UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

REALISTIC MODELING OF HANDOVER EVENTS IN A MULTI-CARRIER 5G NETWORK: A PRELIMINARY STEP TOWARDS COP-KPI RELATIONSHIP REALIZATION

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

Degree of

MASTER OF SCIENCE IN ELECTRICAL AND COMPUTER ENGINEERING

BY

MARVIN C. MANALASTAS
Norman, Oklahoma
2020

REALISTIC MODELING OF HANDOVER EVENTS IN A MULTI-CARRIER 5G NETWORK: A PRELIMINARY STEP TOWARDS COP-KPI RELATIONSHIP REALIZATION

A THESIS APPROVED FOR THE
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

BY

Dr. Ali Imran, Chair

Dr. Thordur Runolfsson

Dr. Samuel Cheng

Acknowledgments

I would like to express my deepest gratitude to my adviser Dr. Ali Imran who guided me throughout my Masters. His dedication and passion inspired me to appreciate the importance of research which led me in devising a practical thesis topic.

I would also like to thank the rest of the committee, Dr. Thordur Ronulfsson and Dr. Samuel Cheng for taking the time reviewing the manuscript and attending my thesis defense.

To all my friends and colleagues in AI4Networks Center who supported and helped me. I am very grateful and proud to be a part of this Center.

Lastly, I would like to dedicate this work to my beloved family who always believed in me, gave me strength and endless encouragement.

Table of Contents

1 Introduction 1

1.1 Introduction and Background 1

1.2 Purpose and Motivation 3

1.3 Related Studies 5

1.4 Contributions 8

1.5 Scope and Limitation 8

1.6 Articles Published and for Publication 9

1.7 Organization 10

2 Standard Handover Events, Handover Related COPs and KPIs 11

2.1 Standard Handover Procedure 11

2.1.1 Types of Handover 14

2.1.2 Measurement Gap 14

2.2 How Standard Events are Used in the Industry 16

2.2.1 Event A1 – Cancel Measurement Gap 17

2.2.2 Event A2 – Start Measurement Gap 18

2.2.3 Event A3 – Intra-Frequency Handover 19

2.2.4 Event A4 – Inter-Frequency Load Balancing 20

2.2.5 Event A5 – Inter-Frequency Handover 20

2.3 Handover Related COPs and KPIs 21

2.3.1 Handover-Related COPs 21

2.3.2 Load Balancing-Related COPs 25

2.3.3 Handover Related KPIs 26

3 Modeling of Standard HO Events 32

3.1 SyntheticNet 32

3.2 Handover Modeling 33

3.2.1 Intra-Frequency HO Modeling 38

3.2.2 Inter-Frequency HO Modeling 39

3.2.3 Measurement Gap Modeling 40
3.2.4 Inter-frequency Load Balancing Modeling 42
3.2.5 Radio Link Failure Modeling 45
3.3 Events Interplay 45

4 Simulation Setup, Data Generation and Validation 48
4.1 Simulation Setup 48
4.2 Data Gathering 50
4.3 Model Validation 50
4.3.1 Intra-frequency HO Model Validation: 51
4.3.2 Inter-frequency HO with Measurement Gap Model Validation: 52
4.3.3 Handover Failure Model Validation: 54
4.3.4 Radio Link Failure Model Validation: 54
4.3.5 Load Balancing Model Validation: 56

5 Use Case: Effects of Varying COPs on KPIs 58
5.0.1 Effects of Changing A3 Offset on HOSR 58
5.0.2 Effects of Changing A3 Offset on RLF and Pingpong Rate . 59
5.0.3 Effects of Changing A3 Offset on SINR and Throughput . . 59
5.0.4 Summary of Results 61

6 Conclusion and Future Work 62

References 63

List of Figures

1.1 COPs and KPIs Related to Mobility in Cellular Network 4
1.2 Inter-Frequency Handover in a Multi-Layer HetNet Scenario 7
1.3 Scope of the Thesis Paper 9

2.1 Handover Procedure Illustration 11
2.2 3GPP Standard Handover Procedure 13
2.3 Types of Handover in Terms of Operating Frequency 14
2.4 Measurement Gap Illustration 15
2.5 Effect of Hysteresis 23
2.6 Effect of Filter Coefficient on RSRP Measurement 24
2.7 Effect of HO Failure one the SINR 28
2.8 Effect of SINR in Throughput 29
2.9 RLF Due to Handover Failure 30
2.10 Illustration of Pingpong HO Phenomena 31

3.1 Current Handover Models 35
3.2 SINR vs BLER 36
3.3 Realistic Handover Failure Modeling 37
3.4 Event A3-Based Handover 39
3.5 Real Data Showing Inter-Frequency HO vs Intra-Frequency HO Attempts 40
3.6 Event A5-Based Handover 41
3.7 Events A1 and A2 Measurement Gap 42
3.8 Modeled Load Balancing Procedure 43
3.9 Event A4-Based Handover 45
3.10 Radio Link Failure Modeling 46

4.1 Network Deployment Simulation 49
4.2 Screenshot from SyntheticNet 51
4.3 Example of a Successful Intra-frequency Handover 52

4.4 Lacking Candidate Target Cell on Similar Layer 53
4.5 Example of a Successful Inter-frequency Handover 53
4.6 Example of Multiple HO Failures 55
4.7 Example of an RLF Occurrence 56
4.8 Example of a Load Balancing Action 57

5.1 Effect of Changing A3 Offset on HOSR 59
5.2 Effect of Changing A3 Offset on RLF and Pingpong Rate 60
5.3 Effect of Changing A3 Offset on SINR and Throughput 60

List of Tables

2.1 3GPP Defined Standard Events 12
2.2 How Events are Used by Major Equipment Vendors 17

3.1 List of Modeled HO Related COPs 34

4.1 Base Station Configuration 48
4.2 Parameter Set Used for Simulation 50
4.3 Parameter Set Used to Show Changes in KPIs with change in COPs 50

Abstract

The ever-increasing demand for mobile data traffic along with new use cases are set to make the current cellular network technology obsolete and give rise to a newer and better one in the form of 5G. This arising technology is coming with a promise of massive capacity, ultra-high reliability and close to zero latency, however, coming alongside is additional complexity. 5G is expected to carry along with it more than 5000 configuration and optimization parameters (COPs). These COPs are the backbone of a network as most of the Key Performance Indicators (KPIs) relies on the proper settings of these COPs. To set these parameters optimally, it is imperative that the relationship between COPs and KPIs be understood. However, to date, this relationship between COPs and KPIs is known to some extend but is not fully realized. But mining the COP-KPI relationship is not a dead end. Machine Learning (ML) can be leveraged to learn KPI behavior with changes in COPs. Yet, ML's full potential is bounded by the lack of representative data in the wireless community to effectively train these models. Gathering these data is, in itself, a challenge. Real data from live network is abundant, yet not representative. Although simulator is a promising source of data, its performance lies on how realistic and detailed the modeling and implementation of its functions are. In this thesis paper, we have presented a realistic and comprehensive modeling of one of the most important functions of a wireless network: the handover function. In line with 3GPP standards, we have modeled and implemented more than 20 handover related COPs. The model is incorporated in a python-based simulator to generate data. Validation and evaluation are done to prove the model accuracy and its effectiveness in capturing real handover procedure. Use cases are also presented to show its capability to simulate different COP settings and show the effects on KPIs. This thesis paper is presented as an initial step in generating representative dataset to train machine learning to model COP-KPI relationship.

CHAPTER 1

Introduction

1.1 Introduction and Background

The demand for mobile data traffic continues to grow rapidly as the volume of capacity- hungry devices increase. To cater this demand, 5G is expected to provide massive coverage and capacity. While new techniques in the physical layer improvement such as massive MIMO, enhanced frame structure and advanced channel coding help address the issue, network densification is considered as the front runner solution [1]. However, this approach has brought alongside new challenges in network management. Deploying such a huge number of base stations (BS) of different types operating in a wide range of frequencies makes network management a nightmare for the operators.

One aspect that will be most impacted by dense base station deployment is mobility management [2]. This is because the number of handovers (HO) is directly related to the number and coverage size of the base stations. This means that deploying dense small cells will result to an enormous number of handovers. As a result, HO related issues like early HO, delayed HO, wrong HO and ping-pong will be more prominent [3]. These issues, if not taken care of, can lead to degradation in several Key Performance Indicators (KPIs) including retainability, throughput, latency and increase in signaling overhead reducing the overall user Quality of Experience (QoE) and Quality of Service (QoS). Thus, it is imperative for a cellular network to be equipped with efficient mobility management systems to avoid KPI degradation.

Designing and maintaining an efficient mobility management is a herculean task. Optimal setting of the mobility related configuration and optimization parameters

(COPs) needs to be ensured as handover performance mainly depends on this [4]. However, finding this optimal parameter setting is always easier said than done. In current LTE network, dozens of handover parameters need to be tuned in order to achieve a desired level of handover performance. In 5G, the number of these parameters is expected to increase considering the rise in complexity of 5G networks making optimal handover parameter setting discovery unfathomable.

The first step to efficiently optimize these parameters is to decipher how handover performance behaves with the variations in COPs. However, given the complexity and high dimensionality of cellular networks, analytical modeling to mine the relationship between parameters and handover performance is not a viable solution. Qualitative analysis being practiced in the industry might provide some insights on how handover related KPIs are affected by changes in COPs. For instance, an optimization engineer might have some intuition, based from experience and domain knowledge, that changing a parameter can affect the handover performance. However, this knowledge is mostly limited to a certain number of COPs and KPI's making this approach insufficient to discover the entirety of the COP-KPI relationship. This calls for a more robust mobility management system which can quantify the complex relationship between mobility parameters and network KPIs.

Machine learning (ML) makes it possible to model and map out functions that cannot be directly or mathematically interpreted in the data [5]. This capability makes ML a promising tool to quantify the complex relationship between mobility parameters and network KPIs. For example, a machine learning model can be trained on the mobility related COP data to learn the behavior of KPIs with changes in these parameters. This model will capture the highly complicated COP-KPI relation which is otherwise impossible through tractable analytical analysis. Once this model is trained, it can estimate the value of the KPIs with values of mobility parameters as input. However, getting a representative and huge dataset of COP-

KPI required to train the model successfully is still a challenge particularly in the wireless communication industry. The need for a dataset to train ML models to learn COP-KPI relationship is long overdue and is a major issue which needs to be addressed.

1.2 Purpose and Motivation

Several studies conducted proved that Artificial Intelligence (AI), in the form of Machine Learning (ML) [6, 7, 8, 9, 10] can be leveraged to improve the cellular network quality in terms of spectral efficiency [11], coverage [12], capacity [13] and mobility [14] to name a few. However, the full potential of ML in unraveling COP-KPI relationship can only be unveil with right and representative data use for training ML models. Unfortunately, the wireless communications domain is lagging behind other domains in terms of availability of dataset. For instance, in computer vision domain, there are tons of readily available data for the research community to use such as Imagenet [15] and MNIST [16].

Obtaining a representative dataset which contains COP-KPI relationship is a major hurdle in designing machine learning models. It is really challenging to collect data from the network operators due to some privacy concerns. Even if the data is available in a few cases, it is not representative of all the COP-KPI relationships. The reason is the valid reluctance of network operators to test most of the combinations of COPs in the live network. Trying all the possible combinations of COPs , even those related only to handover, and observing how KPIs behave in a real network is simply not possible given its sheer size (i.e. 3000 COPs in LTE and 5000 COPs in 5G) and the possibilities of network performance degradation due to these changes. Figure 1.1 shows some list of handover related KPIs and COPs which are directly affecting or affected by the mobility management. Another challenge in getting data from the real network is time. Observing the effect of one set of parameter setting

might require a considerable amount of time ranging from several hours to weeks even.

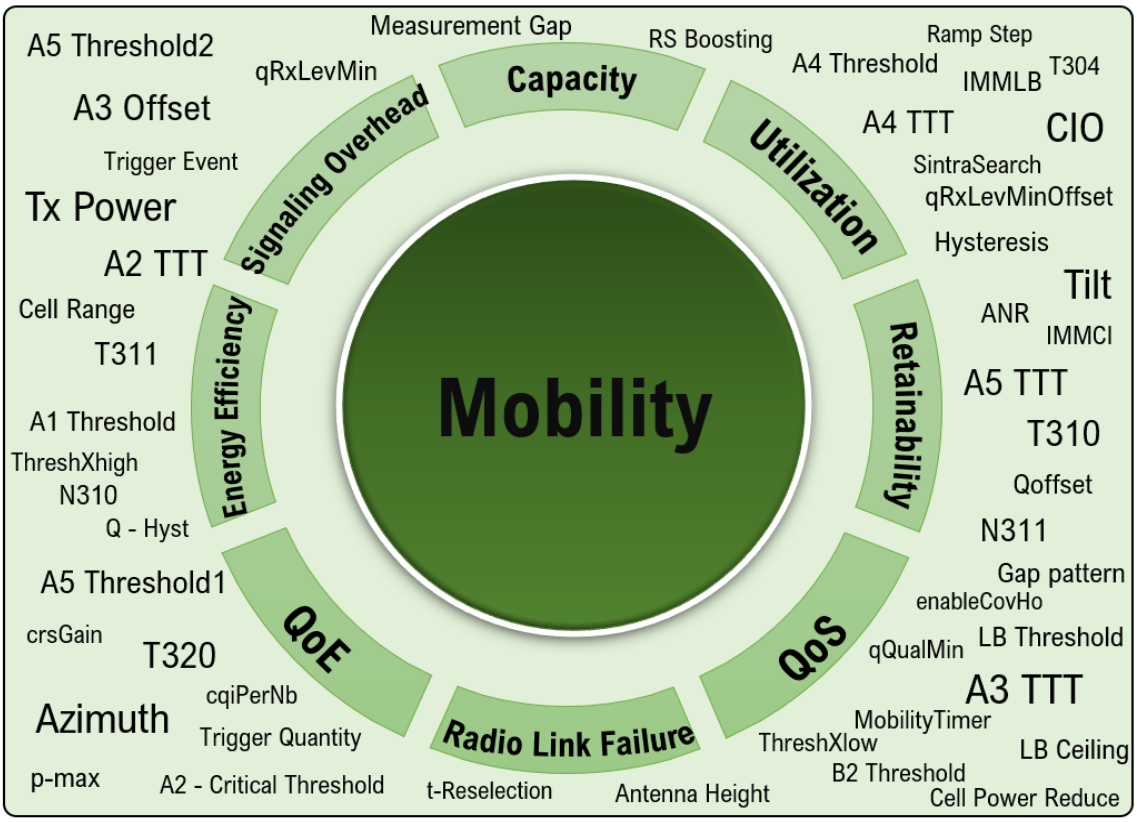


Fig. 1.1: COPs and KPIs Related to Mobility in Cellular Network

This problem of data scarcity can potentially be alleviated by cellular network simulators. With simulators, changes on the parameter values can be done in a wider range without the worry of potential network performance degradation. Moreover, effects can be observed instantly eliminating the hassle of long observation period. However, even simulators have their own flaws. For a simulator to be reliable, realistic modeling of the cellular network functionalities and elements as well as its dynamics is necessary. In terms of mobility, how elaborately and realistically the handover modeling is done can make or break the integrity and usefulness of a simulator. Unfortunately, most of the available simulators model network functions and phenomena unrealistically which makes them inaccurate and analysis using these simulators lacking in depth and conclusiveness.

It is therefore imperative that the call for generating a representative dataset to model COP- KPI relationship be answered. In this thesis paper, we start addressing the issue by presenting a realistic modeling of handover events, parameters and functions together with various KPIs. We focused on modeling handover related parameters as we understand the importance of mobility management. The model is implemented in a simulator which can generate data which can then be used to train ML models. This realistic modeling and implementation are done as a preliminary step in generating a representative dataset and realizing COP-KPI relationship.

1.3 Related Studies

There is no shortage in the availability of simulators for wireless communications [17, 18, 19, 20, 21]. All of these simulators are potential sources of the much-needed representative data discussed in the early part of this thesis. However, a survey of these simulators done by [22] shows that most of the available simulators lack in one very important feature: the support for mobility or handover function.

Of the 13 simulators compared in [22], only 2 supports handover function namely OMNeT++ and ns-3. Among these two, perhaps, the more famous simulator being used in the wireless communication community is the ns-3 simulator. ns-3 is a discrete event network simulator providing support for simulating different scenarios for LTE as well as for 5G [18]. However, ns-3 has its own shortcomings in terms of modeling the handover procedure. First, ns-3 has not modeled how users will behave in an event of handover failure. Instead, in order to avoid unpredicted behavior, they have recommended to avoid handover failures by making sure there is high enough SINR in the simulation network. This cannot be true all the time as SINR in the real network changes dynamically and difficult to control. Hence setting the SINR during the simulation to be always above the threshold of handover failure is an unrealistic.

ns-3 only supports handover of users on the same frequency layer (intra-frequency). Although is caters multi-carrier network deployment, handover between different layers (inter- frequency) is not supported. To add, ns-3 only models very few handover related events (i.e. events A2, A3 and A4) and COPs (hysteresis and TTT). These events and parameters and the importance of implementing much of them as possible is discussed in more details in Chapter 2. Load Balancing (LB) feature is also not modeled and supported by ns-3.

Most of the studies which involve handover performance evaluation to see the effects of changing parameters in KPIs are done using ns-3 simulator. Therefore, given the mentioned limitations of ns-3, these papers lack in comprehensiveness, depth and loss some level of accuracy. The first attempt to evaluate the handover algorithm in LTE network is done by the authors in [23]. In their study, they have evaluated the performance of Event A3 used in intra-frequency handover. Additionally, they have shown the effect of parameters like hysteresis as well as the effect of the user speed in term of handover failure rate.

Most of the available modeling and evaluation of handover events which followed [23] are focus in intra-frequency handover or the handover between cells operating on similar carrier frequency [24, 25, 26]. Moreover, all the mentioned studies are focused on comparison of Event A3 vs a combination of Events A2-A4 used for intra-frequency handover. Studies on evaluating performance of handover events give more attention to intra-frequency handover supported by the notion that this type of handover occurs more often compared to inter-frequency handover. This might hold true for a homogeneous base station type network deployment. However, in a heterogeneous network deployment setting with multiplicity of utilized frequency, inter-frequency handover plays a more crucial role. As shown in Figure 1.2, with multi-frequency deployment, areas where inter-frequency handover are needed outnumber areas where intra- frequency handover are necessary.

