Dependency of Cell Size and Available Time to Trigger Handover on Satellite Height for 5G Non-Terrestrial Networks (NTN)

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Declaration

It is hereby declared that the work presented in this thesis report is the outcome of the research carried out by the candidates under the supervision of Dr. Mohammad Tawhid Kawser, Professor, Department of Electrical and Electronic Engineering, Islamic University of Technology. It is also declared that neither this thesis paper nor any part thereof has been submitted anywhere else for the reward of any degree or any judgement. Any information derived from the published and unpublished work of others has been acknowledged in the text and a list of reference is provided.

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List of Acronyms

3GPP	3rd Generation Partnership Project
5G	5th Generation
BHO	Baseline handover
CHO	Conditional handover
GEO	Geostationary earth orbit
gNB	gNodeB
HAPS	High altitude platform station
LCHO	Location based conditional handover
LEO	Low Earth Orbit
LOS	Line of sight
MEO	Middle earth orbit
MR	Measurement report
NR	New Radio
NTN	Non-Terrestrial Networks
RSRP	Reference signal received power
TN	Terrestrial Networks
TTT	TimeToTrigger
UAS	Unmanned aircraft systems
UE	User equipment
UHO	Unnecessary handover

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Abstract

Advancements in satellite technologies have made 5G integration in satellite networks more plausible than ever before. Especially, LEO satellite based networks are most potent for 5G integration as LEO systems offer smaller latency and low cost. This integration of LEO satellites and 5G network is known as 5G LEO non-terrestrial network (NTN). But 5G LEO NTN comes with various challenges among them, the high mobility of the LEO satellites is a key issue. It affects various mechanisms of the network. Current 5G specifications which are designed for terrestrial systems is not always suitable for LEO based 5G NTN. One of the key affected areas is handover. High mobility of the satellites require frequent and robust handover. But just fast handover leads to unnecessary frequent handovers which creates a massive problem for the whole network. A handover parameter, TimeToTrigger can be used to mitigate the issue to an extent. But available time to trigger handover for a specific scenario is not so easily determined. So, the work presented in this paper, proposes an empirical formula to calculate optimal TimeToTrigger for a given satellite altitude without the need to go through extensive simulation. Additionally, another empirical expression is derived for cell radius to simplify cell radius calculation. The equations essentially demonstrates the dependency of TimeToTrigger and cell radius on satellite height.

Chapter 1

Introduction

The fifth generation (5G) standard has revolutionized wireless communication. One of its key features, seamless global connectivity [1] is not yet realized in current cellular deployments. 5G Satellite networks may enable this but these systems come with their own unique challenges.

1.1 Background and Motivation

The world is more connected than ever before. But only 66 percent of the global populace is connected to the internet [2]. So, there are 2.7 billion people who are still not connected mainly because of lack of network infrastructure. In some areas, terrestrial cellular networks are not that reliable and are prone to natural calamity.

Satellites are able to give global network coverage as they are not limited to geographical constraints. Specially, Low Earth Orbit (LEO) satellites can be a cost-effective solution to complement terrestrial networks (TN). Private space corporations such as SpaceX and OneWeb has already deployed hundreds of LEO satellites for providing broadband internet from space [3]. SpaceX has already deployed 4408 LEO satellites to orbit [4] and OneWeb has deployed 618 satellites [5] in their LEO satellite constellation. These constellations can complement TNs to ensure global coverage.

3rd generation partnership project (3GPP), the consortium that have developed different cellular technologies including 5G, are working to integrate satellite systems with 5G. This led to the recent rise in interest in 5G LEO Non-Terrestrial Networks (NTN) as LEO systems offer the lowest latency and cost efficacy. But LEO satellites have high velocity which poses a challenge to 5G mobility management. Current 5G handover (HO) mechanisms which are designed for TNs are not up to the mark to deal with this high mobility. Several enhancements to conditional handover (CHO) have been proposed to solve this handover problem. But faster HO leads to frequent unnecessary handovers (UHO) or pingpongs. An optimal TimeToTrigger (TTT) may reduce UHOs. This work is motivated from this that is the work aims to find the dependency of TimeToTrigger on one of the key satellite parameters, altitude of the satellite with the goal to simplify TimeToTrigger calculation and reduce the necessity of extra simulation.

1.2 Literature Review

Following the introduction of the 5G standard, the academic community, the satellite industry, and telecommunications firms have all shown an upward trend in interest and involvement in integrated satellite and TN architecture. But research in HO and LEO satellite networks has been going on since 1990s which were initiated by LEO satellite projects such as Iridium and Globalstar [6]. These studies discussed different LEO satellite HO scenarios and schemes [7,8] based on existing technology. With the fall of the Iridium project due to high deployment and operation costs and technological challenges [9], research in this field shrunk.

Researches on the topic resumed when some private corporations such as SpaceX and OneWeb launched their projects. Studies introduced some new mechanism such as game theory based inter-satellite HO system to reduce UHO events but this led to high overhead on the UE [10]. In [11], the authors proposed a deep reinforcement learning based method where UE could take autonomous HO decisions optimizing throughput but this faces the same problem as the scheme proposed in [10]. In [12], the researchers proposed a forecasting-based HO method for LEO, GEO and HAPS integrated multi layered network. In order to increase throughput, the authors of [13] proposed a user centric HO by buffering same user data on several satellites. A HO solution based on graph-based framework was proposed in [14]. But these works neither focus on 5G NTN nor did maintain any 3GPP specifications.

After the release of 3GPP Technical Report 38.811 of release 15, where 5G satellite integration was first reported by 3GPP [15], some researches focused on finding a robust HO mechanism for 5G NTN. The authors of [16] showed the shortcomings of conventional 5G TN baseline handover (BHO). In 3GPP release 16, conditional handover (CHO) is proposed for 5G LEO NTN [17]. In [18], the authors analyzed performance of CHO and found that CHO can enable stable connections but increases unnecessary handovers (UHO) by 60%. The same researchers then proposed enhancements to CHO such as location based conditional handover (LCHO) which utilizes the known trajectory of LEO satellites [19]. In [20], they analyzed and compared existing handover schemes and proposed antenna gain based handover (AGHO) for 5G LEO satellite networks. LCHO and AGHO are new HO mechanisms which is not compatible to 5G yet. In [21], it is suggested to continue considering enhancements to CHO and to keep legacy triggers like TimeToTrigger for predictable performance. TimeToTrigger is still important for reducing pingpongs as CHO suffers badly from UHOs [18]. In light of these, we have analyzed the dependency of TimeToTrigger on satellite height and found a way to relate with tolerable power drops while reducing UHO events.

1.3 Thesis Objectives

This work aims to simplify available TimeToTrigger calculation for CHO in 5G LEO Non-Terrestrial Networks (NTN). In order to reach the goal, the objectives are-

- Simulating intra-satellite HO scenario for 5G LEO NTN
- Analyzing variation in cell sizes for different cell edge power drops
- Analyzing available TimeToTrigger for various tolerable power drops
- Finding dependency of cell size and available TimeToTrigger on satellite altitude
- Deriving empirical equations for TimeToTrigger and cell radius calculation.

1.4 Thesis Outline

There are seven chapters total in this dissertation, including this one. This chapter introduces the thesis topic and conducted work. The following chapters cover several facets of the thesis and as well as the research's findings and future work. Following is a breakdown of the chapters:

Chapter 1: Introduction

This chapter gives a brief description of the study. It discusses existing works and puts forward the objective and an overall outline for the thesis.

Chapter 2: Overview of 5G Non-Terrestrial Networks

This chapter discusses the history of satellite network systems as well as different categories of satellites. It also discusses use of 5G standards in non-terrestrial networks and low earth orbit satellite networks.

Chapter 3: Handover in 5G LEO Non-Terrestrial Networks

Introduces different currently used mobility solutions and challenges faced due to the high speed satellites. It further discusses the procedures and parameters of some handover solutions.

Chapter 4: Methodology

Discusses the complete thesis methodology in details that is it provides some insight into the simulation model and important parameters.

Chapter 5: Simulation

Introduces all the parameters used in the simulations and presents the results. TimeToTrigger and cell radius vs altitude plots are presented in this chapter

Chapter 6: Proposed Empirical Relationship

States and discusses the established empirical equations for TimeToTrigger and cell radius.

Chapter 7: Results and Discussion

Discusses the results achieved from the simulations. Detailed validation for the empirical equations is presented here.

Chapter 8: Conclusion

Summarizes the findings from the study and discusses further research opportunities.

Chapter 2

Overview of 5G Non-Terrestrial Networks

2.1 History of Satellite Mobile Communication

Although 5G NTN is a recent concept but the idea of satellite mobile communication is decades older. In fact satellite communication precedes cellular communication by several decades [22]. These older communications satellites were placed in geostationary earth orbit (GEO) which caused high latency and high cost in terms of launching and maintaining [23]. At the initial phase of cellular services, the network was not that reliable and coverage was scarce and limited to cities but within a decade cellular networks became robust and reliable resulting in widespread use. Iridium launched its LEO constellation around 1998 [24] for satellite mobile communication but by that time terrestrial network has become cheap and reliable and this lead to the failure of LEO communication satellite projects such as Iridium and Globalstar [25]. For the next decade, there was almost no corporate projects in this topic but the academia took interest in it which lead to further research on this topic.

2.2 5G Non-Terrestrial Networks

Non-terrestrial network (NTN) means a network consisting of non-terrestrial equipment such as satellites and high altitude platform station (HAPS) or unmanned aircraft systems (UAS). 5G NTN refers to using 5G standards in a NTN that is RF resources on board a satellite is used for 5G network.

By the start of 2020s, satellite launch and operation cost reduced significantly due to technological advancements. This with the lack of 5G global coverage, 3GPP in release 15 discussed the possibility of 5G NTN and their studies led to an introduction to 5G NR integration with NTN [15].

A satellite can be based on transparent payload or regenerative payload that is it can either work as a network gateway or as a base station (gNB). In this paper, whenever we will be referring to 5G NTN, we will be considering regenerative payload that is a satellite with all the base station (gNB) capabilities.

A typical NTN scenario is shown in the following figure. In case of 5G NTN, this individual satellites will be connected to 5G core network (CN) though satellite gateways and inter-satellite links (ISL).

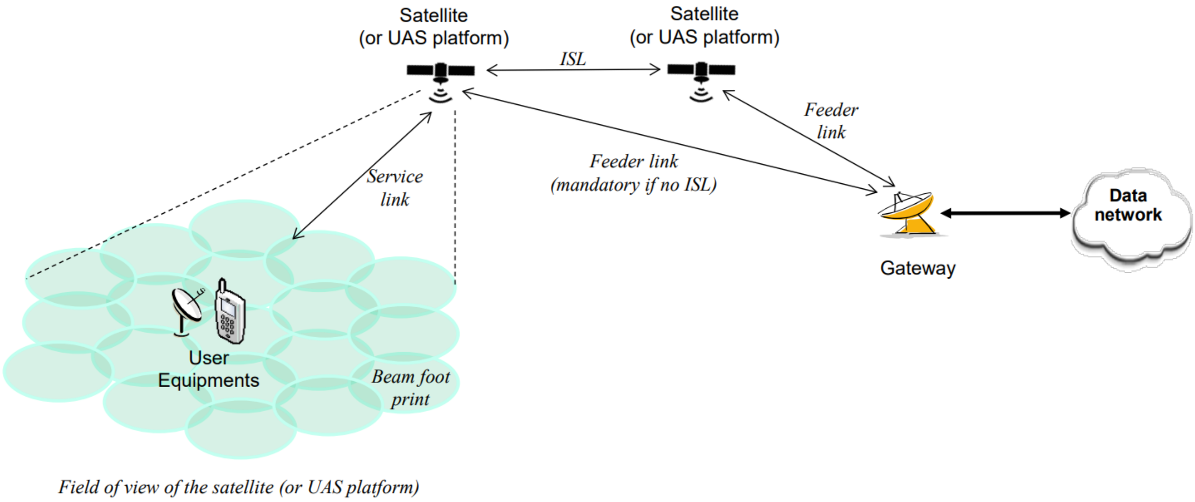

Figure 2.1: Typical non-terrestrial network [15]

2.3 Satellite Categories

There are mainly three types of satellites based on their orbit i.e., distance from the earth. They are GEO, MEO and LEO satellites.

2.3.1 GEO Satellites

Geostationary earth orbit or GEO satellites are satellites which are deployed on the geostationary orbit that is at a distance of 35786 km from earth. This orbit is known as geostationary because the orbital period is 24 hours that is equal to the earth's rotation period along its own axis. As a result, the GEO satellites are located to fixed position from the ground. They are also the furthest communication satellites from the earth which results in increased latency. GEO satellites can cover a huge area as can be seen from figure 2.2.

