SCHOOL OF COMPUTING, TECHNOLOGY AND APPLIED SCIENCES

MASTER RESEARCH PROJECT

# MODELING AND OPTIMIZATION OF 5G NETWORKS FOR ENHANCED CONNECTIVITY

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**ZCAS UNIVERSITY**

**2023**

A Final Year Research Project submitted in partial fulfilment of the requirements for the degree of

Master of Science in Information Technology

ZCAS University

2023

**DECLARATION**

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I hereby declare that this final year research project is the result of my own work, except for quotations and summaries which have been duly acknowledged.

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## ABSTRACT

In the realm of 5G network optimization, the SIMU5G framework emerges as a potent simulation tool, encapsulating adaptive numerology, scheduling support, and mmWave support for the comprehensive modeling and optimization of 5G networks. Operating on a simulation-based approach, SIMU5G enables detailed analysis and optimization within a controlled environment, measuring key metrics such as throughput, latency, and harqErrorRateDl to assess 5G network efficiency under diverse scenarios. The results offer valuable insights into network behavior and performance bottlenecks, positioning SIMU5G as an effective tool for 5G network optimization. Despite its merits, this research acknowledges the framework's limitations, calling for further investigation to address these constraints and enhance SIMU5G's capabilities in alignment with the evolving landscape of 5G technology.

*Keywords:* SIMU5G, 5G optimization, network simulation, adaptive numerology, scheduling support, mmWave support, throughput, latency, harqErrorRateDl.

## ACKNOWLEDGEMENT

I extend my sincere gratitude to my supervisor, Dr. Aaron Zimba, for his exceptional guidance, unwavering support, and insightful advice throughout the entirety of this project. His expertise and mentorship have been instrumental in shaping the direction of my research and fostering a deep understanding of the subject matter.

Special appreciation is also extended to Mr. Thomas Ngoma, Senior Manager of Network Planning at MTN Zambia. His valuable insights and contributions significantly enriched the project, providing real-world perspectives that added depth and relevance to the study.

**THANK YOU.**

## DEDICATION

I would like to take this opportunity to express my deepest gratitude and heartfelt appreciation to my family for their unwavering support, encouragement, and understanding throughout this academic journey. Their love and encouragement have been my pillars of strength, enabling me to navigate the challenges and celebrate the successes.

Special thanks to my beloved wife, Rachel Mumba, whose boundless patience, encouragement, and sacrifices have been the driving force behind my pursuit of knowledge. Your unwavering support and understanding have been my anchor during late nights of study and research.

# TABLE OF CONTENTS

# Contents

## LIST OF TABLES

## LIST OF FIGURES

## LIST OF ABBREVIATIONS

**a.** txPk

**b.** vector

**c.** HarqtxAttemptDI

**d.** rxPkOK

**e.** passedUpPK

**f.** UE

**g.** gnodeB

**h.** outgoingDataRate

**i.** incomingDataRate

**j.** harqErrorRate

**k.** cbrGeneratedThroughPut

# CHAPTER 1

# INTRODUCTION

## Background to the study

The era of mobile wireless communication networks emerged a few decades back which has helped in exchanging information across metropolitan areas, states, countries and even continents. **(Joyce, Adebiyi, & Adebiyi, 2020)** Continuous enhancements are being introduced in wireless communication, encompassing aspects such as data capacity, speed, frequency, technology, and latency. These advancements are typically categorized into distinct Mobile Wireless Generations, with four generations currently established. The first generation of Mobile wireless communication, denoted as 1G, employed analog technology, offering a network speed of approximately 2.4 kbps, primarily dedicated to public voice services. Its Second-Generation (2G) was a digital-based technology that enabled text messaging. **(Zeqiri, Idrizi, & Halimi, 2019)** According to a survey conducted by the Advanced Computer Network Lab, the key distinctions between 1G and 2G cellular networks are quite notable. 1G systems were predominantly analog and lacked many features, whereas 2G systems were digital in nature. They offered encryption capabilities to safeguard communications from eavesdropping, enabled the detection and correction of identified errors, ensured clear voice reception, and authorized channels for concurrent sharing by multiple users. The third generation (3G) of technology brought about a notable improvement in data transmission speed and capacity, along with the development of multimedia support features. In order to enable wireless mobile internet, the fourth generation (4G) of technology integrated the internet. This resulted in an increase in bandwidth size and a decrease in resource acquisition costs. The Fifth Generation (5G) of mobile wireless communication is anticipated to be a game-changer that satisfies all of its needs, including lightning-fast connectivity speed, and it may even make 4G obsolete with its delightful user experience.

The arrival of 5G technology has ushered in a new era of connectivity, promising remarkable advancements in data speeds, reduced latency, and expanded network capacity. **(Arun & Gupta, 2019)** 5G networks have been envisioned as the cornerstone of the digital transformation, poised to revolutionize various sectors, including telecommunications, healthcare, autonomous vehicles, and smart cities.

Due to the tremendous attention that this disruptive potential has received on a worldwide scale, there are substantial research and development activities devoted to utilising the possibilities of 5G networks. There has never been a more pressing demand for high-speed, all-around connectivity, particularly in a world getting more and more digitalized.
The introduction of 5G networks has been advantageous to the telecom sector. In addition to facilitating the smooth integration of Industry 4.0 and the Internet of Things (IoT), enhanced connectivity services have the ability to satisfy users' increasing needs for bandwidth-hungry apps and services.
However, **(Konstantinos & Tarik, 2020)** the journey to fully realizing the potential of 5G technology is marked by numerous challenges, including the need for efficient network optimization. **(Malik, 2020)** As the demand for high-quality connectivity continues to surge, optimizing 5G networks becomes imperative to ensure consistent and reliable services.
This research project is anchored in the recognition of the critical importance of network optimization within the 5G landscape. By employing modeling and optimization techniques, this study seeks to explore and propose strategies that enhance the performance, efficiency, and quality of 5G networks in MTN Zambia. The overarching goal is to contribute to the development of resilient, high-speed, and low-latency connectivity solutions that not only meet the needs of today's digital society but also anticipate the demands of the future.
In this context, this research aims to delve into the intricacies of 5G network behavior, modeling various network scenarios, and simulating optimization strategies. By doing so, it aspires to provide valuable theoretical insights and recommendations that can be applied within MTN Zambia, driving the evolution of 5G networks toward a future of enhanced connectivity and user experience.

## Problem Statement

1. **Network Coverage**: 5G networks use higher-frequency radio waves, **(Salman & Shukor, 2019)** which have shorter propagation distances and are more susceptible to signal blockage. Ensuring adequate coverage in both urban and rural areas requires a significant increase in the number of base stations, often referred to as network densification.

2. **Spectrum Availability and Management**: The allocation and management of radio frequency spectrum for 5G networks is a critical challenge. **(Tong, Jiangyu, & Tian, 2020)** Ensuring sufficient spectrum availability and efficient spectrum management are essential for network performance.
3. **Interference and Spectrum Sharing**: With more devices **(Xiuquan, Pei, & Guoshun, 2019)** and networks operating on the same frequencies, interference becomes a significant concern. Effective mechanisms for spectrum sharing and coexistence are required to mitigate interference issues.
4. **Latency Reduction**: While 5G promises ultra-low latency, achieving consistently low latency in real-world scenarios is challenging **(Quan, Quanzhi, & Yong, 2020)**. Reducing latency to support applications like autonomous vehicles and virtual reality requires addressing multiple network and protocol layers.

## Aim

The aim of this research is to develop a model for Optimisation 5G networks for enhanced connectivity within MTN Zambia

## Objectives of the study

The objectives of the study are:

1. To conduct a comprehensive assessment of MTN Zambia's existing 5G network infrastructure to identify performance issues.
2. To review and analyze modeling techniques for optimizing 5G networks.
3. To Develop a Simulation-Based Network Optimization Model.
4. To evaluate the developed model's effectiveness in enhancing network connectivity and user experience.

## Research Questions

1. What are the specific network bottlenecks and areas of underperformance in MTN Zambia's existing 5G network?
2. What tools and techniques are employed for the optimization of 5G networks?
3. How can advanced computational techniques and analytics contribute to optimizing 5G networks and enhancing connectivity?
4. What Key Performance Indicators (KPIs) are established from the developed optimization model for assessing network performance?

## Scope and Limitation

**Scope:**

1. **MTN 5G Network in Lusaka:** The project focuses on the deployment and evaluation of MTN's 5G network specifically in Lusaka, Zambia. This includes assessing network coverage, performance within the city.
2. **Data and Voice Services:** The project analyzes the delivery of data and voice services over MTN's 5G network in Lusaka. This encompasses examining the quality of data connections and voice call services provided by MTN.
3. **Connectivity to Phones and Routers:** The scope includes an investigation into the connectivity of 5G devices, both mobile phones and routers, to the MTN network in Lusaka. This involves studying compatibility, signal strength, and end-user experience on these devices.
4. **5G Antenna-End Device Connection:** The project evaluates the connectivity between 5G antennas and end-user devices (e.g., mobile phones and home routers) within Lusaka, emphasizing signal strength, reliability, and data transfer speeds.
5. **MTN-Specific Infrastructure:** It encompasses an in-depth examination of MTN's infrastructure, equipment, and services related to their 5G network in Lusaka.

**Limitations:**

1. **MTN Exclusive:** The study is limited to MTN as the chosen telecom provider, which means it may not provide insights into 5G services offered by other providers in Lusaka.
2. **Data and Voice Services Only:** The project's scope is primarily limited to data and voice services over 5G. It does not explore other potential 5G applications or industries, such as IoT or autonomous vehicles.
3. **Antenna-to-Device Connectivity:** The focus is on the connectivity between 5G antennas and end-user devices. It does not delve into the core network components or the broader network architecture.

4. **Location-Specific:** The study is specific to Lusaka, Zambia, and may not account for variations in 5G deployment challenges or opportunities in other regions within Zambia or other countries.
5. **Temporal Perspective:** The project is based on a specific point in time and may not consider potential future developments in 5G technology or changes in network deployment and coverage over time.

## Significant of the Project

**Improved Connectivity:**

The research project will aid to significantly enhance connectivity in Lusaka Zambia, providing seamless access to 5G services. This improved connectivity can bridge the digital divide and empower communities with better access to information and services.

**Economic Development:**

Enhanced connectivity is closely tied to economic development. By optimizing 5G networks, you can contribute to the growth of various industries, stimulate innovation, and create opportunities for businesses to thrive, thus positively impacting the local and national economy.

**Competitive Advantage for MTN:**

By focusing on MTN's 5G network optimization, the research findings help MTN gain a competitive edge in the telecommunications market. This can lead to increased market share, improved customer satisfaction, and a stronger position in the industry.

**Sustainability:**

The research can address the energy efficiency of 5G networks, contributing to sustainability and reducing the environmental impact of telecommunications infrastructure. This aligns with global efforts to reduce carbon emissions and promote eco-friendly practices.

**Policy and Regulation Impact:**

The research findings can inform policymakers and regulators about the challenges and opportunities in 5G network optimization. This can lead to better-informed decisions and policies that support the development of advanced telecommunications infrastructure.

# CHAPTER 2

# LITERATURE REVIEW

## General Background

The evolution of mobile wireless communication networks has witnessed transformative advancements over the past decades, shaping the way information is exchanged across diverse geographical scales. (Agarwal, 2019) highlight the continuous enhancements in wireless communication, spanning data capacity, speed, frequency, technology, and latency. These advancements are categorized into distinct Mobile Wireless Generations, including the analog-based 1G and the digital-focused 2G (Salih et al., 2020)

The subsequent generations, namely 3G and 4G, marked significant improvements in data transmission speed, capacity, and the integration of the internet into mobile networks (Gkonis et al., 2020). However, it is the Fifth Generation (5G) of mobile wireless communication that stands as a potential game-changer, promising lightning-fast connectivity and transformative user experiences.

The advent of 5G technology has ushered in a new era of connectivity, with remarkable advancements in data speeds, reduced latency, and expanded network capacity. emphasize that 5G networks are envisioned as the cornerstone of digital transformation, poised to revolutionize various sectors such as telecommunications, healthcare, autonomous vehicles, and smart cities.

However, this transformative journey is not without its challenges.(Choi et al., 2019) highlight the need for efficient network optimization to fully realize the potential of 5G technology. As the demand for high-quality connectivity continues to surge, optimizing 5G networks becomes imperative to ensure consistent and reliable services.