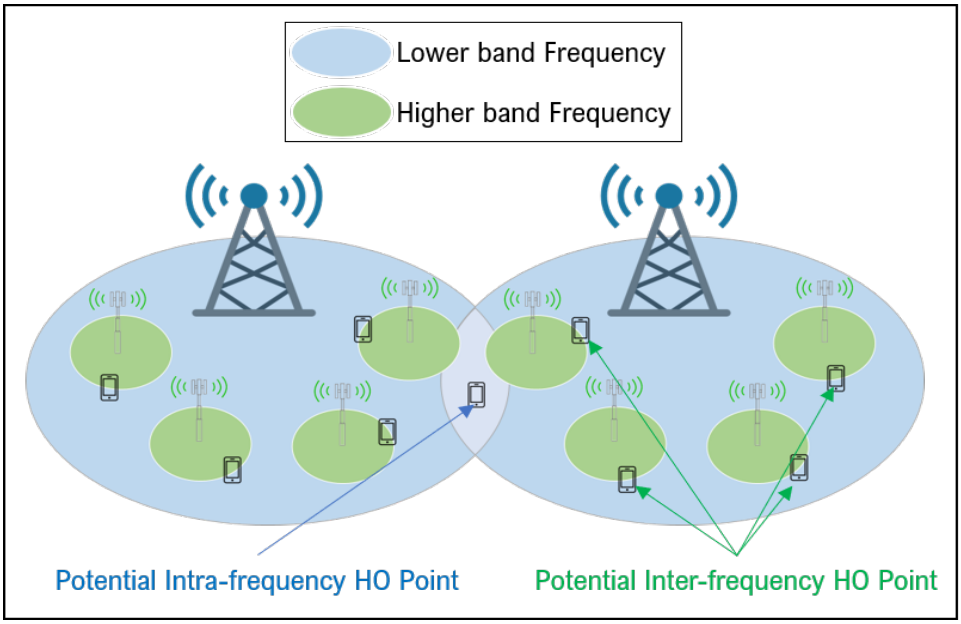


Fig. 1.2: Inter-Frequency Handover in a Multi-Layer HetNet Scenario

A simulated model for LTE intra-handover was presented in [27]. This study shows the variation in handover failures and handover frequency with varying mobility parameters and different user speed. They model Event A3 as the qualifying event of intra- handover. However, they have not modeled the exit condition of A3 as well as periodic report interval in A3. This works also did not consider the handover failures due to highly loaded target cell. Gemeniz et al. [28] modeled handover events in high speed packet access (HSPA). They also compared the simulated results with measurements to verify the simulator. However, the handover events in long term evolution (LTE) are different from that of HSPA and hence HSPA events cannot be used to measure KPIs in LTE.

Authors in [29] analyzed the process of X2-based handover and found some interesting results like how filter coefficient affects in handover. However, the study is lacking in depth and realistic evaluation as experimentation involve on 1 pair of base stations and a UE. This paper also failed to evaluate other events used in handover but is focus only on Event A3.

Based from the review of related study, even the best simulator available today lacks

the capability of modeling a real handover scenario. Thus, this limit the depth of the papers which are written based on these simulators. As we have seen, there are several studies which tried to model the relationship of handover parameters to KPIs but none is able to do so because of the aforementioned limitation.

1.4 Contributions

This thesis is presented to address the current shortcomings of the currently available simulators in providing realistic data related to handover performance of cellular networks. In this paper, modeling is done in line with 3GPP standards [30] with some inspiration from industry practices. The modeled functions are then incorporated to the Handover Module of the SyntheticNet [22], a link level 5G simulator developed at the AI4Networks Center [31]. The main contributions can be summarized as follows:

1. Realistic modeling and simulation of different handover events and parameters for multi-layer cellular networks.

2. Modeling and implementation of handover failures and how it affects system performance.

3. Modeling and implementation of 3GPP defined radio link failure using standard timers and counters.

4. Industry grade modelling and implementation of Mobility Load Balancing function.

1.5 Scope and Limitation

This thesis is focused on the HO events modeling, model implementation to the simulator and model validation and evaluation. As an initial step for potential

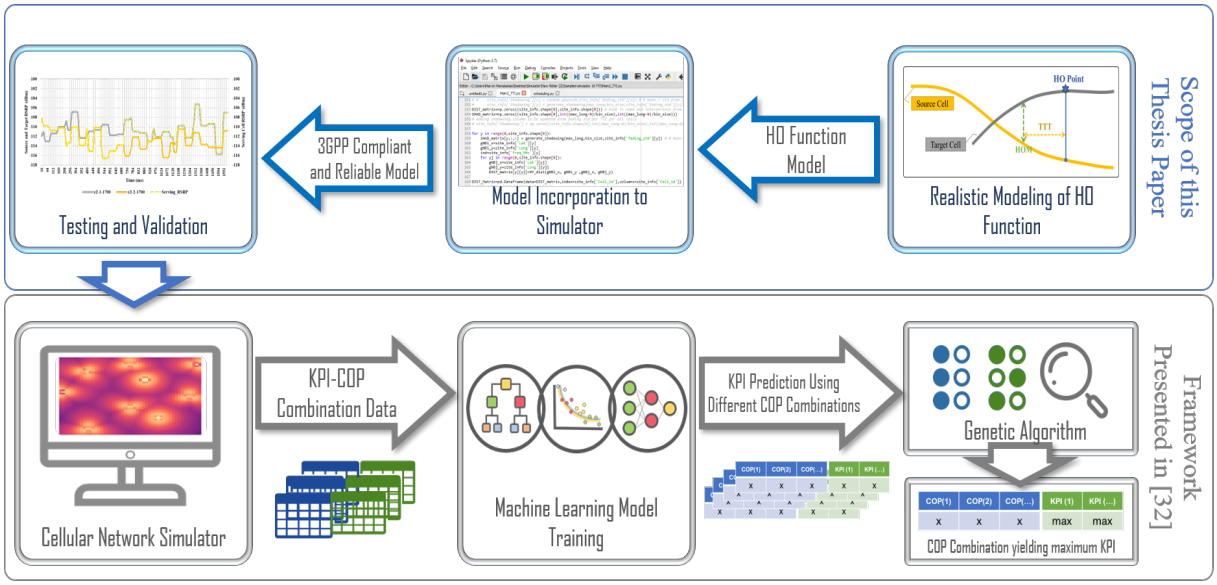


Fig. 1.3: Scope of the Thesis Paper

representative data generation, this thesis does not cover large data gathering as well as Machine Learning model training using the data from the simulator. Scope and limitations of this thesis is in Figure 1.3. The framework presented in [32] is modified to include the work on this thesis.

1.6 Articles Published and for Publication

1. Where to Go Next?: A Realistic Evaluation of AI-assisted Mobility Predictors for Hetnets

Marvin Manalastas, Syed Muhammad Asad Zaid, Hasan Farooq, and Ali Imran Published, 2020 IEEE 17th Annual Consumer Communications Networking Conference (CCNC)

2. SyntheticNET: A 3GPP Compliant Simulator for AI Enabled 5G and Beyond Syed Muhammad Asad Zaid, **Marvin Manalastas**, Hasan Farooq, and Ali Imran Accepted for Publication, IEEE Access 2020

3. A Machine Learning based Framework for KPI Maximization in Emerging Networks using Mobility Parameters

Joel Shodamola, Usama Masood, **Marvin Manalastas** and Ali Imran
Accepted for Publication, IEEE BlackSeaCom 2020

1.7 Organization

The rest of this thesis is organized as follows: Chapter 2 presents the standard HO process as well as the standard events used in the industry. This is followed by defining handover related COPs and KPIs. The actual modeling of these handover events is presented in Chapter 3. A short background about SyntheticNet is included in this chapter. In Chapter 4, simulation setup is discussed. This includes the network layout used for simulations as well as the specifics used for the simulation such as number of base stations, number of users as well as the handover parameters used. Evaluation and analysis of the results from the simulation is also presented. In this chapter the effectiveness and accuracy of the modeling is highlighted. In Chapter 5, a use case showing the effects of variations of COP values in the KPIs is presented. Finally, conclusion and future works are given in Chapter 6.

CHAPTER 2

Standard Handover Events, Handover Related COPs and KPIs

2.1 Standard Handover Procedure

The mechanism to transfer a connected user equipment (UE) from one base station to another is called handover (HO). When a user is moving away from one base station and near to the next, the receive signal level and condition from the serving base station, also called source cell, decrease while increases for the target base station as shown in Figure 2.1. To maintain a continuous service to the UE, the source and target cell must coordinate with each other to assist the UE to perform handover.

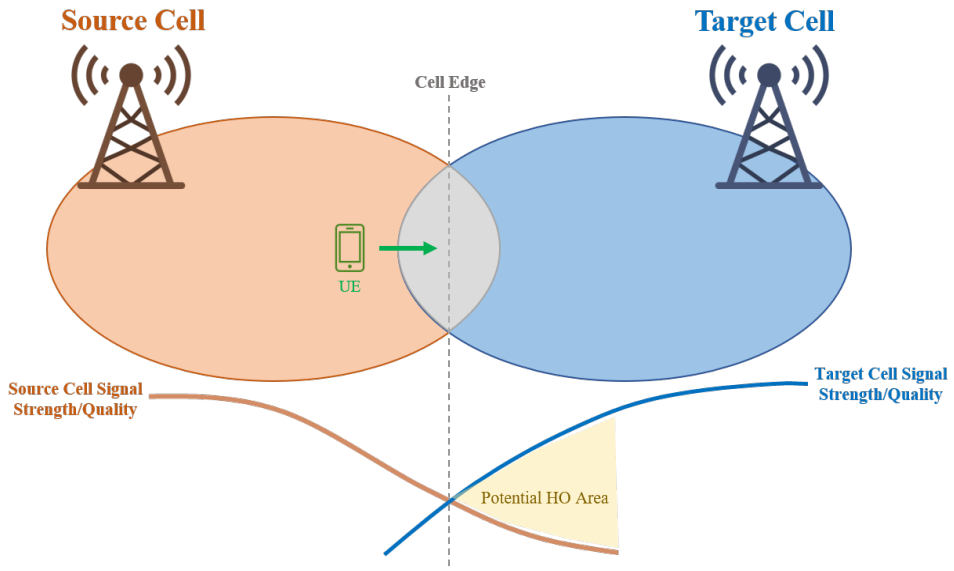


Fig. 2.1: Handover Procedure Illustration

Standard handover procedure defined in 3GPP [33] is shown in Figure 2.2. This standard is made originally for LTE network. However, 3GPP has not released so far any changes in this standard so it is expected similar standard will be used for

Table 2.1: 3GPP Defined Standard Events

Event Name	Event Description
A1	Serving base station becomes better than threshold
A2	Serving base station becomes worse than threshold
A3	Neighboring base station becomes offset better than serving base station
A4	Neighboring base station becomes better than threshold
A5	Serving base station becomes worse than threshold1 and neighbor base station becomes better than threshold2
A6	Neighboring SCell base station becomes offset better than serving SCell base station
B1	Inter RAT neighbor becomes better than threshold
B2	Serving base station becomes worse than threshold1 and inter RAT neighbor becomes better than threshold2

5G network. To keep on track with changes in the signal condition, UE periodically performs downlink radio signal measurement. Specifically, UE measures parameters such as reference symbol received power (RSRP). If any of the event condition described in Table 2.1 is fulfilled, the UE will send a measurement report (MR) to the serving base station. The message contains the RSRP level of the serving cell as well as the target base to which handover is intended. This process marks the start of the handover procedure. Detailed description of how these events are triggered in discussed in Section 2.2.

After receiving the MR from the UE, the serving base station starts the handover preparation by sending a handover request to the target base station. This procedure includes checking the current utilization of the target cell to know if it can provide the required resources the user needs. In return, the target cell will send a handover acknowledgement to the source cell telling that the UE requesting handover can be accommodated. Upon receipt of the acknowledgement, the serving base station will then send a handover command to the UE to begin the handover execution process.

At the beginning of HO execution phase, the source cell sends the Sequence Number (SN) Status Transfer message to the target cell. This message contains the up-

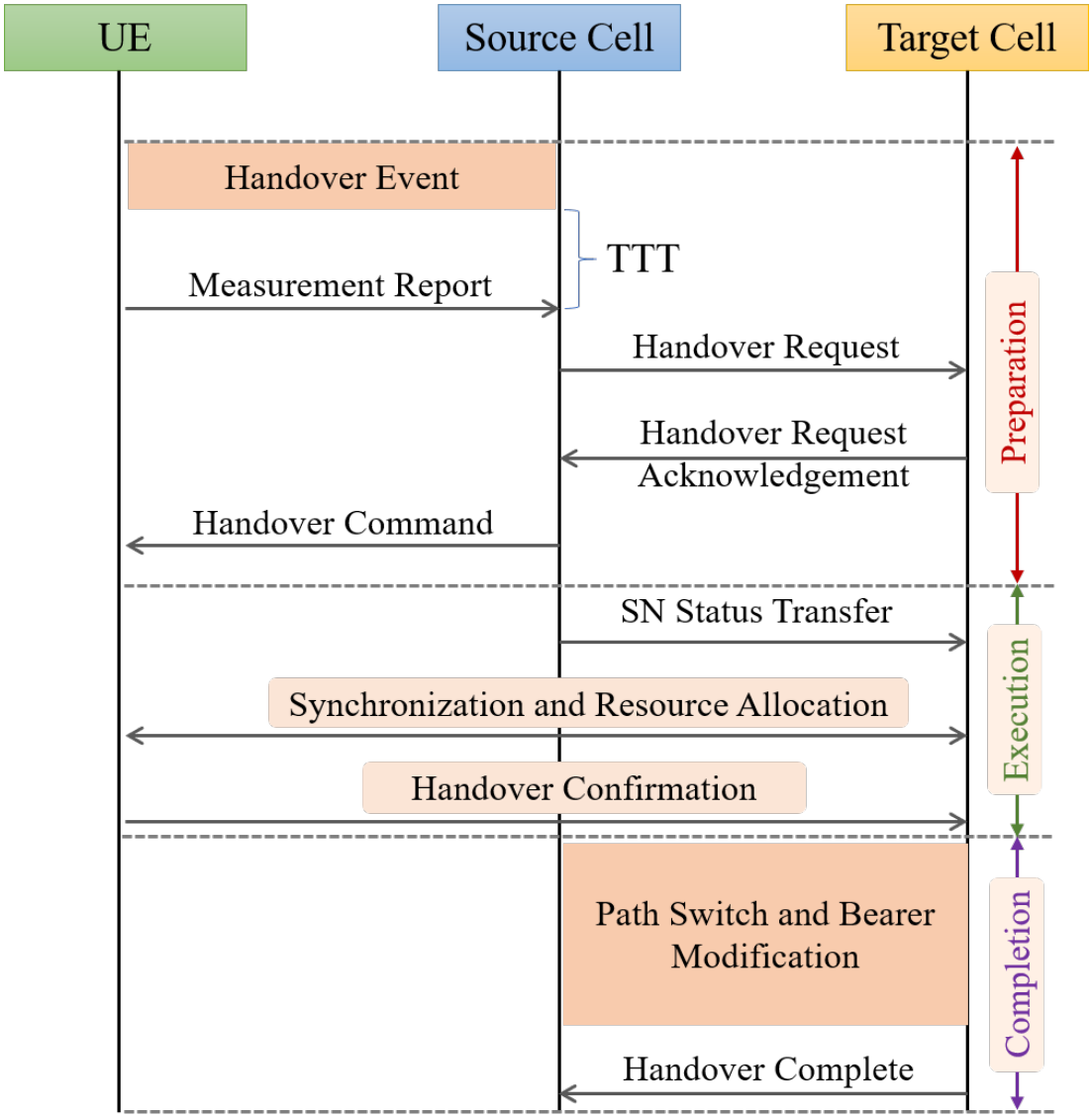


Fig. 2.2: 3GPP Standard Handover Procedure

link (UL) Packet Data Convergence Protocol (PDCP) SN and uplink Hyper Frame Number (HFN) as well as the downlink (DL) PDCP SN and downlink (DL) HFN. These fields are essential to maintain ciphering and service integrity after the handover. While SN Status Transfer is taking place, the UE starts synchronization with the target base station. While on this stage, the UE performs some functions like physical layer synchronization and configuration, Random Access Channel (RACH) procedure and Layer 2 configuration and security key update. At this point, the serving base station releases its connection to the UE. A handover confirmation message is then sent by the UE to the target base station marking the end of the

execution phase and the beginning of the HO completion phase. In this phase, the target base station requests the Mobility Management Entity to switch the data path from the source base station to itself. Bearers are also modified before buffers are flushed and resources from the source base station are released. Handover completion is sent by the target cell to the source cell which indicates the end of the handover process.

2.1.1 Types of Handover

Handover between cells of the same operating frequency layer is called intra-frequency handover. Meanwhile, handover which occurs between cells of different frequency layers is called inter-frequency handover. These types of handovers are shown in Figure 2.3. The process of inter-frequency handover is almost identical with intra-frequency handover with one major difference. As UE can only measure one frequency layer at a time, measuring the signal condition in another layer needs a separate procedure called measurement gap (MG).

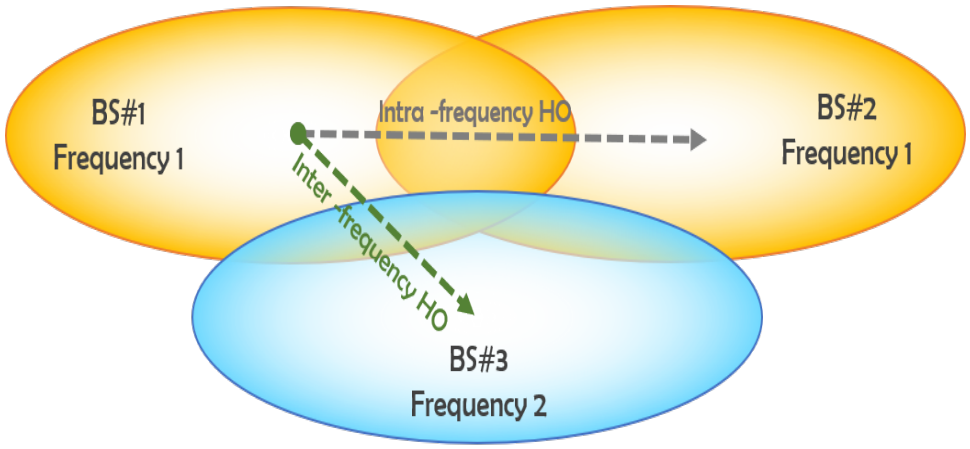


Fig. 2.3: Types of Handover in Terms of Operating Frequency

2.1.2 Measurement Gap

Current UEs are capable of measuring radio conditions of serving and neighboring cells at the same time only if they are operating on similar frequency. This limitation

is due to single RF transceivers present in the UEs. Increasing the RF transceivers inside the UE to accommodate multiple frequency measurement at the same time even though possible, is not a viable approach. One reason is due to the expected increase in the cost of the UE with multiple RF transceivers. However, the more concerning reason why multiple transceiver is not implemented is due to the risk of interference between these transceivers, especially when their operating frequency is close to each other.

These limitations of using multiple transceivers paved way to a technique called measurement gap (MG) which is standardized in 3GPP Release 8. As the name implies, measurement gap creates a 'gap' during the UE operation. 3GPP defined some basic parameters to be used in designing measurement gap. These include: gap offset which identifies the first subframe of each measurement gap, gap length which is equal to 6ms and two gap patterns gp0 (40ms) and gp1 (80ms), which dictates the periodicity of the MG. Figure 2.4 shows an illustration of the measurement gap function and its parameters.