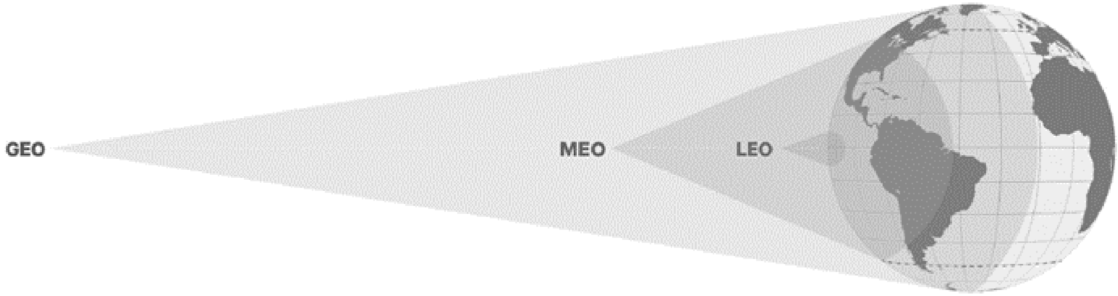

Figure 2.2: Comparison among GEO, MEO and LEO satellites [26]

2.3.2 MEO Satellites

Middle earth orbit satellites rotate around the earth on circular orbits at an altitude of 5000 to 25000 km. They can cover smaller area than GEO and are not stationary relative to the ground. They are seldom used in communication.

2.3.3 LEO Satellites

Low earth orbit or LEO satellites are closest to the earth's surface. They orbit the planet at an altitude of 600 km to 1200km. Their low distance offers lower latency which can be comparable to TNs. LEO satellites are usually smaller in size and moves very fast relative to the ground. They can only cover a small area as their beam footprint size is very small below 1000 km.

Table 2.1 Comparison between GEO and LEO satellite systems [17]

Parameters	GEO Satellite	LEO Satellite
Altitude	35786 km	600-1200 km
Velocity (relative to ground)	0 km	7.5 -7.1 km/s
Typical Beam Footprint size	200-3500 km	100-1000 km
Minimum Round Trip Delay	270.73 ms	12.89 ms

2.4 5G LEO Satellite Networks

When 5G NTN is implemented through LEO satellite networks, it is then referred to as 5G LEO satellite networks or simply 5G LEO NTN. LEO satellites remain closer to the ground as a result signal roundtrip latency is low compared to GEO and MEO systems. This makes LEO systems more capable of 5G integration as low latency is one of the key features of 5G NR. LEO satellites have smaller beam footprint that is smaller coverage area due to low altitude. Also they are very fast, a satellite does not stay at an area for more than a few seconds. So, they need to be deployed in a constellation in order to cover even a smaller area. But their low deployment cost can enable huge LEO constellation such as Starlink from SpaceX.

5G LEO NTN will be able to give global coverage through LEO constellations. As it is a NTN, it will not suffer from damage due to natural disaster. So, 5G LEO networks will be able to give network coverage to disaster prone area and help save lives after a natural calamity. Unlike satellite mobile communication systems like Iridium, 5G LEO NTN will be available for anyone as it will support any device which already supports 5G. Network coverage of 5G is still very poor but 5G LEO NTN will enable a global coverage and benefits of 5G to remotest places on earth.

2.4.1 Earth Moving Cells

A satellite does not transmit its signal uniformly rather it concentrates its signal power to a limited area which is known as a spotbeam or satellite beam. These beams are comparable to cells in TNs. As a LEO satellite moves at a very high speed, its beams also moves with it. In another words, the network cells are moving at a high speed. These cells are known as earth moving cells as the beam footprint is moving on the ground. In case of earth moving cells, the location of the cells are not fixed rather the cell changes location frequently.

2.4.2 Earth Fixed Cells

Unlike earth moving cells, in earth fixed cells, the location of the cells are fixed on the earth, In this case, different satellite beams and eventually different satellites give coverage to that specific cell. This can also be achieved by satellites with steerable beams. Earth fixed cells are not studied elaborately yet. In this paper, earth moving cells will be the default mechanism for 5G LEO NTN.

Chapter 3

Handover in 5G LEO Non-Terrestrial Networks

3.1 Mobility in 5G LEO NTN

LEO systems are thought of as an economically viable means to supplement TN and increase the 5G coverage for their lower cost of deployment than GEO satellites. These LEO satellites has to move very fast at speeds around 7.5 km/s to stay on orbit. So, a single satellite or satellite beam cannot give coverage to a certain location for more than a few seconds. In case of 5G NTN, LEO satellites are the gNBs, so, in this case, the gNBs are highly mobile. But 5G NR technologies are designed for fixed gNBs for terrestrial networks. And in case of 5G TN, the distance between a gNB and UE is not more than several kilometers. LEO satellites are closer than GEO satellites but still at a distance of 600 km which is nowhere comparable to TNs. So, the existing 5G standards for TNs may not be suitable for LEO NTN. In 5G LEO NTN, the gNB is mobile, so UE needs to connect to a different gNB after a short time, that is frequent handover (HO) is important for continuous service.

3.2 Challenges in High Mobility

LEO satellites has high mobility (speeds of around 7.5 km/s) which introduces a new problem that is the UE needs to switch to a new satellite beam or satellite very frequently. This is a challenge in of itself as 5G TN does not normally have this issue. Some of the challenges caused by LEO networks is mentioned in the following:

- LEO satellites move at very high speeds. In this case the base station is moving constantly. Unlike TN, where the mobility is due to the movement of UE, in LEO based NTN, mobility is caused by the highly mobile satellites or base stations.
- In case of TN, the cell size is specified not more than 10 km but in NTN it is 100 km. The satellites are also very far away at least 600 km from the UE.
- Radio channel condition can vary significantly. The distance between the transmitter and receiver is very high as well as line-of-sight (LOS) with the satellite will not be available all the time resulting in signal attenuations.

- Round trip delay in LEO systems is very low (12.89 ms) compared to GEO but still very high compared to TN (0.03 ms). This delay can also increase with the movement of the satellite resulting in measurement challenges.
- A satellite has several spotbeams which is considered as individual cells in 5G NTN. When used with frequency reuse (FR1) scheme, the signal can face interference from neighboring cells

3.3 Handover Scenarios in 5G LEO Networks

Handover is the procedure of connecting to a new cell from the serving cell in the connected state of the UE. In case of TN, handover (HO) is the procedure for UE mobility to connect from one gNodeB to another [27]. Unlike TN, in LEO NTN this mobility is caused by the mobile gNBs that is the UE need to connect to a incoming satellite beam or a new satellite performing a handover.

There can be different HO scenarios depending on the situation. A single LEO satellite has several spotbeams which are equivalent to cells. When one cell moves away from the UE it may connect to the incoming one. But eventually, all of the spotbeams of that particular satellite will move away from UE. This time the UE will be connecting to a new satellite which is basically a new gNB. Depending on these scenarios there can be several types of HO in NTN which are,

- Intra-satellite HO
- Inter-satellite HO
- Inter-RAT HO

3.3.1 Intra-satellite HO

A satellite has several beams which are equivalent to cells. So a satellite has multiple cells. But with the movement of the satellite, the cells will be moving away from a UE requiring it to connect to a neighboring cell of the same satellite. This is known as intra-satellite HO. A satellite cell may have very small area (10 km -100 km), due to the high speed of the satellites, this distance will be covered in a few seconds. This will require frequent handover. So, intra-satellite HO is the most frequent HO necessary for LEO NTN.

3.3.2 Inter-satellite HO

A LEO satellite has a fixed number of cells, comprising a circular area. As the satellite is moving, all of the cells will eventually move away from UE. This will require the UE to connect to a cell of an incoming satellite performing what is known as an inter-satellite HO. In this case, the mobility is between different gNodeBs as individual satellites have gNB capabilities.

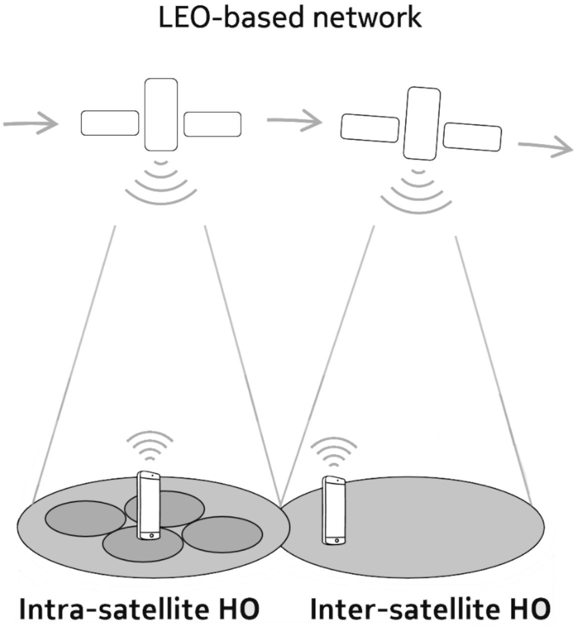

Figure 3.1: Different HO scenario for LEO NTN

3.3.3 Inter- RAT HO

Inter radio access technology (RAT) HO is the handover among different RATs that is between TN and NTN or different types of NTN. This HO will ensure seamless 5G connectivity. A UE will be able to connect to the best network based on the scenario.

In this work, intra-satellite scenario is considered as it is both the most frequent and most challenging due to fast pace of events.

3.4 Handover Mechanisms

Different HO mechanisms has been studied for 5G LEO NTN. These HO mechanisms are discussed in this section.

3.4.1 Baseline HO (BHO)

The conventional HO used in 5G NR TN is named as baseline handover or BHO [28]. This HO is based on UE measurement. When a certain measurement condition is met the handover procedure takes place. BHO is designed to deliver the optimum performance in terrestrial circumstances. When configuring the HO, variables including UE speed, wireless network deployment, propagation conditions, and system load are taken into account. BHO is event triggered and event A3 is mostly used for triggering the HO. Handover hysteresis and TimeToTrigger is also used in BHO.

BHO is a UE assisted-network controlled handover. UE measures RSRP and when event A3 is triggered that is the incoming cell is offset better than the serving cell, the UE sends a measurement report to the serving base station. Then the network gives HO decision and HO command to the UE to initialize HO. This method is not suitable for LEO NTN. As the satellites move very fast, by the time the network will send HO command the UE may disconnect due to poor RSRP resulting in HO failure. In fact BHO has failed badly for NTN in performance analysis done by researchers in [16].

3.4.2 Conditional HO (CHO)

A conditional handover (CHO) is a kind of HO where the UE performs handover when certain handover execution conditions are satisfies [28]. In CHO mechanism, the HO is performed in two major steps that is at first HO preparation is done very early even when the network quality of the serving cell is still good and reliable and then delayed until certain HO execution conditions are not met. CHO is currently recommended for 5G NTN [17].

CHO is a UE assisted-network controlled HO that is the UE still sends measurement report to the network. CHO can be described in two events, one is the handover preparation phase and another is the execution phase. At the first event, measurement report is send to the gNB as early as possible, this is similar to event triggering in BHO but with much lower value or even negative values are used for triggering this initial phase. At this phase, the gNB gives HO decision to the UE. Then the UE waits for the next event that is handover execution. UE gets the handover execution conditions in the HO command and waits for their fulfillment. Overall workflow of the CHO procedure is given in figure 3.2.