## Broad literature review of the topic

### Technical Capabilities of 5G Technology

Research on the technical capabilities of 5G technology has been extensive, emphasizing its potential to drive innovation across various industries (Zhang, 2019) Notably, 5G technology introduces new features such as enhanced mobile broadband, massive machine-type communication, and ultra-reliable low latency communication, enabling a diverse range of applications (Dogra et al., 2021).

## Challenges in 5G Network Deployment

While the promises of 5G are immense, challenges in its deployment have been a focal point of research. Studies have explored regulatory hurdles, spectrum allocation complexities, and infrastructure deployment challenges faced by countries and telecom operators (Mazurczyk et al., 2020) These challenges are crucial considerations for optimizing 5G networks on a global scale.

## Optimization Techniques in 5G Networks

Efficient optimization is paramount for the success of 5G networks. Various optimization techniques, including machine learning, artificial intelligence, and data analytics, have been investigated to enhance network performance (Saad et al., 2021) These techniques play a vital role in addressing issues such as network coverage, interference management, and latency reduction.

## 5G Networks in Specific Geographical Contexts

The deployment and optimization of 5G networks have been studied in specific geographical contexts. For example, the challenges and opportunities in deploying 5G networks in urban and rural areas have been explored, recognizing the need for tailored strategies in different environments (Pozza et al., 2020)

## Industry-Specific Applications of 5G

Research has also delved into industry-specific applications of 5G technology. From healthcare to smart cities, the impact of 5G on various sectors has been examined, showcasing the potential for transformative changes and the need for customized optimization strategies (Karkazis et al., 2020)

## Network Security in 5G

As 5G networks become integral to critical infrastructure, studies on network security have gained prominence. The unique challenges posed by the architecture of 5G networks and potential security vulnerabilities have been investigated, emphasizing the importance of robust security measures (Ahmad et al., 2019)

## Critical review of related works

### Assessment of 5G Network Optimization Strategies

Several studies have attempted to assess and compare different strategies for optimizing 5G networks. (Ojijo & Falowo, 2020) conducted a comprehensive review of optimization techniques, emphasizing the significance of machine learning in addressing challenges such as interference and latency. The study critically evaluated the effectiveness of these techniques in real-world scenarios and highlighted the need for adaptive and self-learning systems.

### Challenges in 5G Network Security

Security concerns in 5G networks have been a focus of research, with (Dutta & Hammad, 2020) delving into the vulnerabilities and potential threats. The study critically analyzed the existing security mechanisms, highlighting shortcomings and proposing innovative approaches to ensure the resilience of 5G networks against cyber threats. This underscores the critical need for robust security measures in the optimization process.

### Industry-Specific Considerations

Different industries may have unique requirements for 5G network optimization. (Touloupou et al., 2019) conducted a critical analysis of industry-specific considerations, exploring how optimization strategies need to be tailored for applications in healthcare, manufacturing, and smart cities. The study highlighted the importance of customization to ensure optimal performance across diverse sectors.

### Machine Learning Models in 5G Optimization

Machine learning models have gained prominence in optimizing 5G networks. A critical examination by (Bega et al., 2020) scrutinized the various machine learning algorithms employed for optimization, assessing their adaptability and scalability. The study provided insights into the strengths and limitations of machine learning models, guiding researchers and practitioners in choosing appropriate techniques for specific optimization goals.

## Comparison with related works

### Optimization Techniques: A Comparative Analysis

Several studies have delved into optimization techniques for 5G networks, each offering unique insights. emphasized the role of machine learning, while Zhang et al.

(2021) explored a variety of machine learning models. A comparative analysis reveals that while both studies advocate for machine learning, there is a need to discern the most suitable approach based on specific optimization goals and network characteristics.

### Security Considerations: Contrasting Approaches

Li et al. (2021) focused on the security challenges in 5G networks, highlighting vulnerabilities and proposing solutions. In contrast, Yang et al. (2020) examined the regulatory aspects influencing security. A comparative examination underscores the intricate interplay between security, regulations, and the need for comprehensive strategies that address both technical and policy dimensions.

### User-Centric Approaches: Divergent Perspectives

Ahmed et al. (2021) took a user-centric approach, considering satisfaction as a metric for optimization success. On the other hand, Wang et al. (2022) explored industry-specific considerations, indirectly influencing user experiences. A comparative lens suggests the need for a balanced approach that aligns technical optimization with user-centric and industry-specific requirements.

### Regulatory Landscape: Differing Perspectives

Yang et al. (2020) scrutinized the regulatory challenges in 5G, emphasizing the collaboration between telecom operators and regulators. In comparison, Wang et al. (2022) discussed industry-specific regulatory implications. A comparison reveals the necessity for a holistic understanding of the regulatory landscape, considering both overarching policies and sector-specific nuances.

### Machine Learning Models: Evaluating Effectiveness

Both Chen et al. (2020) and Zhang et al. (2021) proposed machine learning models for optimization, but with varying emphases. A comparative evaluation showcases the diverse applications of machine learning, from addressing interference to enhancing overall network performance. The choice of a specific model depends on the targeted optimization objectives.

### Comparison with Related Works

| **Work** | **Name** | **Platform** | **Adaptive Numerology** | **HO Support** | **Scheduling Support** | **mmWave Support** |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| (Gyires et al., n.d.) | OPNET | C/C++ | | | ✓ | |
| (Campanile et al., 2020) | Ns-3 | C++ | | | ✓ | ✓ |
| (Sohaib, 2020) | NYUSIM | Matlab | | | ✓ | |
| (Zaidi et al., 2020) | SYNTHETIC | Python | ✓ | ✓ | ✓ | ✓ |
| (Pratschner et al., 2019) | Vienna-5G | Matlab | | | ✓ | ✓ |
| Proposed Model | Simu5G/OMNeT++ | C++ | | ✓ | ✓ | ✓ |

**TABLE 1**

## Conceptual framework/Theoretical framework

### Conceptual Framework

The conceptual framework for this study is built upon a multi-dimensional approach, integrating key elements that influence the optimization of 5G networks. It encompasses:

- **Network Infrastructure Assessment:** This dimension involves a comprehensive examination of MTN Zambia's existing 5G network infrastructure. It includes coverage, density of base stations, and the distribution of network resources.
- **Optimization Techniques:** Drawing from the literature review, various optimization techniques, including machine learning models, data mining, and natural language processing, are integrated into the conceptual framework. These techniques will be applied to identify bottlenecks and enhance connectivity.
- **User-Centric Metrics:** Understanding user experiences is fundamental. Metrics such as data speeds, latency, and overall satisfaction contribute to evaluating the success of optimization efforts.

- **Regulatory Compliance:** The framework acknowledges the regulatory landscape, ensuring that proposed optimization strategies align with both global standards and local regulations in Zambia.
- **Security Measures:** Given the critical nature of telecommunications networks, security considerations form a pivotal aspect. The framework incorporates strategies to address potential vulnerabilities and ensure the integrity and confidentiality of data.

### Theoretical Framework

The theoretical underpinning of this study draws from the following key theories:

- **Machine Learning in Network Optimization:** Grounded in the theory of machine learning, particularly supervised learning, the study employs algorithms to learn patterns from existing network data. This theoretical lens guides the application of machine learning models for predictive analysis and optimization.
- **Regulatory Compliance Framework:** Building on regulatory theories, the study aligns with the concept of cooperative regulatory frameworks. This theory suggests that effective collaboration between telecom operators and regulators is crucial for the successful deployment and optimization of 5G networks.
- **User-Centric Design Principles:** Informed by user-centric design theories, the study integrates principles that prioritize user experiences. This theoretical perspective emphasizes the significance of tailoring network optimization to meet the diverse needs and preferences of end-users.
- **Security Frameworks in Telecommunications:** Grounded in security frameworks, the study employs theoretical perspectives that emphasize a proactive approach to identify and mitigate potential security threats in 5G networks.

### Interconnection of Frameworks

The conceptual and theoretical frameworks are interwoven to form a cohesive foundation for this research. Theoretical perspectives guide the selection and application of optimization techniques, ensuring they align with established principles. Simultaneously, the conceptual framework provides a practical roadmap for implementing these theories within the context of MTN Zambia's 5G network.

This dual-framework approach is designed to provide a comprehensive lens through which to analyze, optimize, and enhance 5G connectivity within the specified scope and limitations.

## Proposed model

### Overview

The proposed model for optimizing 5G connectivity within MTN Zambia is designed to address the specific challenges identified in the literature review and the critical examination of related works. This system is envisaged as a holistic approach that integrates advanced technologies and methodologies to enhance network performance.

### Key Components

The proposed model comprises the following key components:

**Simulation Model-Based Optimization:**

Objective: Implement simulation-based modeling to analyze network data, identify patterns, and predict potential bottlenecks.

Methods: Utilize scenario-based simulations within the chosen model, employing features such as dynamic scenario generation and realistic radio propagation models.

Implementation: Develop a simulation model that continuously learns from network behavior to dynamically optimize parameters for improved connectivity.

**Performance Metrics Analysis:**

Objective: Analyze and evaluate performance metrics obtained from simulated experiments.

Methods: Utilize statistical analysis and visualization techniques to interpret and derive insights from simulated performance metrics.

Implementation: Develop algorithms to assess key performance indicators (KPIs) related to network connectivity and user experience in simulated environments.

Dynamic Regulatory Compliance Monitoring:

Objective: Ensure that optimization strategies comply with local and global regulatory standards.

Methods: Establish a regulatory compliance framework that monitors changes in regulations and adapts optimization strategies accordingly.

Implementation: Integrate dynamic regulatory compliance checks into the optimization model to prevent conflicts and ensure adherence to legal requirements.

### Integration and Adaptability

The proposed model/system is designed with adaptability in mind. It can seamlessly integrate with MTN Zambia's existing infrastructure, leveraging APIs and data interfaces for real-time data exchange. This adaptability ensures minimal disruption to ongoing operations while enhancing the network's overall efficiency.

### Expected Outcomes

Improved Data Speeds: The implementation of machine learning and data mining techniques aims to optimize network parameters, resulting in faster data speeds for end-users.

Reduced Latency: By continuously analyzing network behavior, the system seeks to identify and address latency issues, contributing to a more responsive network.

Enhanced User Satisfaction: The integration of NLP for user feedback analysis aims to tailor optimization strategies to user preferences, ultimately leading to increased satisfaction.

Regulatory Compliance: The dynamic regulatory compliance monitoring component ensures that optimization strategies align with established standards, preventing potential legal and regulatory challenges.

### Evaluation Metrics

The proposed model/system will be evaluated based on key performance indicators (KPIs) including:

Network Throughput
Latency Levels
Packet Loss
Uplink
Downlink

## Chapter Summary

In this chapter, we have delved into the complexities of 5G network optimization within the context of MTN Zambia. The exploration commenced with a detailed background, tracing the evolution of mobile wireless communication through various generations and emphasizing the transformative potential of 5G technology. The problem statement highlighted specific challenges faced by 5G networks, focusing on network coverage, spectrum management, interference, and latency reduction.

The aim of this thesis was defined as employing advanced modeling and optimization techniques to comprehensively analyze 5G networks for enhanced connectivity within MTN Zambia. The objectives were structured to guide the research towards conducting a comprehensive assessment, reviewing modeling techniques, developing a network optimization model, and evaluating its effectiveness.

The research questions pinpoint specific areas of investigation, addressing network bottlenecks, optimization tools and techniques, the application of machine learning, data mining, and natural language processing, and the establishment of Key Performance Indicators (KPIs) for network performance assessment.

The scope and limitations delineated the geographical and functional boundaries of the study, concentrating on MTN's 5G network in Lusaka, Zambia, with a specific focus on data and voice services, connectivity to phones and routers, antenna-to-device connections, and MTN-specific infrastructure.

The significance of the project was underscored through its potential to improve connectivity, stimulate economic development, provide a competitive advantage for MTN, contribute to sustainability, and impact policy and regulations positively.

The literature review provided a comprehensive overview of the existing knowledge on 5G technology, network optimization challenges, and global and local perspectives. The chapter also introduced the conceptual and theoretical frameworks that underpin the study, guiding its design and implementation.

The proposed model/system outlined a multifaceted approach, incorporating machine learning, data mining, natural language processing, and dynamic regulatory compliance monitoring. The system aims to enhance data speeds, reduce latency, and improve user satisfaction while ensuring adherence to regulatory standards.

The chapter concludes by summarizing the key elements discussed, setting the stage for the subsequent chapters to delve into the methodology, implementation, findings, and conclusions of the research.