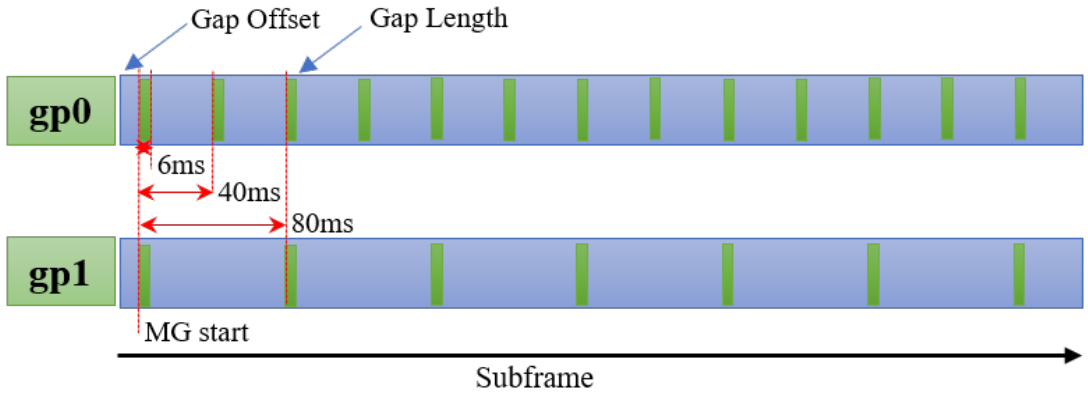


Fig. 2.4: Measurement Gap Illustration

During this gap, no data transmission or reception happens making it possible for UE to switch frequency operation and measure signal conditions of cell in another layer. During MG, UE switch back and forth between its current frequency of operation and measurement of the other layer. Measurement gap allows UE to operate in multiple frequencies using a single RF transceiver however causes negative

impact. Because no transmission or reception of data is done during MG, network performance is affected especially DL and UL throughput. Based from the standard values, measurement gap causes 15% reduction in throughout (6ms/40ms) if gp0 is used while around 7.5% (6ms/80ms) if gp1 is utilized. MG is usually a prerequisite of Inter-frequency handover. Before inter-frequency HO occurs, UE should be able to know the signal condition of the target layer for handover.

2.2 How Standard Events are Used in the Industry

Standard events that can be used to aid handover decision is defined in 3GPP TS 36.331 [33]. There are seven events defined in 3GPP Release 8 namely A1, A2, A3, A4, A5, B1 and B2 with an additional Event A6 in Release 10 as shown in Table 2.1. The first 5 events are usually used for intra-system (e.g.5G to 5G or LTE to LTE) handover while B1 and B2 are used for inter-RAT (e.g. 5G to LTE or 3G) handover. Meanwhile, the newly introduced A6 is used for handover of secondary cell in Carrier Aggregation (CA). As we are focus on evaluating handovers in the same system (e.g. 5G to 5G or LTE to LTE), we forgo the detailed discussion of inter-RAT measurement events as well as the CA related Event A6. Among these, events A3, A4 and A5 are the most commonly used events in evaluating handover decisions. It is apparent from Table 2.1 why these events are used to trigger handover process. All the mentioned events involve measurement of the neighboring cell and evaluation either the condition is better than the serving cell or meeting a certain threshold. Using these events and with the right parameter settings, UE will always camp on the base station with the best signal condition. meanwhile, although not used for HO evaluation, Events A1 and A2 has their own usage as will be discussed next.

How these events work is standardized, however, it is up to the vendors and operators how will they utilized these events in handover decisions. Table 2.2 shows a

summary of how the major vendors are utilizing these events for different types of network operations and handover functions.

Table 2.2: How Events are Used by Major Equipment Vendors

Measurement Event	Function	Vendor 1	Vendor 2	Vendor 3
A1	Cancel Measurement Gap	Yes	Yes	Yes
A2	Start Measurement Gap	Yes	Yes	Yes
A3	Intra-Frequency HO	Yes	Yes	Yes
	Inter-Frequency HO	Yes	No	Yes
A4	Inter-Frequency HO	No	Yes	No
	Inter-Frequency LB	Yes	Yes	Yes
A5	Intra-Frequency HO	No	No	Yes
	Inter-Frequency HO	Yes	Yes	Yes
	Inter-Frequency LB	Yes	No	No

Based from Table 2.2, there is some consensus on how the events are utilized in the current 5G and LTE network. For instance, all the vendors are currently using Event A2 to start measurement gap (MG) and Event A1 to cancel the MG process. Likewise, all three major vendors utilize Event A3 for intra-frequency handover, Event A5 for inter-frequency handover and Event A4 for inter-frequency Load Balancing. However, it is also apparent that some of the events are being utilized by some vendors but not being supported by others. For example, Vendors 1 and 3 support the use of Event A3 for inter-frequency handover while Vendor 2 does not. Moreover, A4-based inter-frequency handover is only being used by Vendor 2.

2.2.1 Event A1 – Cancel Measurement Gap

Event A1 is triggered when the RSRP of the serving base station becomes better than a threshold. Entering condition of event A1 can be expressed as:

$$M_s - hyst > Thres \tag{2.1}$$

where M_s is the measured RSRP value of the serving base station while $hyst$ rep-

resents the hysteresis used to avoid frequent measurement report due to rapid fluctuations of signal condition and $Thres$ is the threshold.

Event A1 is mainly used to cancel measurement gap (MG), a process where in the UE measures signal strength of base stations in another layer. A more detailed discussion of MG is provided at the latter part of the thesis. Based from Table 2.2, all of the major vendors have a consensus about Event A1's function. After measurement gap is triggered, user starts to measure cells in another layer. During measurement gap, no transmission or reception of data happens which causes degradation in user throughput. However, there are times that the radio condition of the serving cell recovers that handover would not be necessary. In this situation, Event A1 is used. Once Event A1 is sent and received, base station will send a command to the UE to stop measurement gap.

2.2.2 Event A2 – Start Measurement Gap

Event A2 is basically the opposite of Event A1. For Event A2 to be triggered, the signal condition (RSRP) of the serving base station must be below a certain threshold. Entering condition of Event A2 can be expressed as:

$$M_s + hyst < Thres \tag{2.2}$$

Event A2 is typically used to trigger mobility-related procedures when a user is moving closer to the cell edge. For instance, Event A2 is used to trigger measurement gap (MG) to start measurement of inter-frequency layer. With this approach, MG will only happen when there is poor coverage where the chances of handover occurrence are high. Just like Event A1, all the major vendors use Event A2 to trigger measurement gap.

2.2.3 Event A3 – Intra-Frequency Handover

Unlike other events which are triggered using some threshold, Event A3 is triggered with an offset. In 5G and LTE, this event is sent once the neighboring base station becomes better than the serving cell by an offset. Event A3 is triggered when the below conditions are met.

$$M_n + O_{n,freq} + O_{n,cell} - hyst > M_s + O_{s,freq} + O_{s,cell} + Offset \tag{2.3}$$

where the left side of the inequality represents parameters for the neighboring cells such as M_n which is the measured RSRP value, $O_{n,freq}$ represents the frequency specific offset while $O_{n,cell}$ is the cell specific offset and finally $hyst$ corresponds to hysteresis. Right side of the expression are the parameters of serving base station with the addition of $Offset$.

For this thesis paper, $O_{n,freq}$, $O_{n,cell}$, $O_{s,freq}$ and $O_{s,cell}$ are all set to 0dB which simplifies (2.3) to:

$$M_n - hyst > M_s + Offset \tag{2.4}$$

Event A3 is mostly used for intra-frequency handover procedure. However, it can also be applied to trigger inter-frequency handover. This event ensures that the UE will perform handover to a cell or layer with a better signal condition by controlling the mobility decision using the offset parameter. It avoids cases where handover to a better cell cannot be made because of misconfigured thresholds of either Events A4 or A5. However, as event A3 only considers the relative difference between source and target cell signal strengths, this mechanism can lead into handovers between cells or layers even at the cell center.

2.2.4 Event A4 – Inter-Frequency Load Balancing

For Event A4 to be triggered, the signal condition of the neighbor base station must be greater than a threshold. Setting $O_{n,freq}$, $O_{n,cell}$ to 0dB , (2.5) should hold true for a user to enter Event A4:

$$M_n - hyst > Thres \tag{2.5}$$

where M_n is the measured RSRP value of the neighbor cells, $hyst$ is the hysteresis and $Thres$ represents the threshold.

Event A4 is usually utilized when there is no need to consider the signal condition of the serving cell. Handover might take place even if the signal condition of the source is better than the target cell. It is therefore trickier to set A4-threshold in comparison to setting an offset in Event A3. An example case where A4 can be utilized is during load balancing where in the signal condition difference between the source and the target cell has lesser weight compared to their load difference. That is, even if the RSRP condition of the target cell is worse than the source cell, as source cell is highly loaded, handover will still be triggered to move some load to the target cell.

2.2.5 Event A5 – Inter-Frequency Handover

Event A5 evaluates both the serving and neighbor cell conditions before it can be triggered. Therefore, two thresholds are being used in Event A5. Serving cell must be less than the first threshold while the neighbor cell must be greater than the second threshold. Simplified expressions for activating event A5 are shown below:

$$M_s + hyst < Thres1 \tag{2.6}$$
$$M_n - hyst > Thres2 \tag{2.7}$$

where M_s and M_n are the RSRP of serving and neighbor cell respectively, $hyst$ is the hysteresis and $Thres1$ and $Thres2$ are the thresholds for serving and neighbor cell respectively.

Compared to event A4, Event A5 introduces more flexibility and control as the signal strengths of both the serving and the target cells are considered. However, instead of checking the target cell's RSRP relative to serving cell as in the case with A3-based HO, separate thresholds are used for source and target cells. This gives Event A5 an advantage over Event A3 to set the thresholds to values making sure handovers to only take place at the cell edge. Event A5 is also used for load balancing in cases where RF condition of source and target cells is also considered.

2.3 Handover Related COPs and KPIs

Cellular network COPs directly impact the networks performance which is usually measured through Key Performance Indicators (KPIs). Badly tuned COPs usually leads to poor network performance and degraded KPIs which ultimately result to unsatisfactory user Quality of Experience (QoE). That is why it is critical to make sure that these parameters are correctly set and adjusted. This subsection presents the handover related COPs and KPIs that are modeled in this thesis.

2.3.1 Handover-Related COPs

Current handover standards for LTE and 5G supports several tunable configuration and optimization parameters (COPs) that are set to provide optimal network performance. These parameters are used to decide when measurement reports should be sent as a prerequisite for handover. Most of these parameters are common on each event but there are also some which are unique for specific events.

A. Offset The parameter Offset is only used in evaluation of Event A3. It corresponds to how much better the signal condition of the target cell must be than the serving cell to perform handover. The higher the value of Offset, the more difficult it will be for a user to switch base station while a lower value will make handover easier. 3GPP set a standard range for offset to be from 0dB to 30dB. Meanwhile, in industry, 3dB offset is usually used.

B. Threshold For all the standard events except for Event A3, threshold is used to evaluate the triggering condition. For all the event using this parameter, it is defined as the level in which the signal condition of the serving or target needs to be above (i.e. A1 Threshold, A4 Threshold, A5 Threshold2) or below (i.e. A2 Threshold, A5 Threshold2) before triggering the event. There is no defined standard range for threshold, thus it needs more care when setting the value.

C. Hysteresis Hysteresis is another parameter which is used in all handover events in LTE and 5G. The role of hysteresis is mostly to avoid frequent triggering and cancellation of measurement reports specially for small and fast signal fluctuation as shown in Figure 2.5. Hysteresis also makes sure that the signal level of the target cell is indeed better than the serving cell. Hysteresis is usually added to the measured RSRP of the serving base station during event entering and is subtracted when UE tries to leave an event. Standard values of hysteresis ranges from 0dB to 15dB.

D. Time to Trigger (TTT) Before any event is triggered, entering condition must remain true for a certain period called Time to Trigger also known as TTT. This parameter is mainly used to avoid frequent measurement reporting of the UE and to make sure that the signal condition of the target cell for handover is actually better and not just because of abrupt fluctuations. TTT is also used to avoid ping-

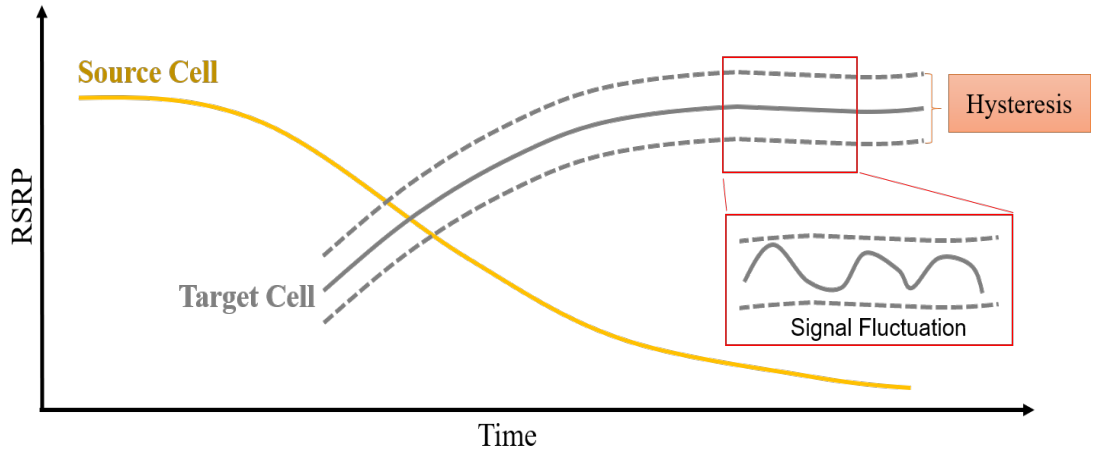


Fig. 2.5: Effect of Hysteresis

pong effect which is the back and forth handover between two cells. 3GPP set standard values of TTT to be are [0, 40, 64, 80, 100, 128, 160, 256, 320, 480, 512, 640, 1024, 1280, 2560, 5120] milliseconds. In current network deployment, each event can have different values of TTT depending on the requirement.

E. Scaling Factor (SF) Depending on the UE velocity, TTT can be adjusted by a scaling factor (SF). SF is first introduced in 3GPP Rel. 10 to address the issue of handover delays for fast moving users. Three SF values are currently standardized for slow, medium and high mobility users. However, the classification of users within these three categories is vendor specific. Expression for TTT with SF is shown in the below equation.

$$TTT' = TTT.\mu, \mu = \begin{cases} 1 \text{ for slow velocity} \\ 0.50 \text{ for medium velocity} \\ 0.25 \text{ for high velocity} \end{cases} \tag{2.8}$$

where TTT is the original set value while μ is the scaling factor and TTT' is the scaled TTT value based on the user velocity.

F. Report Amount and Report Interval UEs are configured to have the capability to send series of periodic reports after an event is triggered. The number of these periodic reports are defined by a parameter called report amount while the time between them is defined in the parameter called report interval. Report amount and interval are used to give user a chance to re-attempt handover in case some problem happened in transmission or reception of the preceding reports. Values of report amount can be set from 1 to infinity (which is the usual case) while the report interval varies from 120ms to 10240ms.

G. Filter Coefficient (FC) Received radio signal suffers from abrupt fluctuations due to factors such as noise and shadowing. Due to these fluctuations, events might be triggered either prematurely or late. To avoid such situations, filter coefficient (FC) is introduced. Layer 3 filtering is defined in 3GPP 36.331 5.5.3.2 [33].

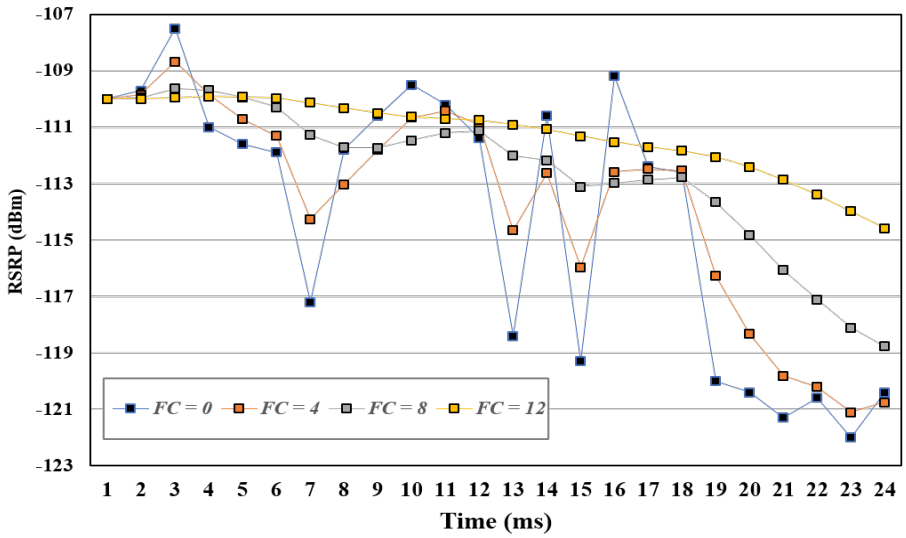


Fig. 2.6: Effect of Filter Coefficient on RSRP Measurement

Filter coefficient values varies from 0 to 19. FC = 0 means no filtering will be done and UE will evaluate reporting criteria based from the raw measured data. As filter coefficient increases, the less fluctuations or the smoother the curves becomes as showed in Figure 2.6. High value of FC is good to filter unnecessary unstable

signal, however, might not be able to capture rapid signal degradation and cause other issues. Mathematically, filtering is done using the below expression.

$$F_n = (1 - a).F_{n-1} + a.M_n \tag{2.9}$$

$$a = 1/2^{(k/4)} \tag{2.10}$$

where M_n is the latest raw RSRP measurement, F_n is the filtered measured RSRP, F_{n-1} is the old filtered RSRP measurement result, in which F_0 is set to M_1 for the initial measurement result and k is the filter coefficient for the corresponding measurement quantity.

2.3.2 Load Balancing-Related COPs

Aside from the handover which occurs due to poor signal condition of the serving cell, there also exist handovers which are triggered by the load of the serving cell. This function is known as load balancing. This process is done to users from a highly loaded base station to a less loaded one. However, unlike coverage-based handovers which have standard procedures, 3GPP has not specified any standards for load balancing. This task is left for the vendors for innovation.

A. Load Balancing Threshold The threshold for inter-frequency load balancing is specified by the parameter called load balancing threshold. Load balancing from one base station to another is triggered when the Physical Resource Block (PRB) utilization of a base station exceeds the sum of this threshold and the load offset. Consequently, when the load of a base station drops below this threshold, the act of load balancing stops. Typically, the value of this threshold is 60% PRB utilization.

B. Load Balancing Offset Load balancing offset or load offset is the value added to the load balancing threshold to trigger the load balancing. This is added to limit

false activation of the load balancing function. In industry, recommended value of this offset is 8% to 10%.

C. Load Balancing Difference To perform load balancing, not only the load of the source cell is considered. There should also be target cells which are suitable to transfer the load. Load balancing difference parameter indicates the minimum load difference between source and other cells for them to be considered as target. Value of 15% is the typically used in the industry.

2.3.3 Handover Related KPIs

Mobility KPIs are mostly concerned with handover performance. However, several other KPIs are directly related on how good the handover performance is. This subsection describes some of this KPIs which are affected by poor handover performance. These are the initial KPIs which are also modeled and incorporated in the simulator.

A. Handover Success Rate (HOSR) Handover Success Rate (HOSR) is the KPI which directly measures the performance of handover in a network. This KPI is divided into two category, Intra and Inter-frequency HOSR. The former is used to quantify and evaluate the success rate for HOs occurring within similar layer while the latter is to evaluate the HOs occurring between different layers. Expressions to calculate this KPI are shown as:

$$HOSR_{Intra} = \frac{HOS_{Intra}}{HOA_{Intra}} \times 100\% \tag{2.11}$$

$$HOSR_{Inter} = \frac{HOS_{Inter}}{HOA_{Inter}} \times 100\% \tag{2.12}$$

$$HOSR_{Total} = \frac{HOS_{Intra} + HOS_{Inter}}{HOA_{Intra} + HOA_{Inter}} \times 100\% \tag{2.13}$$

where $HOSR$ is the HO success rate, HOS is the number of successful HOs and HOA represents the number of HO attempts.