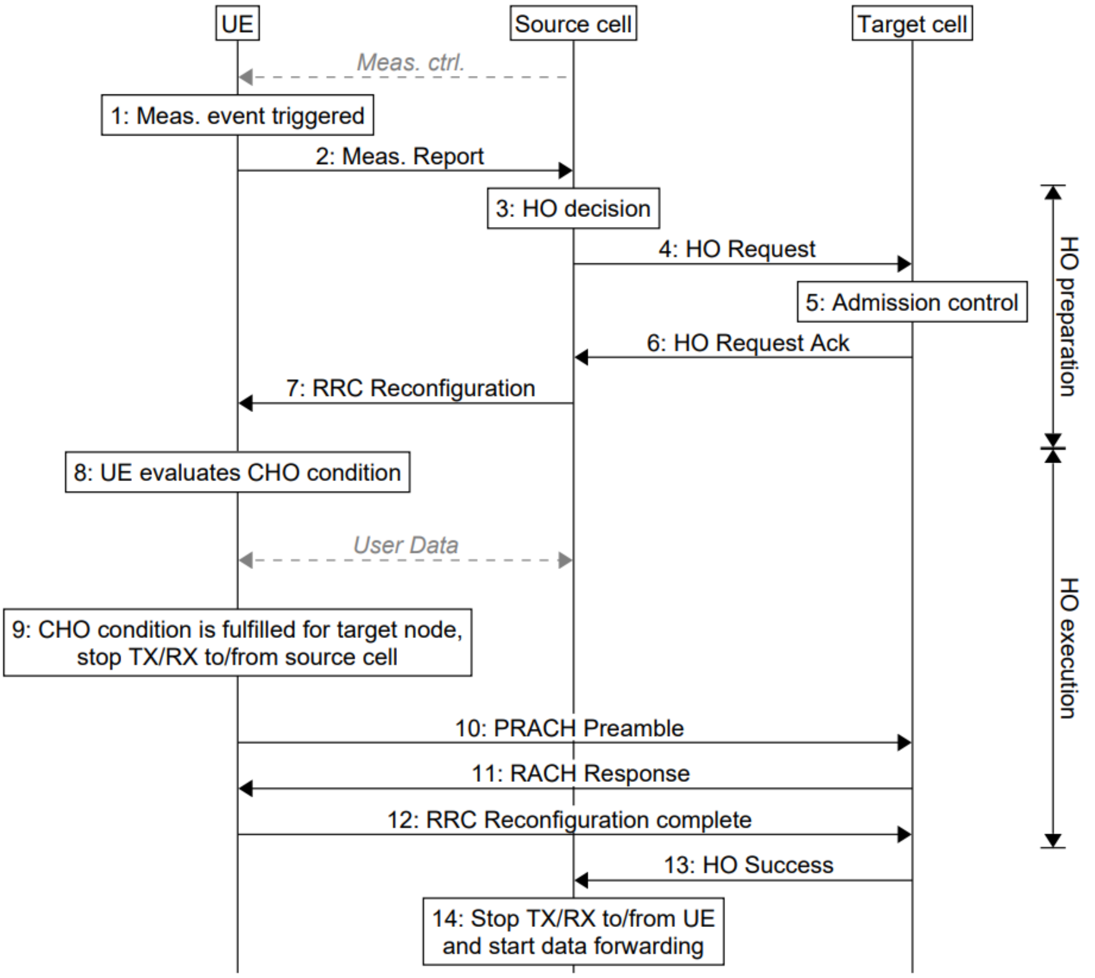

Figure 3.2: Overall steps of CHO [18]

CHO is suitable for 5G LEO NTN as HO preparation can be taken early which eliminates the handover failure problem faced by BHO as the MR is sent very early and HO command is received when the signal is still strong.

Various triggering can be used in conditional handover (CHO) such as measurement based triggering, location based triggering, time based triggering etc. Among them measurement based triggering has the lowest specification impact that is it is compliant with 5G NR terrestrial networks [17].

3.4.3 LCHO

When CHO is configured with location based triggering, it is then known as location based conditional handover or LCHO. In LCHO, measurement based triggering is modified to include location information. LEO satellites follow predictable routes, the location of the satellites can be known. In this case UE needs positioning capabilities. LCHO is a network controlled HO where UE does not have that much impact on HO.

But LCHO results in huge signaling overhead as the location information of both the satellite and UE need to be sent to UE and the network. UE may even HO to a cell which is not operational. LCHO is not possible for UE without any positioning capabilities.

3.5 Handover Parameters

There are several HO parameters which control the HO triggering in case of event triggered HO. HO hysteresis and TimeToTrigger is discussed here.

3.5.1 HO Hysteresis

The network link with the serving cell is biased via handover hysteresis until a neighboring target cell with a sufficiently better signal is found. The UE specifies the hysteresis value, which is then utilized to provide the entry and exiting conditions for a specific event-triggered measurement reporting [27].

3.5.2 TimeToTrigger

TimeToTrigger is a delay parameter which delays the handover to a certain time in order to reduce unnecessary handovers or pingpongs. Due to similar network conditions between two neighboring cell, UE can perform HO immediately after a HO, this is known as pingpongs effect. In order to eliminate pingpongs, a delay is introduced which essentially delays the HO execution to a specified time. By this time, the RSRP of the serving cell will fall far below compared to the target cell. So, after performing the handover, the previous cell will not be comparable to the current serving cell in terms of RSRP because of TimeToTrigger.

Chapter 4

Methodology

4.1 Development of a 5G LEO NTN model

Modelling a 5G LEO non-terrestrial network is a complex task. LEO satellites move very fast at speeds of thousands of kilometers an hour. As a result, the radio link conditions between the satellite and UE at ground changes rapidly [29]. Due to lack of availability of a potent system level simulator which can model the network realistically, a mathematical modelling of the network is done in MATLAB with 3GPP compliant parameter values.

4.1.1 Antenna Pattern

A typical reflector type antenna with a circular aperture is considered in this model. The normalized antenna gain pattern is expressed by [15],

$$\begin{array}{ll} 1 & \text{for } \theta = 0 \\ 4\left|\dfrac{J_1\,(ka\ \sin\theta)}{ka\ \sin\theta}\right|^2 & \text{for } 0 < |\theta| \leq 90^\circ \end{array}$$

Here, $J_1(x)$ is the Bessel function of the first kind and order. θ is the bore sight angle, $k = 2\pi f/c$ is the wave number, f and c are frequency and speed of light respectively and *a* is the aperture radius.

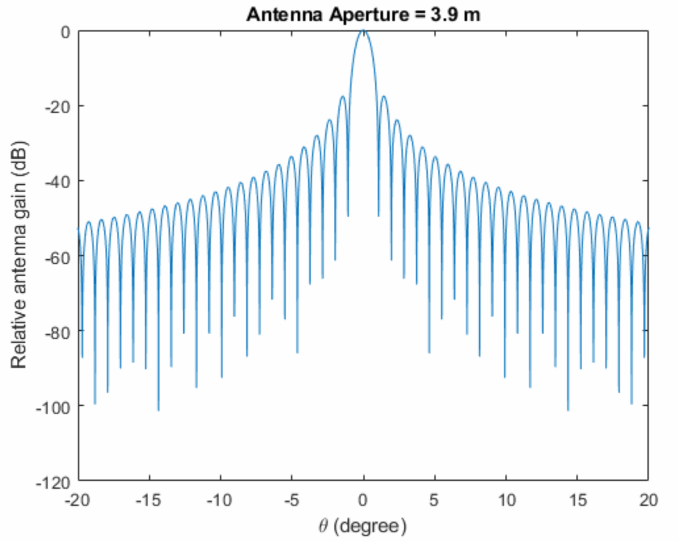

Figure 4.1: Antenna gain pattern

In this work, operational frequency is taken as 10 GHz and corresponding antenna aperture was taken to be 3.9m according to [22,30]. UE antenna parameters were taken in accordance with 3GPP TR 38.821 [17].

4.1.2 Path Loss

According to the suggestions of 3GPP TR 38.811 [15], The path loss (PL) as given in [15, eq. (6.6-1)],

$$PL = PL_B + PL_g + PL_s + PL_e \tag{4.1}$$

Where, PL_b is the basic path loss and others are attenuations due to atmospheric gasses, scintillation and building entry loss in dB respectively. Here, only basic path loss will be our concern as we are considering a LOS outdoor scenario. This implies no building entry loss. Our operational frequency is 10 GHz and at frequencies not more than 10 GHz atmospheric losses can be neglected [15]. Moreover, scintillation is not considered for frequencies above 6 GHz [15].

Here the basic path loss (PL_B) is given by,

$$PL_B = FSPL\,(d, f_c) + SF + CL\,(\alpha, f_c) \tag{4.2}$$

Where, $FSPL\,(d, f_c)$ is the free space path loss, SF and $CL\,(\alpha, f_c)$ are the shadow fading and clutter loss respectively. CL is negligible for LOS case [15]. The free space path loss for an operational frequency f_c in GHz and a separation distance i.e., distance between the satellite and UE, d in meter is calculated from [15, eq. (6.6-2)],

$$FSPL\,(d, f_c) = 32.45 + 20\,\log_{10}(f_c) + 20\,\log_{10}(d) \tag{4.3}$$

Here,

$$d = \sqrt{R_E^2\,\sin^2\alpha + h_0^2 + 2h_0R_E} - R_E\,\sin\alpha \tag{4.4}$$

Where, R_E represents the radius of the earth, h_0 is the satellite altitude and α is the elevation angle.

4.2 Simulation of Handover

The handover simulation was done in MATLAB with simulation parameters included in table 5.1. In case of LEO satellites, the satellites move at a very high velocity (around 7.26 to 7.59 km/s) and their beams on the ground move at speeds of the range of 6.1 to 6.9 km/s. So, contrary to TNs, the cells (beams) are moving at a high velocity. But the handover is similar that is the UE need to connect to the incoming cell. UE is considered to be stationary as UE speed does not make any difference as the speed is very low compared to the beam speed [20].

CHO is event triggered that is when a particular event occurs handover procedure starts. In this simulation event A3 is used. Event A3 occurs when the target or next cell becomes offset better than the serving cell [27]. If event A3 occurs at a distance, d from the center of the serving cell, the actual handover occurs at a distance,

$$d' = d + v \times TTT \tag{4.5}$$

Where, v is the velocity of satellite beams on ground and TTT is the TimeToTrigger. The actual handover gets delayed because of the TimeToTrigger which is basically a delay and during this delay the beam moves further away from the UE. Hence, the UE moves far away from the cell center resulting in significant power loss. For a fixed antenna radiation pattern, this distance corresponds with drop in received power and utilizing this TimeToTrigger is calculated for a set of tolerable power drops.

4.2.1 Tolerable Power Drop

TimeToTrigger delays the actual handover to a certain time, meanwhile the beam moves further away from the UE, which results in received power drop. Although this is a problem but this is done intentionally to reduce unnecessary handovers (UHO). So, a power drop is tolerated in order to get better HO efficiency, this maximum allowed power drop is defined in this work as tolerable power drop (P_{drop}). This can be an operator choice for optimal handover. In this work, P_{drop} has been considered for 3dB, 6dB, 9dB, 12dB, 15dB, 18dB. This power drop is taken after the initial handover triggering that is when event A3 is triggered.

4.2.2 Cell Edge Power Drop

The boundary of a cell can be defined by the drop in received power compared to the cell center. This is defined in this literature as cell edge power drop (P_{edge}). Distance from the cell center increases the half beamwidth angle, θ and a certain P_{edge} corresponds to a certain distance from the cell center. So, for a satellite altitude of h, the cell radius can be defined as,

$$r = h \times \tan \theta \tag{4.6}$$

From the equation, it can be easily seen that cell size is proportional to satellite altitude. This will be further discussed in the simulation chapter.

4.3 Derivation of empirical equations

After simulating the handover with 3GPP compliant parameter values, the TimeToTrigger values for respective tolerable power drops (P_{drop}) is determined. Then the TimeToTrigger values are plotted against satellite altitude for determining relationships between them. Same is done for cell edge power drop and cell radius. Then through extensive simulation and repetitive calculations, empirical relationship is derived between TimeToTrigger, satellite altitude and tolerable power drop. Similarly, empirical equation is derived for cell radius, satellite altitude and cell edge power drop (P_{edge}).

Empirical equations are derived from repetitive calculations and validation. The equations are simplified with the help of approximation to a certain extent. Then the data from the approximated empirical equation is validated against the original simulation data.

Chapter 5

Simulation

The 5G LEO NTN model is simulated using MATLAB. Although we were limited by the lack of access to a potent system level simulator which could simulate the model with more complexity, a mathematical model has been simulated using MATLAB.

5.1 Simulation Parameters

The parameters used in the simulation comply with 3GPP specifications and are contained in the following table.

Table 5.1 Assumed Simulation Parameters

Parameters	Assumptions
Operating Frequency	10 GHz
Satellite Orbit	LEO
Satellite Altitude	550, 600, 650, 700…,1200 km
Satellite antenna aperture	3.9 m
Satellite Tx Power	34 dBm
Satellite Tx max gain	50 dBi
3dB Beamwidth	0.577°
Satellite Beam Diameter	18.5 km (on the ground)
Satellite Elevation Angle	90°
Handover Margin (HOM)	3 dB
UE Transmit Power	23 dBm
UE Tx/Rx Antenna Gain	0 dBi
UE noise Figure	7 dB [15]
Path Loss Model	Free Space Path Loss
HO Triggering Method	Event triggered with event A3

Satellite Antenna radiation pattern is discussed in section 4.1.1 of this dissertation. Handover simulation is done for different satellite altitudes ranging from 550 km to 1200 km which is the specified range of LEO satellites.

5.2 Simulation Results

Various findings from the simulation are presented in this section. The target of this simulation is to find the dependency of cell size and TimeToTrigger on satellite altitude. The received power variation with distance is shown in figure 5.1.