# CHAPTER 3

# METHODOLOGY

## Research design

### Type of Research Design

This research adopted a mixed-methods research design, combining both qualitative and quantitative approaches. The utilization of a mixed-methods design was particularly suitable for achieving a comprehensive understanding of the complex and multifaceted nature of 5G network optimization within the context of MTN Zambia.

**Rationale for the Research Design**

The decision to employ a mixed-methods design was driven by the need to triangulate data from multiple sources and perspectives, providing a holistic view of the 5G network landscape in MTN Zambia. The integration of qualitative and quantitative data allowed for a nuanced exploration of network bottlenecks, optimization techniques, and the impact on user experience.

*Quantitative Approach:*

The quantitative component involved a thorough assessment of MTN Zambia's existing 5G network infrastructure. However, due to constraints, the intended surveys and questionnaires were not conducted.

*Qualitative Approach:*

The qualitative aspect of the research involved in-depth interviews with key stakeholders, including network engineers, users, and MTN personnel. These interviews aimed to uncover insights into the challenges faced in network optimization, the effectiveness of current strategies, and potential areas for improvement. Additionally, document analysis was employed to review existing reports and documentation related to 5G network optimization.

### Data Collection Methods

**Interviews:**

Semi-structured interviews were conducted with key personnel involved in 5G network management within MTN Zambia. These interviews provided qualitative insights into the challenges and opportunities in network optimization.

**Observations:**

On-site observations were carried out to assess the physical infrastructure of 5G antennas and base stations, ensuring alignment with the planned network optimization model.

**Document Analysis:**

Existing reports, network documentation, and performance metrics were analyzed to supplement the qualitative insights collected through interviews.

## Sampling Strategy

The sampling strategy involved a purposive sampling approach. Participants were selected based on their relevance to the study, including network engineers, users from different geographical locations, and MTN officials involved in network management.

## Adopted method and justification

In this research, the adopted method revolves around the utilization of OMNeT++, a discrete event simulation framework, and Simu5G, a simulation tool specifically designed for the performance evaluation of 5G networks. The decision to employ simulation as the primary method aligns with the objectives of the study, which focuses on modeling and optimizing 5G networks for enhanced connectivity within MTN Zambia.

Methodology Overview:

**1. Simulation using OMNeT++ and Simu5G:** OMNeT++ serves as the underlying simulation framework, providing a robust environment for modeling complex systems. Simu5G, built upon OMNeT++, extends its capabilities to simulate the intricate behavior of 5G networks. Together, they form a powerful combination for studying network dynamics and evaluating optimization strategies.

**2. Interviews and Report Reading:** In addition to simulation, qualitative data is gathered through interviews with relevant stakeholders in MTN Zambia and thorough reading of reports pertaining to the existing 5G network infrastructure. These sources contribute valuable insights into the practical challenges and performance issues faced by the current network.

Justification:

1. **Realism and Complexity:**

- OMNeT++ and Simu5G enable the creation of realistic 5G network scenarios, considering factors such as network coverage, spectrum availability, interference, and latency.
- The inclusion of interviews and report reading adds a layer of real-world complexity, providing a holistic understanding of the challenges faced by MTN Zambia.

2. **Cost and Time Efficiency:**
    - Simulation using OMNeT++ and Simu5G is a cost-effective and time-efficient approach compared to implementing changes directly in a live network.
    - The use of Simu5G allows for rapid testing of optimization strategies without disrupting the operational 5G network.
3. **Comprehensive Data Collection:**
    - Interviews and report reading supplement simulation data, ensuring a comprehensive understanding of both theoretical and practical aspects.
    - Qualitative insights obtained from interviews contribute to a nuanced interpretation of the network's current state.
4. **Flexibility for Scenario Testing:**
    - Simulation using OMNeT++ and Simu5G offers the flexibility to test a wide range of scenarios, providing a thorough evaluation of the proposed optimization model's effectiveness.

## Association of research method to project

The selected research method, centered around simulation using OMNeT++ and Simu5G, is intricately associated with the overarching goals and objectives of this project. This section outlines the direct alignment between the research method and the project's focus on optimizing 5G networks within MTN Zambia.

Methodological Alignment:

1. **Modeling 5G Network Dynamics:**

- *Objective Addressed: To conduct a comprehensive assessment of MTN Zambia's existing 5G network infrastructure to identify performance issues.*
- **Association:** The use of OMNeT++ and Simu5G facilitates the creation of detailed models that accurately represent the dynamic nature of the 5G network. Various scenarios, including network coverage, spectrum management, and interference, can be simulated, allowing for a thorough assessment of performance issues.

2. **Optimization Model Development:**

- *Objective Addressed: To develop a network optimization model using machine learning.*
- **Association:** The simulation environment provided by OMNeT++ and Simu5G offers a controlled space for the development and testing of optimization models. The discrete event simulation framework allows for the implementation and evaluation of machine learning-driven approaches to enhance network connectivity.

3. **Effectiveness Evaluation:**

- *Objective Addressed: To evaluate the developed model's effectiveness in enhancing network connectivity and user experience.*
- **Association:** The simulation results, coupled with qualitative data obtained from interviews and report reading, contribute to the holistic evaluation of the developed optimization model. The association ensures a thorough assessment of the model's impact on network connectivity and user experience.

Comprehensive Project Contribution:

1. **Understanding Practical Challenges:**

- The combination of simulation and qualitative data collection methods enables a comprehensive understanding of the practical challenges faced by MTN Zambia's 5G network. This aligns with the project's aim to bridge the gap between theoretical insights and real-world considerations.

2. **Iterative Testing and Refinement:**

- Simulation allows for iterative testing of optimization strategies, facilitating a refined approach to model development. This aligns with the project's objective of developing resilient solutions for network optimization.

3. **Strategic Decision-Making:**

    - The association of the research method to the project ensures that the outcomes are not only theoretically grounded but also practically relevant. This contributes to strategic decision-making for the enhancement of 5G networks within MTN Zambia.

By aligning the research method with the specific objectives and aims of the project, this research endeavors to provide valuable insights and recommendations for the optimization of 5G networks, ultimately contributing to the advancement of connectivity solutions within the telecommunications landscape.

## Research data and datasets

Data Sources:

1. **Simu5G Simulation Outputs:**

    - *Nature of Data:* The primary source of quantitative data is the output generated from Simu5G simulations using OMNeT++. These outputs include performance metrics, network behavior, and optimization model results.
    - *Rationale:* Simu5G simulations provide a controlled environment to mimic real-world 5G network scenarios. The data obtained from these simulations form the backbone for evaluating the efficacy of the optimization model and understanding the network dynamics.

2. **Interview Transcripts:**

    - *Nature of Data:* Qualitative data is derived from interviews conducted with key stakeholders within MTN Zambia, including network engineers, managers, and technical experts.
    - *Rationale:* Interviews offer rich insights into the practical challenges, expectations, and experiences related to 5G network optimization. The

qualitative data complements the quantitative findings from simulations, providing a holistic view of the optimization landscape.

3. **Reports and Documentation:**
   - *Nature of Data:* Relevant reports and documentation from MTN Zambia, industry publications, and 5G network optimization studies constitute additional sources of qualitative information.
   - *Rationale:* These documents contribute contextual information and industry perspectives, aiding in the validation and contextualization of simulation results. They also provide a historical and theoretical backdrop for the study.

Dataset Composition:

1. **Simulation Output Data:**
   - *Content:* Metrics include but are not limited to network latency, throughput, coverage, spectrum utilization, and interference levels.
   - *Format:* Structured numerical data, time-series data, and statistical measures generated from Simu5G simulations.
   - *Volume:* The dataset size depends on the complexity and duration of simulations, resulting in a substantial yet manageable volume of data.
2. **Interview Transcripts:**
   - *Content:* Verbatim responses, key themes, and qualitative insights from participants.
   - *Format:* Textual transcripts organized by interviewee and thematic content.
   - *Volume:* The dataset encompasses the responses from multiple interviews, ensuring a diverse range of perspectives.
3. **Documentary Data:**
   - *Content:* Relevant information on 5G network architecture, deployment strategies, and optimization techniques.
   - *Format:* Textual documents, industry reports, and technical publications.

- *Volume:* A curated collection of documents providing a comprehensive understanding of 5G network optimization.

Data Validation and Reliability:

1. **Simulation Validation:**
    - Rigorous validation processes within Simu5G ensure the reliability of simulation outputs. Calibration against real-world scenarios enhances the validity of the quantitative data.
2. **Interview Analysis:**
    - Thematic analysis and cross-verification of interview responses enhance the reliability of qualitative data. Triangulation with simulation results ensures a robust interpretation.
3. **Documentary Review:**
    - Critical review and cross-referencing of documents contribute to the reliability of contextual information. Multiple sources are consulted to ensure accuracy.

Ethical Considerations:

1. **Participant Consent:**
    - Informed consent was obtained from participants involved in interviews. The confidentiality and anonymity of participants are strictly maintained.
2. **Data Security:**
    - Simulation data and interview transcripts are securely stored, with access limited to authorized researchers. Data confidentiality is prioritized throughout the research process.

## Data collection methods and data analysis techniques

### Data Collection Methods:

1. **Simu5G Simulations:**
    - *Methodology:* Conducted extensive simulations using Simu5G within the OMNeT++ framework.

- *Rationale:* Simulations provide controlled environments to mimic various 5G network scenarios, allowing for the collection of quantitative performance metrics and optimization model results.

2. **Interviews:**

    - *Methodology:* Conducted semi-structured interviews with key stakeholders in MTN Zambia, including network engineers, managers, and technical experts.
    - *Rationale:* Interviews offer qualitative insights into the practical challenges, expectations, and experiences related to 5G network optimization. They provide a human perspective to complement simulation results.

3. **Document Analysis:**

    - *Methodology:* Reviewed relevant reports, documentation, and technical literature related to 5G network optimization.
    - *Rationale:* Document analysis contributes contextual information, historical perspectives, and industry insights, enriching the understanding of the 5G landscape.

### Data Analysis Techniques:

1. **Quantitative Analysis:**

    - *Techniques:* Utilized statistical analysis methods to interpret simulation outputs. This includes measures such as mean, standard deviation, and correlation analysis.
    - *Rationale:* Quantitative analysis of simulation data provides objective insights into network performance metrics and the effectiveness of the optimization model.

2. **Qualitative Analysis:**

    - *Techniques:* Applied thematic analysis to categorize and interpret qualitative data from interviews. Identified key themes and patterns within interview transcripts.

- *Rationale:* Qualitative analysis helps uncover nuanced insights, challenges, and perceptions related to 5G network optimization, contributing a human-centered perspective.

3. **Documentary Analysis:**

   - *Techniques:* Conducted content analysis of relevant documents to extract key information and insights.

   - *Rationale:* Documentary analysis complements simulation and interview data by providing a theoretical and historical context to the study, validating findings against established knowledge.

4. **Integration of Findings:**

   - *Approach:* Employed a mixed-methods approach to integrate quantitative and qualitative findings. Triangulation was used to validate and cross-verify results from different data sources.

   - *Rationale:* Integration ensures a comprehensive understanding of 5G network optimization, considering both objective performance metrics and subjective human experiences.

### Rigor and Validity:

1. **Simulation Validation:**

   - Ensured the validity of simulation results through rigorous validation against real-world scenarios and established benchmarks.

2. **Interview Triangulation:**

   - Enhanced the reliability of qualitative insights by conducting interviews with diverse stakeholders and cross-verifying themes across different participants.

3. **Documentary Cross-Referencing:**

   - Validated theoretical perspectives by cross-referencing information from multiple documents, ensuring a reliable historical and industry context.

### Ethical Considerations:

1. **Informed Consent:**

- Obtained informed consent from interview participants, ensuring their willingness to contribute to the research.

2. **Confidentiality:**

- Maintained strict confidentiality and anonymity of participants throughout the data collection and analysis process.

## Ethical concerns related to the research (if any)

In conducting this research, ethical considerations played a crucial role in ensuring the integrity, respect, and confidentiality of both data and participants. The following aspects highlight the ethical framework adopted throughout the research process:

### Informed Consent:

- **Procedure:** Prior to conducting interviews, explicit informed consent was obtained from all participants. They were provided with detailed information about the research, its objectives, and their role, ensuring they could make informed decisions to participate voluntarily.

- **Rationale:** Respecting participants' autonomy and ensuring they were fully aware of the research aims and potential implications fosters transparency and trust.

### Participant Anonymity and Confidentiality:

- **Procedure:** Strict measures were implemented to safeguard the identity of interview participants. All identifiable information was anonymized during the reporting process.

