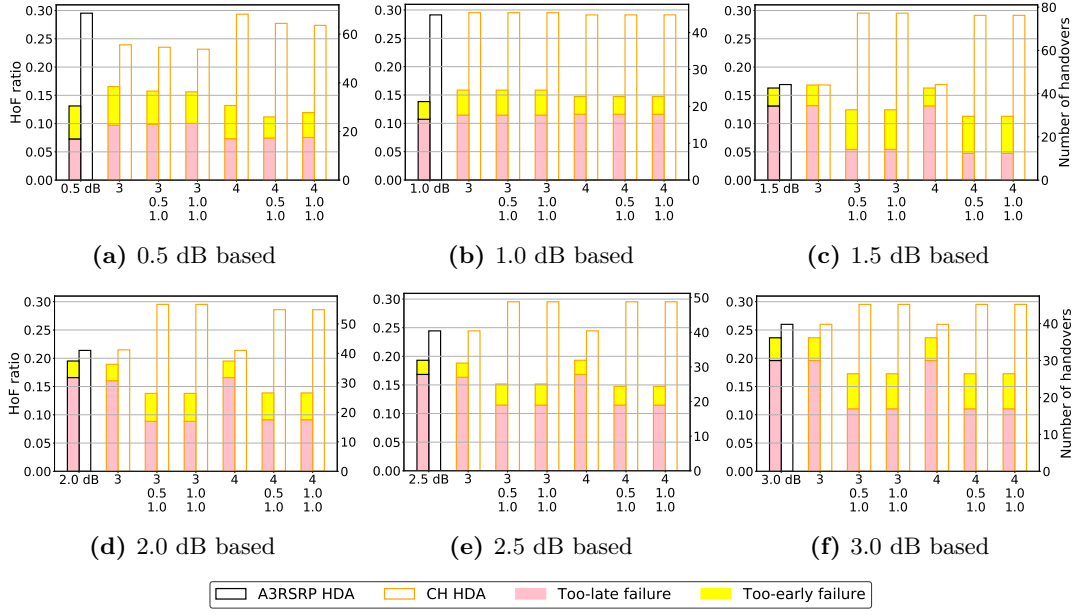


Figure 5.10: Comparison of the HoF ratio and number of handovers for the A3RSRP and CH HDAs at 3 m/s speed

This is because there are few number HoFs when the initial $Offset_n$ is raised to 2.0 dB, and the number of handovers by the A3RSRP HDA has been substantially suppressed, which makes it difficult to further improve the HoF ratio by the CH HDA with the current parameters combination. Meanwhile, the CH HDA reduces the HoF ratio by 5% when the T_{CQI_1} is 3 and 4 and HC is considered, although the number of handovers and TEFs increase by 110% and 50%, and the number of TLFs is the same as that of the A3RSRP HDA, which implies that CH HDA can maintain a higher handover success rate by correctly determine the timing of handover trigger without substantially increase in the number of HoFs.

Fig. 5.8e shows that the HoF ratio of A3RSRP HDA is 10%, and only the TLFs can be observed. This indicates that most of the TEF caused by fading can be avoided in the case of A3RSRP by an initial $Offset_n$ of 2.5 dB. Therefore, this parameter is optimal for A3RSRP HDA in this movement scenario. In contrast, the CH HDA exhibits the same as the A3RSRP HDA with and without HC when the T_{CQI_1} is 3 and 4 based on the results in Fig. 5.8e and Fig. 5.9e. This is because the current initial $Offset_n$ is the optimal parameter setting under this scenario. Therefore, it is not recommended to use the H^- in HC to reduce the number of TLFs based on this $Offset_n$, since additional TEFs may be induced.

Fig. 5.8f shows that the HoF ratio for the A3RSRP HDA is 15%. In contrast, the CH HDA reduces the HoF ratio by 7% when T_{CQI_1} 3 and 4 with HC compared with the A3RSRP and reduces the number of TEFs by 100%, achieving zero TEF, while the HoF ratio of the CH HDA is the same as the A3RSRP HDA when the T_{CQI_1} is 3 and

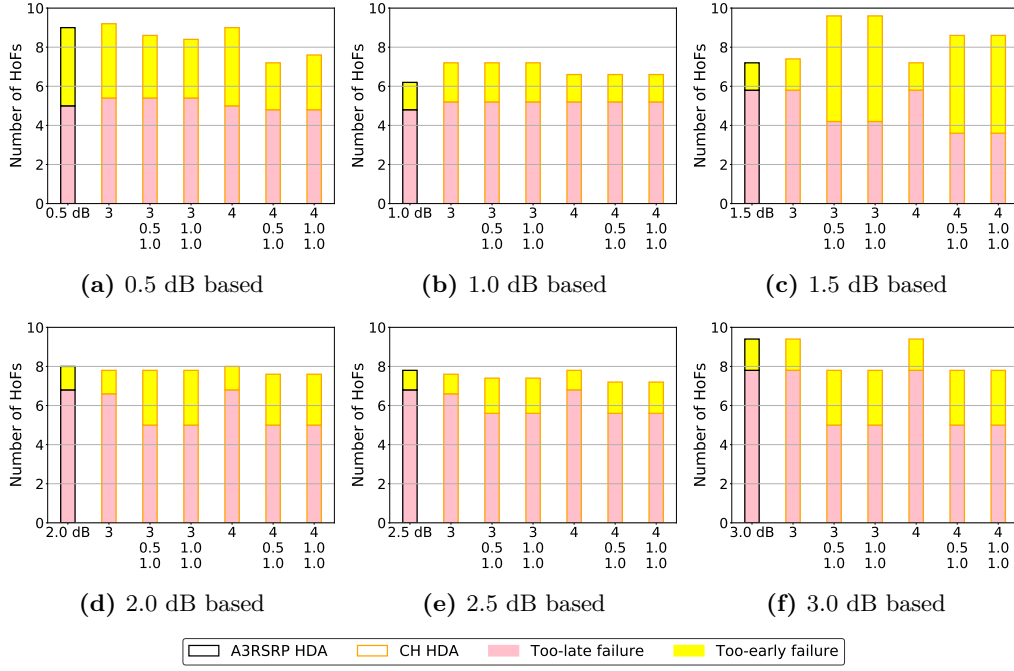


Figure 5.11: Comparison of the number of HoFs for the A3RSRP and CH HDAs at 3 m/s speed

4 without HC. Moreover, the number of TLFs and TEFs decreased by 25% and 100%, respectively, while the number of handovers increased by 16% when the T_{CQI_1} is 3 and 4 with HC, and the result of the CH HDA is the same as A3RSRP HDA when there is no HC compared with the A3RSRP HDA based on the result in Fig. 5.9f. This is because CH HDA performance can still be maintained well by correctly determining the trigger timing of the handover in the case where $Offset_n$ continues to increase from 2.5 dB, while the performance of A3RSRP HDA degrades obviously.

Based on the comparison results of Fig. 5.8 and Fig. 5.9, it can be seen that the CH HDA reduces the HoF ratio effectively when the initial $Offset_n$ is in the interval of less than and more than optimal $Offset_n$ 2.5 dB, which increases the number of handovers while obtaining better performance. In addition, it can also be effective in reducing the number of specific types of HoF, TLFs, or TEFs.

5.5.3.3 Evaluation of UE moving with 3 m/s

Fig. 5.10 shows the HoF ratio and number of handovers of two HDAs when the T_{CQI_2} is fixed to 2, and the UE moves at 3 m/s.

Fig. 5.10a shows that the HoF ratio for A3RSRP HDA is 13%. In contrast, the CH HDA reduces the HoF ratio by 2% and no change, respectively, when the T_{CQI_1} is 4 with and without HC, while the CH HDA increases the HoF ratio by 2% and 3%, respectively, when the T_{CQI_1} is 3 with and without HC, respectively, compared with

the A3RSRP HDA. Moreover, the number of handovers and TEFs reduces by 18% and 5%, respectively, while the number of TLFs increases by 8% for CH HDA compared to A3RSRP HDA when the T_{CQI_1} is 3 without HC based on the result in Fig. 5.11a. Additionally, the number of handovers and TEFs decreases by 20% and 20%, respectively, while the number of TLFs increases by 8% when the T_{CQI_1} is 3 with HC and the sum of H is -0.5 dB, and the number of handovers and TEFs reduces by 21% and 25% when the T_{CQI_1} is 3 and the sum of H is 0 dB, while the number of TLFs increases by 8%. As mentioned, the reduction in the number of handovers and TEFs and the increase in the number of TLFs is because of the substantial suppression effect of the T_{CQI_1} 3.

Meanwhile, the number of handovers, TLFs, and TEFs are reduced by 6%, 4%, and 40%, respectively, when the T_{CQI_1} is 4 with HC and the sum of H parameters is -0.5 dB. In addition, the number of handovers, TLFs, and TEFs is reduced by 7%, 6%, and 30%, respectively, when the T_{CQI_1} is 4 with HC and the sum of H parameters is 0.0 dB. Although the suppression of handovers and TEFs is degraded when the T_{CQI_1} is 4 compared to the T_{CQI_1} is 3, the improvement by the T_{CQI_1} 4 is better than the T_{CQI_1} 3, because the shifted trigger timing of handover by the HC is more suitable with T_{CQI_1} 4 than with T_{CQI_1} 3 at a moving speed of 3.0 m/s.

Fig. 5.10b shows that the HoF ratio for the A3RSRP HDA is 14%. In contrast, the HoF ratio of CH HDA is 15% when the T_{CQI_1} is 4 with or without HC, and the HoF ratio of CH HDA is 16% when the T_{CQI_1} is 3 with or without HC compared with the A3RSRP HDA. Moreover, the CH HDA increases the number of handovers, TLFs, and TEFs by 2%, 8%, and 42%, respectively, when the T_{CQI_1} is 3 based on the in Fig. 5.11b. When T_{CQI_1} is 4, the number of handovers and TEFs does not change, while the number of TLFs increases by 8% compared with the A3RSRP HDA. Because an initial $Offset_n$ value of 1.0 dB is the optimal parameter for A3RSRP HDA with a speed of 3 m/s, and the same reason as in Fig. 5.8e.