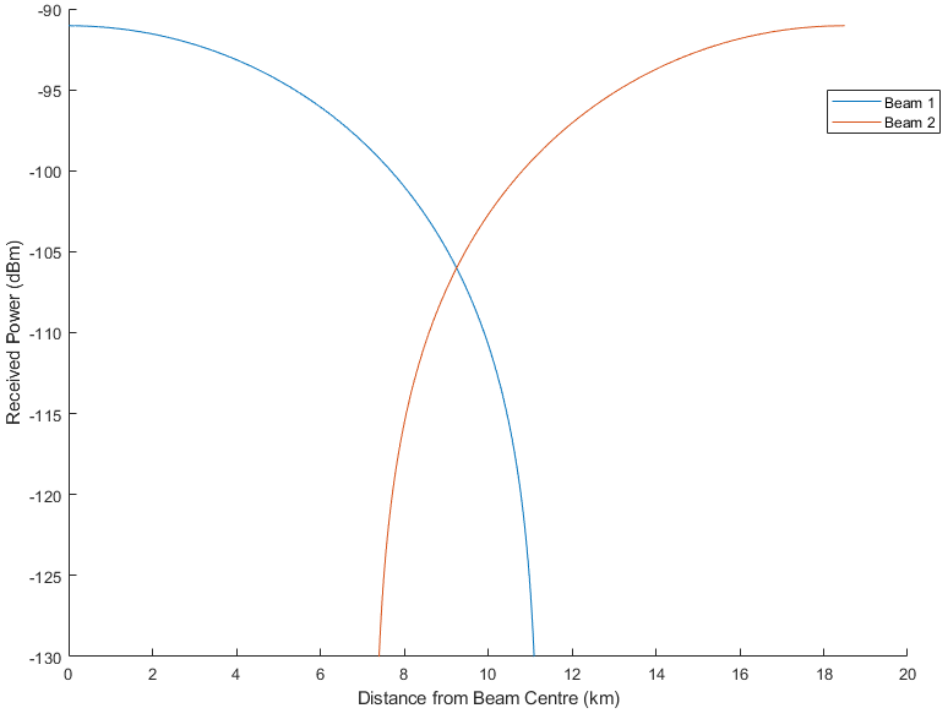

Figure 5.1: UE received power vs distance from the cell center at 600 km satellite altitude

From this figure, we can see that received power falls significantly after 9 km distance from the beam (cell) center. Here, beam 2 represents the incoming beam or cell. After a certain point, the received power from cell 1 falls below that of cell 2. When the received power from cell 1 is 3 dB less than cell 2, event A3 is triggered. TimeToTrigger timer starts at this point and after this delay the actual handover initializes. The next sections will include TimeToTrigger and cell radius vs satellite altitude plots and derivation of empirical equations through curve fitting.

5.2.1 TimeToTrigger Plots

In this section, TimeToTrigger is plotted against satellite altitude for various tolerable power drops (P_{drop}) and the relationship between them will be discussed. TimeToTrigger vs altitude plot has been generated for various P_{drop} values including 3 dB, 6 dB, 9 dB, 12 dB, 15 dB and 18 dB.