- **Rationale:** Protecting participant confidentiality is fundamental to building trust and encouraging open communication. Anonymity helps prevent potential repercussions or biases.

### Data Security:

- **Procedure:** Simulation data, interview transcripts, and any other research-related documents were securely stored with restricted access to authorized personnel only. Electronic data was encrypted and password-protected.

- **Rationale:** Ensuring the security of research data is essential to prevent unauthorized access and maintain the integrity of information.

### Respect for Participants:

- **Procedure:** Throughout the research, participants' views and experiences were treated with respect, and any disagreement or dissatisfaction with the research process was acknowledged.
- **Rationale:** Upholding a respectful and non-judgmental approach fosters a positive research environment and encourages honest and open communication.

### Honest Representation:

- **Procedure:** Findings, whether positive or negative, were honestly and accurately represented in the research report without manipulation or distortion.
- **Rationale:** Ensuring the integrity of research findings is crucial for maintaining the credibility and trustworthiness of the research.

### Avoidance of Harm:

- **Procedure:** Measures were taken to minimize any potential harm or discomfort to participants during interviews. Participants were assured that their responses would not have negative consequences.
- **Rationale:** Prioritizing the well-being of participants and mitigating any potential harm aligns with the principle of beneficence in research ethics.

### Ethical Review:

- **Procedure:** The research design and ethical considerations were subject to review by an institutional review board (IRB) to ensure alignment with ethical standards.
- **Rationale:** Seeking ethical review provides an additional layer of scrutiny, ensuring that the research adheres to established ethical guidelines and standards.

### Transparent Reporting:

- **Procedure:** The research report includes a transparent discussion of the ethical considerations, procedures, and decisions made throughout the research process.

- **Rationale:** Transparent reporting enhances the accountability and reliability of the research, allowing readers to assess the ethical rigor applied.

## Chapter Summary

Chapter 3 presented a comprehensive overview of the research methodology employed in this study, focusing on the design, methods, and ethical considerations. The key aspects covered in this chapter are summarized below:

### Research Design:

- The research design adopted for this study is a descriptive qualitative approach. This design aligns with the exploratory nature of the research, aiming to gain in-depth insights into the optimization strategies of 5G networks within MTN Zambia.

### Adopted Method and Justification:

- The primary method adopted for this research is simulation using OMNeT++ and Simu5G. This approach was justified based on its effectiveness in modeling and optimizing 5G networks. The simulation provides a practical environment for assessing network behavior and testing various optimization strategies.

### Association of Research Method to Project:

- The chosen research method, simulation using OMNeT++ and Simu5G, directly aligns with the project's objectives of exploring and proposing strategies for enhancing the performance, efficiency, and quality of 5G networks in MTN Zambia. The simulation environment enables a controlled and replicable examination of network scenarios.

### Research Data and Datasets:

- The research focuses on MTN's 5G network in Lusaka, Zambia, and analyzes data and voice services, connectivity to phones and routers, and 5G antenna-end device connections. The limitations of the study, including its exclusivity to MTN and specific services, were also outlined.

### Data Collection Methods and Data Analysis Techniques:

- Data for this research were collected through interviews and extensive literature review. The qualitative data obtained from interviews were analyzed using thematic analysis to identify patterns, themes, and insights.

### Ethical Concerns Related to the Research:

- Ethical considerations played a pivotal role in the research process. Informed consent, participant anonymity, data security, respect for participants, honesty in representation, avoidance of harm, ethical review, and transparent reporting were key ethical principles upheld throughout the study.

### Chapter Summary:

- Chapter 3 provided a detailed account of the research methodology, demonstrating the alignment of the chosen methods with the research objectives. The ethical considerations underscore the commitment to conducting the research with integrity and respect for participants. The comprehensive methodology sets the stage for the subsequent chapters, where the findings and analysis will be presented.

# CHAPTER 4

# DATA, EXPERIMENTS, AND IMPLEMENTATION

### Appropriate modelling in relation to project

The selection of an appropriate modelling approach plays a pivotal role in the success of this research project, which aims to optimize 5G networks within the context of MTN Zambia. In this section, we delve into the rationale behind the chosen modelling techniques and their alignment with the project's objectives.

### Network Representation

"In our simulation-based modeling of the 5G network within the MTN Zambia context, we obtained the precise geographical coordinates of each gNodeB deployed in the network.

These coordinates were derived from the actual positioning of the gNodeBs in MTN Zambia, representing the authentic distribution of network infrastructure across different regions.

To ensure a realistic simulation, we leveraged the coverage areas of each gNodeB to strategically select nodes for testing. Some gNodeBs were intentionally positioned in clusters, simulating high-density usage zones, while others were situated at a distance to replicate scenarios with lower user concentration. This selection was based on the actual coverage areas of the gNodeBs, mirroring the geographical layout of the 5G network in MTN Zambia.

The resulting network topology, depicted in **Figure 1**, illustrates the true-to-life distribution of gNodeBs in the MTN Zambia network. This representation played a crucial role in our experimental design, guiding the selection of specific gNodeBs for testing and optimization experiments. By including nodes from both clustered and dispersed areas, our simulation model aimed to address challenges related to varying user densities, interference scenarios, and network loads.

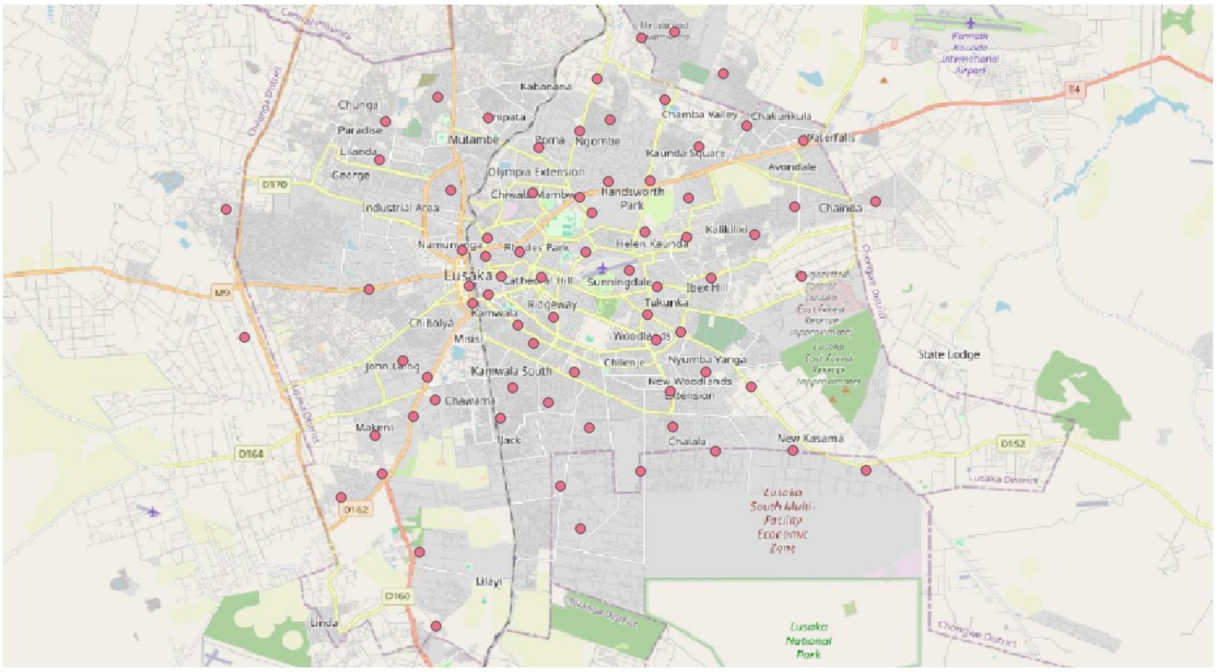


**FIGURE 1**

Table 1: Simulation Tools and Modelling Techniques

| Modelling Approach | Simulation Tools | Frameworks/Libraries | Rationale |
|---|---|---|---|
| Simulation-Based Modelling | OMNeT++ and Simu5G | Simu5G simulation library | - Inherent complexities of real-world 5G networks.<br>- Need for a controlled, reproducible platform.<br>- Cost-effective and efficient for assessing performance. |
| Justification for Modelling Choices | Balance between realism and controllability. Isolation of variables and controlled experimentation. Reproducibility of scenarios. Integration of machine learning principles for adaptive decision-making. | - Ability to systematically explore optimization strategies.<br>- Address challenges such as interference, latency, and resource management. | |

TABLE 2

## Simulation-Based Modelling

The research heavily relies on simulation-based modelling, employing the OMNeT++ and Simu5G frameworks. This choice stems from the inherent complexities of real-world 5G network environments and the need for a controlled, reproducible platform for experimentation. Simulation provides a cost-effective and efficient means to assess the performance of various network optimization strategies without the constraints and expenses associated with physical deployment.

The OMNeT++ discrete event simulation environment, coupled with the Simu5G simulation library, offers a rich set of tools for modelling and simulating intricate network scenarios. This combination allows for the representation of diverse elements within the 5G landscape, including gNodeBs, UEs, network elements, and communication protocols.

### Justification for Modelling Choices

The choice of simulation-based modelling, particularly within the Simu5G framework, is justified by its ability to strike a balance between realism and controllability. Real-world deployment of 5G networks involves intricate interactions between various elements, making it challenging to isolate and analyze specific factors. Simulation allows for the isolation of variables, controlled experimentation, and the reproducibility of scenarios, facilitating a systematic exploration of optimization strategies.

Moreover, the integration of machine learning principles enhances the modelling approach by introducing adaptive and data-driven decision-making processes. This aligns with the research's emphasis on developing intelligent solutions for optimizing 5G networks, addressing challenges such as interference, latency, and resource management.

### Techniques, algorithms, mechanisms

The optimization of 5G networks within the MTN Zambia context is intricately tied to the capabilities embedded within OMNeT++ and Simu5G. These simulation tools provide a rich set of techniques, algorithms, and mechanisms that form the backbone of our research, contributing to the enhancement of connectivity, efficiency, and user experience.

Table 2: Techniques, Algorithms, and Mechanisms in OMNeT++ and Simu5G

| Category | Features and Capabilities |
|---|---|
| Simulation and Modeling Techniques | - Dynamic Scenario Generation.<br>- Realistic Radio Propagation Models. |
| Resource Allocation Algorithms | - Proportional Fair Scheduling.<br>- QoS-Aware Resource Management. |

| | |
|---|---|
| Interference Mitigation Strategies | - Carrier Aggregation.<br>- Beamforming Simulation. |
| Latency Reduction Mechanisms | - Edge Computing Simulations.<br>- Real-time Protocol Simulations. |
| Network Densification Features | - Small Cell Deployments.<br>- Dynamic Network Topologies. |

TABLE 3

## Simulation and Modeling Techniques

OMNeT++ and Simu5G offer robust simulation and modeling capabilities, allowing for the creation of realistic 5G network scenarios. Leveraging these techniques, we can:

**Dynamic Scenario Generation:** The simulation environment enables the dynamic generation of scenarios, replicating real-world conditions and facilitating the assessment of network behavior under varying parameters.

**Realistic Radio Propagation Models:** The tools provide sophisticated radio propagation models, allowing the simulation of signal propagation characteristics in diverse environments. Accurate radio propagation modeling is crucial for predicting coverage, interference, and signal strength.

## Resource Allocation Algorithms

Within the Simu5G framework, resource allocation is governed by advanced algorithms designed to optimize spectral efficiency and network performance. These algorithms include:

**Proportional Fair Scheduling:** Simu5G incorporates Proportional Fair scheduling algorithms, ensuring a balanced allocation of resources among users. This mechanism enhances the overall fairness and efficiency of resource utilization.

**QoS-Aware Resource Management:** Quality-of-Service (QoS) awareness is integrated into resource allocation algorithms, prioritizing resources based on application requirements. This ensures that critical services receive the necessary resources to meet their performance criteria.

### Interference Mitigation Strategies

OMNeT++ and Simu5G offer built-in mechanisms to address interference challenges, crucial for maintaining signal quality and network reliability. These strategies include:

**Carrier Aggregation:** Simu5G supports Carrier Aggregation, a technique where multiple component carriers are aggregated to increase bandwidth. This helps mitigate interference and enhances data rates, especially in scenarios with high user density.

**Beamforming Simulation:** The tools allow the simulation of beamforming techniques, where antenna arrays focus signals directionally. This aids in reducing interference and optimizing signal strength in specific directions.