Fig. 5.10c shows that the HoF ratio for the A3RSRP HDA is 16%. In contrast, the HoF ratio for CH HDA decreases by 4% when the T_{CQI_1} is 3 with HC, while the HoF ratio increases little when the T_{CQI_1} is 3 without HC compared with the A3RSRP HDA. The HoF ratios remain unchanged when T_{CQI_1} is 4 without HC compared with the A3RSRP HDA. Moreover, the number of TLFs decreases by 27% while the number of handovers and TEFs increase by 74% and 285%, respectively, when the T_{CQI_1} is 3 with HC, while the number of TEFs remains the same and the number of handovers increases little when T_{CQI_1} is 3 without HC compared with the A3RSRP HDA based on the in Fig. 5.11c. The reason for the higher increase in the number of TEFs is that in order to reduce the TLFs dominated in the HoFs, the H^- dominates in HC. Thus, the number of handovers and TEFs is increased while the number of TLFs is reduced. Meanwhile, the number of TLFs decreases by 38% while the number of handovers and TEFs increases by 41% and 257%, respectively, when the T_{CQI_1} is 4 with HC, whereas the results are unchanged when the T_{CQI_1} 4 without HC compared with the A3RSRP

HDA.

Fig. 5.10d shows that the HoF ratio for the A3RSRP HDA is 19%. In contrast, the CH HDA decreases the HoF ratio by 5% when T_{CQI_1} is 3 with HC, and the HoF ratio decreases slightly when T_{CQI_1} is 3 without HC compared with the A3RSRP HDA. The HoF rate decreases by 5% when T_{CQI_1} is 4 with HC, and there is no change in the HoF rate when the T_{CQI_1} is 4 without HC. Moreover, the number of TLFs reduces by 2% while the number of handovers increases by 38%, and the number of TEFs remains unchanged when T_{CQI_1} is 3 without HC, and the number of TLFs reduces by 30% while the number of handovers and TEFs increase by 38% and 250%, respectively, when the T_{CQI_1} is 3 with HC compared with the A3RSRP HDA based on the in Fig. 5.11d. Meanwhile, the number of TLFs reduces by 28% while the number of handovers and TLFs increases by 33% and 200% when T_{CQI_1} is 4 with HC, the number of handovers, TLFs, and TEFs remain unchanged when T_{CQI_1} is 4 without HC compared with the A3RSRP HDA.

Fig. 5.10e shows that the HoF ratio for the A3RSRP HDA is 19%. In contrast, the HoF ratio for the CH HDA reduces by 4% when T_{CQI_1} is 3 with HC and reduces less when the T_{CQI_1} is 3 without HC. The HoF ratio reduces by 4% when T_{CQI_1} is 4 with HC, while the HoF ratio remains unchanged when T_{CQI_1} is 4 without HC. Moreover, the number of TLFs reduces by 3%, while the number of handovers and TEFs remains the same when T_{CQI_1} is 3 without HC. The number of TLFs reduces by 17% while the number of handovers and TEFs increases by 20% and 80%, respectively, when T_{CQI_1} is 3 with HC compared with the A3RSRP HDA based on the in Fig. 5.11d. Meanwhile, the number of TLFs reduces by 17% while the number of handovers and TEFs increases by 17% and 60%, respectively, when T_{CQI_1} is 4 with HC, and the number of handovers and HoFs is the same when T_{CQI_1} is 4 without HC compared with the A3RSRP HDA.

Fig. 5.10f shows that the HoF ratio of A3RSRP HDA is 24%. In contrast, the CH HDA reduces the HoF ratio by 6% when T_{CQI_1} are 3 and 4 with HC compared to the A3RSRP HDA, while the HoF ratio of the CH HDA remains unchanged compared to the A3RSRP HDA when T_{CQI_1} are 3 and 4 with no HC. Moreover, the number of TLFs decreases by 37%, while the number of handovers and TEFs increases by 13% and 100%, respectively, and all results remain unchanged when T_{CQI_1} are 3 and 4 without HC based on the result in Fig. 5.11f.

Based on the results of the scenario with a speed of 3.0 m/s, the difference compared to the scenario with a moving speed of 1 m/s is that the effect of CH HDA to reduce the HoF ratio is mainly provided by the H^- of 1.0 dB, which is raised by 0.5 dB compared to the scenario with a speed of 1 m/s. This is due to the increase in the ratio of TLFs in HoFs with an increased speed, a higher H^- parameter is required to reduce the difficulty of the handover triggering to reduce the higher ratio of TLFs in HoFs. Simultaneously, the CH HDA reduces the HoF ratio, while the number of TLFs while slightly increasing the absolute number of TEFs. In addition, the same as in the 1 m/s scenario, the optimal parameter $Offset_n$ changes from 2.5 dB to 1.0 dB for the A3RSRP HDA due

Table 5.3: Optimal parameters setting for the small-scale environment

HDA	Speed	$Offset_n$	T_{CQI_1}	T_{CQI_2}	H^+	H^-
A3RSRP	0.5 m/s	3.0 dB	n/a	n/a	n/a	n/a
	1 m/s	2.5 dB	n/a	n/a	n/a	n/a
	3 m/s	1.0 dB	n/a	n/a	n/a	n/a
CH	0.5 m/s	3.0 dB	3	1	n/a	n/a
		3.0 dB	3	1	1.0 dB	0.0 dB
	1 m/s	3.0 dB	3	2	1.0 dB	0.5 dB
		3.0 dB	4	2	1.0 dB	0.5 dB
	3 m/s	1.5 dB	3	2	0.5 dB	1.0 dB
		1.5 dB	4	2	0.5 dB	1.0 dB

to the increase of moving speed, while the improvement of the HoF ratio by the CH HDA on the optimal parameter is not desirable.

5.5.3.4 Optimal parameter setting on small scale environment

To achieve the best CH HDA performance in different environments, for example, it is recommended to use a larger H^+ parameter to reduce the number of FHOs and TEFs with the combination of T_{CQI_1} 3 and T_{CQI_2} 1 to reduce the HoF ratio in a low-speed scenario.

Simultaneously, with increasing speed, it is recommended to use a larger H^- parameter to reduce the number of TLFs under the combination of T_{CQI_1} 3 and T_{CQI_2} 2.

Meanwhile, the proposed CH HDA has multiple parameters in addition to $Offset_n$ compared with the A3RSRP HDA, and multiple parameter combinations exist that can enable the CH HDA to show the best performance on the HoF ratio, and there exhibits two settings of optimal parameters for CH HDA in different scenarios.

Therefore, based on the simulation results in Fig. 5.6, 5.8, 5.10, the optimal parameter combinations for the two HDAs in the HetNet environment are shown in Table 5.3.

5.5.4 Large-scale environment simulation

The large-scale environment is illustrated in Fig. 5.12. Two macro-cells are placed at (0, 0) and (1000, 0), and five small-cells are placed at (500, 200), (500, 100), (500, 0), (500, -100), and (500, -200). The distance between the small-cells is 100 m. The UEs are randomly placed on the range of the X-axis [200, 800] and Y-axis [-200, 200]. The simulation parameter settings for the rest of the environment are the same as for the small-scale environment, refer to Table 5.2.

In the small-scale environment, the optimal parameter setting for the $Offset_n$ was

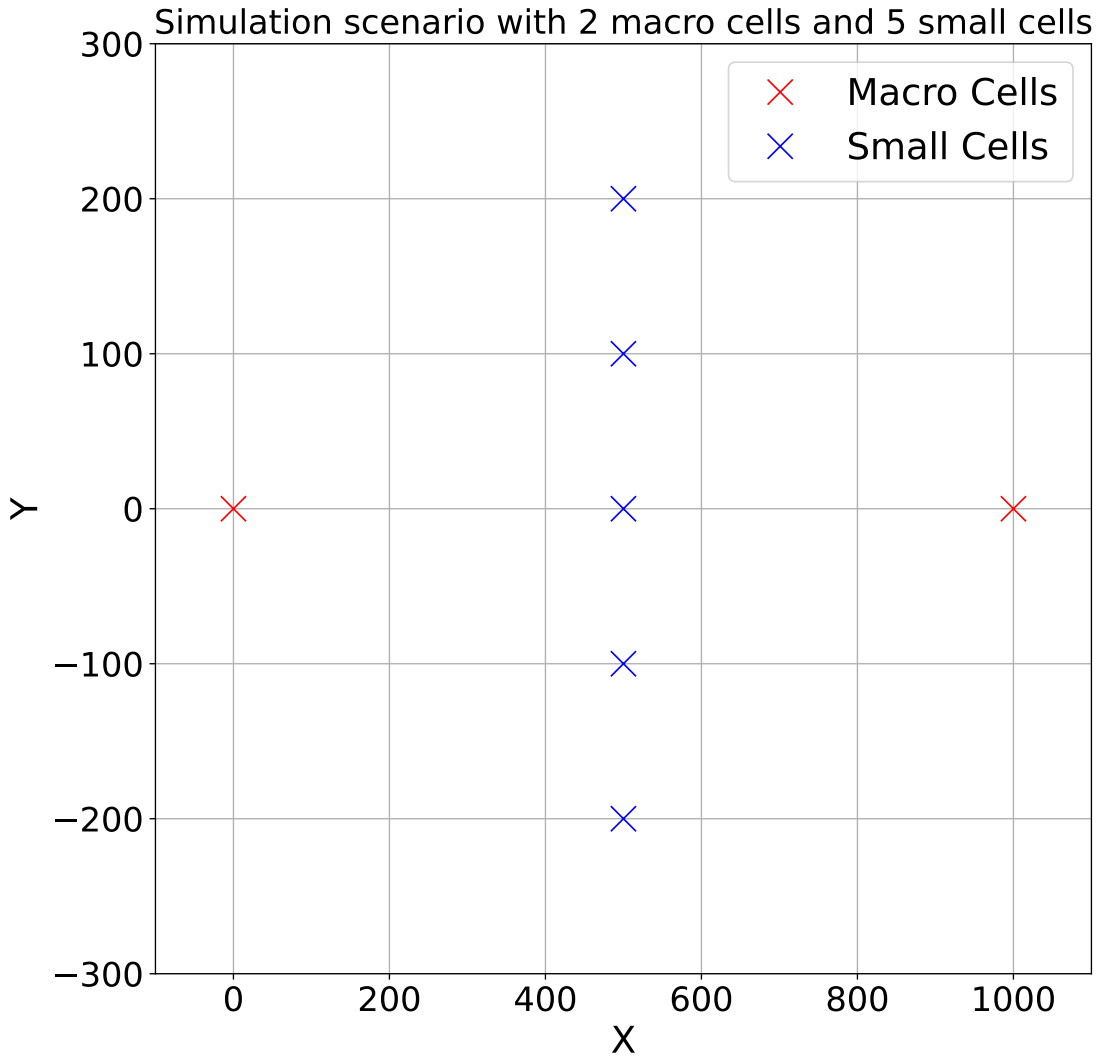


Figure 5.12: Simulation environment with large scale

found in the range of (0.5, 3.0) dB. Therefore, in the large-scale environment, the values of the optimal $Offset_n$ (1.0 dB, 2.5 dB, and 3.0 dB) are used to compare the performance of the two HDAs.