Some of the common causes of poor HOSR includes poor radio condition, high interference, high traffic in the target cell and problematic neighboring relation such as handover to overshooting cells. Industry practice to resolve poor HOSR includes tuning of hard parameters such as antenna tilt, antenna azimuth and transmit power. Aside from that, tuning of handover related soft parameters such as offset, hysteresis, threshold and TTT are also done. It is very important to make sure HOs are successfully occurring not only to make sure continuous service are provided to mobile users but also to avoid other related KPIs to degrade.

B. Signal to Interference and Noise Ratio (SINR) SINR is a measure of the quality of the received signal. It is, however, not defined as a standard measurement in 3GPP specifications but is widely used by the UE and equipment vendors. As it is not a standard measurement, SINR is not reported by the UE to the base station. Instead, it is converted to what is called as Channel Quality Indicator (CQI) which estimates the condition of the received signal. In its simplest definition, SINR can be expressed as the ratio of serving base station signal strength and interference strength with the additional noise. Mathematically, SINR is expressed as:

$$SINR = \frac{S}{I + N} \tag{2.14}$$

where S is the received signal power for the serving base station, I is the average power of the interfering base stations and N indicates the background noise.

SINR plays a vital role in determining the performance, quality and hence user experience in the cellular networks. A large set of accessibility, performance, and

retainability metrics, such as coverage and capacity are heavily dependent on SINR. However, SINR is heavily influenced by the handover performance. Data from a real network measurement in Figure 2.7 shows that during handover, UE will enter an area where SINR has negative values because of the strong interference from the target cell and other neighboring cells. Ideally, this poor SINR area should only last for a short period of time until HO is completed. However, in case of a handover failure, this poor SINR period is prolonged degrading user quality of experience as shown in Figure 2.7.

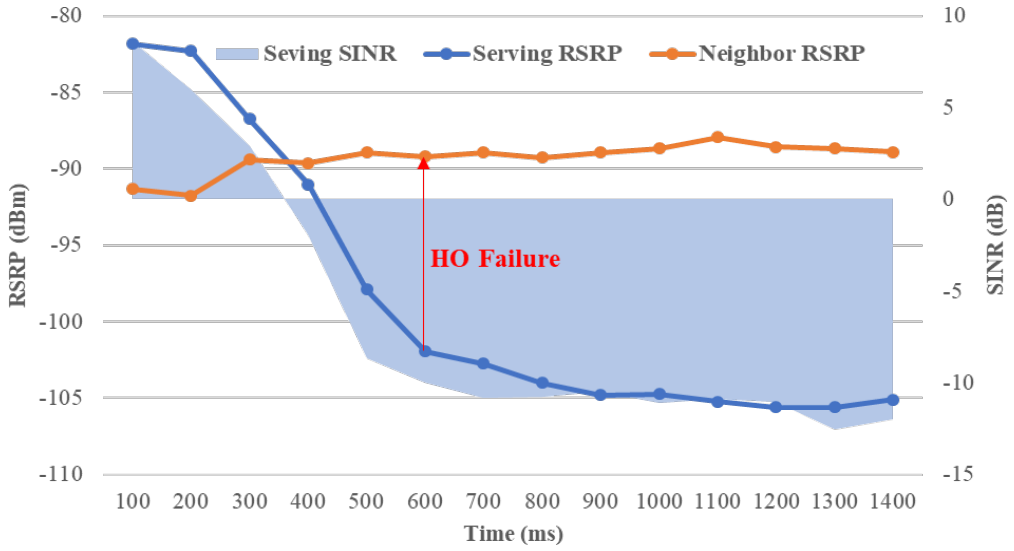


Fig. 2.7: Effect of HO Failure one the SINR

C. User Throughput (TP) Throughput is defined as the speed at which packets are transferred over the air interface. Throughput (TP) mainly depends on two factors, allocated PRB bandwidth (BW) and SINR. The relationship is defined by using Shannon Equation as shown in expression (2.14).

$$TP = BWlog_2(1 + SINR) \tag{2.15}$$

Handover performance affects TP as it is directly related to SINR. As previously mentioned, unlike RSRP, SINR is not directly reported by the UE to the base station. It is first converted to Channel Quality Indicator (CQI). This CQI indicated

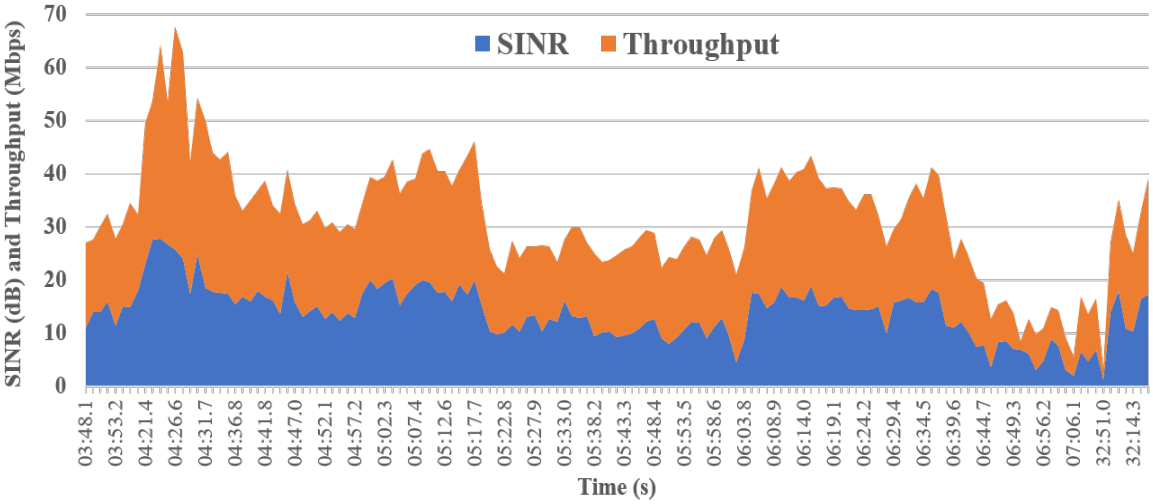


Fig. 2.8: Effect of SINR in Throughput

the quality of the channel being used for communications. CQI is then mapped to Modulation Coding Schemes (MCS) Index. Modulation and coding scheme determine the number of bits transferred in 1ms TTI/transport block size (TBS). This index helps the base station to decide the appropriate MCS (i.e. QPSK, 16 QAM, 64 QAM) to use depending on the channel condition. Relationship from SINR and TP can then be summarized as follows: the higher the SINR, the better the CQI is, which results to the higher the MCS and ultimately to higher throughput. Real data from field test shown in Figure 2.8 shows how TP directly vary with changes in SINR values.

D. Radio Link Failure (RLF) Rate When UE is in connected mode, it is said to be in RRC Connected State. However, under certain conditions this RRC connection can fail and the user declares Radio Link Failure (RLF). When signal strength deteriorates below a certain level, users find it difficult to maintain a good connection to the serving base station thus RLF is performed. As RLF terminates the bad connection and gives the UE a chance to camp on a better cell in the vicinity. If no RLF is performed, and UE continues in poor signal condition, UE experience will be badly affected. Also, there are times when UE will try to increase

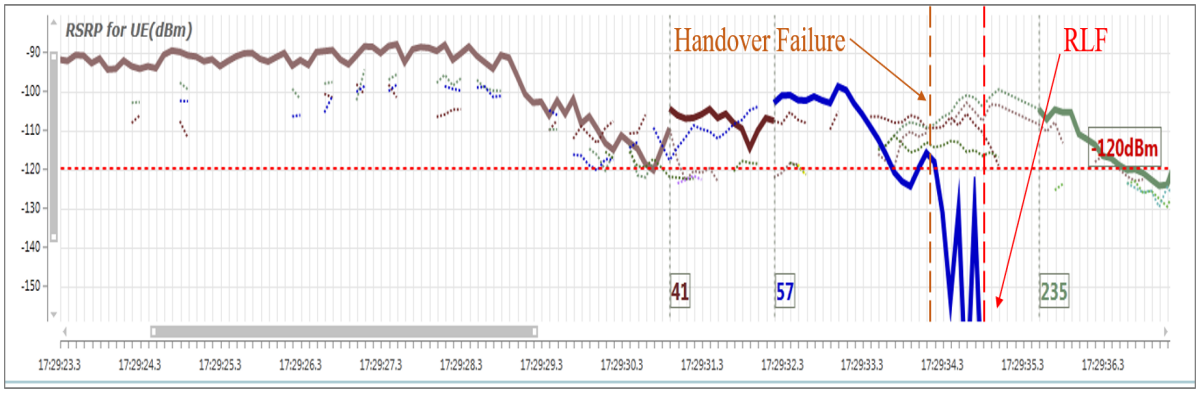


Fig. 2.9: RLF Due to Handover Failure

its uplink power to compensate which results high UL interference.

RLF happens for different reasons, however the most common is due to handover failures. When HO is failing from source to target cell, the UE enters a poor SINR area. The longer the handover takes, the longer the UE stays in poor SINR area then the more chances of RLF occurrence. An actual RLF instance from field test data is shown in Figure 2.9

In this thesis paper, we quantify RLF in terms of its occurrence over the total number of HOs as shown in expression below.

$$RLF_{Rate} = \frac{RLF_{total}}{HO_{total}} \times 100\% \tag{2.16}$$

$$HO_{total} = IntraHOAttempt + InterHOAttempt \tag{2.17}$$

where RLF_{total} is the total number of RLF observed and HO_{total} is the total number of handover attempts, both intra-frequency and inter-frequency.

E. Pingpong HO Rate Pingpong HO is one of the most common issue in mobility. Pingpong HO is defined as two or more subsequent HOs between the source and target base stations and vice versa as shown in Figure 2.10. This phenomena causes several problems such as increase in signaling, call drops and reduction in total network performance. There are several reasons why pinpong happens includ-

ing lack of dominant cell, high signal fluctuation on the cell edge, the location of the user, user trajectory and speed to name a few.

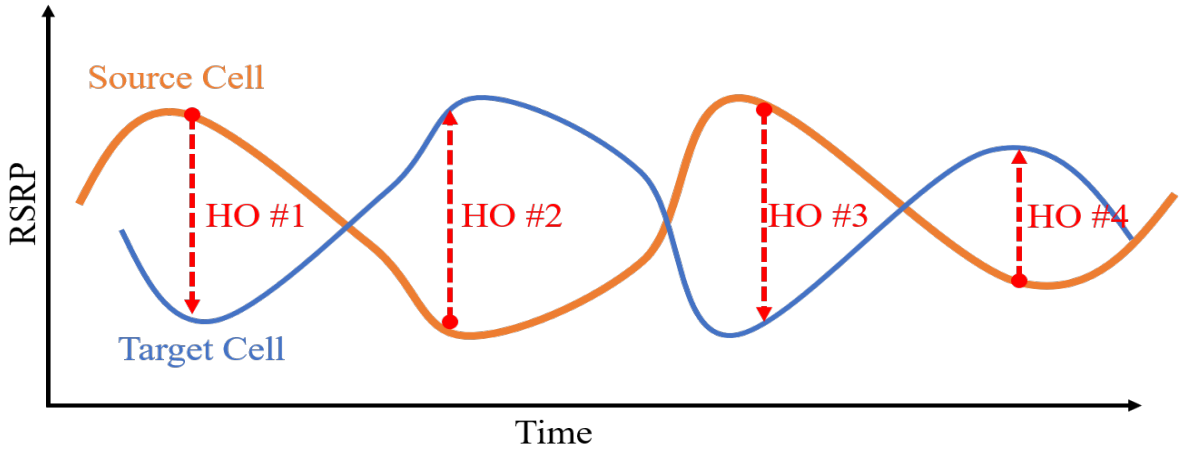


Fig. 2.10: Illustration of Pingpong HO Phenomena

In this thesis paper, we have quantify pinpong in terms of pingpong rate expressed below:

$$PP_{Rate} = \frac{PP_{total}}{HO_{total}} \times 100\% \tag{2.18}$$

where PP_{total} is the total number of pingpong observed and HO_{total} is the total number of handover attempts, both intra-frequency and inter-frequency.

CHAPTER 3

Modeling of Standard HO Events

User mobility has been the *raison d'etre* of wireless cellular systems. To maintain reliable connection, it is incumbent upon the mobile users to perform HO from serving cell to the next suitable cell along their trajectory. HO frequency is mainly dependent on the mobile user speed and network deployment characteristics (BS density, heterogeneity, HO parameter configuration etc.). 5G networks will have a large HO rate, primarily because of network densification and a large fraction of mobile UEs. 5G standard follows break-before-make HO approach like LTE where mobile user may observe HO failure due to poor signal strength of participating BSs, sub- optimal HO parameter configuration or high user velocity.

Unlike most of handover modeling done in existing simulators that consider only one or two basic HO parameters thus offer inaccurate results on mobility related KPIs, the HO modeling in the thesis paper incorporates all 20+ 3GPP defined configuration parameters that affect mobility in a real network. Modeling these parameters in a simulator is a key step to enable holistic AI enabled network automation. These parameters not only affect mobility related KPIs but also determine overall signaling overhead, capacity, UE battery life and QoE. In this chapter, we present the modeling process of standard handover events and how they are incorporated to the simulator.

3.1 SyntheticNet

While many system level simulators for 4G and 5G exist today, there is particularly a dire need for a 3GPP compliant system level holistic and realistic simulator that

can support evaluation of the plethora of AI-based network automation solutions being proposed in literature. To address this need, a simulator called SyntheticNet [22] is developed. SyntheticNet is a cellular network simulator built in Python for 4G, 5G and beyond networks in compliance with 3GPP Release 15 [34]. It is a modular, flexible and versatile simulator supporting advanced features like adaptive numerology, handover and futuristic database-aided edge computing to name a few. In this thesis, handover event models are incorporated to Handover Module of the SyntheticNet for testing, data generation and analysis.

3.2 Handover Modeling

Realistic modeling of different handover events in LTE and 5G networks is done in adherence to 3GPP standards described in the previous section. We have implemented this model in a python-based simulator, SyntheticNet then evaluated the results. Handover events are modeled based on how they are used in the industry. As shown in Figure 3.1, current modeling of handover process in literature and implementation in the simulators [18, 19] is very simplistic. This approach fails to capture most of the procedure and evaluation happening during a handover process. Currently, most handover models only consider parameters such as handover margin (HOM) and time to trigger (TTT). With current handover models, handover will take place once HOM is maintained for the duration of TTT. However, this kind of modeling is not sufficient and unrealistic.

In our modelling, we have considered more than 20 of these handover related parameters and used them based from how major equipment vendors utilized them in the industry. Incorporating all these parameters instead of just few as in the current models make the model in this thesis more realistic and results are more reliable. Table 4.1 shows the HO related parameters used and modeled in this paper.

Aside from incorporation of dozens of HO related parameters in our model, another

Table 3.1: List of Modeled HO Related COPs

Number	COP	Definition
1	Cell Individual Offset (CIO)	Offset value for the neighbor cell. Use to make cell look better (+ CIO) or worse (-CIO)
2-6	Hysteresis (A1, A2, A3, A4, A5)	Values added/subtracted to the measurement to make sure an event must be triggered.
7-11	Time to Trigger (A1, A2, A3, A4, A5)	Length of time the target cell signal level is better than the serving cell before the UE initiates a handover request.
12	A1 Threshold	A1 event is triggered when the serving cell's signal level becomes better than the A1 threshold.
13	A2 Threshold	A2 event is triggered when the serving cell's signal level becomes worse than the A2 threshold.
14	A3 Offset	The offset value which target should be greater than the serving for event A3.
15	A5 Threshold1	A5 event is triggered when the serving cell becomes worse than Threshold1.
16	A5 Threshold2	A5 event is triggered when the target cell becomes better than Threshold2.
17	A4 Threshold	Event A4 is triggered when the target cell's signal level becomes better than the A4 threshold.
18	Scaling Factor	A factor multiplied to TTT depending on the speed of the user to make HO faster for high mobility users.
19	Report Amount	The number of periodic measurement reports
20	Report Interval	The time between the periodic measurement reports
21	Filter Coefficient	A linear filter used to normalize the measured signal strength.
22	Load Balancing Threshold	This parameter specifies the threshold for inter-frequency load balancing.
23	Load Difference Threshold	This parameter specifies the minimum load difference between two cells that triggers load balancing.
24	Load Balancing Offset	This parameter specifies an offset applied to the threshold value for triggering load balancing.
25	T310	Waiting time for radio link failure.
26	N310	Maximum number of consecutive "out of sync" indications received from lower layers.
27	N311	Maximum number of consecutive "in-sync" indications received from lower layers.

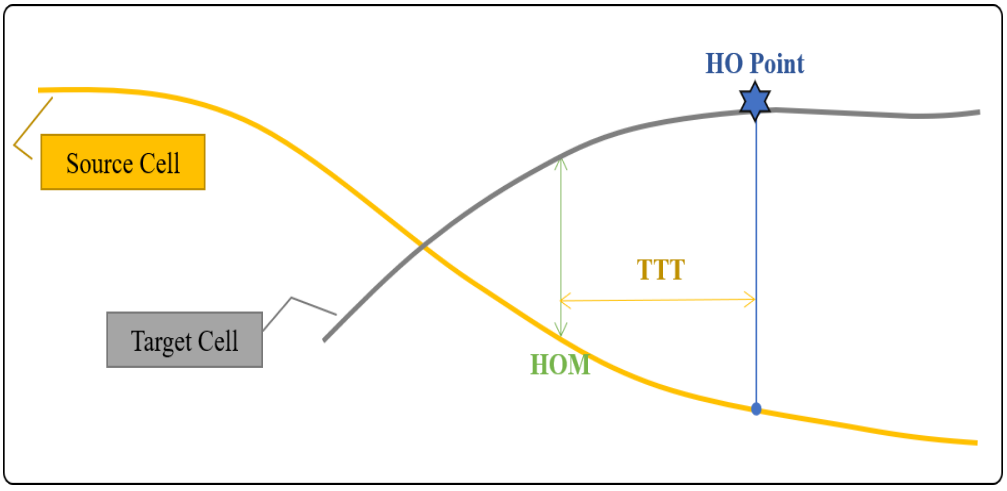


Fig. 3.1: Current Handover Models

enhancement in comparison with the current HO models is the modeling of handover failure. In our model, we have considered the critical points where handover failures usually take place. There is no hard and fast rule to define handover failure points. However, since handover success of proper reception and decoding of message between UE and the base stations, most HO failures are due to poor signal quality and condition.

During handover process, there is a back and forth exchange of signaling messages from UE to source and target base station (i.e. measurement report, handover command, handover confirmation). Since these messages are transmitted via air interface, the reception and decoding of these messages will depend on the channel quality and signal condition [35]. Thus, these messages are prone to failures if the signal condition between the UE and base station, both source and target, is not good enough.