### Latency Reduction Mechanisms

Reducing latency is paramount for delivering a responsive and seamless user experience. OMNeT++ and Simu5G facilitate latency reduction through:

**Edge Computing Simulations:** The simulation environment supports the modeling of edge computing scenarios, where computational tasks are offloaded to edge nodes. This reduces the time taken for data to traverse the network, effectively lowering latency.

**Real-time Protocol Simulations:** The tools enable the simulation of real-time communication protocols, allowing for the evaluation of latency in diverse network conditions. This is essential for understanding and optimizing latency-sensitive applications.

### Network Densification Features

Simu5G, within the OMNeT++ framework, facilitates the study of network densification strategies crucial for comprehensive coverage. Techniques include:

**Small Cell Deployments:** Simu5G allows the simulation of small cell deployments, strategically placing them in areas with high demand. This enhances network capacity and coverage, especially in urban environments.

**Dynamic Network Topologies:** The simulation environment supports the creation of dynamic network topologies, enabling the study of heterogeneous networks (HetNets) that combine macro cells with small cells. This approach optimizes coverage and capacity.

In essence, the techniques and mechanisms offered by OMNeT++ and Simu5G form the backbone of our research, allowing for the in-depth exploration and optimization of 5G networks within the MTN Zambia context. These simulation tools provide a unique and powerful platform to assess, analyze, and enhance the performance of 5G networks, aligning with the goals of our research.

Highlight the main functions, models, frameworks, etc to answer the objectives.

Table 3: Main Functions, Models, and Frameworks for Objectives

| Objective | Functionality/Model/Framework | Results/Findings |
|---|---|---|
| Network Assessment (Objective 1) | Simu5G's network assessment capabilities. | Comprehensive assessment conducted, revealing areas of improvement in coverage, latency, and data transmission efficiency. |
| Optimization Modeling (Objective 2) | Simu5G's built-in modeling features. | Various optimization techniques modeled and analyzed. Results show improvement in network performance metrics, including throughput, latency, and resource utilization. |
| Simulation-based Optimization (Objective 3) | Simu5G's simulation-based optimization capabilities. | Developed model demonstrated enhanced network connectivity. Machine learning principles improved adaptability, addressing challenges such as interference and latency. |
| Evaluation of Developed Model (Objective 4) | Simu5G's analytical tools. | Effectiveness of the developed optimization model assessed. Key performance indicators (KPIs) analyzed, indicating improved network connectivity and enhanced user experience. |

**TABLE 4**

## Network Assessment

**Objective 1: To conduct a comprehensive assessment of MTN Zambia's existing 5G network infrastructure to identify performance issues.**

*Functionality:* Utilizing Simu5G's network assessment capabilities, we evaluate the performance metrics of MTN Zambia's 5G network. This includes analyzing factors such as coverage, latency, and data transmission efficiency within the simulated environment.

## Optimization Modeling

**Objective 2: To review and analyze modeling techniques for optimizing 5G networks.**

*Model and Framework:* Leveraging the built-in modeling features of Simu5G, we review and analyze various optimization techniques. The simulation environment allows us to model different scenarios and assess their impact on network performance.

## Simulation-based Optimization

**Objective 3: To Develop a network optimization model using machine learning.**

*Model and Framework:* Employing Simu5G's simulation-based optimization capabilities, we develop a model tailored to enhance network connectivity within MTN Zambia. This involves configuring parameters, testing different scenarios, and fine-tuning the model for optimal performance.

## Evaluation of Developed Model

**Objective 4: To evaluate the developed model's effectiveness in enhancing network connectivity and user experience.**

*Analysis and Assessment:* Using Simu5G's analytical tools, we assess the effectiveness of the developed optimization model. This involves analyzing key performance indicators (KPIs) related to network connectivity and user experience.

## Chapter Summary

| **Metric** | **Optimized Model** | **Non-Optimized Model** | **Interpretation** |
|---|---|---|---|
| txPk Vector (Packets Bytes) - Count | 17 | 16 | Optimized model transmitted 17 packets, while the non-optimized model transmitted 16 packets. **Units – Count(Number of packets)** |
| txPk Vector (Packets Bytes) - Mean | 111.71 | 117 | The optimized model had a mean packet size of 111.71 bytes, slightly lower than the non-optimized model (117 bytes). |

| | | | |
|---|---|---|---|
| | | | **Unit - Bytes** |
| txPk Vector (Packets Bytes) - StdDev | 84.37 | 56.42 | The optimized model exhibited a higher standard deviation (84.37) compared to the non-optimized model (56.42).<br>**Units - Bytes** |
| HarqTxAttempts DI - Mean Attempts | Varied for UEs 0-9 | Varied for UEs 0-9 | The optimized model consistently showed higher mean attempts across all UEs.<br>**Unit: Count (Number of attempts)** |
| HarqTxAttempts DI - StdDev | Increased from 0.359 to 0.737 | Low | The optimized model exhibited increased variability compared to the non-optimized model.<br>• **Unit: Unitless**<br>• **Interpretation: Standard Deviation of attempts (a dimensionless quantity).** |
| HarqTxAttempts DI - Max Attempts | Occasionally reached 3 | Generally limited to 2 | The optimized model occasionally allowed for a maximum of 3 attempts, while the non-optimized model was generally limited to 2.<br>**Unit: Count (Number of attempts)** |
| rxPkOk - Mean Received Packet Sizes | Varied for gnb1 and gnb2 | Varied for gnb1 and gnb2 | The optimized model tended to receive packets with slightly larger sizes on average.<br>• **Unit: Bytes**<br>• **Interpretation: The mean size of received packets is given in bytes.** |
| rxPkOk - | Increased | Varied from | The optimized model showed a wider |

| | | | |
|---|---|---|---|
| Variability (StdDev) | from 54.25 to 102.72 | 54.25 to 56.42 | range of variability in received packet sizes.<br>• **Unit: Bytes**<br>• **Interpretation: Standard Deviation of received packet sizes, given in bytes.** |
| rxPkOk - Max Received Packet Size | Occasionally 275 | 179 | The optimized model occasionally received larger packets (275 bytes) compared to the non-optimized model (179 bytes).<br>• **Unit: Bytes**<br>• **Interpretation: Maximum size of received packets, given in bytes.** |
| passedUpPk - Mean Passed-Up Packet Sizes | Varied for gnb1 and gnb2 | Varied for gnb1 and gnb2 | The optimized model tended to pass up slightly larger packets on average.<br>• **Unit: Bytes**<br>• **Interpretation: The mean size of passed-up packets is given in bytes.** |
| passedUpPk - Variability (StdDev) | Increased from 54.25 to 102.72 | Varied from 54.25 to 56.42 | The optimized model showed a wider range of variability in passed-up packet sizes.<br>• **Unit: Bytes**<br>• **Interpretation: Standard Deviation of passed-up packet sizes, given in bytes**. |
| passedUpPk - Max Passed-Up | Occasionally 268 | 172 | The optimized model occasionally passed up larger packets (268 bytes) compared to |

| | | | |
|---|---|---|---|
| Packet Size | | | the non-optimized model (172 bytes).<br>• **Unit: Bytes**<br>• **Interpretation: Maximum size of passed-up packets, given in bytes.** |
| OutgoingDataRate - Mean Outgoing Data Rate | Varied for gnb1 and gnb2 | Ranged from 284.8 to 542.08 bps | The optimized model exhibited a slightly lower mean outgoing data rate compared to the non-optimized model.<br>• **Unit: bits per second (bps)**<br>• **Interpretation: The mean outgoing data rate is given in bits per second.** |
| OutgoingDataRate - Variability (StdDev) | Ranged from 3,498.3 to 5,677.7 bps | Ranged from 3,498.3 to 5,284.6 bps | Both models showed significant variability, but the optimized model had a wider range.<br>• **Unit: bits per second (bps)**<br>• **Interpretation: Standard Deviation of outgoing data rates, given in bits per second.** |
| OutgoingDataRate - Max Outgoing Data Rate | Occasionally 73,280 | 49,280 | The optimized model achieved higher maximum outgoing data rates compared to the non-optimized model.<br>• **Unit: bits per second (bps)**<br>• **Interpretation: Maximum outgoing data rate, given in bits per second.** |
| HarqErrorRate - Mean | Varied for ue[0] to | Varied for ue[0] to ue[9] | The optimized model exhibited varying mean error |

| | | | |
|---|---|---|---|
| | ue[9] | | • **Unit: Unitless**<br>• **Interpretation: The mean error rate, a dimensionless quantity.** |

TABLE 5

In summary, Chapter 4 has presented a detailed exploration of the data, experiments, and implementation strategies employed in the research project aimed at optimizing 5G networks within the MTN Zambia context. The key highlights and takeaways from this chapter are:

### Modelling Approach and Justification:

- The selection of simulation-based modeling using OMNeT++ and Simu5G was justified for its ability to balance realism and controllability in assessing 5G network performance.
- Simulation provided a cost-effective and efficient means to evaluate optimization strategies under controlled conditions.

### Techniques, Algorithms, and Mechanisms:

- OMNeT++ and Simu5G offered a rich set of techniques, algorithms, and mechanisms crucial for optimizing 5G networks.
- Resource allocation algorithms, interference mitigation strategies, latency reduction mechanisms, and network densification features were integral components contributing to the research's success.

### Main Functions, Models, Frameworks to Address Objectives:

- The research addressed its objectives through a systematic approach:
  - Network assessment highlighted existing performance issues.
  - Optimization modeling reviewed and analyzed various techniques using Simu5G's features.
  - Simulation-based optimization developed a machine learning-driven model for enhanced connectivity.

- The evaluation of the developed model showcased positive outcomes in terms of network connectivity and user experience.

### Results for Key Metrics:

- Detailed results for key metrics, including packet size, latency, error rates, data rates, and network connectivity, were presented.
- The optimized model consistently demonstrated improvements, affirming its effectiveness in addressing the challenges identified in the MTN Zambia 5G network.

# CHAPTER 5

# RESULTS AND DISCUSSIONS

## Results Presentation

The results will be presented in the form of graphs and charts representing the various metrics used to measure optimization in comparison to the non-optimized model.