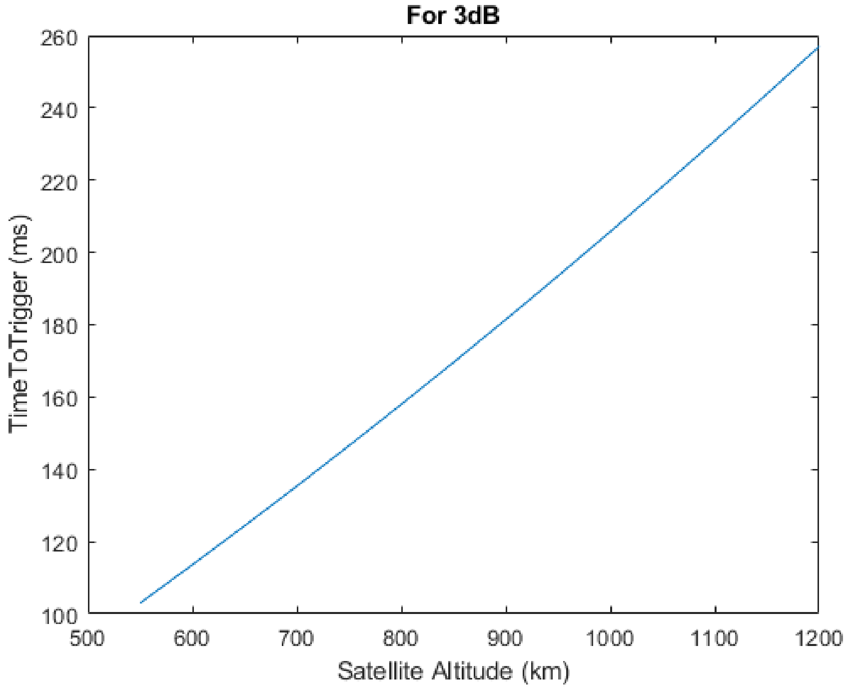

Figure 5.2: TimeToTrigger vs satellite altitude for P_{drop} = 3dB

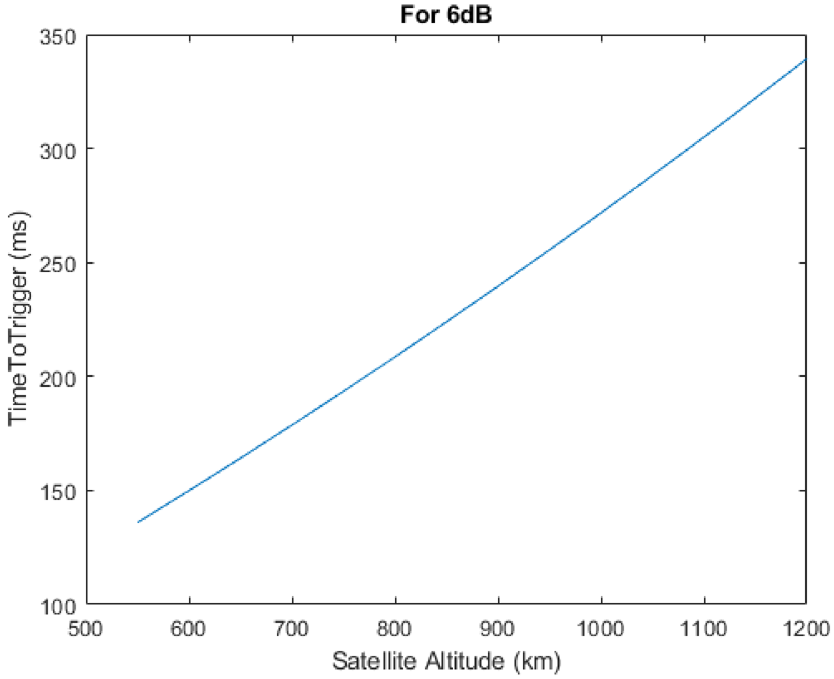

Figure 5.3: TimeToTrigger vs satellite altitude for P_{drop} = 6dB

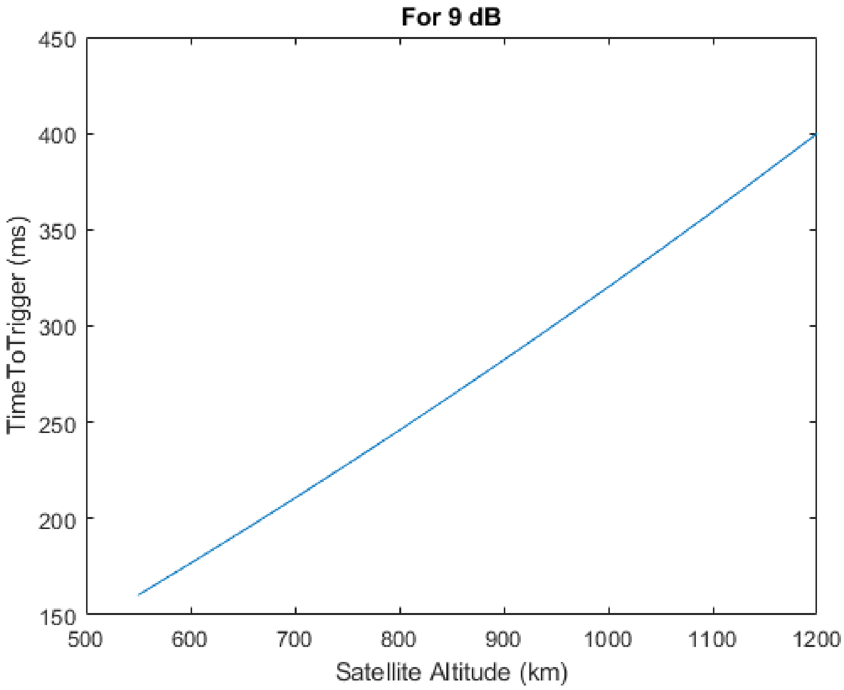

Figure 5.4: TimeToTrigger vs satellite altitude for P_{drop} = 9dB

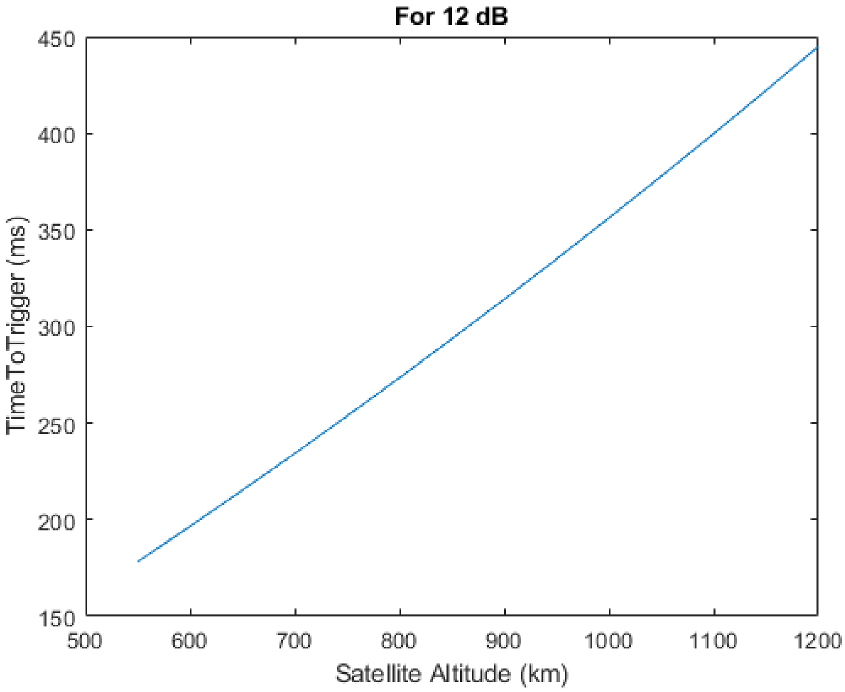

Figure 5.5: TimeToTrigger vs satellite altitude for P_{drop} = 12dB

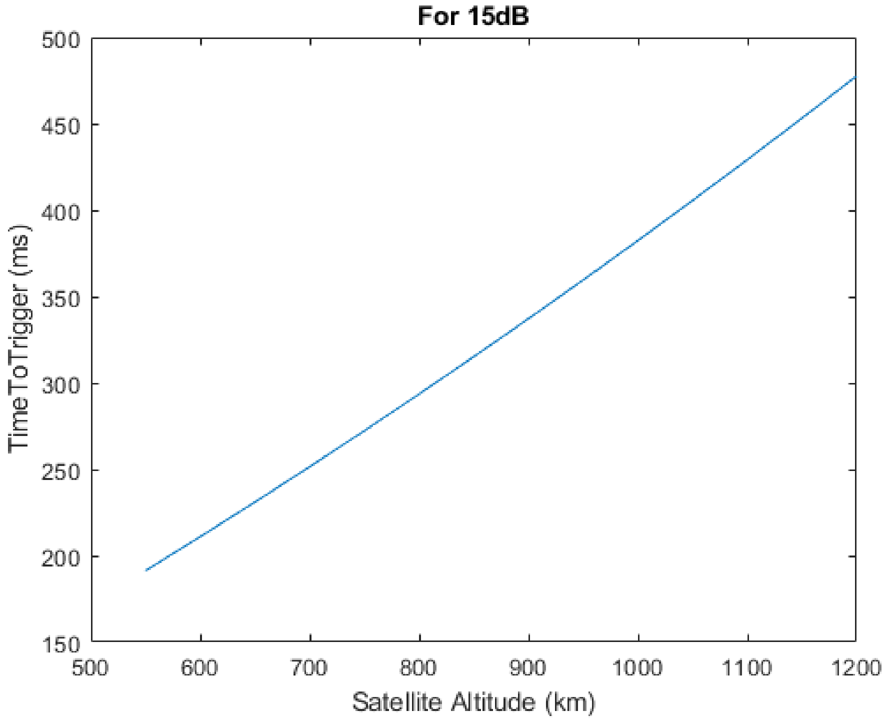

Figure 5.6: TimeToTrigger vs satellite altitude for P_{drop} = 15dB

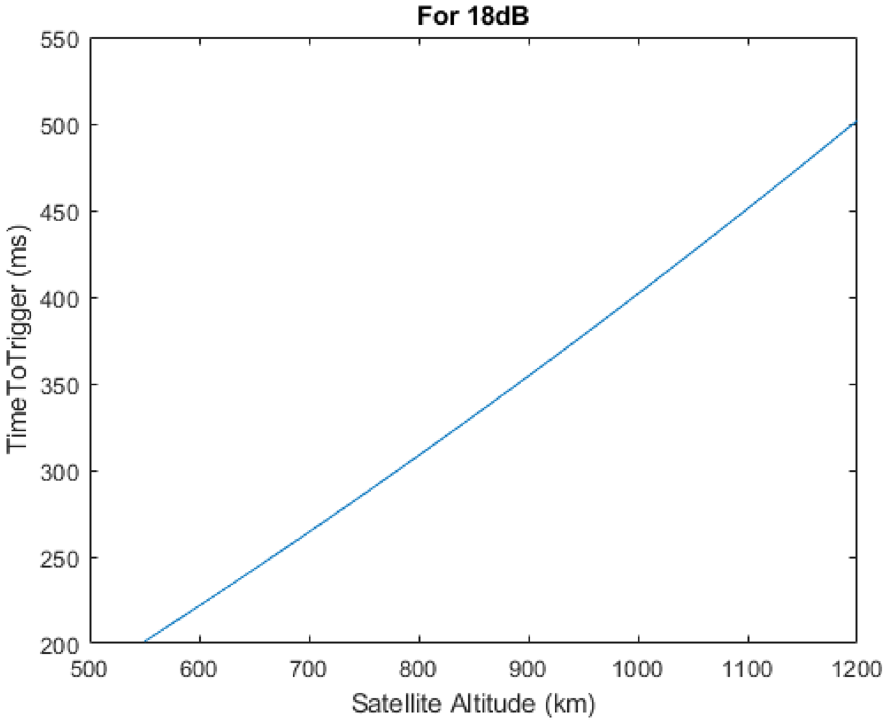

Figure 5.7: TimeToTrigger vs satellite altitude for P_{drop} = 18dB

As expected, larger power drops can offer more TimeToTrigger and vice versa. TimeToTrigger also increases with altitude which can be easily seen here. The increase with P_{drop} increase can be easily understood from figure 5.6.

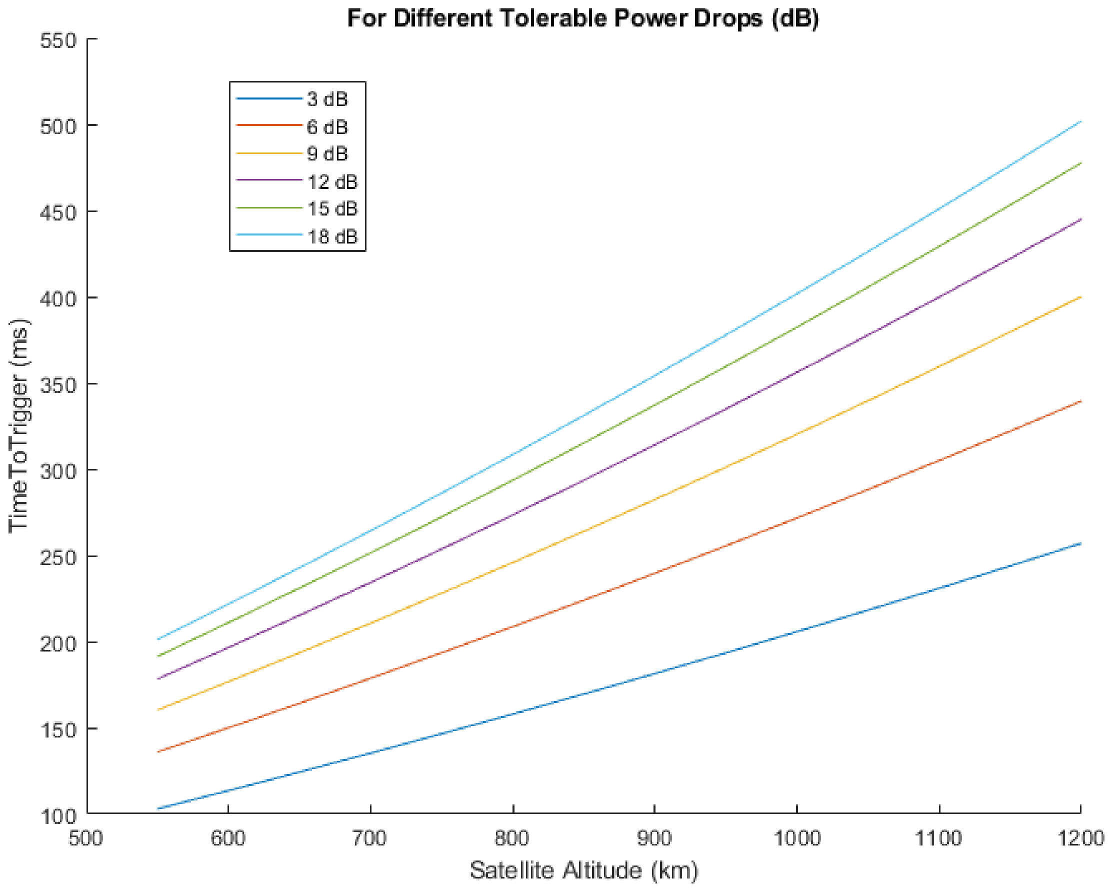

Figure 5.8: TimeToTrigger vs satellite altitude for different power drops

So, we can see that TimeToTrigger can be increased for higher altitude and higher power drop tolerance. This is more clear in the following tables.

Table 5.2 TimeToTrigger values at 600 km altitude

P_{drop} (dB)	3dB	6dB	9dB	12dB	15dB	18dB
TimeToTrigger (ms)	114	150	177	197	211	222

Table 5.3 TimeToTrigger values at different satellite altitudes (P_{drop}=3dB)

Altitude (km)	600	700	800	900	1000	1200
TimeToTrigger (ms)	114	135	158	181	206	257

TimeToTrigger values are rounded to the nearest integer for both of the tables. As we can see from the graphs and tables that with higher satellite altitude and power drop tolerance TimeToTrigger has almost a linear increase.

5.2.2 Cell Radius Plots

In this section cell radius is plotted against satellite altitude for various cell edge power drops (P_{edge}). Cell radius vs altitude has been plotted for various cell edge power drops in the following figures.