As mentioned earlier, SINR is one of the most commonly used measure of signal quality in a network. Therefore, to model handover failure we used SINR as the base parameter. Using the study conducted by [36], values of SINR are mapped to Block Error Rate (BLER) percentage. Relationship of BLER % and handover failure needs a deeper understanding. However, since the messages between UE and

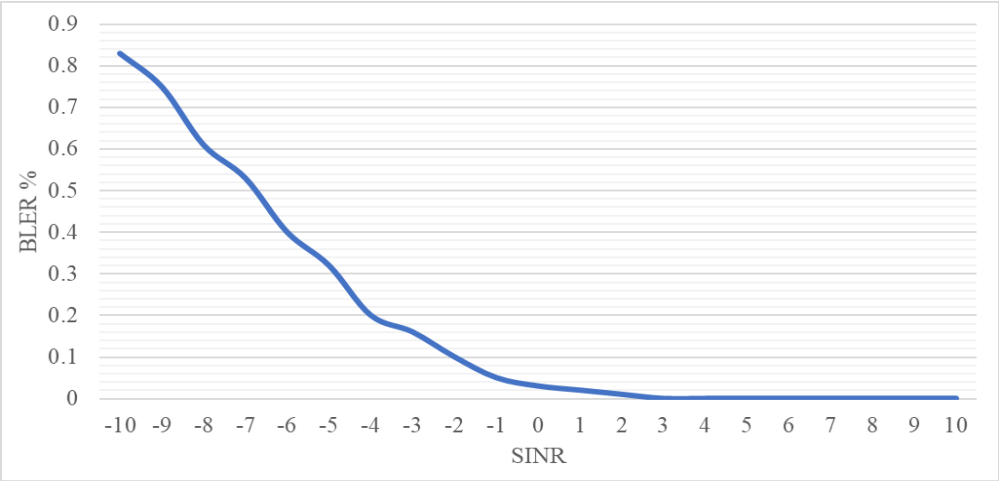
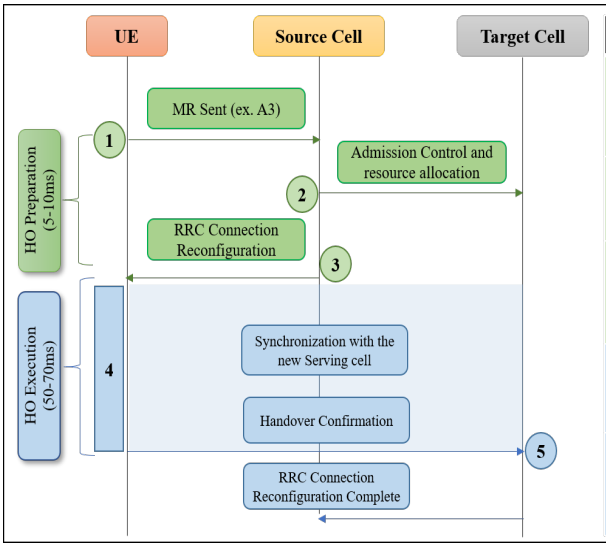


Fig. 3.2: SINR vs BLER

base stations need to be decoded for HO to succeed, we have relate the BLER % directly to HO failure percentage. For instance, if BLER % is equal to 10%, there is 10% chances that HO message will not be received or decoded hence 10% chances of HO failure at a certain point. Looking at Figure 3.2, it is apparent that as SINR decreases, BLER percentage increases, thus chances of HO failure also increase.

In our model, we have identified five critical points where HO might fail as shown in Figure 3.3. First point is when UE sends a measurement report to the base station. During this period, the uplink signal condition of the user should be good enough for the base station to decode the measurement report sent. The mapping of SINR to BLER % is checked and depending on the BLER %, the probability of HO preparation success or fail is calculated.

The second critical point identified is during the admission control and resource allocation. Before serving cell sends a handover request to the target base station, target cell should have enough available PRB to cater the incoming user. During this process, the source cell will check the current PRB utilization of the target cell to make sure it can support the demand of the incoming user. If target cell can allocate the required PRB to the UE, then the second phase of HO preparation will succeed. However, if for instance the is high load in the target cell and is not



	Evaluation	Condition
1	Check UL SINR	Based from SINR vs BLER Mapping, chances of HO failure is calculated
2	Check Load Condition of the Target Cell	If Target resources are not enough to accommodate new user, HO failure will happen
3	Check DL SINR of the Source Cell	Based from SINR vs BLER Mapping, chances of HO failure is calculated
4	Check UL SINR and DL SINR of the Target Cell	Based from SINR vs BLER Mapping, chances of HO failure is calculated
5	Check DL SINR of the Target Cell	Based from SINR vs BLER Mapping, chances of HO failure is calculated

Fig. 3.3: Realistic Handover Failure Modeling

capable of catering another UE, then a HO preparation failure is recorded.

After the admission control and resource allocation, source cell will send an RRC Connection Reconfiguration message to UE informing the UE the details about the target cell. This RRC Connection Reconfiguration message should be received and decoded successfully for HO to commence. This is where the third potential HO failure point lies. At this stage, we evaluate the SINR of the serving base station, map it to BLER % and again, calculate HO failure chances.

For the fourth point of interest, we considered the synchronization with the target cell phase. Here, there is a continuous communication between the UE and the target cell for synchronization and resource allocation purposes. During this period, we have evaluated the UL SINR as well as the target ell SINR to calculate HO failure chances. If at any point failure is detected, we declare HO execution failure at this stage.

The fifth and last potential HO failure point is during the time were HO confirmation is sent form UE to the target base station. Since the direction is from UE to base station, BLER % mapping to UL SINR is evaluated, and HO chances are calculated.

We have modelled the time from UE sending MR to the serving base station to

reception of the RRC Connection Reconfiguration to be between 5 to 10 ms while 50 to 70ms from synchronization to HO completion as these are the specified latency allowed as per 3GPP specifications. This general modeling approach is applied for both intra-frequency and inter-frequency handovers. In the next subsection, detailed modelling of intra and inter-frequency HOs is discussed.

3.2.1 Intra-Frequency HO Modeling

Event A3 is the most common event used for intra-frequency handover. This is because event A3 assures that users will camp on the best cell in term of signal strength and quality. UE constantly measures neighboring cells on the same frequency as the serving cell and sends measurement report once the signal condition of these neighboring cells becomes better than the serving.

We have modeled Event A3 handover for intra-frequency handover. We have implemented the parameters used for intra-frequency handover such as A3 offset, A3 hysteresis and A3 time to trigger (TTT). Aside from these three parameters, cell individual offset has also been considered. HO evaluation procedure initiates when RSRP of target cell exceeds the RSRP of serving cell by HOM. In this context, HOM is a collective term which simply means the total of offset, hysteresis and CIO applied to the neighboring cell. Mathematically, HOM is expressed as:

$$HOM = A3Offset + A3Hyst + CIO_n \tag{3.1}$$

Once event A3 is triggered, the UE will send the report to the base station containing the RSRP the serving as well as well as the RSRP of the target base station for handover. From this point on wards, the process of HO will follow the model discussed in the previous subsection. Figure 3.4 shows how Event A3 intra-frequency handover is modeled.

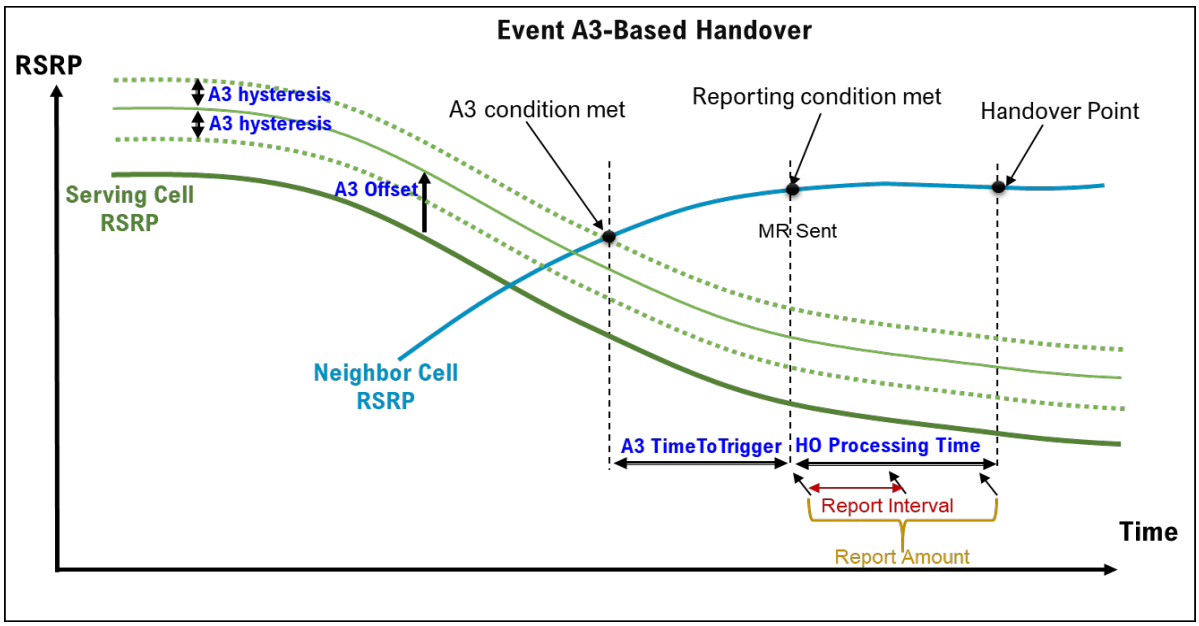


Fig. 3.4: Event A3-Based Handover

3.2.2 Inter-Frequency HO Modeling

Most of the currently available simulators only supports intra-frequency handovers or handover between base stations with similar frequency due to its convenience in terms of implementation. Due to its additional complexity such as modeling measurement gap, incorporation of inter-frequency handover or handover between different frequencies is mostly taken for granted. However, we realized the importance of inter-frequency handover specially in a heterogenous networks where base stations operate in multiplicity of frequencies. Real data collected for 24 hours for 7 base stations show that inter-frequency handover attempts is almost double compared to intra- frequency handover attempts as shown in Figure 3.5. This data show that capturing the behavior of users performing inter-frequency HO is important and need to be modeled.

We have modeled inter-frequency HO almost identical to intra-frequency HO with two major differences. First, to activate inter-frequency HO, MG is a pre-requisite. Second, we have used Event A5 instead of Event A3 as it is the one being supported by all the major vendors in the industry.

Base Station	Inter-Frequency HO Attempts	Intra-Frequency HO Attempts
Cell_A_Sector_1	3135	7575
Cell_A_Sector_2	30152	9984
Cell_A_Sector_3	3278	3115
Cell_B_Sector_1	14223	6031
Cell_B_Sector_2	2094	5753
Cell_B_Sector_3	11479	9461
Cell_C_Sector_1	26091	14555
Total	**90452**	**56474**

Fig. 3.5: Real Data Showing Inter-Frequency HO vs Intra-Frequency HO Attempts

To model Event A5 based inter-frequency handover, we have implemented A5 Threshold1, A5 Threshold2, A5 Hysteresis and A5 TTT. Once MG is activated, evaluation of the source as well as the neighboring RSRP condition starts. UE will monitor the RSRP condition of the serving base station while keeping track of the RSRP of the neighbors on the other layer. Once the RSRP of the serving base station becomes lower than A5 Threshold1 and RSRP of the target becomes better than A5 Threshold2 with hysteresis considered, TTT will start. If the condition holds true until TTT is exhausted, an MR will be sent from UE to the serving base station which marks the start of inter-frequency HO process. A5-based HO process is illustrated in Figure 3.6

It should be noted that A3-based intra-frequency HO and A5-based inter-frequency HO can be evaluated at the same time but only the first MR event sent is considered for HO. Once UE enters the HO processing period, no other event can be triggered. Again, this approach is based on 3GPP standard HO procedure.

3.2.3 Measurement Gap Modeling

As previously mentioned, to activate inter-frequency HO, measurement gap is a pre-requisite. To model MG, several parameters are implemented within the simulator

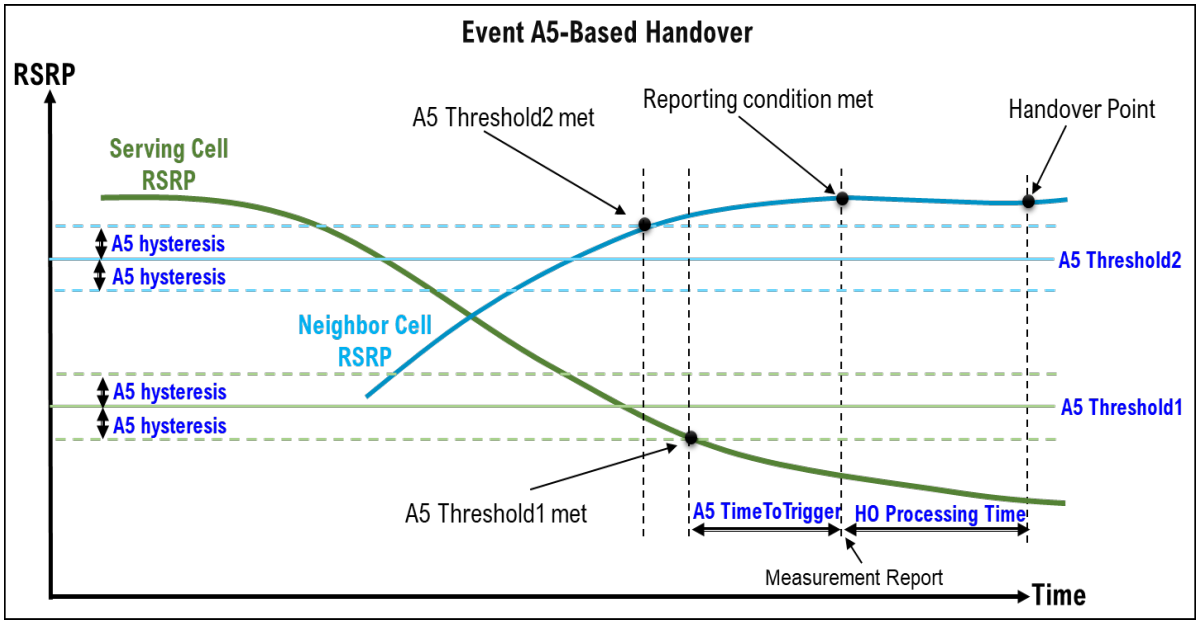


Fig. 3.6: Event A5-Based Handover

including A2 Threshold, A2 Hysteresis and A2 TTT. Aside from these parameters, pap pattern, measurement gap length and gap offset are also modeled. Figure 3.7 shows a realistic modeling of measurement gap using Event A2 as well as MG cancellation using Event A1. Once RSRP condition becomes lower than A2 Threshold taking into account A2 hysteresis, UE will wait for a certain period of A2 TTT. If the condition holds true until TTT expires, Event A2 is sent by the UE to the base station. In response, serving base station will send a command to the UE to start measurement gap. Measurement gap will not start until gap offset is exhausted. As MG is an expensive process in terms of throughput, gap offset is added to make sure measurement gap is necessary. After gap offset is exhausted and signal condition remains below A2 Threshold (i.e. Event A1 not activated), measurement gap starts.

3GPP defined 2 gap patterns UE must abide during MG namely gap pattern 0 (gp0) and gap pattern 1 (gp1). In gp0, measurement gap is done for 6ms every 40ms. On the other hand, using gp1, MG is done for a similar period of 6ms for a longer interval of 80ms. During the 6ms MG, no transmission and reception of data can be done by the UE and base stations affecting throughput performance of the network. From these gap patterns, it is apparent that using gp0 will result to

a greater number of MG compares to gp1. Inter-frequency evaluation will be more accurate as measurement is more but in expense of less throughput performance.

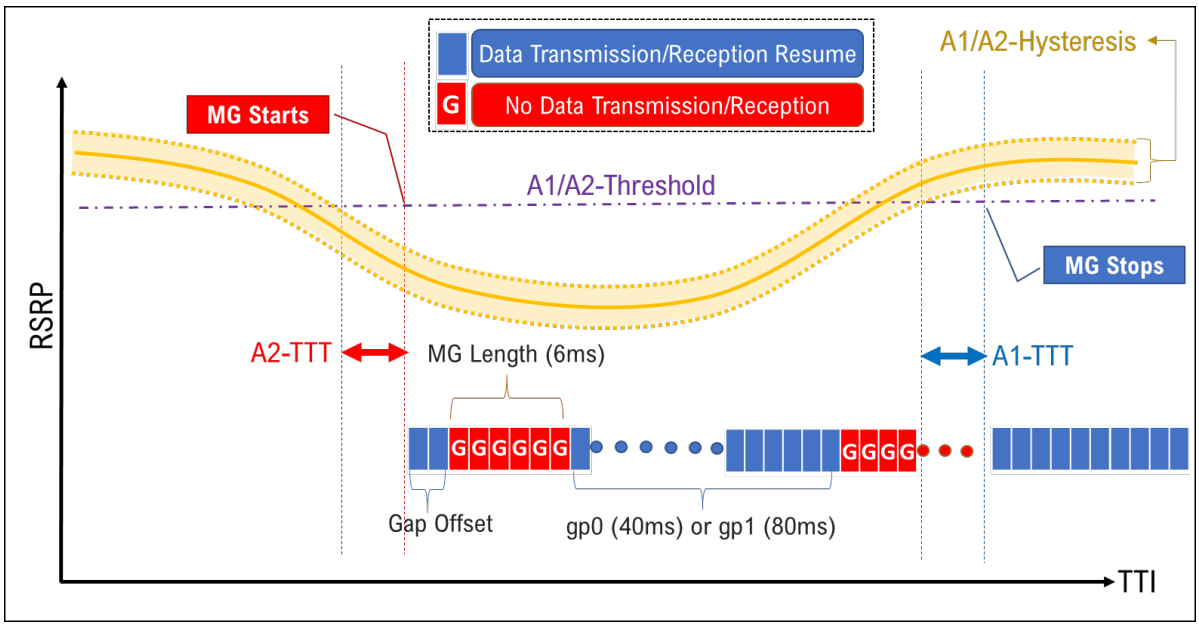


Fig. 3.7: Events A1 and A2 Measurement Gap

For instances wherein the RSRP condition of the serving base station recovers, MG is cancelled by reporting Event A1. For Event A1 to be triggered, RSRP level of the serving cell should be greater than A1 threshold with A1 hysteresis taken into account for a certain period of time defined by A2 TTT.

3.2.4 Inter-frequency Load Balancing Modeling

Though heavily researched, load balancing is still a challenge in today's cellular network. Since 3GPP left the load balancing algorithm open for innovative purposes, we have modeled the approach being used by major wireless equipment vendors. In our model, load is referred to as the Physical Resource Block (PRB) utilization of the base station expressed in percentage. PRB is the basic unit of resource allocation and scheduling both in LTE and 5G networks. PRB utilization of a base station is expressed as follows:

$$PRB_{Util} = \frac{PRB_{Alloc}}{PRB_{Total}} \times 100\% \tag{3.2}$$

where PRB_{Alloc} is the used or allocated PRBs to the users while PRB_{Total} is the total available PRB of a base station.