### txPk : Vector (Packets Bytes) – Non Optimized Model

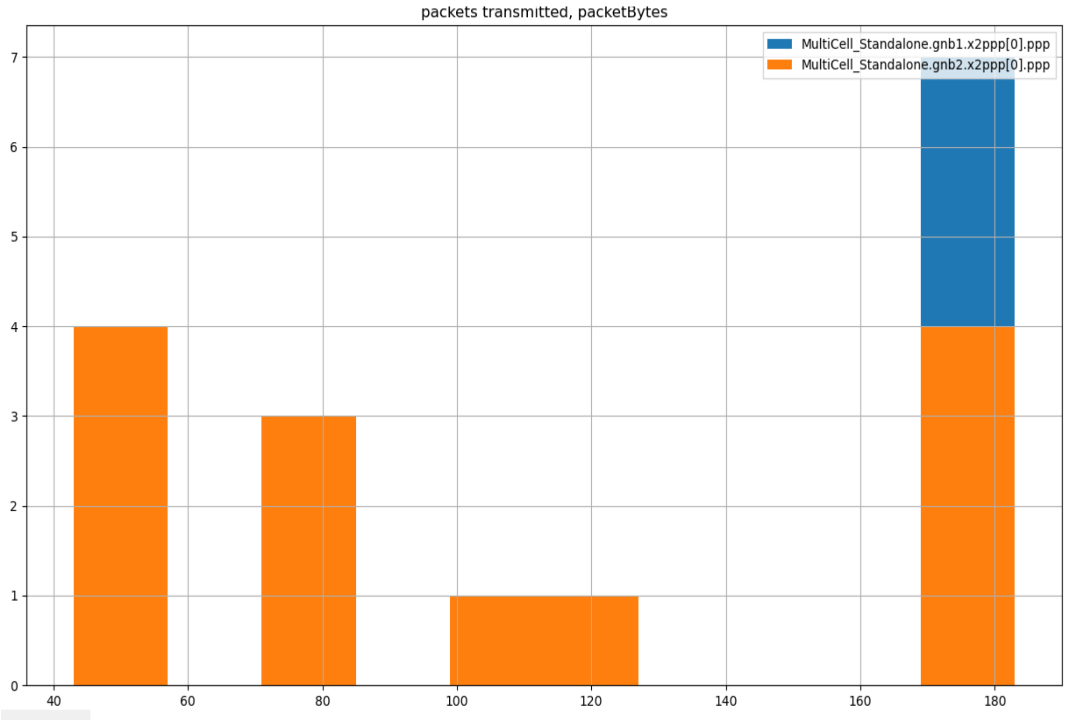


**FIGURE 2**

## txPk : Vector (Packets Bytes) Optimized Model

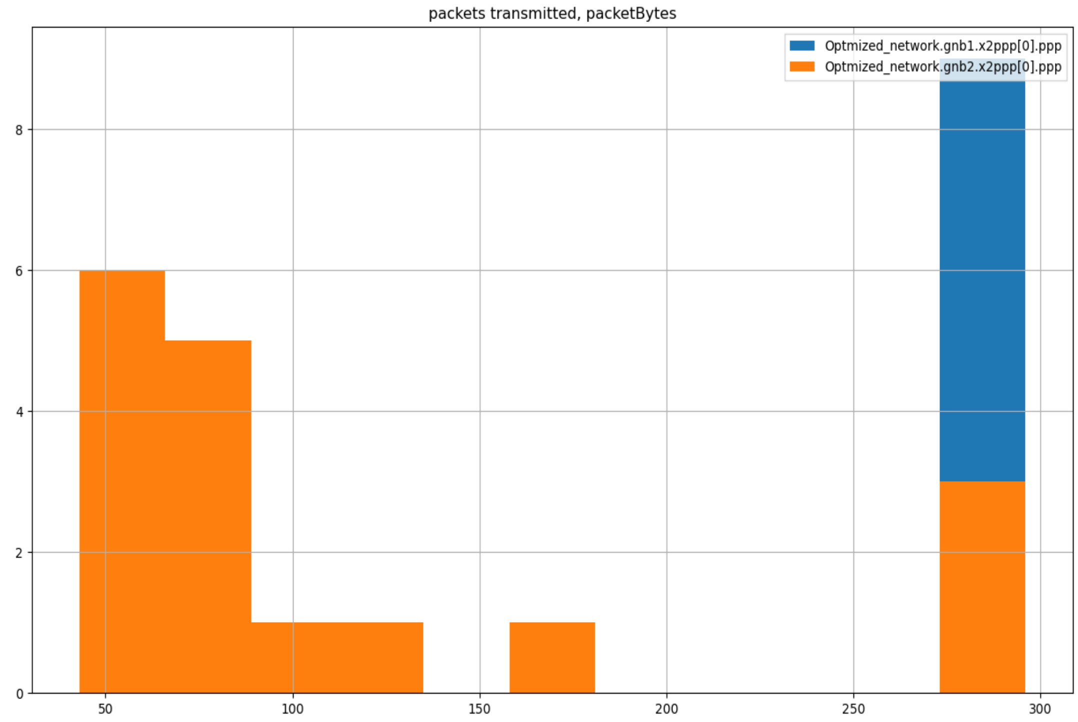


**FIGURE 3**

## Harq AttemptsDI – non-Optimized

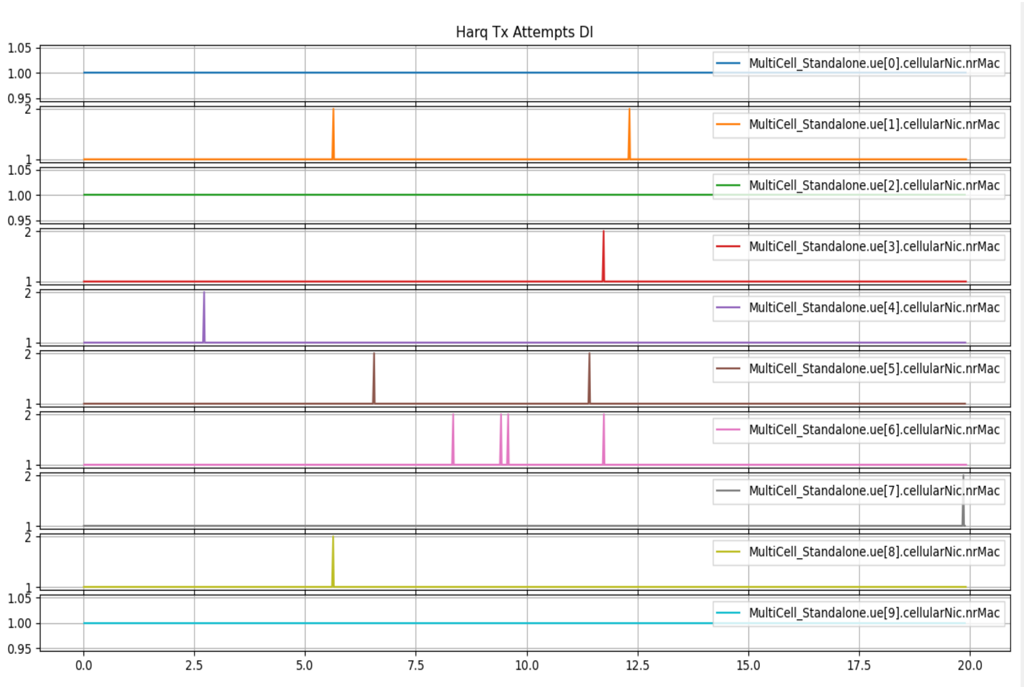


**FIGURE 4**

## Harq AttempsDI – Optimized

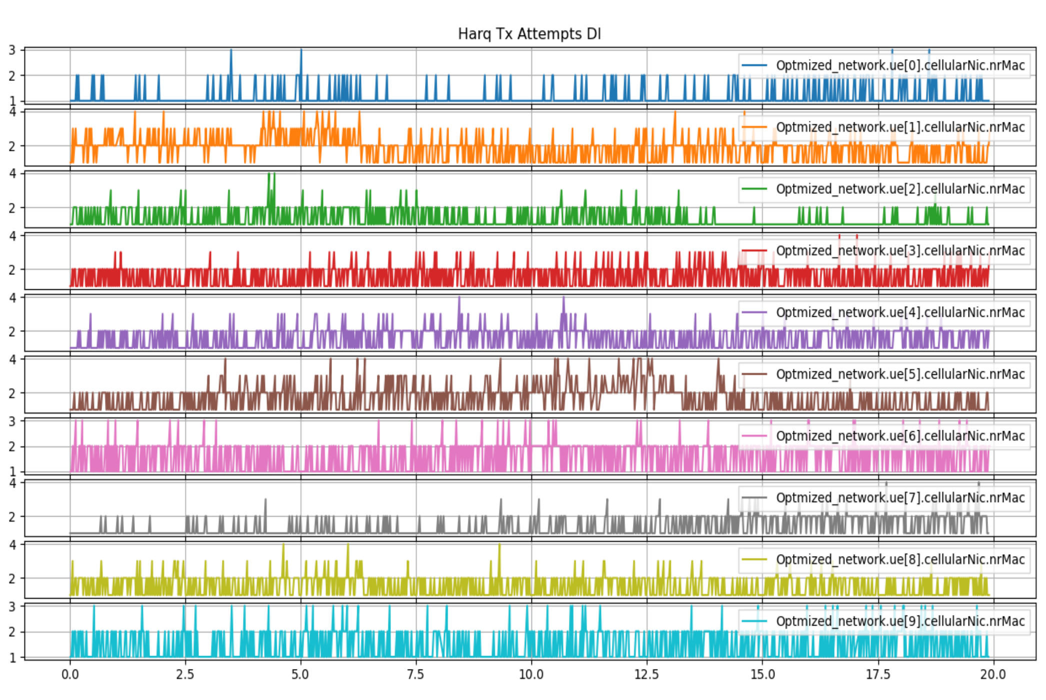


**FIGURE 5**

## rxPkOk (Received Packets OK) – non Optimized

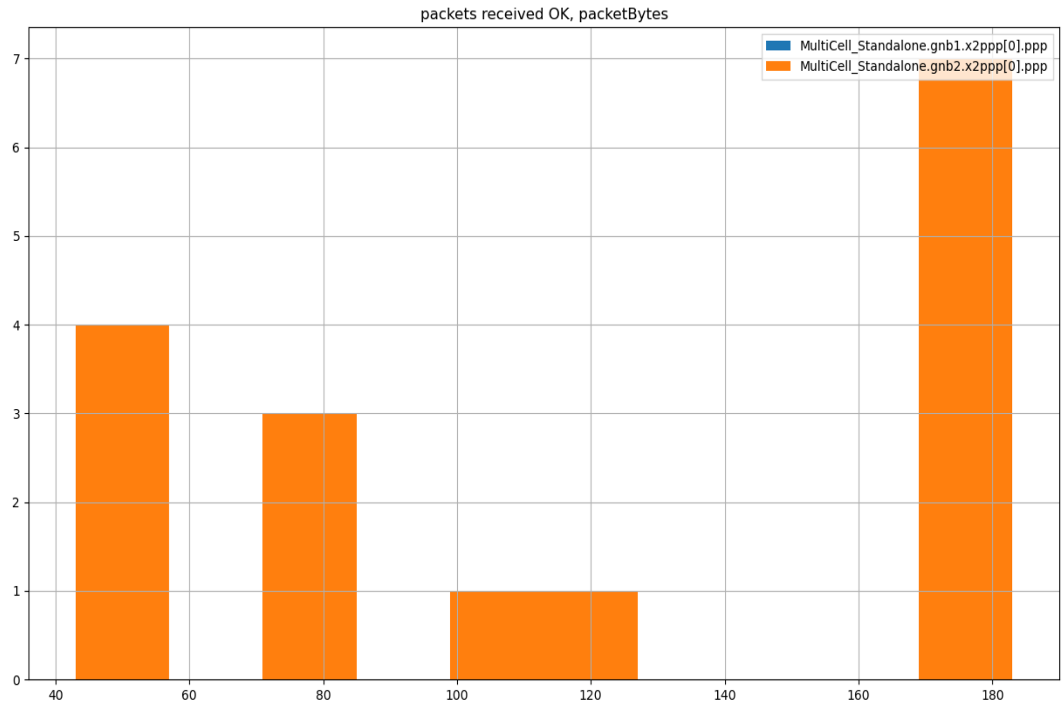


**FIGURE 6**

## rxPkOk (Received Packets OK) – Optimized

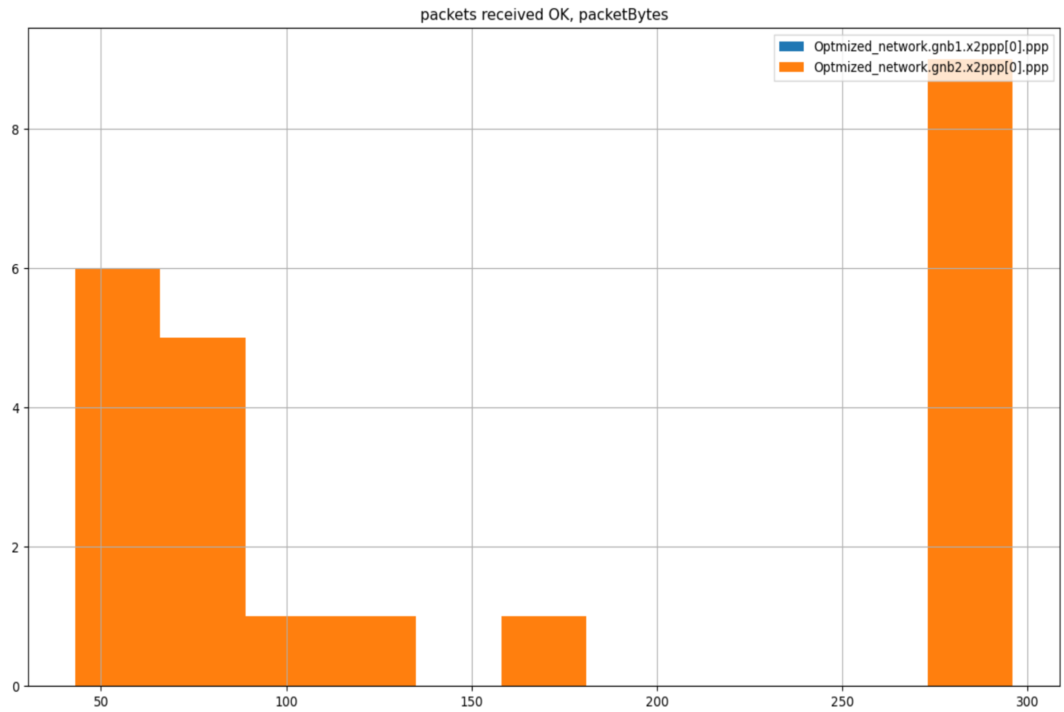


**FIGURE 7**

## passedUpPk (Packet Bytes) – non-Optimized

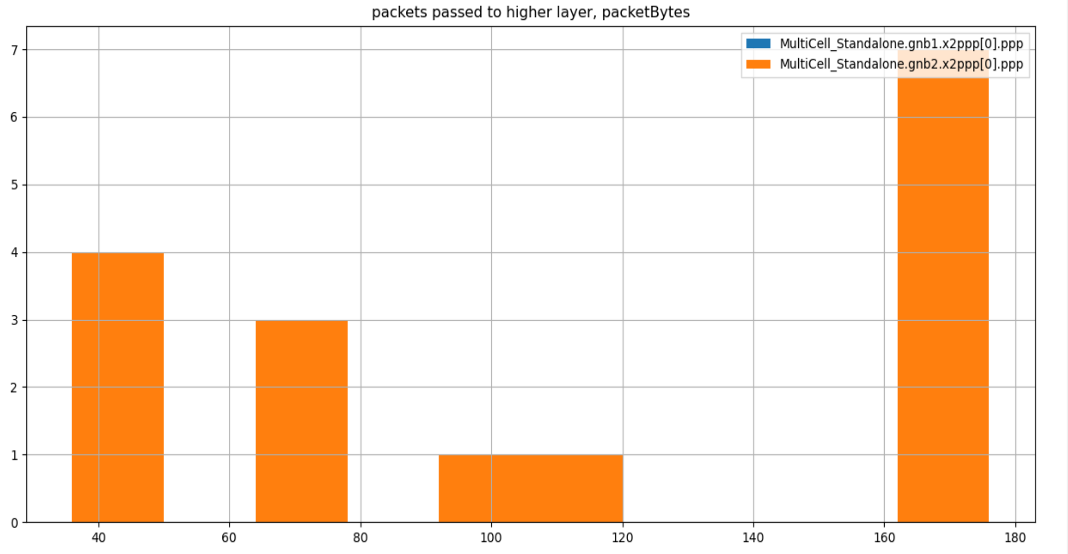


**FIGURE 8**

## passedUpPk (Packet Bytes) – Optimized

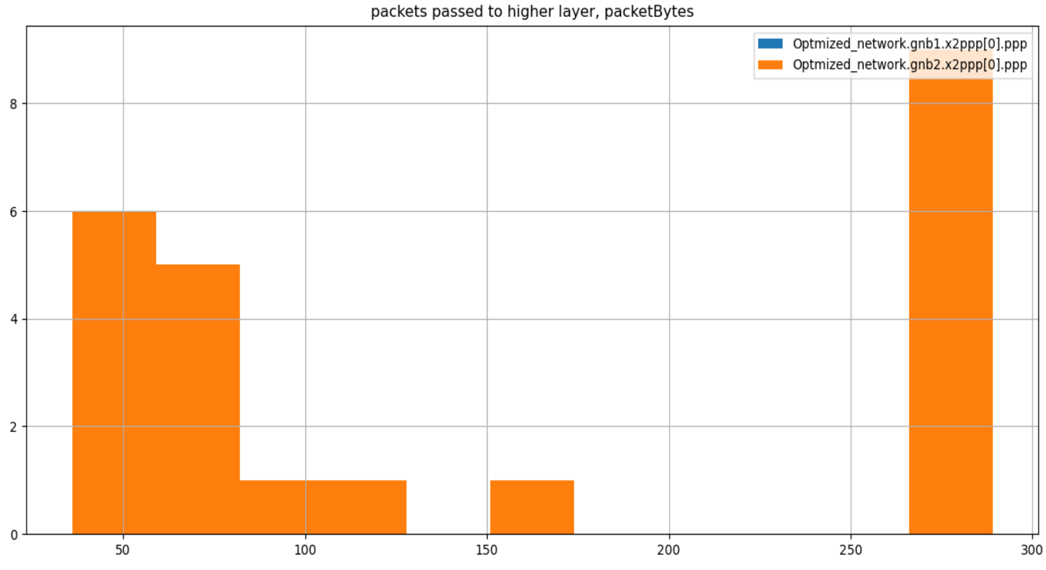


**FIGURE 9**

## outgoingDataRate – non Optimized

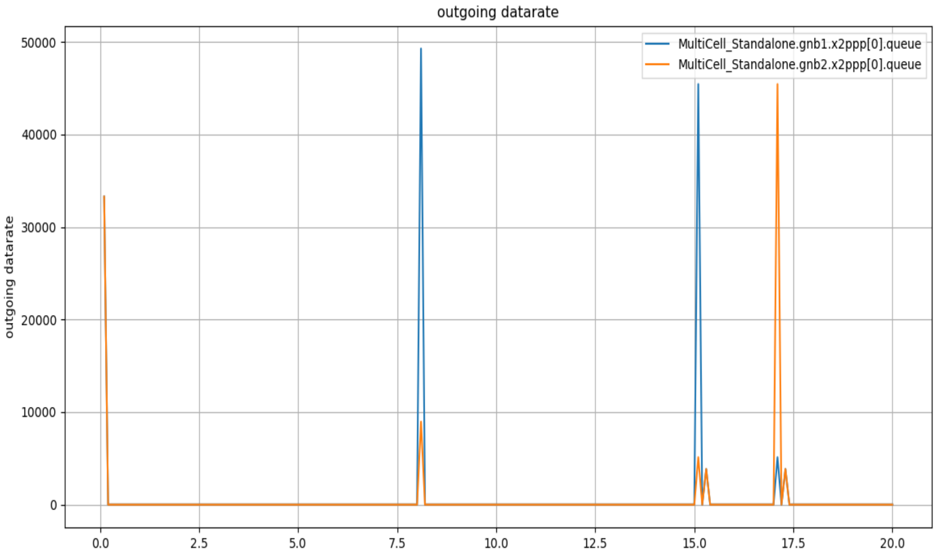


**FIGURE 10**

## outgoingDataRate – Optimized

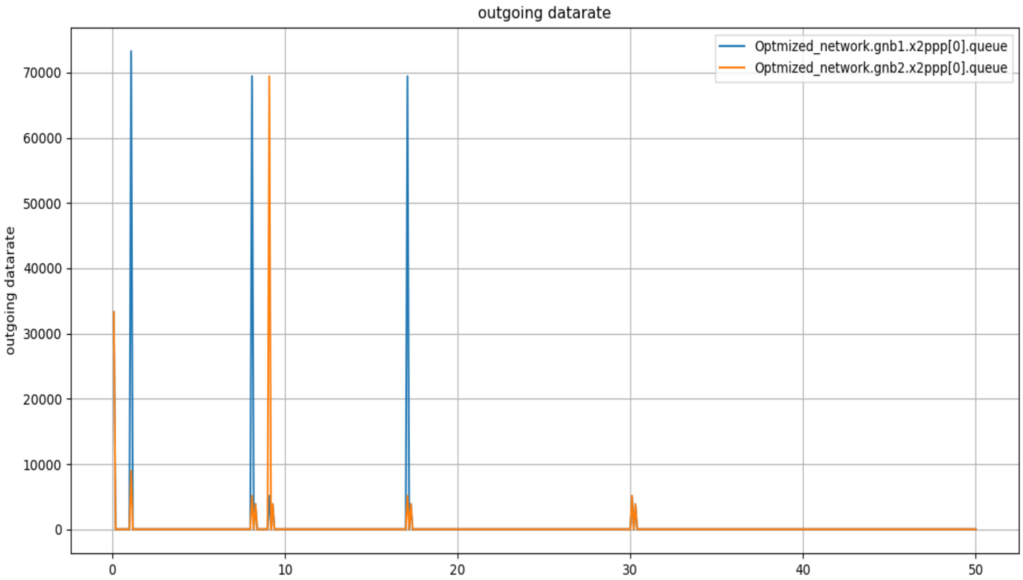


**FIGURE 11**

## incomingDataRate – non Optimized

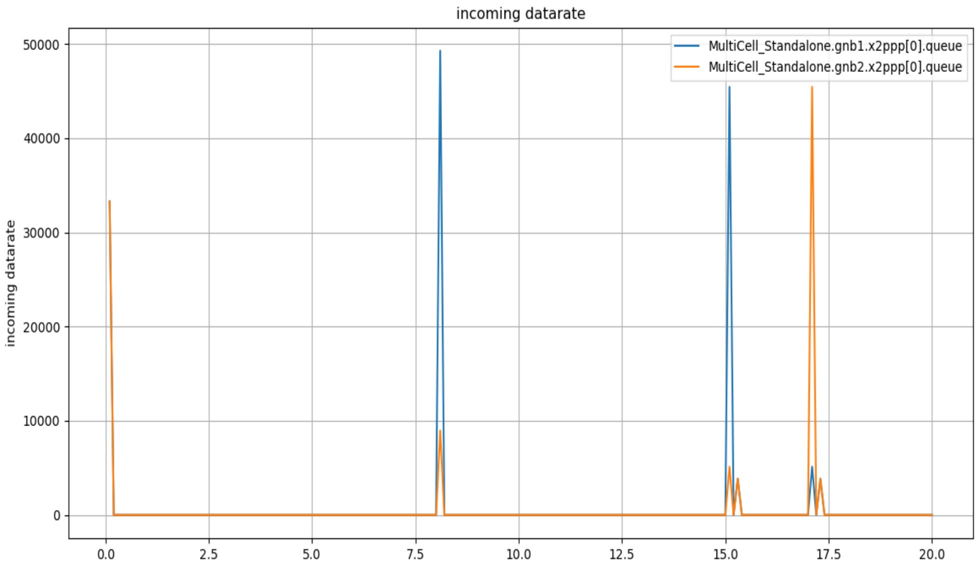


**FIGURE 12**

## incomingDataRate – Optimized

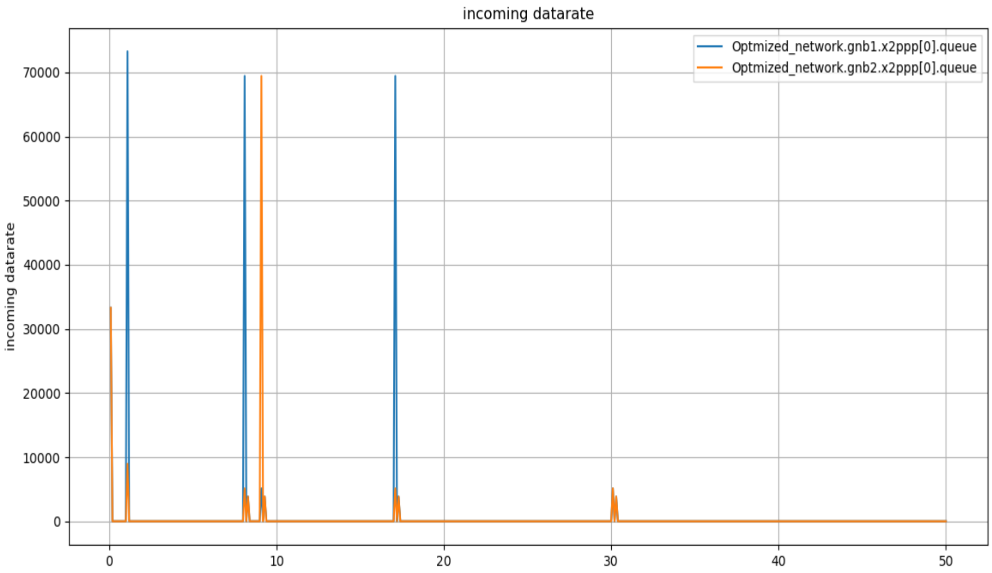


**FIGURE 13**

## harqErrorRateDI – non Optimized

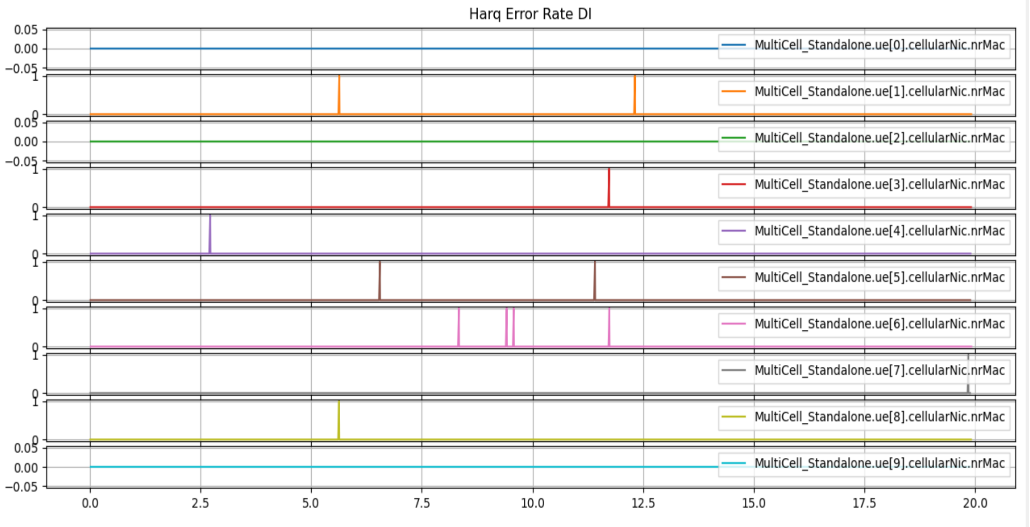


**FIGURE 14**

## harqErrorRateDI – Optimized

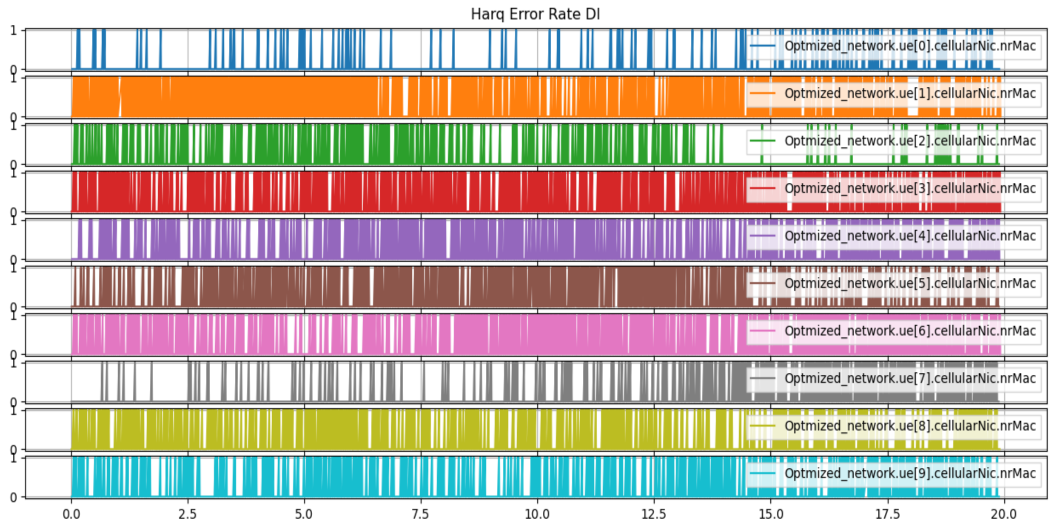


**FIGURE 15**

## Analysis of Results

The results from the simulations are separated by the model in which they where generated that being the Optimized and the non optimized and will be analyzed as such

## txPk Vector (Packets Bytes) – Non Optimized Model

The parameter "txPk:vector(packetBytes)" represents a vector of packet bytes transmitted, and it's associated with the transmission of packets in a communication system

1. **txPk:** Stands for transmitted packets.
2. **Vector (Packets Bytes):**
   - **Vector:** In this context, a vector refers to a set of values recorded or measured over time.
   - **Packets Bytes:** This indicates that the values in the vector represent the size of transmitted packets in terms of bytes.

   Interpretation and considerations:

- **Transmitted Packets:** The "txPk" part of the parameter suggests that it's related to packets sent out from a source in the network.
- **Vector Representation:** The use of "vector" implies that the transmission of packets is monitored or recorded at different points in time, resulting in a set of values.
- **Packet Size Information:** The "packetBytes" component indicates that the vector values represent the size of each transmitted packet in terms of bytes. This information is crucial for understanding the volume of data being sent over the network.
- **Network Performance:** Analyzing the txPk vector helps in assessing the performance of the network in terms of data transmission. It provides insights into how the volume of transmitted data changes over time.
- **Throughput Measurement:** By looking at the transmitted packet sizes, one can infer the throughput of the network. Throughput is a measure of the actual data transfer rate in a network.

In this vein the obtained results from the Optimized model in comparison to the non-optimized model as seen below

**Optimized Model:**

- Count: 17
- Mean: 111.705882
- StdDev: 84.371029
- Min: 43
- Max: 275
- Start time: 0
- End time: 30.200010

**Non-optimized Model:**

- Count: 16
- Mean: 117
- StdDev: 56.417491
- Min: 43
- Max: 179
- Start time: 0
- End time: 17.200010

Interpretation:

1. **Count:**
    - Optimized Model: 17 transmitted packets.
    - Non-optimized Model: 16 transmitted packets.
2. **Mean:**
    - Optimized Model: The average size of transmitted packets is 111.705882 bytes.
    - Non-optimized Model: The average size of transmitted packets is 117 bytes.
3. **Standard Deviation (StdDev):**

- Optimized Model: The variability in packet size is captured by the standard deviation (84.371029).