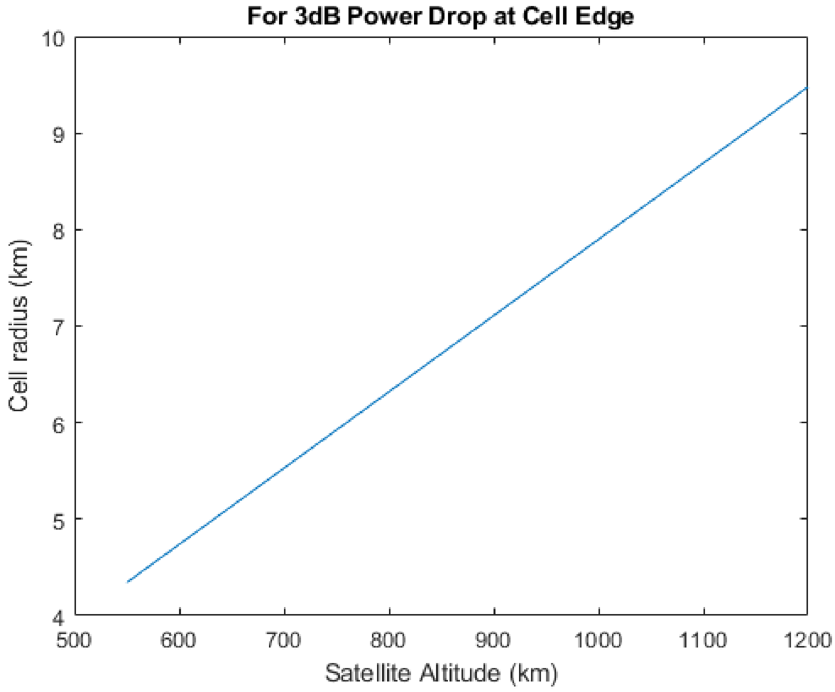

Figure 5.9: Cell radius vs satellite altitude for 3 dB cell edge power drop

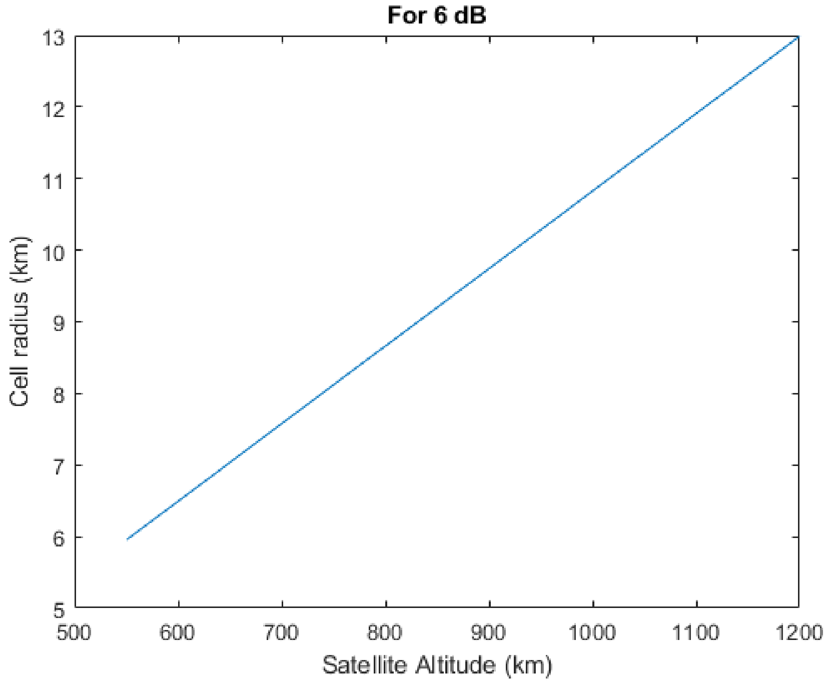

Figure 5.10: Cell radius vs satellite altitude for 6 dB cell edge power drop

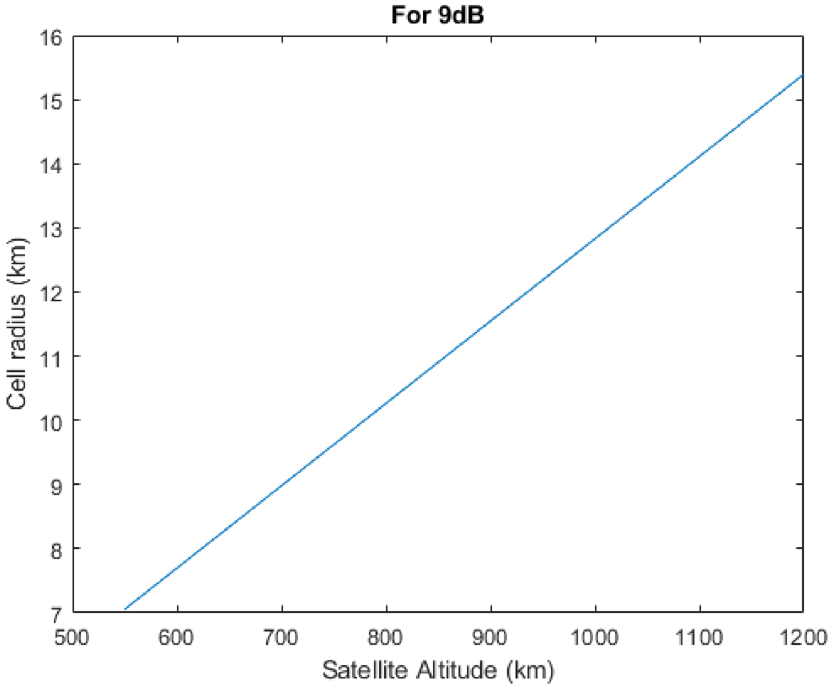

Figure 5.11: Cell radius vs satellite altitude for 9 dB cell edge power drop

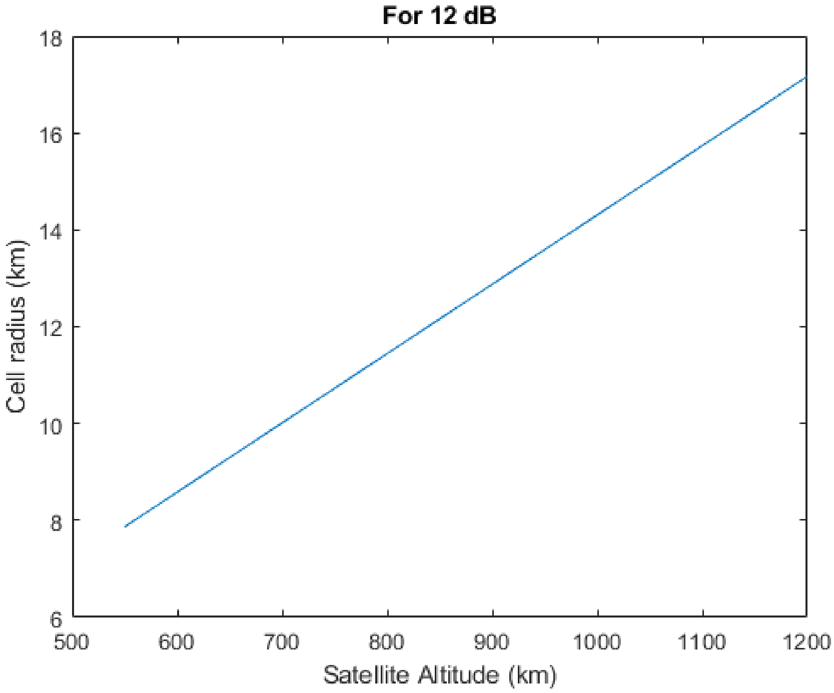

Figure 5.12: Cell radius vs satellite altitude for 12 dB cell edge power drop

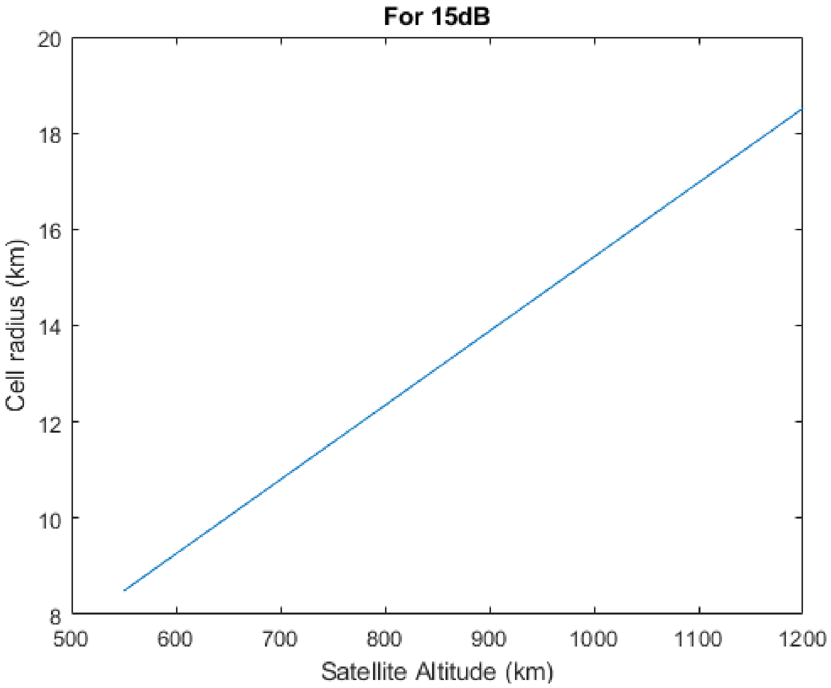

Figure 5.13: Cell radius vs satellite altitude for 15 dB cell edge power drop

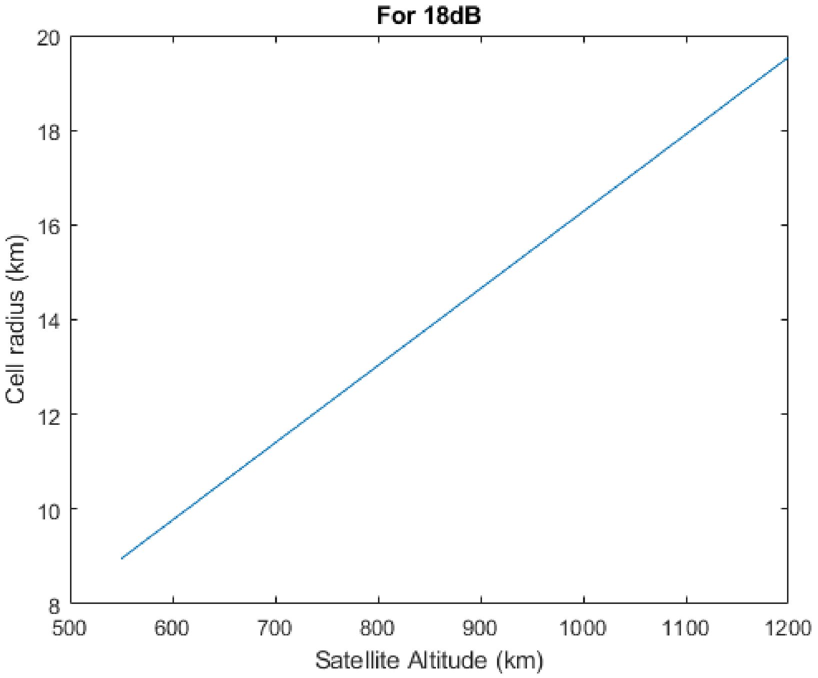

Figure 5.14: Cell radius vs satellite altitude for 18 dB cell edge power drop

As we can see, cell radius increases linearly with increase in altitude. But the relation with cell edge power drop is not clear in these figures. This can be visualized by plotting all the plots for different cell edge power drops in a single figure.

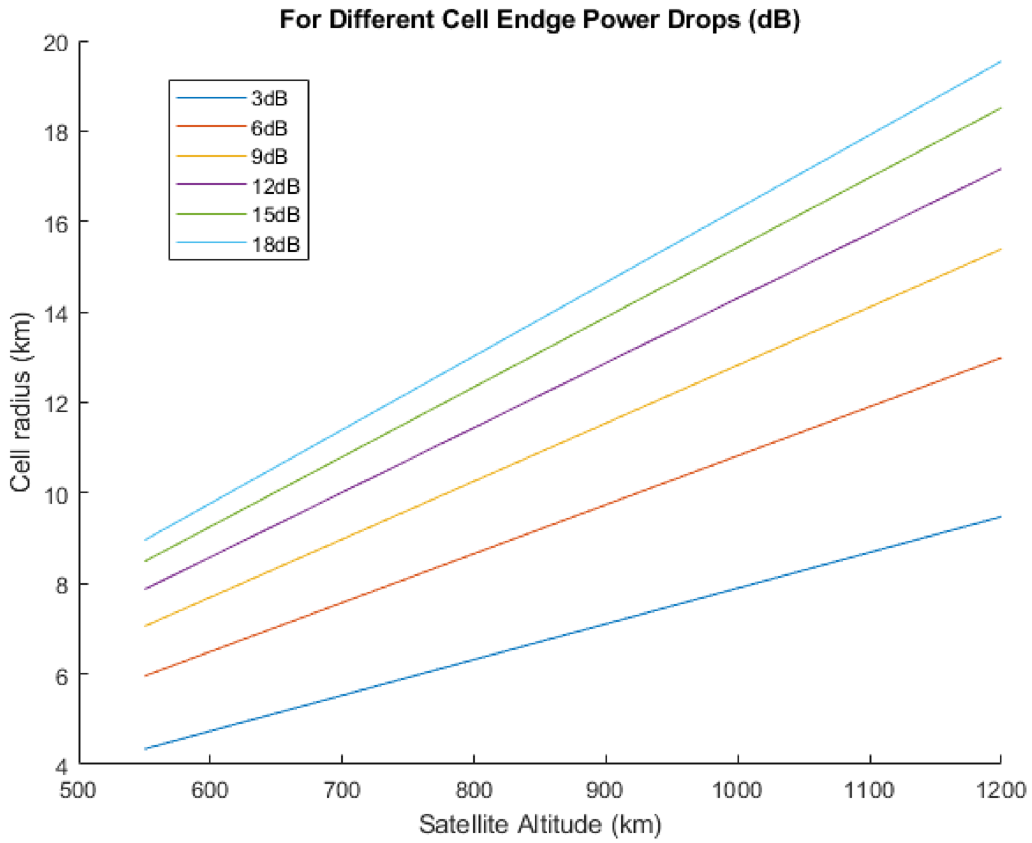

Figure 5.15: Cell radius vs satellite altitude for different cell edge power drops

Although the linear relationship between cell radius and satellite altitude is clear but the variation for different cell edge power drop is not so obvious. But it can be implied that the slopes of this lines depend on P_{edge} which will be utilized latter for deriving empirical formula.

Table 5.4 Cell radius values at 600 km satellite altitude

P_{edge} (dB)	3dB	6dB	9dB	12dB	15dB	18dB
Cell Radius (km)	4.739	6.495	7.696	8.584	9.258	9.771

Table 5.5 Cell radius values at different satellite altitudes (P_{edge}= 3dB)

Altitude (km)	600	700	800	900	1000	1100
Cell Radius (km)	4.739	5.528	6.318	7.108	7.898	8.688

What is clear from these figures and tables is that cell radius increases linearly with satellite altitude. Cell edge power drop (P_{edge}) increase also increases cell radius but this relationship is not linear as can be seen in figure 5.11 and table 5.4.

Chapter 6

Proposed Empirical Relationship

One of the key challenges of 5G LEO non-terrestrial network is the requirement of frequent and reliable connected mode mobility that is performing a handover in an optimal way. Handover in 5G LEO NTN is different compared to TN as the overall mobility scenario is quite different. Due to the ultra-fast movement of the LEO satellites, UE at any location have to perform handover within a few seconds. Each satellite has multiple beams or cells, a UE need to perform handover from one cell to another in order to remain connected to the network. Because of changes in radio link conditions, two adjacent cells may have similar RSRP measurements. Without a delay like TimeToTrigger, a UE could end up performing a second handover just after doing one to the next cell and connect back to the previous cell only to be performing another handover to the next cell in order to stay connected, which is known as pingpongs. It may even result in radio link failure (RLF). In order to avoid RLF and reduce pingpongs, TimeToTrigger is introduced to delay the handover execution until the serving cell is easily distinguishable from the next cell in terms of RSRP. This essentially reduces UHO events and RLFs.

Optimal TimeToTrigger is an important issue for a successful handover execution. Due to high velocity of the satellites, a delay of few milliseconds results in a significant drop in RSRP. So, a random value of TimeToTrigger may lead to bad signal quality and decreased throughput. Different TimeToTrigger will lead to different level of drop in RSRP. So, an optimal TimeToTrigger is necessary for avoiding unnecessary handovers and at the same time retaining good signal quality. But determining the optimal TimeToTrigger for a tolerable drop in power is not that simple, rather it requires complex simulation which costs time and resources. In this work, we propose an empirical relationship between TimeToTrigger and tolerable power drop which will enable simple calculation of optimal TimeToTrigger.

Similarly, an empirical expression for relationship between cell radius and its defining cell edge power drop is proposed in this thesis. This will further simplify overall calculation for a 5G LEO based NTN and decrease the requirement of complex simulation for these parameters.

6.1 Empirical Equation for TimeToTrigger

Through extensive simulation, observations, repetitive computations and validation, we have found that TimeToTrigger for CHO in 5G LEO non-terrestrial network can be expressed by,

$$TTT = P_{drop}^{0.4} \times (0.15\, h_{sat} - 18) \tag{6.1}$$

Where,

TTT = TimeToTrigger in ms

P_{drop} = Tolerable power drop in dB

h_{sat} = Satellite altitude or height in km

Equation (6.1) represents TimeToTrigger in terms of tolerable power drop and satellite altitude. This empirical expression essentially shows the dependency of TimeToTrigger on satellite altitude. It also demonstrates the relation between TimeToTrigger and tolerable power drop. So, for a specific satellite orbit i.e., satellite altitude, TimeToTrigger can be easily calculated from the tolerable power drop configuration.

For example, for a satellite height of 600 km and tolerable power drop of 6 dB, the optimal TimeToTrigger will be,

$$TTT = 6^{0.4} \times (0.15 \times 600 - 18) = 147.43 \text{ ms}$$

By rounding to the next integer, we find $TTT \cong 148$ ms.

From table 5.2 we can see the value of TimeToTrigger for 6dB power drop tolerance is 150 ms

So, the approximated empirical equation is within a 1.3% margin from the simulated data which is fairly acceptable in this case as TimeToTrigger is in milliseconds and a couple of milliseconds do not have any significant impact in practical scenario. Detailed validation for the formula is given in the next chapter.

TimeToTrigger value for a given scenario can be simply calculated using this empirical formula given in equation (6.1) and time consuming simulation will not be required. This equation is true for 5G LEO NTN only.