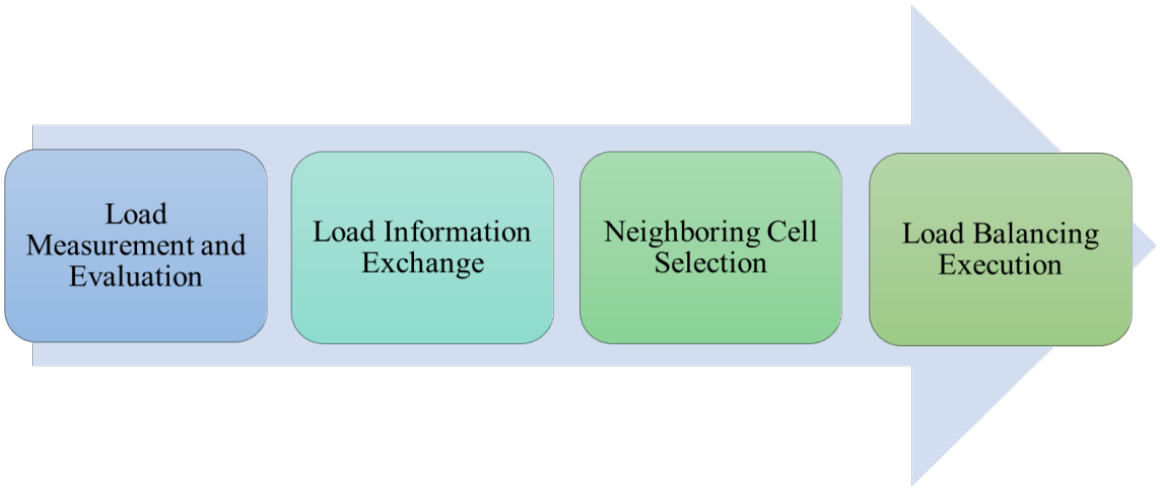


Fig. 3.8: Modeled Load Balancing Procedure

Our model of the end to end process of load balancing is composed of four steps as shown in Figure 3.8. First step in the load measurement and evaluation. At this stage, load of the serving base station is evaluated and compared to the parameter known as load balancing threshold. If the load of the serving base station goes above this threshold plus the additional load balancing offset for a certain period, load balancing is triggered. This step is followed by the second step which involves load information exchange from the source to target cells for load balancing. In this process, the source will assess its neighbors if they are suitable for load balancing. This suitability is decided by a parameter which is known as load balancing difference. This parameter is the minimum difference between the loads of two cells which triggers load balancing. Depending on the load difference threshold, the source base station will shortlist the neighboring cells which fulfill the condition given below:

$$Load_s - Load_n \geq Thres_{diff} \tag{3.3}$$

where $Load_s$ is the PRB utilization of the source base station, $Load_n$ is the PRB uti-

lization of the neighboring base station and $Thres_{diff}$ is the load difference threshold. All the neighboring cells which passes (3.2) condition will be tagged as potential target for load balancing. Selection of the target cells ends the third step and starts the fourth step. The fourth and final step is the actual load balancing execution. Source base station will decide which UEs will be offloaded depending on their PRB requirement. The maximum number of PRB/UE that can be transferred is limited for each load balancing cycle. The total number of UEs that will be moved per cycle should have a total PRB utilization expressed below:

$$PRB_{req} \leq \frac{Thres_{diff}}{2} \tag{3.4}$$

where PRB_{req} is the total PRB required by the UEs and $Thres_{diff}$ is the load difference threshold. This constraint is done to avoid potential over loading of the target cell.

Unlike coverage-based HO where Event A2 needs triggering to start inter-frequency measurement, load-based handover does not. The source base station will send a command for the users to perform MG. After MG is activated, event A4 is used to evaluate the suitability of the target base stations in terms of their signal condition. Event A4 is usually used for inter-frequency load balancing as this process gives more weight on the load than on the coverage of the target cell. Thus, there is no need to compare the signal condition of the source to target. Usually, A4 parameters are set to values which can be easily fulfilled.

To model Event A4 based inter-frequency load balancing, we have implemented A4 Threshold, A4 Hysteresis and A4 TTT. Once MG is activated, evaluation of the neighboring RSRP condition starts. UE will monitor the RSRP condition of the neighboring cells on the other layer. Once RSRP of the target becomes better than A4 Threshold with hysteresis taken into account, TTT will start. If the condition holds true until TTT is exhausted, an MR will be sent from UE to the serving base

station which marks the start of inter-frequency load balancing handover process. A4-based HO process is illustrated in Figure 3.6

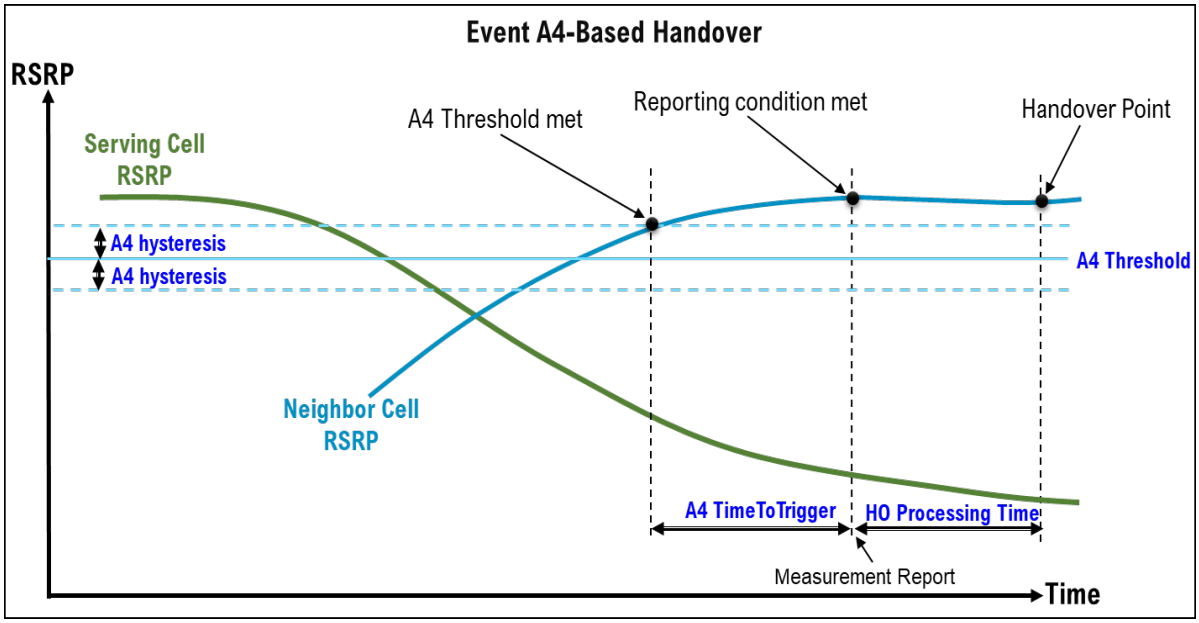


Fig. 3.9: Event A4-Based Handover

3.2.5 Radio Link Failure Modeling

To model RLF, we have used counters like N310 and N311 and timers such as T310. The quality of the DL radio link is estimated by the UE in terms of Physical Downlink Control Channel (PDCCH) BLER %. When BLER goes above a certain threshold, which is usually 10%, the counter N310 starts. This counter corresponds to the number of consecutive out-of-sync packets received by the base station. Once the set count is met, T310 is triggered. In the absence of N311, or the in-sync indicator, T310 will continue to exhaust and once expired, RLF is declared. Figure 3.10 shows an illustration of RLF declaration process.

3.3 Events Interplay

As UE can check for the entering condition of more than one event, the interplay between the events should be modeled as well. For example, the entering condition

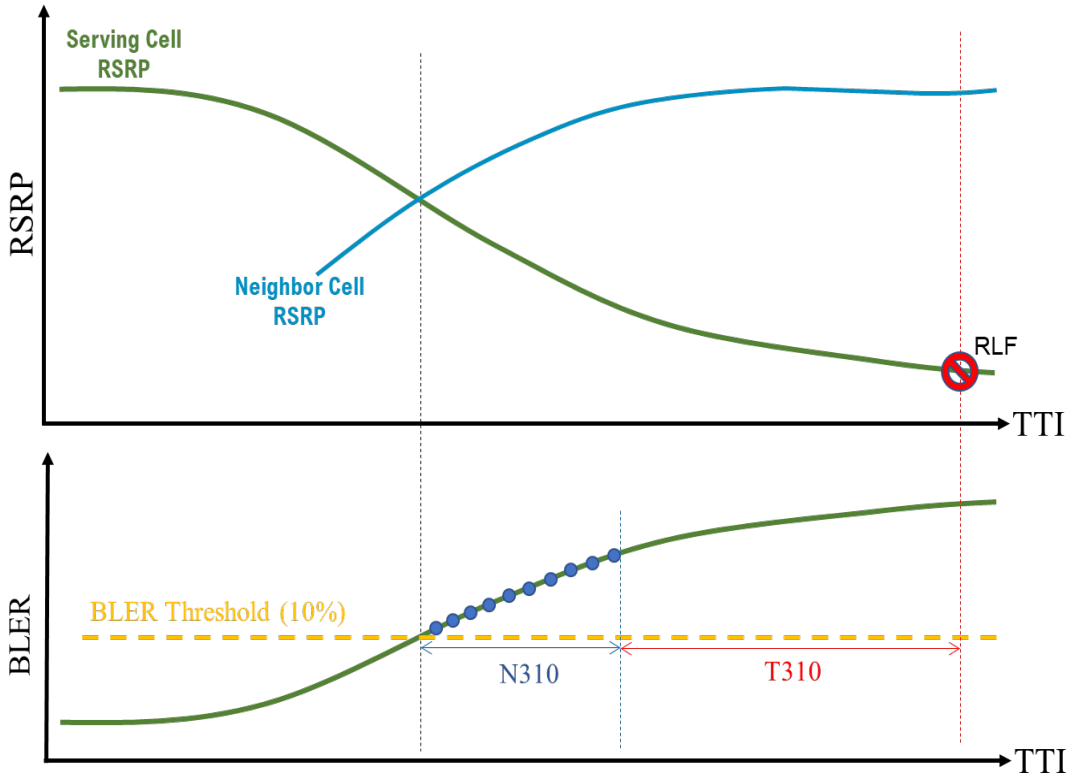


Fig. 3.10: Radio Link Failure Modeling

of more than one event involving handover might become true simultaneously or the entering condition for one event involving handover becomes true for a UE and the UE is already checking TTT for the other event involving handover. UE can only perform handover to one target BS at a time. We employ the domain knowledge of cellular networks to resolve this issue. We know that only one handover request for a UE can execute at one time instant. We use this knowledge and allow multiple events involving handover to start their respective TTT. However, the event which finishes the TTT earlier starts the HO process. As soon as the HO process for an event of a UE starts, we cancel all the other events of handover. This makes sure that only one handover is happening for a UE at a time. The flexibility of having multiple TTTs running simultaneously for a UE models the practical network. We present an example to signify this flexibility. Consider the condition of A3 is met at time instant 32ms and A3 TTT starts at this time instant. The condition of A5 is met at time instant 48ms and A4 TTT can start now. Also consider the value of A3

TTT is 128ms and the value of A5 TTT is 64ms. In this case, the A5 TTT will end at time instant 112ms while A3 TTT will end at time instant 160 ms. As A5 TTT has ended sooner than A3 TTT, the HO process for A5 will start and event A3 will be cancelled in our model. On the other hand, if we had not allowed simultaneous TTT for multiple events then event A5 would have never started. This would be wrong model as we already know that the user should do handover with event A5.

CHAPTER 4

Simulation Setup, Data Generation and Validation

In this chapter, we present the simulation setup used to test the effectiveness of our modeling process. This includes the network layout used, number of users and the values of handover parameters as well as other details related to the simulation. We then generate the data and present some examples of each modeling done. Analysis of the generated data as far as the effect of parameters to KPIs is concerned is also presented in this chapter.

4.1 Simulation Setup

A 3GPP-based simulator named SyntheticNet [22] is used to gather the data for the evaluation of handover functions and events modeling. An area of size 5km x 5km is used for the simulation. A multi-carrier network composed of 3 frequency layers is deployed inside the area. 1.7Ghz and 2.1Ghz cells are positioned co-located with each other with similar azimuth and tilt values. Meanwhile, cells operating at 3.5Ghz are placed in a random manner. Figure 4.1 shows the layout with RSRP values of the multi-carrier network used while Table 4.1 shows the base station configuration used.

Table 4.1: Base Station Configuration

Configuration	**1.7Ghz and 2.1Ghz**	**3.5Ghz**
Cell Type	Macro Cell	Small Cell
Antenna Type	Directional	Omni
Number of Cells	27 for each layer	16
Transmit Power	40dBm	30dBm
Bandwidth	10Mhz/15Mhz	20Mhz
Base Station Height	30m	20m

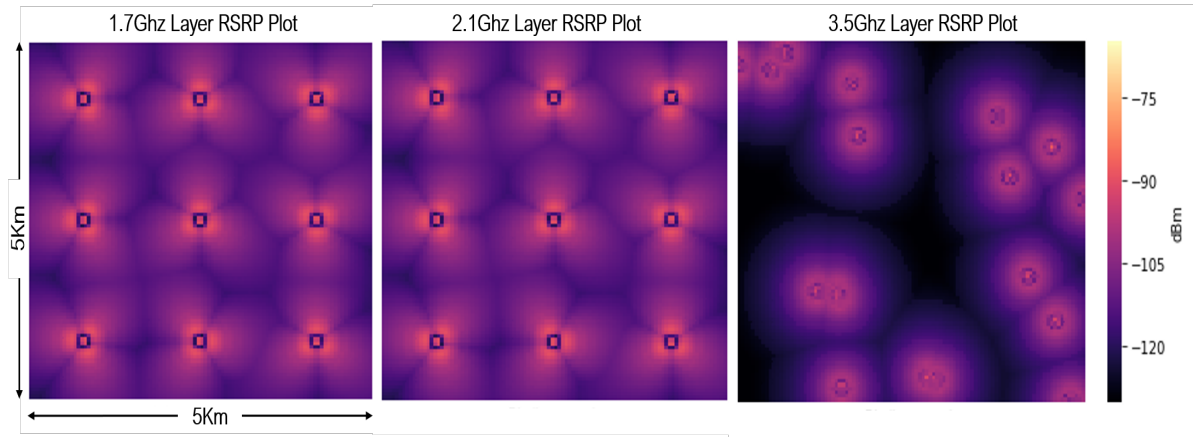


Fig. 4.1: Network Deployment Simulation

A total of 150 users are randomly distributed inside the network which are made to follow a random waypoint mobility model. Speed of the users are also assigned randomly from 60kph, 120kph and 240kph.

To maintain a fair comparison and evaluation of each handover events, initial cell selection, user mobility, and RSRP matrix are pre-generated and preserved. By doing this, each UE will select the same base station at the beginning of each simulation. In addition, mobility pattern of each user is also maintained throughout different simulations. Lastly, the level of RSRP with shadowing is put unchanged for each simulation. Aside from fair comparison, using this pre-generation method also makes the simulation run faster. Each simulation is run to accumulate data equivalent to 10 seconds with a sampling interval of 16ms.

In our simulations, we have used Event A3 for intra-frequency HO, event A5 for inter-frequency HO and event A4 for load balancing. Parameters are chosen based from Gold Standard (GS) setting of one of the leading operators in the USA shown in Table 4.2 .

In addition, to show the effect of changing handover related COPs to KPIs, we have run sets of simulations using the parameter setting shown in Table 4.3. With this simulations, we showed that our model is able to capture the expected changes in KPI performances with changes in COPs.

Table 4.2: Parameter Set Used for Simulation

Parameter	Value	Parameter	Value
Filter Coefficient	8	A5 Threshold2	-112dBm
CIO	0dB	A5 Hysteresis	1dB
A3 Offset	2dB	A5 TTT	64ms
A3 TTT	64ms	A4 Threshold	-100dBm
A3 Hysteresis	1dB	A4 Hysteresis	1dB
A1 Threshold	-110dBm	A4 TTT	64ms
A1 Hysteresis	1dB	LB Threshold	60% PRB Util.
A1 TTT	64ms	LB Offset	10% PRB Util.
A2 Threshold	-110dBm	LB Difference	15% PRB Util.
A2 Hysteresis	1dB	T310	512ms
A2 TTT	64ms	N310	16
A5 Threshold1	-112dBm	N311	16

Table 4.3: Parameter Set Used to Show Changes in KPIs with change in COPs

Parameter	Value
A3 Offset	0dB, 1dB, 2dB, 3dB, 5dB, 8dB, 12dB

4.2 Data Gathering

Using the parameter setting and base station configuration discussed on the previous subsection, simulations are run using SyntheticNet. First, pre-generation of RSRP matrix and user mobility is done. After this process, data generation started. Figure 4.2 shows a screenshot from the SyntheticNet while the simulations are running. After simulations are done, output files are generated for presentation and analysis. For each simulation, the simulator is run to gather data equivalent to 10s.

4.3 Model Validation

To validate that the models are working properly, we have presented selected users from the simulations done. For each validation, we discussed the behavior of that user and what happened that trigger the handover or handover failure. For naming of the base station, we have used the following convention: z$C - S - F$ where C is

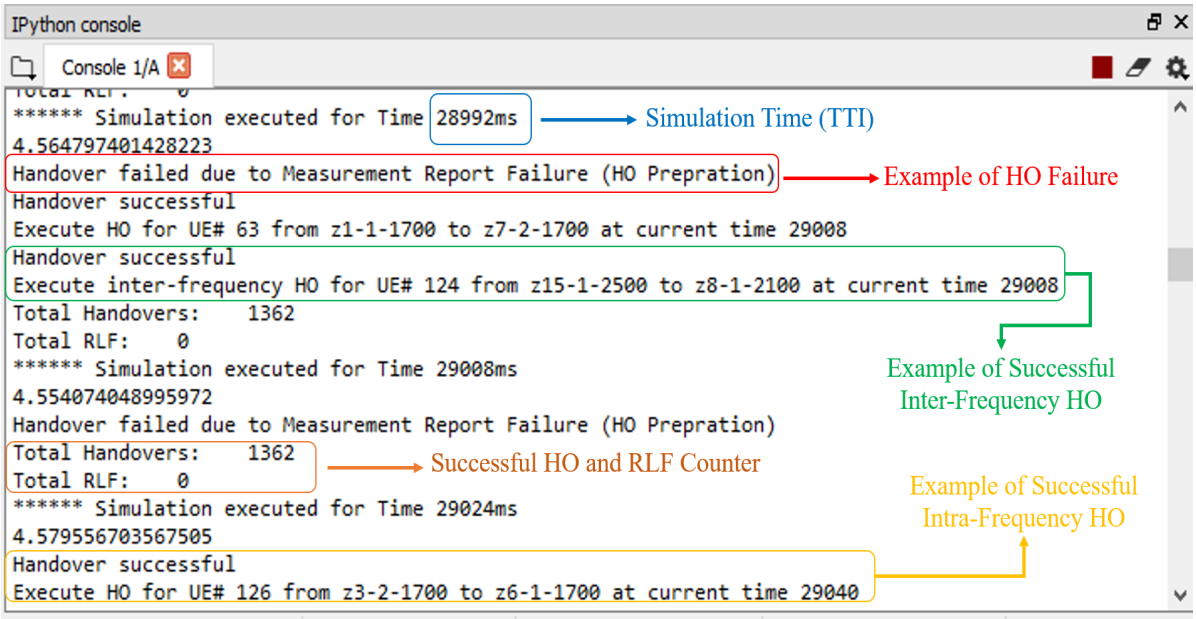


Fig. 4.2: Screenshot from SyntheticNet

the base station number, S is the sector number and F is the operating frequency. For instance, z8-1-1700 means base station number 7, sector number 1 operating in 1.7Ghz frequency.

4.3.1 Intra-frequency HO Model Validation:

Validation of the intra-frequency HO modeling is done using a visualized presentation from the generated data. An example of a successful intra-frequency handover is presented in Figure 4.3. Here, event A3 is used for with offset equal to 3dB, hysteresis 1dB, CIO of 0dB and TTT of 64ms. A user moving at a speed of 60km/h is camped on cell z2-1-1700 initially. As seen from Figure 4.3, the RSRP of the serving cell (z2-1-1700) and the neighboring cell (z2-2-1700) are very close to each other. There are several times in which the RSRP of the target base station became higher than the serving. However, HO cannot be made as other conditions such as TTT is not fulfilled. Once HOM (offset + hyst + CIO) is fulfilled and TTT lapsed while maintaining the event A3 condition to be true, handover happened and serving cell switched from z2-1-1700 to z2-2-1700. Take note that since user is moving

at 60kph, scaling factor for TTT is equal to 1.