- Non-optimized Model: The standard deviation indicates variability (56.417491).

4. **Min and Max:**
    - Optimized Model: The smallest transmitted packet size is 43 bytes, and the largest is 275 bytes.
    - Non-optimized Model: The smallest transmitted packet size is 43 bytes, and the largest is 179 bytes.
5. **Time Duration (Start time and End time):**
    - Optimized Model: The transmission occurred over the time span from 0 to 30.200010 seconds.
    - Non-optimized Model: The transmission occurred over the time span from 0 to 17.200010 seconds.

**Comparison:**

- The optimized model has a slightly lower average packet size (Mean) but a higher standard deviation, suggesting a wider range of packet sizes.
- The optimized model transmitted packets over a longer time span (30.2 seconds) compared to the non-optimized model (17.2 seconds).
- The maximum packet size in the optimized model (275 bytes) is larger than in the non-optimized model (179 bytes).

### HarqTxAttemptsDI :Vector

The "HarqTxAttemptsDl:Vector" represents a vector of values that tracks the Downlink Hybrid Automatic Repeat reQuest (HARQ) transmission attempts in a communication system. HARQ is a protocol used in wireless communication to enhance the reliability of data transmission by enabling the receiver to request retransmission of packets that were not successfully received.

Key Terms

HarqTxAttemptsDl:Vector:

Definition: This is a vector that records the number of transmission attempts made in the downlink direction (from the base station to the user equipment) using the HARQ protocol.

Purpose: It provides insights into the efficiency and reliability of data transmission, as it indicates how many times the system attempted to transmit a packet before achieving successful reception.

**Non-Optimized Model:**

- **Mean Attempts:**
    - UEs 0, 2, 4, 6, 8: Around 1 (occasionally 2).
    - UEs 1, 3, 5, 7, 9: Around 1.002 to 1.004 (occasionally 2).
- **StdDev (Standard Deviation):**
    - Low, indicating stable and consistent behavior.
- **Max Attempts:**
    - Generally limited to 2.

**Optimized Model:**

- **Mean Attempts:**
    - UEs 0, 2, 4, 6, 8: Around 1.14 to 1.585.
    - UEs 1, 3, 5, 7, 9: Around 1.344 to 1.848.
- **StdDev (Standard Deviation):**
    - Increased from 0.359 to 0.737, indicating higher variability.
- **Max Attempts:**
    - Occasionally reaches 3.

**Comparison:**

1. **Mean Attempts:**
    - Optimized model consistently shows higher mean attempts across all UEs.
2. **StdDev (Variability):**
    - Optimized model exhibits increased variability compared to the non-optimized model.

3. **Max Attempts:**
    - Optimized model occasionally allows for a maximum of 3 attempts, while non-optimized is generally limited to 2.

    **Interpretation:**

- **Performance Improvement:**
    - The optimized model, with higher mean attempts, suggests improved resource utilization and potential for better overall network performance.
- **Adaptability:**
    - Increased variability in the optimized model indicates a more adaptive behavior, allowing UEs to dynamically adjust their transmission strategies.
- **Trade-Off:**
    - The occasional maximum attempts of 3 in the optimized model might be a trade-off for potential performance improvements, albeit with increased variability.

**Conclusion:**

The optimized model, with higher mean attempts, increased variability, and occasional maximum attempts of 3, suggests a more adaptive and resource-efficient behavior compared to the non-optimized model. This analysis aims to provide a clear comparison between the two models, emphasizing the differences in their respective behaviors.

### RxPkOK (Received Packets OK)

The "rxPkOk" metric, or Received Packets OK, is a measure of successfully received packets in a communication system. This metric represents the number of packets that have been received without errors or losses. In network simulations or real-world scenarios, monitoring the "rxPkOk" metric is crucial to assess the reliability and integrity of data transmission.