However, the co-frequency interference in the large-scale environment is more significant than in the small-scale environment owing to the increased number of cells using the same frequency.

As a result, the increase in interference after more cells using the same frequency leads to a degradation in the CQI of UE at the trigger timing of the handover. Specifically, in the small-scale environment, the value of CQI when the UE triggers a handover is generally 2 or 3. Conversely, the CQI value when the UE triggers a handover in the large-scale environment is generally 1 or 2.

Therefore, to ensure that the CH HDA is able to correctly determine the trigger timing of the handover and the suppression effect on the FHO and TEF even in a large-

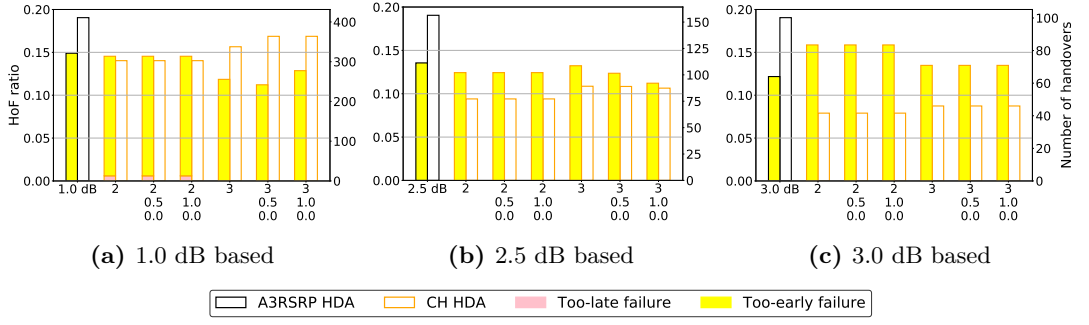


Figure 5.13: Comparison of HoF ratio and number of handovers for the A3RSRP and CH HDAs at 0.5 m/s speed

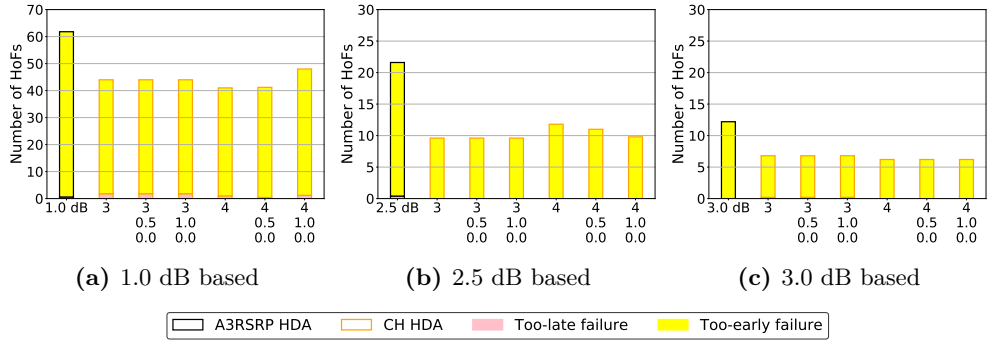


Figure 5.14: Comparison of number of HoFs for the A3RSRP and CH HDAs at 0.5 m/s speed

scale environment with strong interference. We reduce the threshold value of T_{CQI_1} and use 2 and 3 as the T_{CQI_1} parameter and 1 as the T_{CQI_2} parameter in the large-scale environment. The relationship between the number of cells with co-frequency interference and the selection of T_{CQI_1} is not considered in this paper.

In addition, with an increase in the number of cells, the UE receives signals from more co-frequency interference cells, thereby enhancing the effect of multipath propagation in signal propagation, leading to severe fading compared to small-scale environments. Therefore, in the large-scale environment, the HC has a positive effect on the parameter H^+ . The performance results for the large-scale environment are shown in Fig. 5.13, 5.14, 5.15, 5.16, 5.17, and 5.18, respectively.

5.5.4.1 Evaluation of UE moving with 0.5 m/s

The simulation results are shown in Fig. 5.13 and Fig. 5.14 when the UE is moving at 0.5 m/s with the $Offset_n$ is 1.0 dB, 2.5 dB, and 3.0 dB.

Fig. 5.13a shows that the HoF ratio of A3RSRP HDA is 15%. Moreover, because of the severe fading caused by the inclusion of more cells, a large number of handovers occur despite the UE moving at a very low speed of 0.5 m/s. This occurrence is attributed

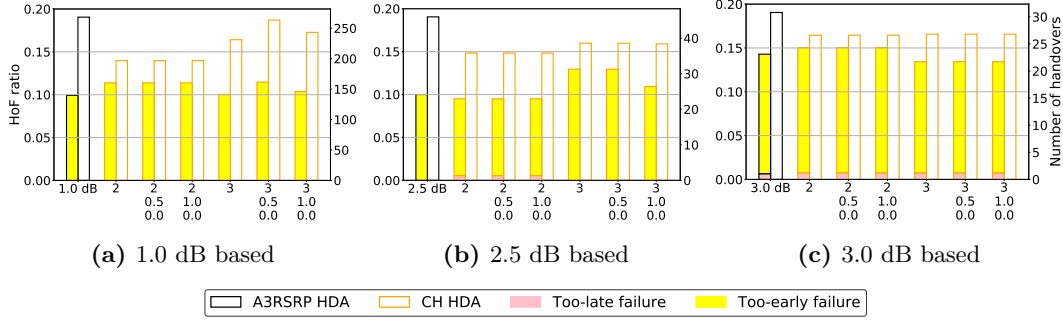


Figure 5.15: Comparison of HoF ratio and number of handovers for the A3RSRP and CH HDAs at 1 m/s speed

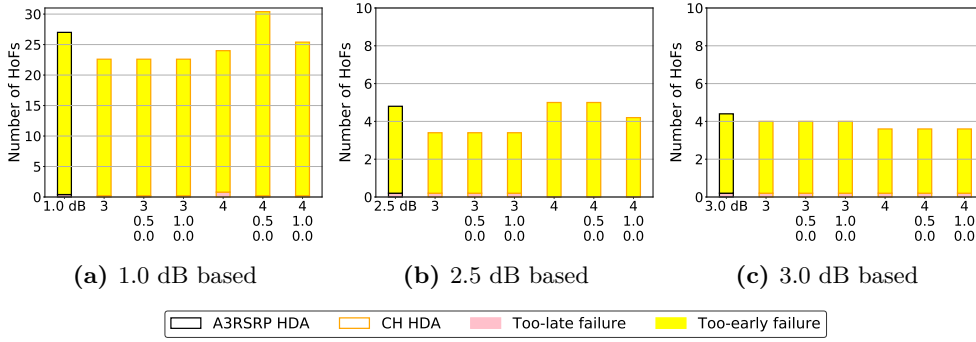


Figure 5.16: Comparison of number of HoFs for the A3RSRP and CH HDAs at 1 m/s speed

to the large number of handovers caused by the selection of a smaller $Offset_n$ as a threshold value in the fading environment. This result is the same as that in Fig. 5.6a.

In contrast, the CH HDA slightly reduced HoF ratios when T_{CQI_1} is 2 with or without HC. Moreover, the number of handovers and TEFs is reduced by 26% and 31%, respectively, while the number of TLFs slightly increases when T_{CQI_1} is 2 with or without HC compared with A3RSRP HDA based on the result in Fig. 5.14a. This is because as with T_{CQI_1} 3 in the small-scale environment, T_{CQI_1} 2 suppresses a large number of handovers but it also significantly shifts the timing of handover trigger, resulting in a slight increase in the number of TLFs.

Meanwhile, the CH HDA reduces the HoF ratio by 4% and 3% when T_{CQI_1} is 3 and with or without HC, respectively. Moreover, the number of handovers and TEFs for CH HDA decreases by 17% and 34%, respectively, and the number of TLFs increases slightly compared to A3RSRP HDA when T_{CQI_1} is 3 without HC. For the current scenario with a small initial $Offset_n$, 1.0 dB, the result by the sum of the H of 0.5 dB is better than the sum of 1.0 dB for determining the timing of the handover trigger. This is the same as in Fig. 5.6b.