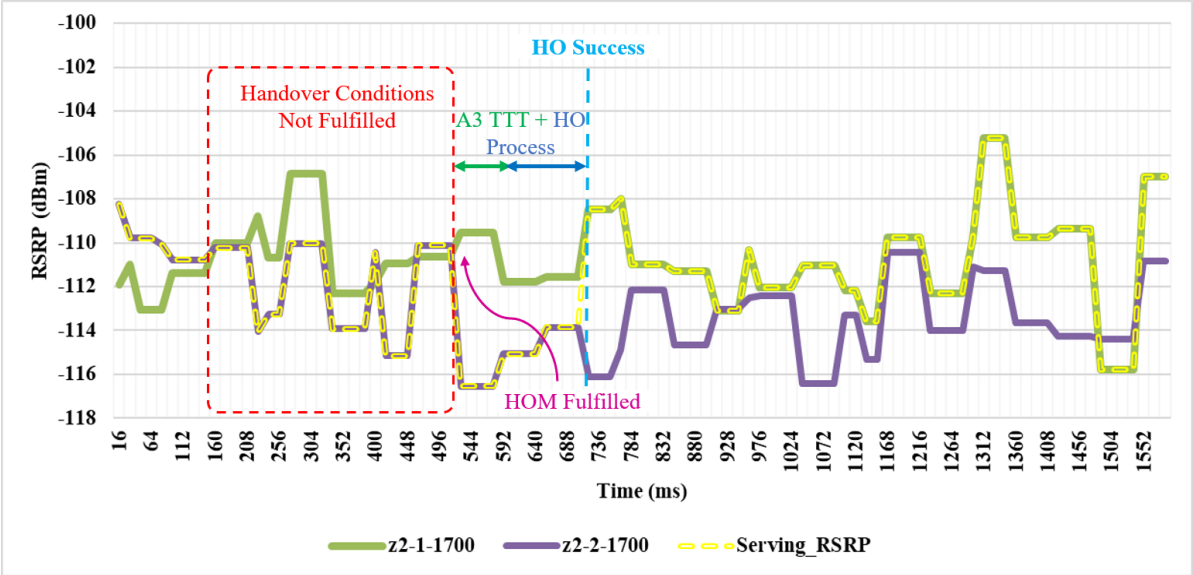


Fig. 4.3: Example of a Successful Intra-frequency Handover

4.3.2 Inter-frequency HO with Measurement Gap Model Validation:

Figure 4.4 shows a situation where there is no candidate target cell to do the handover on the same layer. It can be seen from the figure that RSRP condition of serving cell z5-1-2100 dropped at 192ms, however there is no neighboring cell on the same layer which is better than the current serving cell based from intra-frequency parameter setting. In this situation, inter-frequency HO is necessary.

Inter-frequency model validation is shown in Figure 4.5. As there is no available cell on the same layer for the UE to handover from z5-1-2100, inter-frequency HO is used. As mentioned earlier, MG is a pre-requisite of inter-frequency HO. Based from the figure, at around 48ms, A2 threshold with hysteresis considered is fulfilled. Take note that since user is moving at a of 120kph, scaling factor used is 0.50, thus reducing the TTT from 64ms to 32ms. After A2 TTT is exhausted, measurement of other layers starts. As seen from Figure 4.5, A5 Threshold 2 with hysteresis considered is fulfilled right after A2 measurement gap, where in the RSRP of the target crosses the threshold. However, as Event A5 needs two conditions to be true,

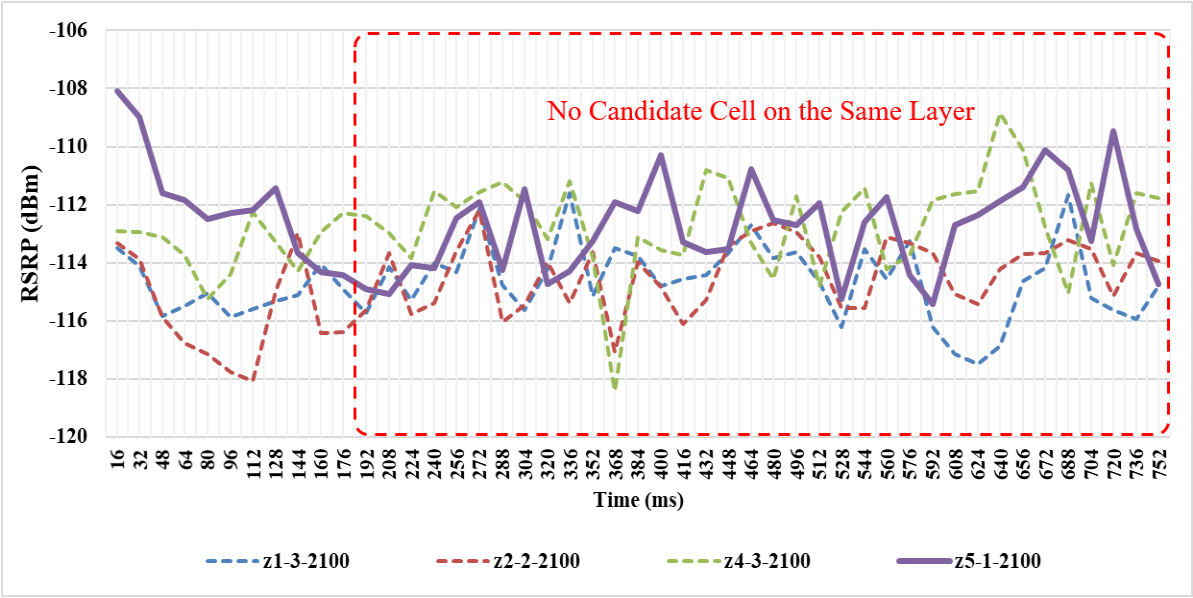


Fig. 4.4: Lacking Candidate Target Cell on Similar Layer

A5 TTT has not kicked in. At around 144ms, the RSRP of the source cell crossed A5 Threshold2. At this point, both conditions are meet and A5 TTT started. After the TTT is exhausted, MR is sent and the HO process started and at time 208ms, inter-frequency HO from 2.1Ghz layer cell z5-1-2100 to 3.5Ghz layer cell z26-1-3500.

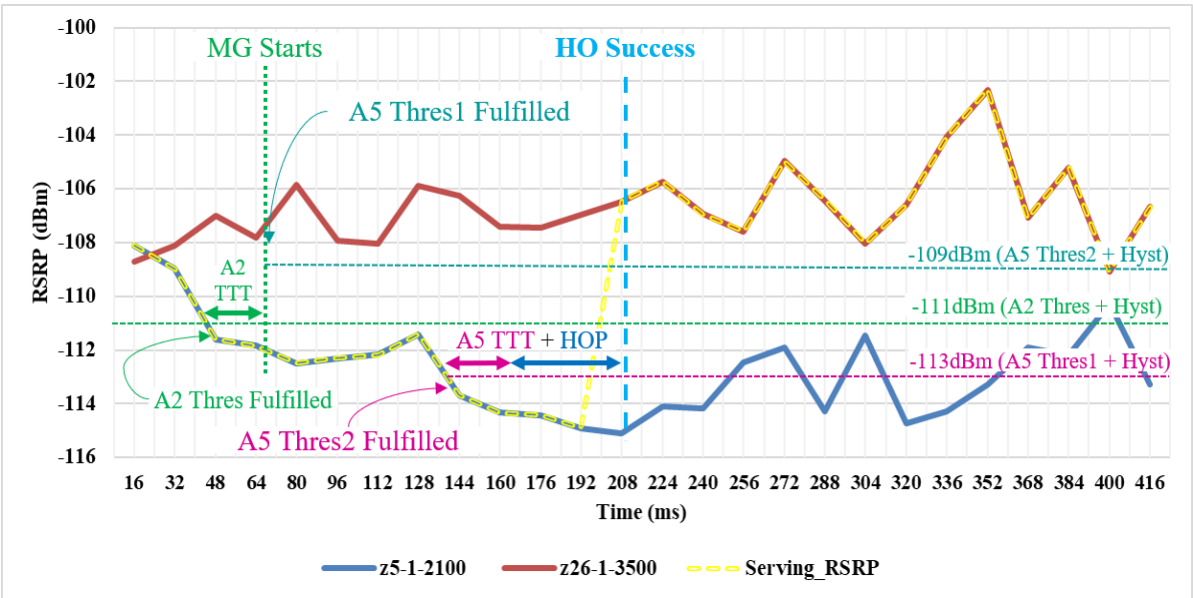


Fig. 4.5: Example of a Successful Inter-frequency Handover

4.3.3 Handover Failure Model Validation:

RSRP plot of a user camped on serving cell z7-3-2100 is shown in Figure 4.6. In this plot, we have include the strongest intra-frequency (z8-2-2100) and inter-frequency (z8-2-1700) neighbor of the serving cell. Base from the plot, at time 64ms, due to degrading RSRP, MG is triggered. However, no inter-frequency base stations are able to meet event A5 requirements. At time 240ms, the use attempted to do intra-frequency handover towards z8-2-2100, however at this point the SINR of the serving cell is already in the bad condition making the HO attempt to fail. Several more intra-frequency HOs are attempted but to no avail due to poor SINR. Even though there is a better target cell in the other layer (z8-2-1700), the user cannot perform HO to that cell because Event A3 is triggered first. This validates the events interplay discussed earlier that once an event triggered a HO process, any other events cannot be reported by the user. Finally, at 512ms, user tried to perform inter-frequency HO towards z8-2-1700. However, due to poor SINR, this HO attempt also failed.

Figure 4.6 is intended to show not only HO failure instances but also the effect of HO failures in SINR and throughput. As expected, due to handover failure to a better cell, the UE experienced poor SINR most of the time. With poor SINR also comes poor throughput performance as seen from Figure 4.6. Aside from poor SINR affecting throughput, Figure 4.6 also shows how measurement gap (MG) affects the throughput. As discussed earlier, during MG, there is no transmission or reception of data happening resulting to zero throughput.

4.3.4 Radio Link Failure Model Validation:

An example of RLF occurrence is shown in Figure 4.7. A user here is seen camped to base station z26-1-3500. However sudden drop in RSRP is noted at time 32ms. Out-of-sync started because of poor RSRP and SINR condition. Once N310 hits the

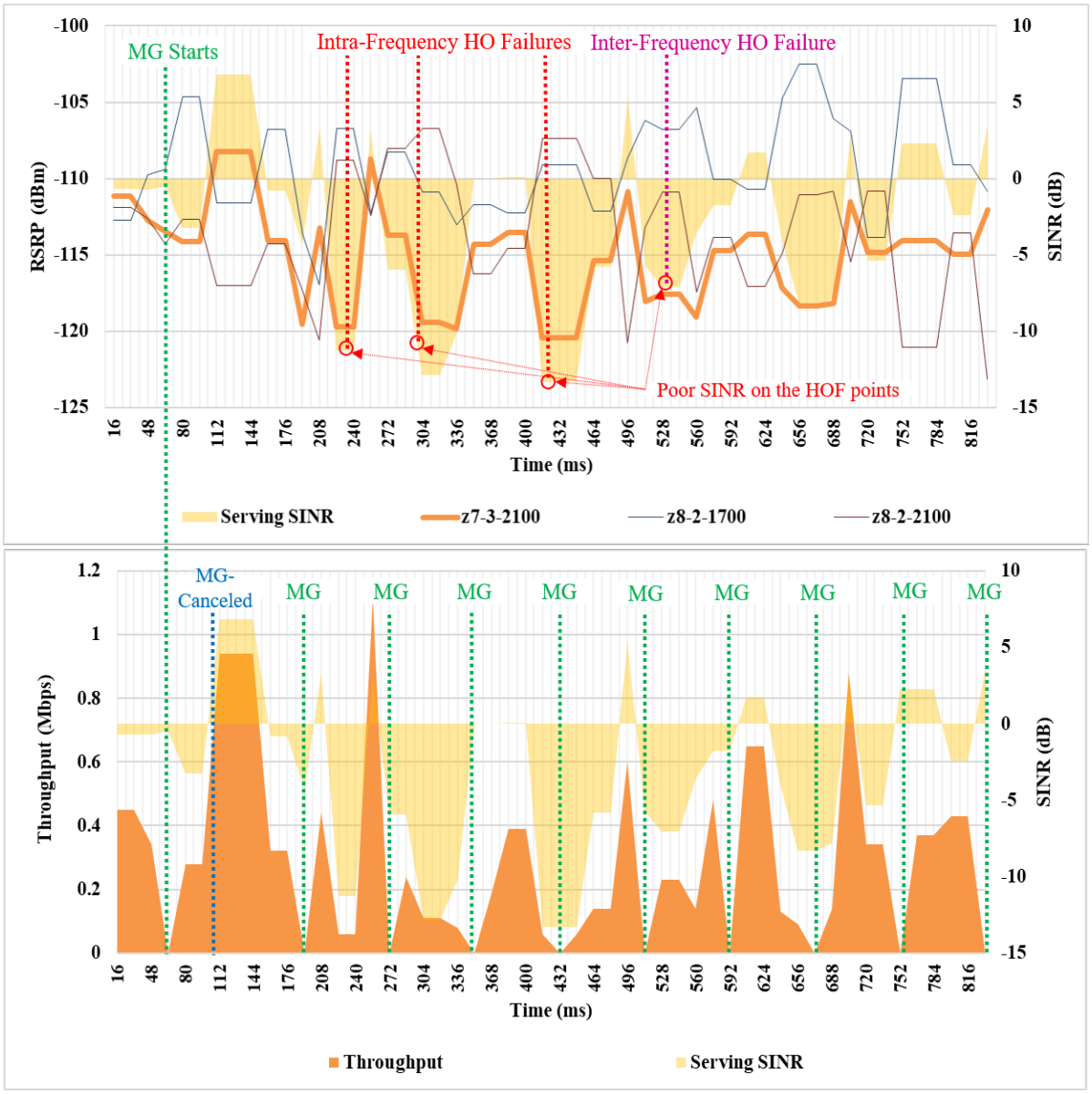


Fig. 4.6: Example of Multiple HO Failures

set amount, T310 started at around 48ms. However, unlike the example from Figure 4.6 where the RSRP and therefore SINR recovers for some time avoiding RLF, in this particular example, RSRP and SINR have not recovered for the entire duration of T310 which is set to 512ms. Thus, upon T310 exhaustion at time 512ms, RLF is declared. It is worth note taking that during this entire period before the RLF happened, UE tried to handover to better inter-frequency cells but failed multiple times due to very poor SINR condition.

After RLF is declared, UE will have to re-establish its connection to the network. We have modeled this by implementing a timer which corresponds to this re-connection period. It can be seen from the figure that this re-connection model is working properly. After this period, UE camps to the best cell in terms of RSRP, in this case to z1-3-2100.

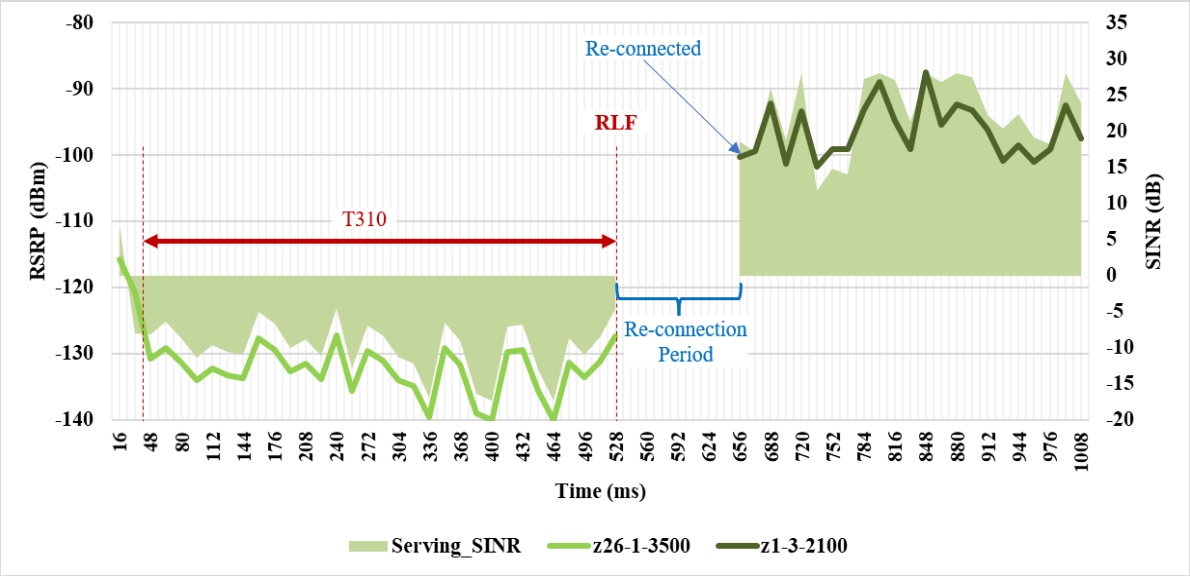


Fig. 4.7: Example of an RLF Occurrence

4.3.5 Load Balancing Model Validation:

Load balancing model validation is shown in figure 4.8. During the simulation, base station z1-2-1700 became loaded. As can be seen from the figure, starting at time 64ms, the load has already reached above the LB threshold of 75% including the 15% LB offset. Because of this, load balancing function is activated. LB process includes the time in which the loaded base station checks for target cell, choose UE to offload and perform the handover using Event A4.

In this example, target cell for load balancing happens to be z1-2-2100. This choice is logical as this cell is co-located with the loaded cell, thus their coverage area is overlapping. After some of the users moved from z1-2-1700 to z1-2-2100, it can be seen that the load of the serving base station dropped while the load of the target

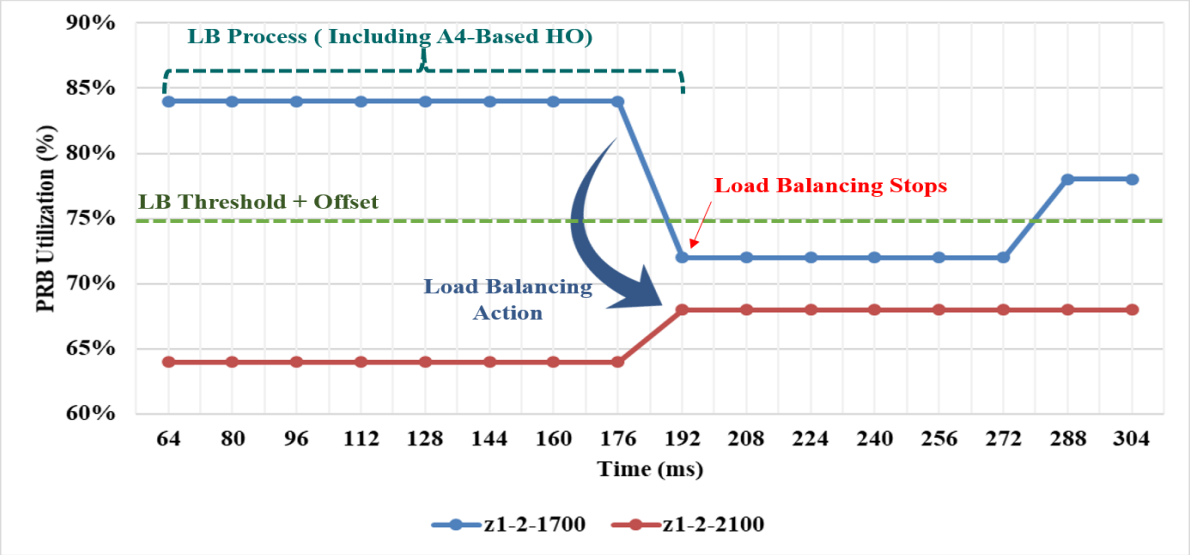


Fig. 4.8: Example of a Load Balancing Action

increased. Once the load of the serving cell goes below the LB threshold taking into account the offset, load balancing stopped. This validation shows how the load is being balanced between layers during LB process.