6.2 Empirical Equation for Cell Radius

Through extensive simulation, observations, repetitive computations and validation, we have found that, cell radius for a 5G LEO non-terrestrial network can be expressed by,

$$r_{cell} = P_{edge}^{0.4} \times 0.0053\, h_{sat} \tag{6.2}$$

Where,

r_{cell} = Cell radius in km

h_{sat} = Satellite altitude in km

P_{edge} = Cell edge power drop in dB

Equation (6.2) represents cell radius in terms of satellite altitude and cell edge power drop. The empirical equation shows the dependency of cell radius on satellite altitude for a defined cell edge power drop. This equation is essentially an equation of a straight line which can be represented by $y = mx$ equation where slope of the line m is $P_{edge}^{0.4}$. For a given cell edge power drop, P_{edge} is constant, so, cell radius is directly proportional to satellite altitude.

Like TimeToTrigger expression this equation also enables simple calculation of cell radius for a given satellite altitude and defined cell edge power drop. For example, for a satellite altitude of 600 km and 6 dB cell edge power drop, cell radius will be,

$$r_{cell} = 6^{0.4} \times 0.0053 \times 600 = 6.512 \text{ km}$$

From table 5.4, we find the cell radius for this case is 6.495 km. So, the approximated value from the empirical equation is 17m more than the simulated data which is within a mere 0.26% margin from the simulation. This difference is insignificant, so the calculated cell radius is acceptable. Detailed validation for the formula is given in the next chapter.

Chapter 7

Results and Discussion

In this section, the proposed empirical equations is validated against raw simulation data. Comparison between the simulation and approximated empirical equations is demonstrated through various graphs and tables.

7.1 Validation of TimeToTrigger Equation

The proposed empirical equation is given in equation (6.1) which is derived through extensive simulation and repetitive computations. TimeToTrigger values calculated from this equation is compared with the TimeToTrigger values found from the simulation which followed the methodology described in section 4.2. The values are compared through the use of graphs and tables. The empirical formula as given in equation (6.1) is given by,

$$TTT = P_{drop}^{0.4} \times (0.15\, h_{sat} - 18) \tag{6.1}$$

7.1.1 Summery

The equation is validated for all the tolerable power drops used in simulation, from 3dB to 18 dB. Data comparison for 6 dB case is given in the following table.

Table 7.1 Comparison of approximated and simulated TimeToTrigger values for 6dB power drop

Altitude (km)	600	700	800	900	1000	1100	1200
Simulation (ms)	149.96	178.73	208.6	239.6	271.73	305	339.42
Approximation (ms)	147.43	178.15	208.86	239.58	270.29	301.01	33.72
Deviation (%)	1.68	0.32	0.12	0.009	0.53	1.3	2.27

From the table, we can see, deviation between the results obtained through simulation and the approximated empirical equation is very low.

7.1.2 Comparison Plots

Comparison between the simulated TimeToTrigger data and calculated data from empirical equation is presented here as graphs of TimeToTrigger vs Altitude plots.

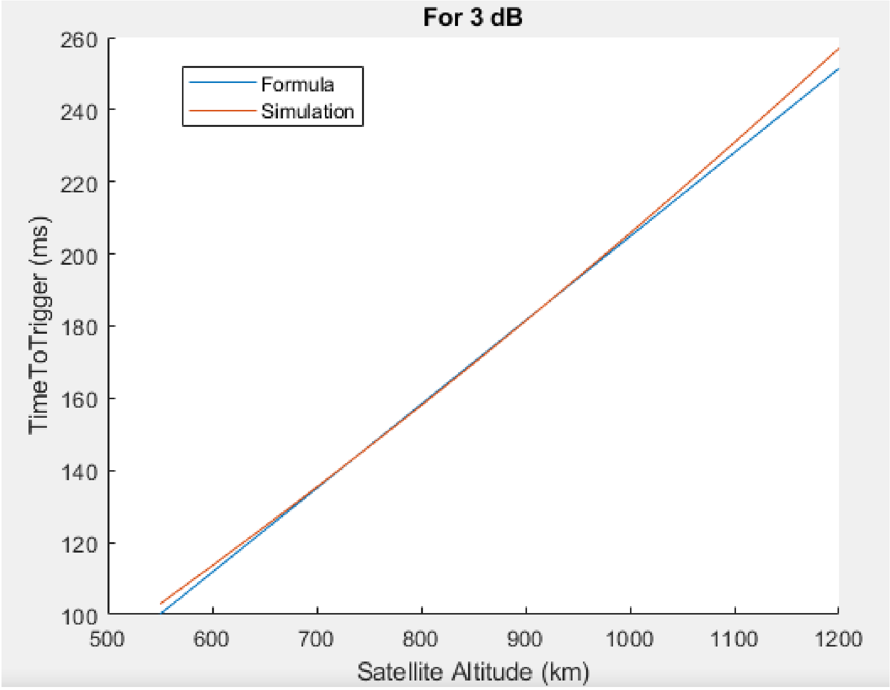

Figure 7.1: Empirical formula vs simulation of TimeToTrigger data for 3 dB

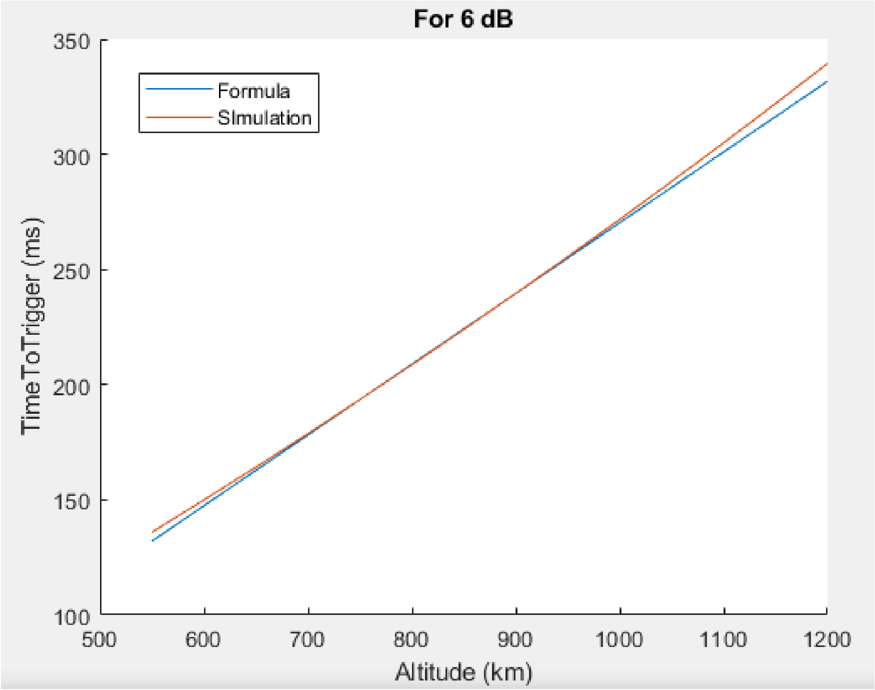

Figure 7.2: Empirical formula vs simulation of TimeToTrigger data for 6 dB

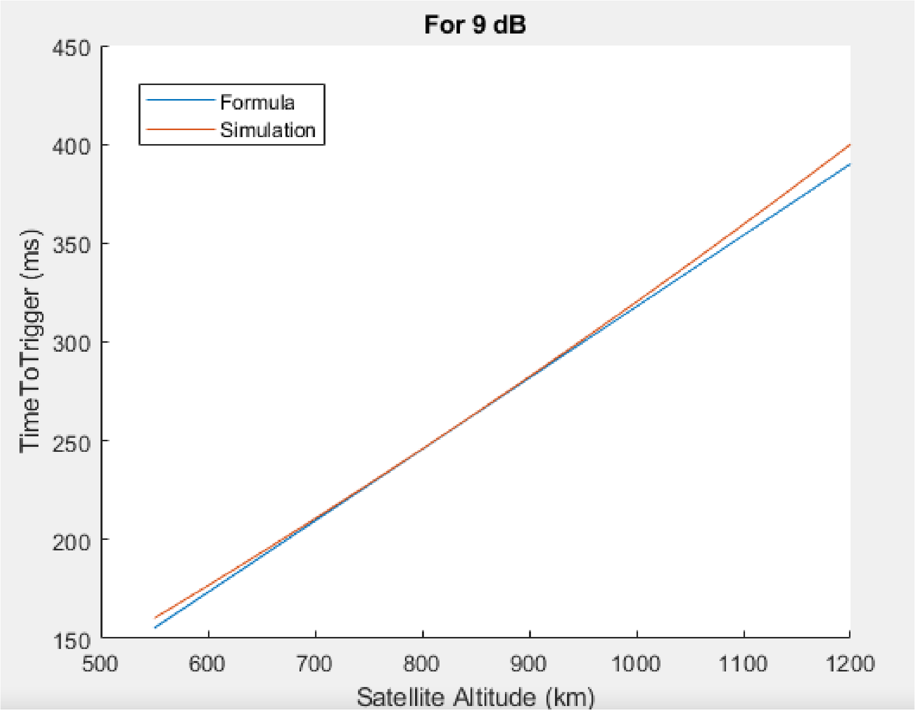

Figure 7.3: Empirical formula vs simulation of TimeToTrigger data for 9 dB

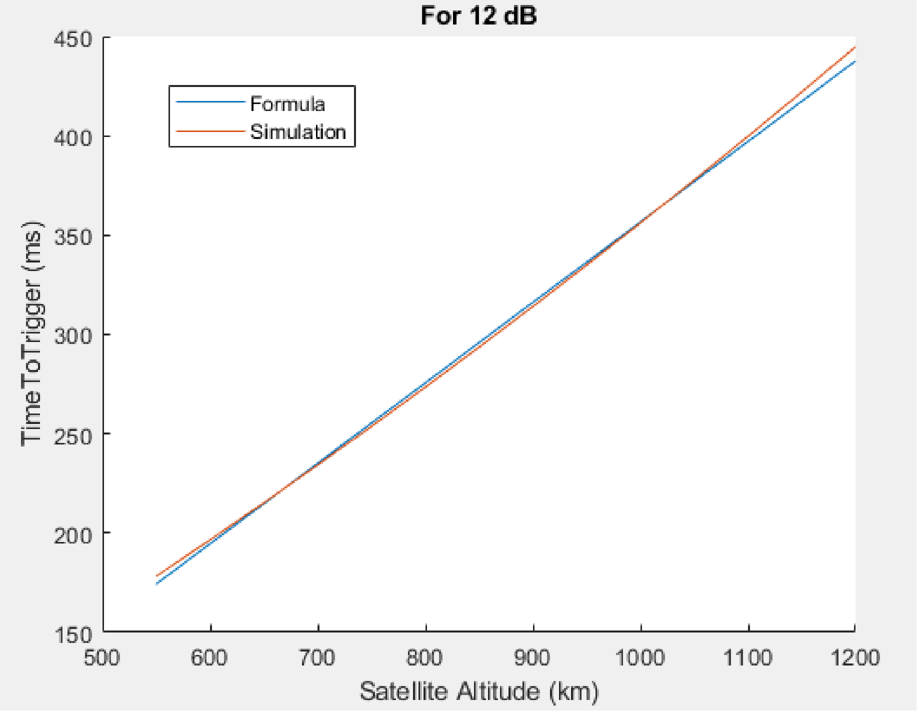

Figure 7.4: Empirical formula vs simulation of TimeToTrigger data for 12 dB

We can see, that the results are very close and within negligible margin of deviation for tolerable power drop values of 3 dB, 6dB, 9dB and 12dB.

7.2 Validation of Cell Radius Equation

The proposed empirical equation is given in equation (6.2) which is derived through extensive simulation and repetitive computations. Cell radius values calculated from this equation is compared with the cell radius values found from the simulation which followed the methodology described in section 4.2. The values are compared through the use of graphs and tables. The empirical formula as given in equation (6.2) is given by,

$$r_{cell} = P_{edge}^{0.4} \times 0.0053\, h_{sat} \tag{6.2}$$

7.2.1 Summery

The equation is validated for all the cell edge power drops used in the simulation, from 3dB to 18 dB. Data comparison for 6 dB case is given in the following table.

Table 7.2 Comparison between simulated and approximated cell radius data for 6dB

Altitude (km)	600	700	800	900	1000	1100	1200
Simulation (km)	6.495	7.577	8.660	9.742	10.825	11.907	12.990
Approximation (km)	6.512	7.597	8.682	9.767	10.853	11.938	13.023
Deviation (%)	0.25	0.25	0.25	0.25	0.25	0.25	0.25

Table 7.3 Comparison between simulated and approximated cell radius data for 9dB

Altitude (km)	600	700	800	900	1000	1100	1200
Simulation (km)	8.584	10.015	11.446	12.887	14.307	15.738	17.169
Approximation (km)	8.592	10.024	11.456	12.888	14.320	15.752	17.184
Deviation (%)	0.089	0.089	0.089	0.089	0.089	0.089	0.089

From table 7.2 and 7.3 it is evident that the empirical equation provides cell radius values which are almost similar to the values obtained through the simulation. Deviation between simulated and approximated data is very low. There are a difference of several meters at best which is not impactful at all.