Fig. 5.13b shows that the HoF ratio for the A3RSRP HDA is 13%. In contrast, the

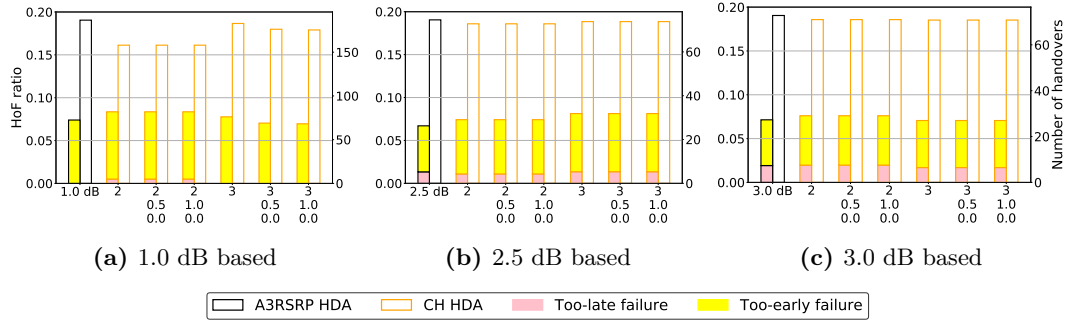


Figure 5.17: Comparison of HoF ratio and number of handovers for the A3RSRP and CH HDAs at 3 m/s speed

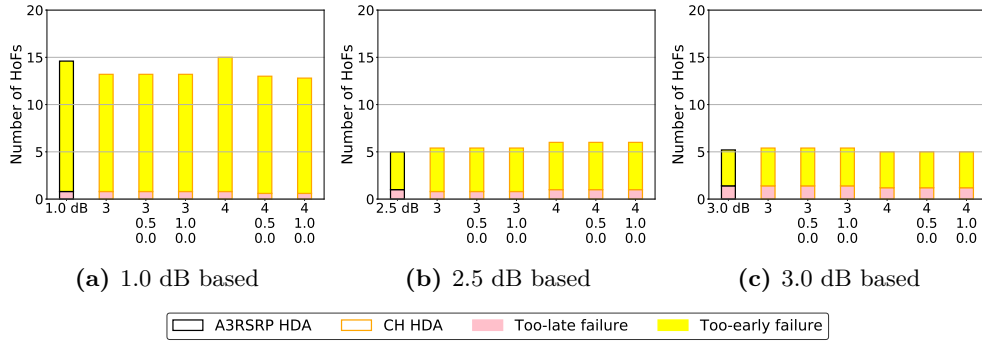


Figure 5.18: Comparison of number of HoFs for the A3RSRP and CH HDAs at 3 m/s speed

CH HDA reduces the HoF ratio by 1% when T_{CQI_1} is 2 with or without HC. Moreover, the number of TLFs reduces by 100% with an absolute zero, and the number of TEFs reduces by 54% when T_{CQI_1} is 2 with or without HC compared with the A3RSRP HDA. The number of handovers, TLFs, and TEFs reduces by 43%, 100%, and 44%, respectively, while the HoF ratio does not change when T_{CQI_1} is 3 without HC, while the number of handovers, TLFs, and TEFs reduces by 44%, 100%, and 53%, respectively, when HC is considered with the sum of the H 1.0 dB compared with the A3RSRP HDA based on the result in Fig. 5.14b. Compared to the result in the small-scale environment, the reduction of the HoF ratio by CH HDA is smaller compared with the A3RSRP HDA because the CH HDA suppresses a large number of FHOs. Therefore, although the improvement in the HoF ratio is slightly smaller for the CH HDA, the effect of the CH HDA in reducing FHO and HoFs is substantial.

Fig. 5.13c shows that the HoF ratio of the A3RSRP HDA is 12%. In contrast, the HoF ratio of the CH HDA increases by 4% and 1% compared with the A3RSRP HDA when T_{CQI_1} is 2 and 3, respectively. Moreover, the number of handovers reduces by 58% and 54%, and the number of TELs reduces by 46% and 49%, respectively, while a small increase in the number of TLFs occurs when T_{CQI_1} is 2 based on the result in Fig. 5.14c.

5.5.4.2 Evaluation of UE moving with 1.0 m/s

The simulation results when the moving speed of UE is 1.0 m/s, and $Offset_n$ is 1.0 dB, 2.5 dB, and 3.0 dB are shown in Fig. 5.15 and Fig. 5.16.

Fig. 5.15a shows that the HoF ratio increased by 1% with the T_{CQI_1} of 2 and with and without HC compared with A3RSRP HDA. Nevertheless, the number of handovers and TEFs reduced by 26% and 15%, respectively, while the number of TLFs reduced slightly compared with A3RSRP HDA based on the result in Fig. 5.16a. Meanwhile, the HoF ratio does not change when T_{CQI_1} is 3 and without HC compared with A3RSRP HDA. The number of handovers and TEFs reduced by 13% and 12%, respectively, while the number of TLFs increased slightly compared with A3RSRP HDA. The number of handovers reduces by 1% and 9% compared to A3RSRP HDA when T_{CQI_1} is 3 with HC, respectively, while the number of TEFs increases by 13% when the sum of H is 0.5 dB and it for the same reason as the results in Fig. 5.8b.

Fig. 5.15b shows that the HoF ratio for the CH HDA is reduced by 1% with a T_{CQI_1} of 2 and with and without HC, while the HoF ratio for the CH HDA is increased by 2% with a T_{CQI_1} of 3, compared with the A3RSRP HDA. Moreover, the number of handovers and TEFs is reduced by 22% and 30%, respectively, while the number of TLFs is unchanged at a T_{CQI_1} of 2 compared with A3RSRP HDA based on the result in Fig. 5.16b. At the T_{CQI_1} of 3 and the sum of H of 1.0 dB, the number of handovers and TEFs reduces by 16% and 8%, respectively, while the number of handovers reduces by 16% and the number of TEFs increases by 8% at a sum of H of 0.5 dB, and the reason for this is the same as in Fig. 5.8e.

Fig. 5.15c shows that the HoF ratio of CH HDA reduces by 1% when the T_{CQI_1} is 3, while the HoF ratio increases by 1% when the T_{CQI_1} is 2 compared with A3RSRP HDA. Moreover, the number of handovers and TEFs is reduced by 13% and 9%, respectively, when the T_{CQI_1} is 2 compared to A3RSRP HDA, and the number of handovers and TEFs is reduced by 13% and 19%, respectively, when the T_{CQI_1} is 3, while the number of TLFs remains unchanged based on the result in Fig. 5.16c.

5.5.4.3 Evaluation of UE moving with 3.0 m/s

The simulation results show that the moving speed of UE is 3.0 m/s, and $Offset_n$ of 1.0 dB, 2.5 dB, and 3.0 dB are shown in Fig. 5.17 and Fig. 5.18.

Fig. 5.17 and Fig. 5.18 show that the HoF ratios of the two HDAs are almost the same. The CH HDA still has a significant effect on reducing the number of handovers compared with the A3RSRP HDA.

Based on the results shown in Fig. 5.13, 5.14, 5.15, 5.16, 5.17, and 5.18, it can be observed that the HoF ratio in the large-scale environment is lower than the HoF ratio in the small-scale environment, because the increased number of cells that enhances the effect of fading, which results in significantly larger number of handovers than in

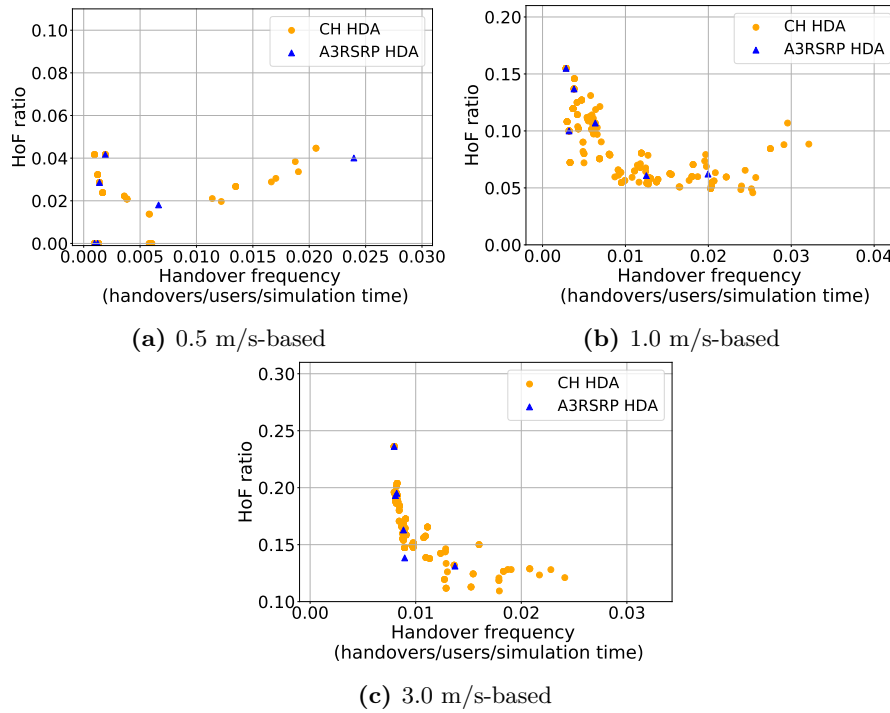


Figure 5.19: Trade-off between HoF ratio and handover frequency by two HDAs

the small-scale environment, and most of these handovers is the FHO, i.e., unnecessary handovers. Furthermore, the HoF ratios are lower when the UE is moving at 1 m/s and 3 m/s than when the movement speed is 0.5 m/s because handover demand increases with moving speed. This observation is the same as that described in [82], [48], i.e., UEs moving at low speed are more severely subjected to the fading and experience more TEFs.

Moreover, it is recommended to prioritize the HDA with fewer handovers when the difference in the HoF ratio between two HDAs is less than 2%. Because the HDA with fewer handovers is more stable in performance, it enables a more stable communication environment for the UE.

5.6 Discussion

In this section, first, we discuss the optimal parameters regarding the two HDAs in different speed scenarios in a small-scale environment. As well as the HoF ratio and trade-off of handover frequency. Finally, the effect of CH HDA on suppressing the handover triggering and TEF is explained through a case study by using variations of both RSRP and CQI.