CHAPTER 5

Use Case: Effects of Varying COPs on KPIs

In this chapter, we site some use cases where in we presented how KPI varies with changes in COPs. This chapter aims to show that the models built are capable of generating data regarding COP-KPI relationship. Aside from that, we show how the COPs and KPIs are intertwined and to some extent show the complexity of COP-KPI relationship that is currently uninterpretable. We will show that by just changing on COP how KPI performances are greatly affected. In this use case, we have selected to vary A3 Offset and observe what will be the effect on KPIs such as HOSR, RLF rate, pingpong rate as well as effects on SINR and throughput. Other handover related parameters used are fixed based from Table 4.2.

5.0.1 Effects of Changing A3 Offset on HOSR

Figure 5.1 shows how HOSR varies with changes in A3 offset. As expected, as A3 offset increases, the lesser the intra-frequency HO numbers become. This is because the higher offset means harder to perform HO. However, not only the number of intra-frequency HOs decreased. The intra HOSR rate also decline. This decline is logical to think that the higher the A3 offset is, the stronger the interference form the target cell becomes resulting to lower SINR and thus high handover failure. One interesting observation to note is how the inter-frequency HOSR is also affected by the changes in A3 offset. It can be seen that up til 3dB of A3 offset, inter-frequency HOSR still can compensate to the declining number of intra-frequency HOs. However, at A3 offset of 5dB, even the performance of inter-frequency HO started to degrade. Results show how parameters and KPIs are intertwined with each other. For instance, we have seen that a change in parameter used for intra-

frequency HO also affects KPI of inter-frequency HO.

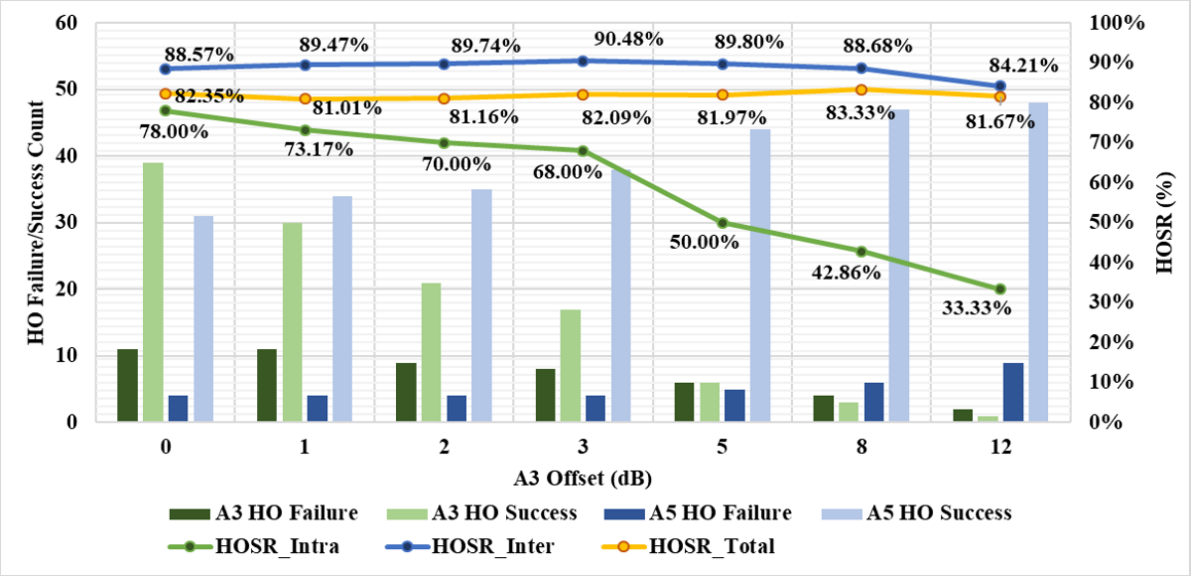


Fig. 5.1: Effect of Changing A3 Offset on HOSR

5.0.2 Effects of Changing A3 Offset on RLF and Pingpong Rate

Results shown in Figure 5.2 show how RLF rate and pingpong rate are affected by varying A3 offset value. Without this data and just by looking at the results from 5.1, one might think that A3 offset setting equal to 0dB is the optimal. However, as shown in 5.2, using a very low value of A3 offset can lead to a high pingpong rate. The higher the offset value becomes, the lower the chances of pingpong occurrence. On the other hand, RLF rate trend is totally opposite. With higher offset, RLF rate also increases. This is due to the decrease in number of HOs but the number of RLF occurrences remain constant. The data shows how complex the cellular network is, such that an optimal COP setting for one KPI, might be the worse for another.

5.0.3 Effects of Changing A3 Offset on SINR and Throughput

Unlike the effects on HOSR, RLF and pingpong which seem more predictable as they follow a pattern with changes in A3 offset values, the effect on SINR and Throughput

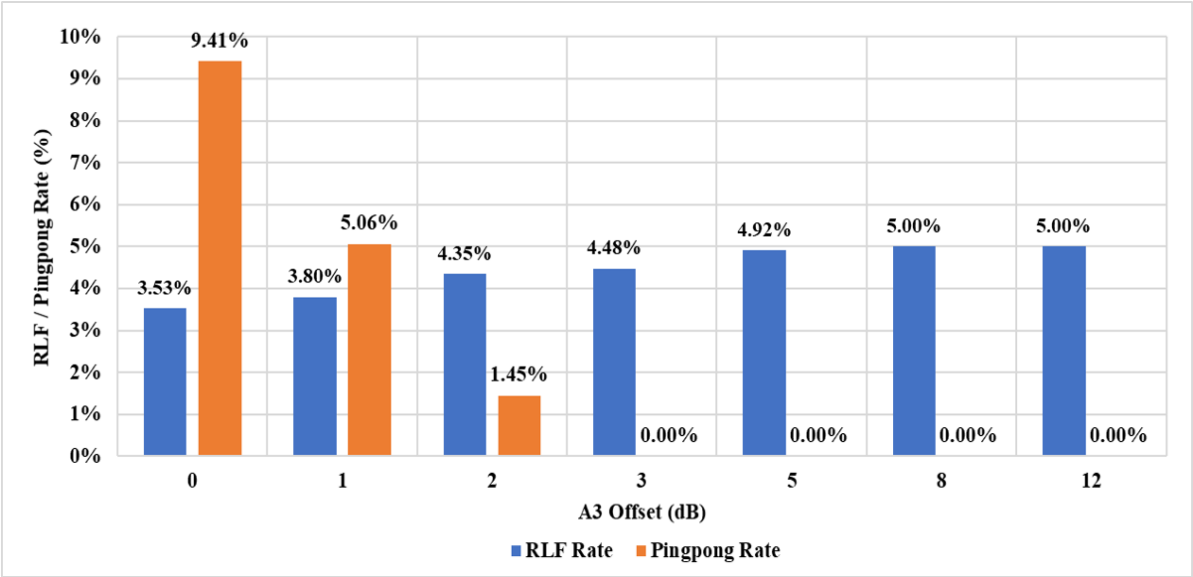


Fig. 5.2: Effect of Changing A3 Offset on RLF and Pingpong Rate

is more unpredictable. This is due to network dynamics such as resource allocation and scheduling. This dynamics in the network is very difficult to manually interpret without any aid (i.e from machine learning). The effect of varying offset in these two KPIs are more difficult to capture. Based from the results, excluding offset of 1dB, SINR and throughput started to decrease at 5dB offset. This is due to the fact that as HOs are not happening, users tend to stay under the coverage of a base station with poor SINR.

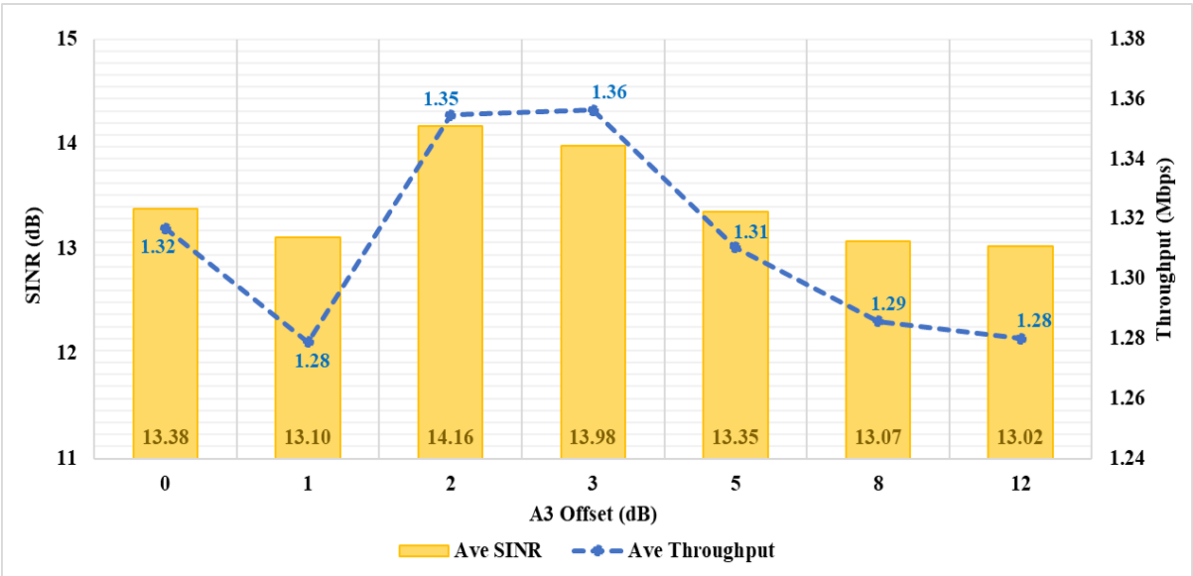


Fig. 5.3: Effect of Changing A3 Offset on SINR and Throughput

5.0.4 Summary of Results

After looking at the three results, we have shown how we can generate data containing COPs and KPIs. The results gathered from the modeling done are logical and realistic. With these results, we are able to have some intuition on how variations in COP setting affects KPI (i.e. how A3 affects HOSR). However, take note that we have only focused on a single parameter. Yet, we have seen how this single parameter affects all the KPIs that we have considered. Thus, it is difficult to imagine how to get intuition when around 5000 parameters are needed to be tuned. We have also shown some dynamics in a cellular network in the form of SINR and Throughput. This dynamicity is very difficult to catch and interpret without any aid. Network complexity and how parameters are intertwined are also shown from the results.

CHAPTER 6

Conclusion and Future Work

In this thesis paper, we have done a realistic modeling of standard handover events in LTE and 5G networks. We have modeled intra and inter-frequency HOs, Load Balancing and Radio Link Failure based from 3GPP defined standards and industry practices. We have implemented at least 27 handover parameters in a 3GPP compliant simulator. This modeling is the first step towards the creation of a representative dataset that will be able to capture COP-KPI relationship by training ML models.

We have validated the effectiveness of the modeling by showing some examples of each model using data gathered from the simulator. Moreover, a use case showing that we can generate realistic COP-KPI data is presented. Aside from that, we have shown that this approach of data generation can address some key issues related to real network data collection including: 1) Tried wide range of parameter settings which are otherwise absurd to do in a real network (i.e. 8 or 12 dB A3 Offset) due to negative impact it might bring; 2) we have gathered the data instantly without the need to wait for a long period and lastly 3) no privacy has been breached. Hence, this thesis work brings us one step closer to the ultimate goal of generating a representative COP-KPI relationship dataset for the wireless community to utilize.

For future works, we will gather a representative dataset to train Machine Learning models to capture COP-KPI relationship. Using these results, we will be able to find the optimal COP combinations which maximize the KPIs.

Bibliography

[1] W. Feng, Y. Wang, D. Lin, N. Ge, J. Lu, and S. Li, "When mmwave communications meet network densification: A scalable interference coordination perspective," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 7, pp. 1459–1471, 2017.

[2] M. Mollel, M. Ozturk, M. Kisangiri, S. Kaijage, O. Onireti, M. A. Imran, and Q. H. Abbasi, "Handover management in dense networks with coverage prediction from sparse networks," in *2019 IEEE Wireless Communications and Networking Conference Workshop (WCNCW)*, 2019, pp. 1–6.

[3] B. Zhang, W. Qi, and J. Zhang, "An energy efficiency and ping-pong handover ratio optimization in two-tier heterogeneous networks," in *2018 IEEE 8th Annual Computing and Communication Workshop and Conference (CCWC)*, 2018, pp. 532–536.

[4] D. V. Zavyalova, M. L. Rolich, and A. V. Andreev, "Definition the optimal parameters of handover procedures in lte networks," in *2016 17th International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices (EDM)*, 2016, pp. 110–113.

[5] A. Imran, A. Zoha, and A. Abu-Dayya, "Challenges in 5g: how to empower son with big data for enabling 5g," *IEEE Network*, vol. 28, no. 6, pp. 27–33, 2014.

[6] A. Galindo-Serrano and L. Giupponi, "Self-organized femto-to-macro interference coordination with partial information," in *2013 IEEE 24th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC Workshops)*, 2013, pp. 111–116.

[7] J. G. Andrews, S. Singh, Q. Ye, X. Lin, and H. S. Dhillon, "An overview of load balancing in hetnets: old myths and open problems," *IEEE Wireless Communications*, vol. 21, no. 2, pp. 18–25, 2014.

[8] U. S. Hashmi, A. Rudrapatna, Z. Zhao, M. Rozwadowski, J. Kang, R. Wuppalapati, and A. Imran, "Towards real-time user qoe assessment via machine learning on lte network data," in *2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall)*, 2019, pp. 1–7.

[9] H. Gebrie, H. Farooq, and A. Imran, "What machine learning predictor performs best for mobility prediction in cellular networks?" in *2019 IEEE International Conference on Communications Workshops (ICC Workshops)*, 2019, pp. 1–6.

[10] B. Hughes, S. Bothe, H. Farooq, and A. Imran, "Generative adversarial learning for machine learning empowered self organizing 5g networks," in *2019 International Conference on Computing, Networking and Communications (ICNC)*, 2019, pp. 282–286.

[11] O. Onireti, A. Imran, and M. A. Imran, "Coverage, capacity, and energy efficiency analysis in the uplink of mmwave cellular networks," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 5, pp. 3982–3997, 2018.

[12] U. Masood, H. Farooq, and A. Imran, "A machine learning based 3d propagation model for intelligent future cellular networks," in *2019 IEEE Global Communications Conference (GLOBECOM)*, 2019, pp. 1–6.

[13] Y. Yang, Y. Li, K. Li, S. Zhao, R. Chen, J. Wang, and S. Ci, "Decco: Deep-learning enabled coverage and capacity optimization for massive mimo systems," *IEEE Access*, vol. 6, pp. 23 361–23 371, 2018.

[14] M. Manalastas, H. Farooq, S. M. Asad Zaidi, and A. Imran, "Where to go next?: A realistic evaluation of ai-assisted mobility predictors for hetnets," in *2020 IEEE 17th Annual Consumer Communications Networking Conference (CCNC)*, 2020, pp. 1–6.

[15] J. Deng, W. Dong, R. Socher, L. Li, Kai Li, and Li Fei-Fei, "Imagenet: A large-scale hierarchical image database," in *2009 IEEE Conference on Computer Vision and Pattern Recognition*, 2009, pp. 248–255.

[16] Y. LeCun, "The mnist database of handwritten digits," 1998. [Online]. Available: http://yann.lecun.com/exdb/mnist/

[17] Matlab, "Why Use MATLAB and Simulink for 5G?" Tech. Rep. [Online]. Available: https://www.mathworks.com/solutions/wireless-communications/5g.html

[18] ns 3, "mmWave Cellular Network Simulator," Tech. Rep. [Online]. Available: https://omnetpp.org/

[19] OMNeT++, "OMNeT++: Discrete Event Simulator," Tech. Rep. [Online]. Available: https://apps.nsnam.org/app/mmwave/

[20] OPNET, "OPNET: Optimum Network Performance," Tech. Rep. [Online]. Available: https://www.openairinterface.org/

[21] OpenAirInterface, "OpenAirInterface: 5G Software Alliance for Democratising Wireless Innovation," Tech. Rep. [Online]. Available: http://opnetprojects.com/opnet-simulator/

[22] A. Zaidi, M. Manalastas, H. Farooq, and A. Imran, "Syntheticnet: A 3gpp compliant simulator for ai enabled 5g and beyond," *IEEE Access*, 2020.

[23] Yanbin Yuan, Muqing Wu, and Ziqing Chen, "A study of algorithm for lte intra-frequency handover," *International Conference on Computer Science and Service System (CSSS)*, 2011.

[24] Hendrawan, Ayu Rosyida Zain, and Sri Lestari Harja, "Performance evaluation of a2-a4-rsrq and a3-rsrp handover algorithms in lte network," *Jurnal Elektronika dan Telekomunikasi (JET)*, vol. 19, no. 2, pp. 64–374, Dec 2019.

[25] J. C. Chaparro-Marroquín, "Comparison between measurement events for lte handover in rural and urban scenarios involving femto-cell deployment," *Latest Trends on Communications*, 2014.

[26] Tarciana C. de B. Guerra, Ycaro R. Dantas, and Vicente A. de Sousa Jr., "Performance analysis of handover strategies in the 3gpp small cell scenario," *International Conference on Computational Science and Computational Intelligence*, 2017.

[27] P. Legg, G. Hui, and J. Johansson, "A simulation study of LTE intra-frequency handover performance," in *2010 IEEE 72nd Vehicular Technology Conference-Fall*. IEEE, 2010, pp. 1–5.

[28] L. C. Gimenez, S. Barbera, M. Polignano, K. I. Pedersen, J. Elling, and M. Sorensen, "Validation of mobility simulations via measurement drive tests in an operational network," in *2015 IEEE 81st Vehicular Technology Conference (VTC Spring)*. IEEE, 2015, pp. 1–5.

[29] Konstantinos Alexandris, Navid Nikaein, Raymond Knopp, and Christian Bonnet, "Analyzing x2 handover in lte/lte-a," *International Workshop on Wireless Network Measurements and Experimentation*, 2016.

[30] "3gpp ts 36.423: "evolved universal terrestrial radio access network (e-utran); x2 application protocol (x2ap)."."

[31] "AI4Networks Research Center, University of Oklahoma Tulsa." [Online]. Available: http://bsonlab.com/

[32] J. Shodamola, U. Masood, M. Manalastas, and A. Imran, "A machine learning based framework for kpi maximization in emerging networksusing mobility parameters," *2020 IEEE BlackSeaCom.*

[33] "3gpp ts 36.331: "evolved universal terrestrial radio access (e-utra); radio resource control (rrc) protocol specification"."

[34] 3GPP, "Technical Report 21.915 Release 15 Description," Tech. Rep., 2019.

[35] "Fujitsu Whitepape: Enhancing LTE Cell-Edge Performance via PDCCH ICIC."

[36] M. Kawser, N. Imtiaz Bin Hamid, M. Hasan, M. Alam, and M. Rahman, "Limiting harq retransmissions in downlink for poor radio link in lte," vol. 2, 09 2012, pp. 707–709.