7.2.2 Comparison Plots

Comparison between the cell radius data obtained from the simulation and calculated data from the derived empirical equation is presented here as cell radius vs satellite altitude plots.

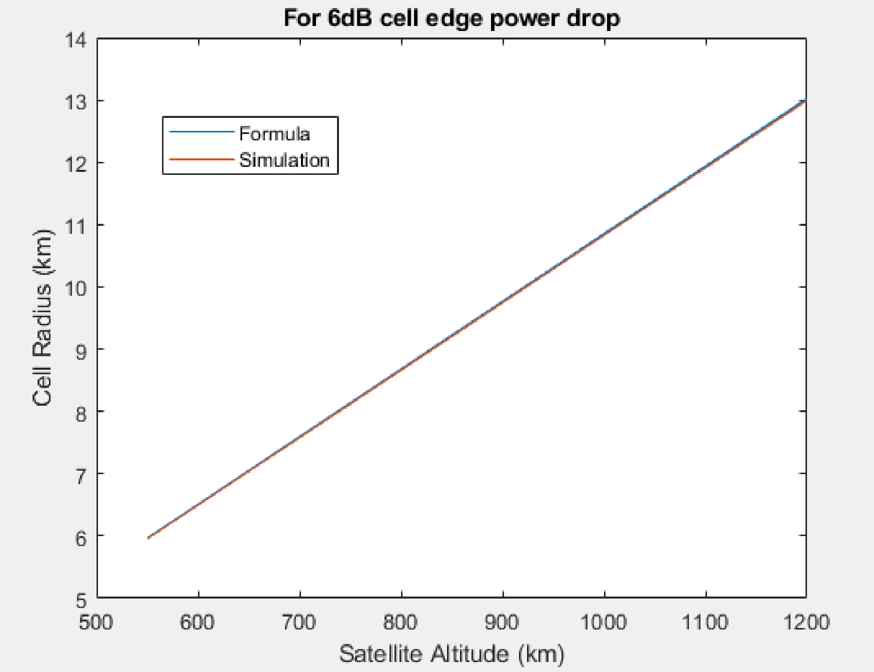

Figure 7.5: Empirical formula vs simulation data of cell radius for 6 dB cell edge power drop

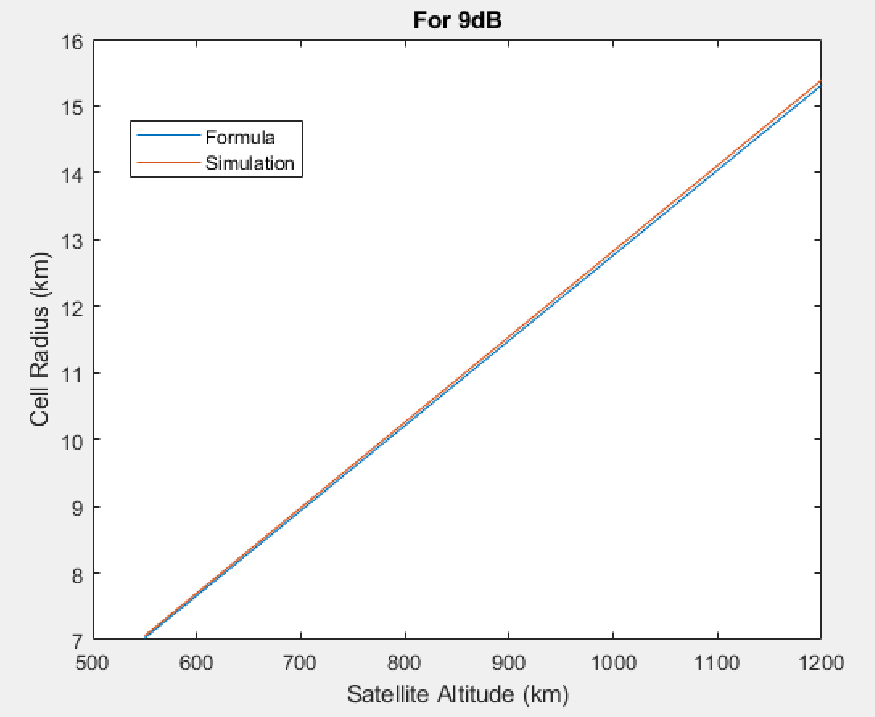

Figure 7.6: Empirical formula vs simulation data of cell radius for 9 dB cell edge power drop

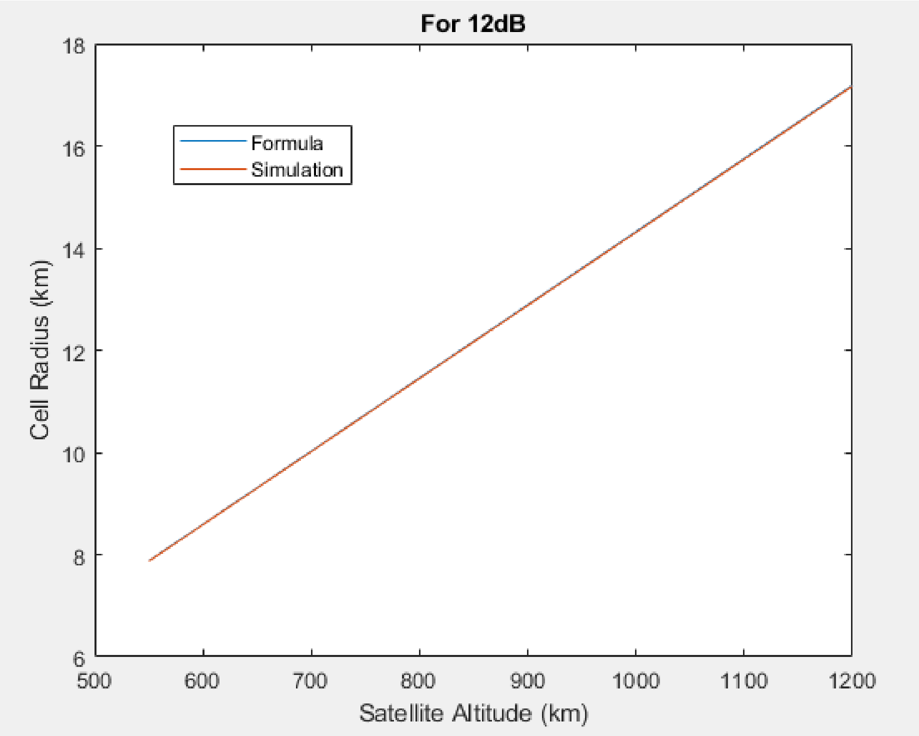

Figure 7.7: Empirical formula vs simulation data of cell radius for 12 dB cell edge power drop

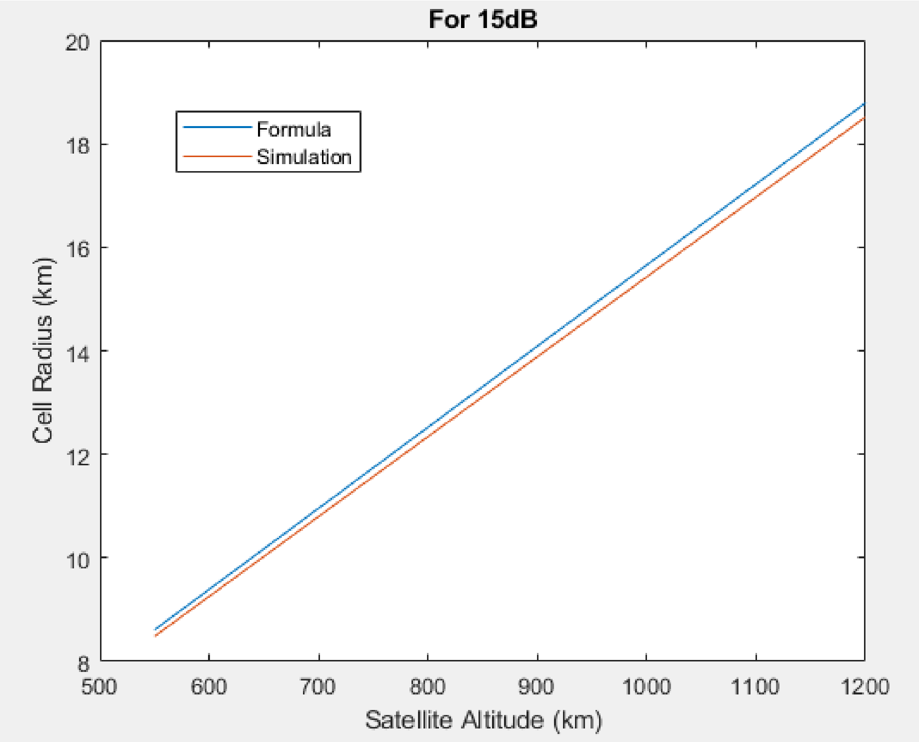

Figure 7.8: Empirical formula vs simulation data of cell radius for 15 dB cell edge power drop

As we can see, the empirical equation can give acceptable results for cell radius across different cell edge power drops.

7.3 Discussion

In this work, we have proposed two empirical equations relating TimeToTrigger and cell radius with satellite altitude and power drops. These equations can provide satisfactory results without the need to go through extensive simulation just to determine these parameters. The equations also show the dependency of available time to trigger handover i.e., TimeToTrigger and cell size through cell radius on satellite altitude. The equations are results of extensive simulation, observation and repetitive calculations. These are empirical equations based on the observation of the simulated data. Detailed validation of the equation is provided in this text. The values calculated from the empirical expressions are almost similar to data obtained from simulation.

TimeToTrigger is an important handover parameter. It delays handover execution to a certain time and effectively reduces unnecessary handover. Optimal TimeToTrigger is vital for optimal network condition. In 5G LEO non-terrestrial networks, optimal handover is crucial in order to avoid service disruption. And for an optimal handover, TimeToTrigger is a crucial parameter. The work presented in this paper contributes to making the determination of this TimeToTrigger easier.

The simulation is done only for 10 GHz operational frequency deployment. Although the equations may work effectively for other deployments, it is not validated in this work. The simulation model is not probabilistic that is the model does not take account any probabilistic variation in the parameters which could better represent the realistic 5G NTN scenario. Simplistic mathematical modelling was done because we could not get access to any powerful system level simulator which could simulate the 5G LEO satellite system. In fact there are some potent simulators but they are proprietary and only used in in house research and development projects of large telecommunication corporations. But despite this the model is sufficient enough to use in this case as this work focused on developing empirical relationships between specific mathematical parameters.

Chapter 8

Conclusion

8.1 Synopsis

This work proposes empirical equations for TimeToTrigger and cell radius for 5G LEO non-terrestrial networks. The equations as stated in equation (6.1) and (6.2) are,

$$TTT = P_{drop}^{0.4} \times (0.15\, h_{sat} - 18) \tag{6.1}$$

And,

$$r_{cell} = P_{edge}^{0.4} \times 0.0053\, h_{sat} \tag{6.2}$$

These equation represents relation of TimeToTrigger and cell radius with satellite altitude and demonstrates their dependency on it. Equation (6.1) represents TimeToTrigger in terms of max tolerable power drop and satellite altitude and equation (6.2) represents cell radius in terms od cell edge power drop and satellite altitude. The empirical equations are validated through comparison between the simulated data and approximated data calculated from the equations. The equations enable simpler calculation for determining TimeToTrigger and cell radius without the need of complex and time consuming simulations.

5G LEO non-terrestrial networks (NTN) can be a major enabler of worldwide 5G availability. Through current technological advancement in terms of satellite technology, 5G LEO NTN is more plausible than ever before. This raises a big challenge of optimizing the 5G standards for use in non-terrestrial scenario. This work adds a small contribution to solving this challenge.

8.2 Future Work

The work is limited to derivation of two empirical equations which represent the dependency of available time to trigger handover i.e., TimeToTrigger and cell radius on satellite altitude. But in future, we plan to also determine their effect on overall throughput and signal quality.

The proposed empirical equations is defined for some specific power drop values which are cell edge power drop and tolerable drop in power. But TimeToTrigger can affect throughput, SINR, downlink speed etc. These parameters can be included in the calculation of determining TimeToTrigger for an optimal handover and optimal network operation.

The simulation is done only for 10 GHz deployment. Proposed deployment for 5G NTN ranges from 2-30 GHz and above [17] . So, we plan to simulate the model for all the planned deployments and determine the effect of frequency in our calculations. In future, when a potent system level simulator can be used to simulate the model, more accurate and realistic calculation can be done.

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