5.6.1 Trade-off between the HoF ratio and handover frequency

In the context of handover research, examining the HoF measure is crucial to evaluate the advantages and disadvantages of an algorithm. The HoF ratio calculated by (5.1) objectively assesses whether the number of HoFs in an HDA is low and whether an HDA is usable.

Unfortunately, a single performance measure, such as the HoF ratio, is not sufficient to completely evaluate an HDA. For example, if the conditions for determining the handover trigger by a HDA are excessively relaxed, such as the results for the A3RSRP HDA in Fig. 5.6a and Fig. 5.13a, it results in a large number of handovers, the FHO, and the HoF ratio will be a small value, as calculated using (5.1). Especially for a low-speed UE of 0.5 m/s, frequent handovers within a short period pose significant risks.

Therefore, the evaluation of the trade-off between the HoF ratio and handover frequency is another important work to evaluate the merits and drawbacks of an HDA. In this paper, the measure of handover frequency is based on the formula in [83], as follows:

$$HF_{\text{freq}} = \frac{N_{\text{ho}}}{N_{\text{user}} \times T_{\text{sim}}}, \quad (5.2)$$

where HF_{freq} represents the handover frequency, which indicates the number of handovers per second for each UE. Thus, a higher number indicates a greater frequency of handover for a UE. N_{ho} denotes the number of all handovers, N_{user} denotes the number of UEs, and T_{sim} denotes the simulation time. Using the handover frequency from (5.2) and the HoF from (4.1), the trade-off between the HoF ratio and the handover frequency can be evaluated for an HDA.

Fig. 5.19a shows that the CH HDA has a lower handover frequency than the A3RSRP HDA for all parameter combinations, which is a crucial result for UE moving at low speed because a UE moving at a low-speed has an extremely low requirement for handover and a high handover frequency will result in a severely unstable communication environment. Meanwhile, the CH HDA takes the result of the zero HoF as described in Fig. 5.6d, hence, the CH HDA has more zero points at the origin than the A3RSRP HDA, and the overall performance is better than the A3RSRP HDA.

Fig. 5.19b shows that the CH HDA can achieve a lower HoF ratio and handover frequency compared with the A3RSRP HDA. However, the CH HDA has a higher handover frequency than the A3RSRP HDA for certain parameter combinations in order to reduce the HoF ratio.

Fig. 5.19c shows that the CH HDA has a lower HoF ratio while slightly increasing the frequency of handovers when the CH HDA reduces the HoF ratio and the number of TLFs.

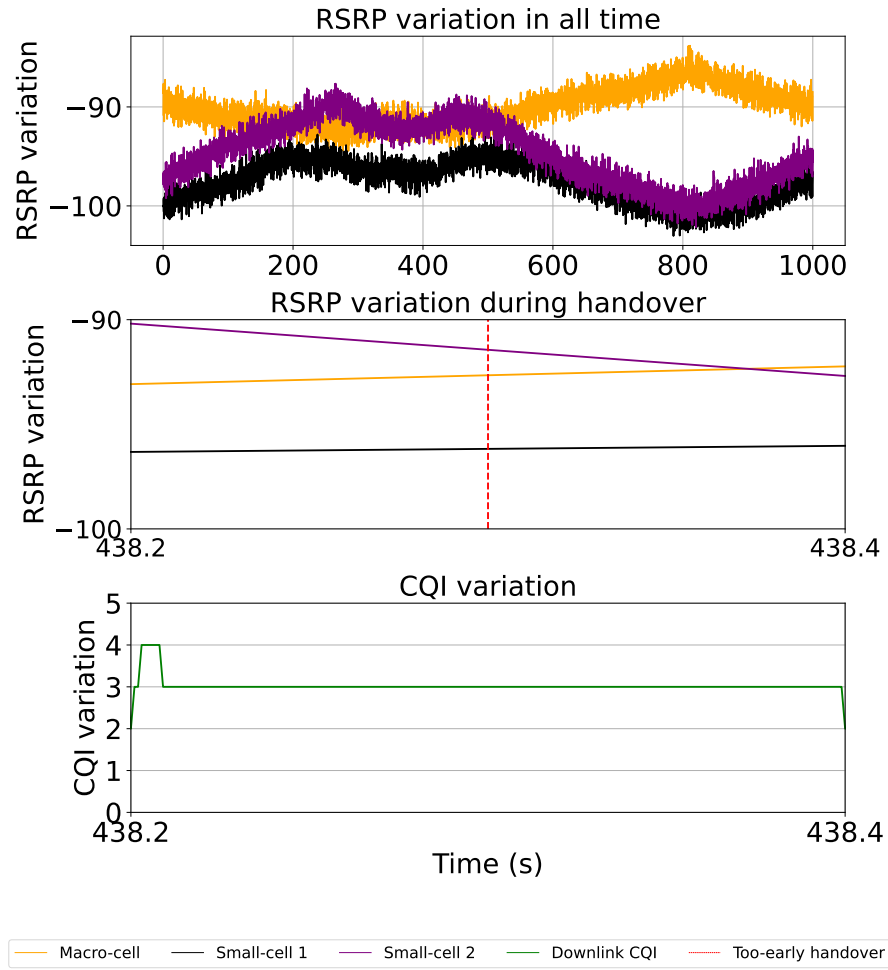


Figure 5.20: The CQI and RSRP fluctuations during a simulation

5.7 A case study on CQI-based HDMA

In Fig. 5.20, there are three subfigures representing, from top to bottom: the changes in RSRP of the three cells received by the UE during the simulation time 1000 s, the changes in RSRP of the surrounding three cells for 100 ms before and after the handover trigger timing of 438.3 s, and the changes in downlink CQI for 100 ms before and after the handover trigger timing of 438.3 s. The sub-figure on top shows that the UE receives RSRP from three cells that are undergoing fading and changing drastically. The middle subplot indicates that the UE has satisfied the trigger condition for handover by the $Offset_n$ value of 2.0 dB based on (4.1) at 438.2 s, and the handover from macro-cell to small-cell 2 is triggered at 438.3 s after a TTT of 100 ms. However, the RSRP received by the UE from the macro-cell is again greater than the RSRP received from the small-cell 2 at 438.4 s, 100 ms after the handover is triggered due to the fading, which causes a TEF to occur.

On the other hand, for the CH HDA and when the T_{CQI_1} is 3, it can be seen that

the CQI of the UE is not less than 3 during the 200 ms period from 438.2 s to 438.4 s. Therefore, the CH HDA can prevent the occurrence of the handover, TEF, and reduce the handover of the UE based on the handover trigger condition of the CH HDA in Algorithm 2. Furthermore, note that not all TEFs can be solved by increasing the TTT because the effect of the fading is difficult to predict, and increasing the TTT may lead to a substantial increase in the number of TLFs and a high HoF ratio. Consequently, the CH HDA shows a substantial effect in suppressing the number of handovers and the number of TEFs based on such a case study in Fig. 5.20.

5.8 Summary

In this Chapter, we propose a novel CQI and HC-based HDA, CH HDA, that prioritizes improving the HoF ratio, followed by the number of handovers and HoFs by shifting the timing of the handover trigger using downlink CQI and HC.

Based on ns-3 simulations, a lower HoF ratio, as well as a lower number of handovers and HoFs, can be achieved using CH HDA compared to the existing A3RSRP HDA. Hence, we show the effectiveness of the proposed CH HDA in achieving the objectives.

Specifically, the proposed CH HDA has a lower number of handovers and HoFs than the A3RSRP HDA and achieves the result of zero HoF ratio at a low speed of 0.5 m/s scenario in the small-scale environment, which indicates that the HoFs can be effectively prevented using the proposed CH HDA, enabling a 100% success rate of handover for the UE moving at low-speed. Meanwhile, the CH HDA is effective in reducing the HoF ratio and the number of HoFs at 1 m/s and 3 m/s, which effectively reduces the higher TLF ratio in the HoF ratio, while the number of handover and a few TEFs are increased. Moreover, the proposed CH HDA reduces a significant number of handovers and HoFs compared with the A3RSRP HDA at 0.5 m/s, 1 m/s, and 3 m/s in the large-scale environment, hence the improvement in HoF ratio is not as efficient as in the small-scale environment.

Therefore, the CH HDA shows a maximum improvement of 100% in HoF ratio and 5% and 100% in handover and number of HoFs, respectively, compared with the A3RSRP HDA in the small-scale environment with a speed of 0.5 m/s and an initial $Offset_n$ of 2.0 dB. In contrast, CH HDA shows a minimum improvement of -4% in HoF ratio and 58% and 44% improvement in handover and number of HoFs, respectively, compared with the A3RSRP HDA in the large-scale environment with a speed of 0.5 m/s and an initial $Offset_n$ of 3.0 dB.

Finally, at the end of the paper, we further discuss the trade-off between the proposed CH and A3RSRP HDA in terms of the HoF ratio and handover frequency, as well as explain the specific actions of CH HDA in reducing the HoF ratio, the number of handovers, and the number of HoFs by a case study. The trade-off results show that the proposed CH HDA shows better performance than the A3RSRP HDA in both HoF

ratio and handover frequency in the scenarios of 0.5 m/s, 1 m/s, and 3 m/s, whereas it is worse than the A3RSRP HDA in terms of handover frequency in the scenario of 3 m/s. In the case study, we explain the effectiveness of the CH HDA in suppressing the handover and HoF.

In future work, we will investigate a method that reduces both HoFs (TLF and TEF) simultaneously, even in a high-speed scenario, and use it in the CH HDA. It may be necessary to assume a specific movement and observe the fading-induced changes in CQI and RSRP to estimate accurately the successful timing of the handover trigger to improve our HDA. In addition, the changes in interference strength caused by the different numbers of co-frequency cells lead to variations in the parameters setting for the CH HDA. Therefore, we will discuss the relationship between the parameters setting of the CH HDA and the number of co-frequency cells in HetNet to further improve the robustness of our CH HDA in different HetNet environments. Moreover, since the proposed CH HDA has a lower HoF ratio and the number of handovers and HoFs, the proposed CH HDA does not need to consume a lot of computation time and resources. Thus, the CH HDA has the potential to be applied to real LTE or 5G scenarios to improve the high handover latency and low throughput due to the high HoF ratio and provide a better user experience.

Chapter 6

Conclusion

6.1 Summary of contributions

This dissertation has presented a comprehensive investigation into handover analysis in 5G heterogeneous networks through both theoretical modeling and simulation-based approaches. The research contributions can be summarized as follows:

First, we developed a novel probabilistic framework integrating Poisson Point Processes (PPP) with Stochastic Petri Nets (SPN) to model HetNet dynamics. This framework provided valuable insights into the performance impacts of handover parameters by analyzing packet loss rates between new and handover users under full-load network conditions, establishing a robust theoretical foundation for handover optimization.

Second, we proposed the Do-SPN-PPP framework, an innovative continuous-time analytical model for examining A3 event-based handovers. This framework demonstrated superior accuracy in predicting UE residence time and evaluating Handover Margin (HOM) parameters compared to traditional discrete-time Markov models. Notably, it achieved a 96% reduction in computational time compared to conventional simulation methods, marking a significant advancement in computational efficiency.

Third, we developed and validated the CQI- and HC-based Handover Decision Algorithm (CH HDA) using ns-3, a network simulator implementing 3GPP standards. The simulation results demonstrated the algorithm's effectiveness in reducing both handover failure ratios and the number of handovers, particularly achieving perfect HoF prevention in low-speed small-scale environments.

6.2 Future research directions

Based on our findings, several promising directions for future research have been identified:

6.2.1 Optimization of handover parameters

A critical area for future investigation is the optimization of Handover Margin (HOM) parameters to balance the trade-off between Handover Time (HoT) and Handover Failure (HoF). This optimization problem requires careful consideration of both metrics to achieve optimal handover performance. Furthermore, given the significant impact of HOM parameters on UE residence time, developing proactive channel resource allocation schemes for both M2S and S2M handovers represents an important direction for network-side optimization.

6.2.2 Enhancement of CH HDA Performance

Several aspects of the CH HDA warrant further investigation: Development of methods to simultaneously reduce both types of HoFs (TLF and TEF) in high-speed scenarios; analysis of movement patterns and fading-induced changes in CQI and RSRP to more accurately determine optimal handover trigger timing; Investigation of the relationship between CH HDA parameter settings and the number of co-frequency cells in HetNets to enhance algorithm robustness across different network environments.

6.2.3 Towards real-world implementation

The demonstrated efficiency of CH HDA, particularly its low computational overhead and resource requirements, suggests promising potential for real-world deployment in LTE or 5G networks. Future work should focus on: Adaptation of the algorithm for practical implementation in real network environments; Evaluation and optimization of the algorithm's performance in addressing high handover latency and low throughput issues; Development of mechanisms to ensure consistent performance across varying network conditions.

6.3 Concluding remarks

This dissertation has made significant contributions to both the theoretical understanding and practical implementation of handover optimization in 5G HetNets through two complementary approaches. The modeling-based studies have provided deep insights into handover characteristics with potential applications in optimization strategies, while the simulation-based investigation using 3GPP standard-compliant ns-3 has validated the effectiveness of proposed solutions, establishing a foundation for future real-world implementations. The identified future research directions offer promising paths for further advancing mobility management in next-generation wireless networks.

The findings and methodologies presented in this work not only contribute to the current state of knowledge in wireless communications but also provide practical frameworks for improving handover processes in future 5G network deployments. As mobile

networks continue to evolve and become more complex, the importance of efficient and reliable handover mechanisms will only grow, making the contributions of this research increasingly valuable to the field.

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Appendix A

Appendix

Derivation of the cumulative distribution function of $SINR_S$ is as follows.

$$\begin{aligned} F_{SINR_S}(T1) &= \Pr \{ SINR_S < T1 \} \\ &= \Pr \left\{ \frac{P_{S_{i,k}} G_{a_i} D_{a_i}^{-\eta}}{I_1 + I_2 + \sigma^2} < T1 \right\}. \end{aligned}$$

By using the nature of the marginal distribution and using the definition of Eq. (3.3) with respect to the random variable G_{a_i} , the following derivation can be obtained,

$$\begin{aligned} F_{SINR_S}(T1) &= \int_0^\infty \Pr \left\{ G_{a_i} < \frac{T1 (I_1 + I_2 + \sigma^2)}{P_{S_{i,k}} D_{a_i}^{-\eta}} \right\} f_{D_{a_i}}(D_a) dD_a \\ &= 1 - \int_0^\infty \exp \left\{ -\frac{\mu_a T1 \sigma^2}{P_{S_{i,k}} D_{a_i}^{-\eta}} \right\} \mathcal{L}_{I_1} \left(\frac{\mu_a T1}{P_{S_{i,k}} D_a^{-\eta}} \right) \mathcal{L}_{I_2} \left(\frac{\mu_a T1}{P_{S_{i,k}} D_a^{-\eta}} \right) \\ &\quad \cdot 2\pi \lambda_a D_a \exp \{ -\lambda_a \pi D_a^2 \} dD_a \\ &= 1 - \int_0^\infty 2\pi \lambda_a D_a \exp \left\{ -\lambda_a \pi D_a^2 - \lambda_b \pi D_a^2 \sqrt{\frac{\mu_a P_{M_k} T2}{\mu_b P_{S_k}}} \arctan \left(\frac{D_a^2 \sqrt{\frac{\mu_a P_{M_k} T2}{\mu_b P_{S_k}}}}{RHO_a^2} \right) \right. \\ &\quad \left. - \lambda_a \pi D_a \sqrt{T2} \arctan \left(\frac{D_a^2 \sqrt{\frac{\mu_a P_{M_k} T2}{\mu_b P_{S_k}}}}{RHO_a^2} \right) \right\} dD_a. \end{aligned} \tag{A.1}$$

where $\mathcal{L}_{I_1}(\cdot)$ and $\mathcal{L}_{I_2}(\cdot)$ are the Laplace transform of the probability density function of the random variable I_1 and I_2 [23], respectively.

Similarly, by using the property of marginal distribution and using the definition of Eq. (3.3) with respect to the random variable G_{b_i} , the cumulative distribution function can be obtained with respect to $SINR_M$,

$$\begin{aligned}
 F_{SINR_M}(T2) &= \Pr \{ SINR_M < T2 \} \\
 &= \Pr \left\{ \frac{P_{M_{i,k}} G_{b_i} D_{b_i}^{-\eta}}{I_3 + I_4 + \sigma^2} < T2 \right\} \\
 &= \int_0^\infty \Pr \left\{ \frac{P_{M_{i,k}} G_{b_i} D_b^{-\eta}}{I_3 + I_4 + \sigma} < T2 \right\} f_{D_{b_i}}(D_b) dD_b \\
 &= \int_0^\infty \Pr \left\{ G_{a_i} < \frac{T2(I_3 + I_4 + \sigma^2)}{P_{M_{i,k}} D_b^{-\eta}} \right\} f_{D_{b_i}}(D_b) dD_b \\
 &= \int_0^\infty \left[1 - \left\{ \exp \left(\frac{-\mu_b T2 \sigma^2}{P_{M_{i,k}} D_b^{-\eta}} \right) \exp \left(\frac{-\mu_b T2 I_3}{P_{M_{i,k}} D_b^{-\eta}} \right) \exp \left(\frac{-\mu_b T2 I_4}{P_{M_{i,k}} D_b^{-\eta}} \right) \right\} \right] \\
 &\quad \cdot f_{D_{b_i}}(D_b) dD_b \\
 &= 1 - \int_0^\infty \exp \left(\frac{-\mu_b T2 \sigma^2}{P_{M_{i,k}} D_b^{-\eta}} \right) \mathcal{L}_{I_3} \left(\frac{\mu_b T2}{P_{M_{i,k}} D_b^{-\eta}} \right) \mathcal{L}_{I_4} \left(\frac{\mu_b T2}{P_{M_{i,k}} D_b^{-\eta}} \right) \\
 &\quad \cdot 2\pi \lambda_a D_b \exp(-\lambda_b \pi D_b^2) dD_b, \tag{A.2}
 \end{aligned}$$

where $\mathcal{L}_{I_3}(\cdot)$ and $\mathcal{L}_{I_4}(\cdot)$ are the Laplace transform of the probability density function of the random variable I_3 and I_4 , respectively. Moreover, in this paper, the power of the macro cell considered is 40 times that of the small cell, thus, the following closed-form equation can be obtained after ignoring the interference from the small cell and noise.

$$\begin{aligned}
 F_{SINR_M}(T2) &= 1 - \int_0^\infty 2\pi \lambda_b D_b \exp \left(-\pi \lambda_b D_b^2 \sqrt{T2} \arctan(\sqrt{T2}) - \lambda_b \pi D_b^2 \right) dD_b \\
 &= 1 - \frac{\lambda_b}{\lambda_b + \lambda_b \sqrt{T2} \arctan(\sqrt{T2})} \\
 &= \frac{\lambda_b \sqrt{T2} \arctan(\sqrt{T2})}{\lambda_b + \lambda_b \sqrt{T2} \arctan(\sqrt{T2})}. \tag{A.3}
 \end{aligned}$$

Finally, assume that the random variables $SINR_s$ and $SINR_m$ are A and B , respectively. Therefore, by using the property of convolution, the following integral can be obtained,

$$\begin{aligned}
 \zeta_s &= F_{\text{cellasso}} = \Pr \{ SINR_s - SINR_m > 0 \} \\
 &= \Pr \{ A - B > 0 \} \\
 &= \int_b F_A(b) f_B(b) db, \tag{A.4}
 \end{aligned}$$

where the cumulative distribution function of $F_A(b)$, $F_{SINR_s}(\cdot)$ has been obtained in the

previous, and it is only necessary to derive $F_B(b)$, $F_{SINR_m}(\cdot)$ to obtain $f_B(b)$, thus the final form ζ_s is shown in Eq. (3.6).

Regarding the derivation of the cumulative distribution function of $RSRQ_S$ and $RSRQ_M$ as follows.

$$\begin{aligned}
F_{RSRQ_S}(T3) &= \Pr \{RSRQ_S < T3\} \\
&= \Pr \left\{ \frac{N_S P_{S_k} G_{a_i} D_{a_i}^{-\eta}}{\sum_{a_i \in \Phi_1} P_{S_k} G_{a_i} D_{a_i}^{-\eta} + \sum_{b_i \in \Phi_2} P_{M_k} G_{b_i} D_{b_i}^{-\eta} + \sigma_{\text{noise}}^2} < T3 \right\} \\
&= \int_0^\infty \Pr \left\{ G_{a_i} < \frac{T3 D_a^{-\eta} \left(\sum_{a_i \in \Phi_1} P_{S_k} G_{a_i} D_{a_i}^{-\eta} + \sum_{b_i \in \Phi_2} P_{M_k} G_{b_i} D_{b_i}^{-\eta} + \sigma_{\text{noise}}^2 \right)}{N_S P_{S_k}} \right\} \\
&\quad \cdot f_{D_{a_i}}(D_a) dD_a \tag{A.5} \\
&= 1 - \int_0^\infty \exp \left\{ -\frac{\mu_a T3 D_a^{-\eta} \sigma_{\text{noise}}^2}{N_S P_{S_k}} \right\} \mathcal{L}_{RSSI_S} \left(\frac{\mu_a T3 D_a^{-\eta}}{N_S P_{S_k}} \right) \mathcal{L}_{RSSI_M} \left(\frac{\mu_a T3 D_a^{-\eta}}{N_S P_{S_k}} \right) \\
&\quad \cdot f_{D_{a_i}}(D_a) dD_a \tag{A.6} \\
&= 1 - \int_0^\infty \exp \left\{ -\frac{\mu_a T3 D_a^{-\eta} \sigma_{\text{noise}}^2}{N_S P_{S_k}} \right\} \exp \left\{ -\frac{\pi^2 \lambda_a D_a^2}{2} \sqrt{T3} \right\} \exp \left\{ -\frac{\pi^2 \lambda_b D_a^2}{2} \sqrt{p_2 T3} \right\} \\
&\quad \cdot 2\pi \lambda_a D_a \exp \left\{ -\lambda_a \pi D_a^2 \right\} dD_a. \tag{A.7}
\end{aligned}$$

where $\mathcal{L}_{RSSI_S}(\cdot)$ and $\mathcal{L}_{RSSI_M}(\cdot)$ are the Laplace transform of the probability density function of the random variable $\sum_{a_i \in \Phi_1} P_{S_k} G_{a_i} D_{a_i}^{-\eta}$ and $\sum_{b_i \in \Phi_2} P_{M_k} G_{b_i} D_{b_i}^{-\eta}$, respectively. The following closed-form equation can be obtained after ignoring the noise.

$$\begin{aligned}
F_{RSRQ_S}(T3) &= 1 - \frac{2\lambda_a}{2\lambda_a + \lambda_a \pi \sqrt{T3} + \lambda_b \pi \sqrt{p_2 T3}} \\
&= \frac{\lambda_a \pi \sqrt{T3} + \lambda_b \pi \sqrt{p_2 T3}}{2\lambda_a + \lambda_a \pi \sqrt{T3} + \lambda_b \pi \sqrt{p_2 T3}}. \tag{A.8}
\end{aligned}$$

Similar to the derivation of $RSRQ_S$, the cumulative distribution function of $RSRQ_M$

can be obtained as follows.

$$\begin{aligned}
 F_{RSRQ_M}(T4) &= \Pr \{RSRQ_M < T4\} \\
 &= \Pr \left\{ \frac{N_M P_{M_k} G_{b_i} D_{b_i}^{-\eta}}{\sum_{a_i \in \Phi_1} P_{S_k} G_{a_i} D_{a_i}^{-\eta} + \sum_{b_i \in \Phi_2} P_{M_k} G_{b_i} D_{b_i}^{-\eta} + \sigma_{\text{noise}}^2} < T4 \right\} \\
 &= \int_0^\infty \Pr \left\{ G_{b_i} < \frac{T4 D_b^{-\eta} \left(\sum_{a_i \in \Phi_1} P_{S_k} G_{a_i} D_{a_i}^{-\eta} + \sum_{b_i \in \Phi_2} P_{M_k} G_{b_i} D_{b_i}^{-\eta} + \sigma_{\text{noise}}^2 \right)}{N_M P_{M_k}} \right\} \\
 &\quad \cdot f_{D_{b_i}}(D_b) dD_b \\
 &= 1 - \int_0^\infty e^{-\frac{\mu_b T4 D_b^{-\eta} \sigma_{\text{noise}}^2}{N_M P_{M_k}}} \mathcal{L}_{RSSI_S} \left(\frac{\mu_b T4 D_b^{-\eta}}{N_M P_{M_k}} \right) \mathcal{L}_{RSSI_M} \left(\frac{\mu_b T4 D_b^{-\eta}}{N_M P_{M_k}} \right) f_{D_{b_i}}(D_b) dD_b \\
 &= 1 - \int_0^\infty \exp \left\{ -\frac{\mu_b T4 D_b^{-\eta} \sigma_{\text{noise}}^2}{N_M P_{M_k}} \right\} \exp \left\{ -\frac{\pi^2 \lambda_a D_b^2}{2} \sqrt{p_1 T4} \right\} \exp \left\{ -\frac{\pi^2 \lambda_b D_b^2}{2} \sqrt{T4} \right\} \\
 &\quad \cdot 2\pi \lambda_b D_b \exp \{ -\lambda_b \pi D_b^2 \} dD_b \\
 &= 1 - \frac{2\lambda_b}{2\lambda_b + \lambda_a \pi \sqrt{p_1 T4} + \lambda_b \pi \sqrt{T4}} \\
 &= \frac{\lambda_a \pi \sqrt{p_1 T4} + \lambda_b \pi \sqrt{T4}}{2\lambda_a + \lambda_a \pi \sqrt{p_1 T4} + \lambda_b \pi \sqrt{T4}}. \tag{A.9}
 \end{aligned}$$

Regarding the derivation of cumulative distribution function of celloffset $\zeta_{\text{offset}_{\text{sm}}}$ and $\zeta_{\text{offset}_{\text{ms}}}$ are shown as follows, and the derivation of $\zeta_{\text{offset}_{\text{sm}}}$ can be obtained by deriving $RSRQ_S$ based on the same principle as the derivation of ζ_s by using the property of convolution, and the specific process is shown as follows.

$$\begin{aligned}
 \zeta_{\text{offset}_{\text{sm}}} &= \Pr \{RSRQ_M - RSRQ_S > C_0\} \\
 &= \Pr \left\{ \frac{N_M P_{M_k} G_{b_i} D_{b_i}^{-\eta}}{\sum_{a_i \in \Phi_1} P_{S_k} G_{a_i} D_{a_i}^{-\eta} + \sum_{b_i \in \Phi_2} P_{M_k} G_{b_i} D_{b_i}^{-\eta} + \sigma_{\text{noise}}^2} \right. \\
 &\quad \left. - \frac{N_S P_{S_k} G_{a_i} D_{a_i}^{-\eta}}{\sum_{a_i \in \Phi_1} P_{S_k} G_{a_i} D_{a_i}^{-\eta} + \sum_{b_i \in \Phi_2} P_{M_k} G_{b_i} D_{b_i}^{-\eta} + \sigma_{\text{noise}}^2} > C_0 \right\} \\
 &= \Pr \{A - B > C_0\} \\
 &= \int_b F_A(C_0 + b) f_B(b) db \\
 &= \frac{\lambda_a \pi \sqrt{p_2 (C_0 + T3)} + \lambda_b \pi \sqrt{C_0 + T3}}{2\lambda_a + \lambda_a \pi \sqrt{C_0 + T3} + \lambda_b \pi \sqrt{p_2 (C_0 + T3)}} \cdot \frac{\lambda_a \pi \left(\lambda_a \sqrt{T3} + \lambda_b \sqrt{p_2 T3} \right)}{\left[\left(2 + \pi \sqrt{T3} \right) + \lambda_b \pi \sqrt{p_2 T3} \right]^2 (T3)}. \tag{A.10}
 \end{aligned}$$

Similarly to $\zeta_{\text{offset}_{\text{sm}}}$, the following $\zeta_{\text{offset}_{\text{ms}}}$ can be obtained.

$$\begin{aligned}
\zeta_{\text{offset}_{\text{ms}}} &= \Pr \{ RSRQ_S - RSRQ_M > C_1 \} \\
&= \Pr \left\{ \frac{N_S P_{S_k} G_{a_i} D_{a_i}^{-\eta}}{\sum_{a_i \in \Phi_1} P_{S_k} G_{a_i} D_{a_i}^{-\eta} + \sum_{b_i \in \Phi_2} P_{M_k} G_{b_i} D_{b_i}^{-\eta} + \sigma_{\text{noise}}^2} \right. \\
&\quad \left. - \frac{N_M P_{M_k} G_{b_i} D_{b_i}^{-\eta}}{\sum_{a_i \in \Phi_1} P_{S_k} G_{a_i} D_{a_i}^{-\eta} + \sum_{b_i \in \Phi_2} P_{M_k} G_{b_i} D_{b_i}^{-\eta} + \sigma_{\text{noise}}^2} > C_1 \right\} \\
&= \Pr \{ A - B > C_0 \} \\
&= \int_b F_A(C_0 + b) f_B(b) db \\
&= \frac{\lambda_a \pi \sqrt{C_1 + T_4} + \lambda_b \pi \sqrt{p_1(C_1 + T_4)}}{2\lambda_a + \lambda_a \pi \sqrt{p_1(C_1 + T_4)} + \lambda_b \pi \sqrt{C_1 + T_4}} \cdot \frac{\lambda_a \pi (\lambda_a \sqrt{T_4} + \lambda_b \sqrt{p_1 T_4})}{\left[(2 + \pi \sqrt{T_4}) + \lambda_a \pi \sqrt{p_1 T_4} \right]^2 (T_4)}.
\end{aligned} \tag{A.11}$$

$$\begin{aligned}
\mathcal{L}_{I_s}(s) &= \mathbb{E} \{ e^{-s I_s} \} \\
&= \mathbb{E} \left\{ e^{-s \left(\sum_{x_{s_i} \in \Phi_{x_s}} P_s G_{(x_{\text{UE}}, x_{s_i})} D_{(x_{\text{UE}}, x_{s_i})}^{-\eta} \right)} \right\} \\
&= \mathbb{E} \left\{ \prod_{x_{s_i} \in \Phi_{x_s}} e^{-s \left(P_s G_{(x_{\text{UE}}, x_{s_i})} D_{(x_{\text{UE}}, x_{s_i})}^{-\eta} \right)} \right\} \\
&= \mathbb{E} \left\{ \prod_{x_s \in \Phi_{x_s}} \mathbb{E}_{G_{(x_{\text{UE}}, x_{s_i})}} \left\{ e^{-s \left(P_s G_{(x_{\text{UE}}, x_{s_i})} D_{(x_{\text{UE}}, x_{s_i})}^{-\eta} \right)} \right\} \right\} \\
&\stackrel{\text{Laplace transform of exp}}{=} \mathbb{E} \left\{ \prod_{x_{s_i} \in \Phi_{x_s}} \frac{\mu_s}{\mu_s + s P_s D_{(x_{\text{UE}}, x_{s_i})}^{-\eta}} \right\} \\
&\stackrel{\text{PGFL}}{=} \exp \left\{ -2\pi \lambda_s \int_d^\infty \left(1 - \frac{\mu_s}{\mu_s + s P_s d_{s_interf}^{-\eta}} \right) d_{s_interf} \mathbf{d} d_{s_interf} \right\} \\
&\stackrel{\text{completed LT}}{=} \\
&= \exp \left\{ -2\pi \lambda_s \int_d^\infty \left(1 - \frac{1}{1 + \frac{T_1}{N_s d^{-\eta}} d_{s_interf}^{-\eta}} \right) d_{s_interf} \mathbf{d} d_{s_interf} \right\} \\
&= \exp \left\{ -2\pi \lambda_s \int_d^\infty \left(\frac{1}{1 + \frac{N_s d^{-\eta}}{T_1 d_{s_interf}^{-\eta}}} \right) d_{s_interf} \mathbf{d} d_{s_interf} \right\} \\
&\stackrel{\text{Integration by substitution}}{=} \exp \left\{ -\pi \lambda_s T^{\frac{2}{\eta}} d^2 \int_{T_1^{\frac{2}{\eta}}}^\infty \left(\frac{1}{1 + y^{\frac{\eta}{2}}} \right) dy \right\} \\
&\stackrel{\eta=4}{=} \exp \left\{ -\pi \lambda_s T^{\frac{2}{\eta}} d^2 \left(\frac{\pi}{2} - \arctan(\sqrt{T_1}) \right) \right\}
\end{aligned} \tag{A.12}$$

$$\begin{aligned}
 \mathcal{L}_{I_m}(m) &= \mathbb{E} \left\{ e^{-sI_m} \right\} \\
 &= \mathbb{E} \left\{ e^{-sN_m P_m G_{(x_{UE}, x_m)} D_{(x_{UE}, x_m)}^{-\eta}} \right\} \\
 &= \mathbb{E} \left\{ \mathbb{E}_{G_{(x_{UE}, x_m)}} \left\{ e^{-sP_m G_{(x_{UE}, x_m)} D_{(x_{UE}, x_m)}^{-\eta}} \right\} \right\} \\
 &\stackrel{\text{LT of exp}}{=} \mathbb{E} \left\{ \frac{\mu_m}{\mu_m + sN_m P_m D_{(x_{UE}, x_m)}^{-\eta}} \right\} \\
 &= \exp \left(-2\pi\lambda_m \int_{d_{m_interf}}^{\infty} \left(1 - \frac{\mu_m}{\mu_m + sN_m P_m d_{m_interf}^{-\eta}} \right) \cdot d_{m_interf} dd_{m_interf} \right) \\
 &\stackrel{\text{completed LT}}{=} \\
 &= \exp \left(-2\pi\lambda_m \int_{d_{m_interf}}^{\infty} \left(1 - \frac{\mu_m}{\mu_m + (\frac{\mu_s T_1 N_m P_m}{N_s P_s d^{-\eta}}) d_{m_interf}^{-\eta}} \right) \cdot d_{m_interf} dd_{m_interf} \right) \\
 &\stackrel{\text{Integration by substitution}}{=} \exp \left\{ -2\pi\lambda_m d^2 \sqrt{\frac{T_1 N_m P_m}{N_s P_s}} \cdot \left(\frac{\pi}{2} - \arctan \left(\sqrt{\frac{N_s P_s}{T_1 N_m P_m}} \right) \right) \right\}
 \end{aligned} \tag{A.13}$$

The A3 event formulation derivation within the A3RSRP HDAM,

$$\begin{aligned}
 F_{D_{\frac{m}{s}}}(d) &= \mathbb{P} \left\{ \left(\frac{D_m}{D_s} \right)^{\eta} < d \right\} \\
 &= \int_0^{\infty} F_{D_m} \left(d^{\frac{1}{\eta}} D_s \right) f_{D_s}(D_s) dD_s \\
 &= \int_0^{\infty} \left(1 - \exp \left(-\lambda_m \pi d^{\frac{2}{\eta}} D_s^2 \right) \right) \\
 &\quad \cdot 2\pi\lambda_s D_s \exp \left(-\pi\lambda_s D_s^2 \right) dD_s \\
 &= 1 - \int_0^{\infty} 2\pi\lambda_s D_s \exp \left(-\pi D_s^2 (r^{\frac{2}{\eta}} \lambda_m + \lambda_s) \right) dD_s \\
 &= 1 - \frac{\lambda_s}{d^{\frac{2}{\eta}} \cdot \lambda_m + \lambda_s}, \quad 0 \leq d \leq \infty.
 \end{aligned} \tag{A.14}$$

$$\begin{aligned}
 F_{G_{\frac{m}{s}}}(g) &= \mathbb{P} \left\{ \frac{G_m}{G_s} < g \right\} \\
 &= \int_0^{\infty} F_{G_m} (g G_s) f_{G_s}(G_s) dG_s \\
 &= \int_0^{\infty} \left(1 - \exp(-\mu_m \cdot g \cdot G_s) \right) \cdot \mu_s \exp(-\mu_s \cdot G_s) dG_s \\
 &= 1 - \frac{\mu_s}{g \cdot \mu_m + \mu_s}, \quad 0 \leq G_s \leq \infty.
 \end{aligned} \tag{A.15}$$

$$\begin{aligned}
\zeta_{\text{sm}} &= \mathbb{P}\{RSRP_{\text{m}} - RSRP_{\text{s}} > T_{\text{HOM}}\} \\
&= \mathbb{P}\{10 \log_{10} P_{\text{m}} G_{m_i} D_{m_i}^{-\eta} - \\
&\quad 10 \log_{10} P_{\text{s}} G_{s_i} D_{s_i}^{-\eta} > 10 \log_{10} T_{\text{HOM}}\} \\
&= \mathbb{P}\left\{\frac{P_{\text{m}} G_{m_i} D_{m_i}^{-\eta}}{P_{\text{s}} G_{s_i} D_{s_i}^{-\eta}} > T_{\text{HOM}}\right\} \\
&\stackrel{[23]}{=} \int_{g \geq 0} F_{D_{\frac{\text{m}}{\text{s}}}}\left(\frac{P_{\text{m}}}{P_{\text{s}} \cdot T_{\text{HOM}}} g\right) \cdot f_{G_{\frac{\text{m}}{\text{s}}}}(g) dg \\
&\stackrel{(A.14), (A.15)}{=} \int_0^\infty \left[\left(1 - \exp\left(-\lambda_{\text{m}} \pi \left(\frac{P_{\text{m}}}{P_{\text{s}} \cdot T_{\text{HOM}}} g\right)^{\frac{2}{\eta}} D_{\text{s}}^2\right)\right) \right. \\
&\quad \cdot 2\pi \lambda_{\text{s}} D_{\text{s}} \exp(-\lambda_{\text{s}} \pi D_{\text{s}}^2) dD_{\text{s}} \\
&\quad \cdot \left. [(1 - \exp(-\mu_{\text{m}} \cdot g \cdot G_{\text{s}})) \cdot \mu_{\text{s}} \exp(-\mu_{\text{s}} \cdot G_{\text{s}}) dg]' \right] \\
&= 1 - \int_0^\infty \frac{\lambda_{\text{s}}}{\lambda_{\text{m}} \left(\frac{P_{\text{m}}}{P_{\text{s}} \cdot T_{\text{HOM}}} g\right)^{\frac{2}{\eta}} + \lambda_{\text{s}}} \cdot \frac{\mu_{\text{s}} \mu_{\text{m}}}{(g \lambda_{\text{m}} + \mu_{\text{s}})^2} dg. \tag{A.16}
\end{aligned}$$

$$\begin{aligned}
\zeta_{\text{ms}} &= \mathbb{P}\{RSRP_{\text{s}} - RSRP_{\text{m}} > T_{\text{HOM}}\} \\
&\stackrel{(\text{??})}{=} 1 - \int_0^\infty \frac{\lambda_{\text{m}}}{\lambda_{\text{s}} \left(\frac{P_{\text{s}}}{P_{\text{m}} \cdot T_{\text{HOM}}} \cdot g\right)^{\frac{2}{\eta}} + \lambda_{\text{m}}} \cdot \frac{\mu_{\text{s}} \mu_{\text{m}}}{(g \lambda_{\text{s}} + \mu_{\text{m}})^2} dg \tag{A.17}
\end{aligned}$$

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