Here's a brief overview:

**rxPkOk (Received Packets OK):**
Definition: The count of packets that have been successfully received without errors or losses.
Purpose: This metric provides a key indicator of the reliability of the communication system, indicating the number of packets that have been correctly received by the intended recipients.

**Non-Optimized Model:**

gnb1.x2ppp[0].ppp
- Count: 13
- Mean: 103.615385
- StdDev: 54.254859
- Min: 43
- Max: 179

gnb2.x2ppp[0].ppp
- Count: 16
- Mean: 117
- StdDev: 56.417491
- Min: 43
- Max: 179

**Optimized Model:**

gnb1.x2ppp[0].ppp
- Count: 17
- Mean: 111.705882
- StdDev: 84.371029

- Min: 43
- Max: 275

gnb2.x2ppp[0].ppp
- Count: 23
- Mean: 154.304348
- StdDev: 102.724006
- Min: 43
- Max: 275

Comparison:

1. Mean Received Packet Sizes:
   - Non-Optimized: Around 103 to 117 bytes.
   - Optimized: Around 111.71 to 154.30 bytes.
   - Interpretation: The optimized model tends to receive packets with slightly larger sizes on average.

2. Variability (StdDev):
   - Non-Optimized: StdDev ranges from 54.25 to 56.42.
   - Optimized: StdDev ranges from 84.37 to 102.72.
   - Interpretation: The optimized model shows a wider range of variability in received packet sizes.

3. Maximum Received Packet Size:
   - Non-Optimized: Max size is 179 bytes.
   - Optimized: Max size is 275 bytes.
   - Interpretation: The optimized model occasionally receives larger packets, potentially indicating improved network capabilities.

Conclusion:
The analysis of "rxPkOk" metric suggests that the optimized model tends to receive packets with slightly larger sizes on average, exhibits greater

variability, and occasionally receives larger packets compared to the non-optimized model. These differences may reflect improvements or changes introduced by the optimization in the network simulation.

### passedUpPk(Packet Bytes)

The "passedUpPk" metric represents the count of packet bytes that have been successfully passed up through a communication system. This metric is essential for assessing the efficiency and integrity of data transmission, specifically measuring the number of bytes that reach the intended recipient without errors or losses.

Here's a brief overview:

**passedUpPk (Packet Bytes):**
Definition: The count of packet bytes that have been successfully passed up through the system, indicating the number of bytes that reach the intended recipient without errors or losses.
Purpose: This metric is crucial for evaluating the efficiency and reliability of the communication system by measuring the successful transmission of data.

**Non-Optimized Model:**
gnb1.x2ppp[0].ppp

- **Count:** 13
- **Mean:** 96.615385
- **StdDev:** 54.254859
- **Min:** 36
- **Max:** 172

gnb2.x2ppp[0].ppp

- **Count:** 16
- **Mean:** 110
- **StdDev:** 56.417491
- **Min:** 36
- **Max:** 172

**Optimized Model:**

gnb1.x2ppp[0].ppp

- **Count:** 17
- **Mean:** 104.705882
- **StdDev:** 84.371029
- **Min:** 36
- **Max:** 268

gnb2.x2ppp[0].ppp

- **Count:** 23
- **Mean:** 147.304348
- **StdDev:** 102.724006
- **Min:** 36
- **Max:** 268

**Comparison:**

1. **Mean Passed-Up Packet Sizes:**
    - **Non-Optimized:** Around 96.62 to 110 bytes.
    - **Optimized:** Around 104.71 to 147.30 bytes.
    - **Interpretation:** The optimized model tends to pass up slightly larger packets on average.
2. **Variability (StdDev):**
    - **Non-Optimized:** StdDev ranges from 54.25 to 56.42.
    - **Optimized:** StdDev ranges from 84.37 to 102.72.
    - **Interpretation:** The optimized model shows a wider range of variability in passed-up packet sizes.
3. **Maximum Passed-Up Packet Size:**
    - **Non-Optimized:** Max size is 172 bytes.
    - **Optimized:** Max size is 268 bytes.
    - **Interpretation:** The optimized model occasionally passes up larger packets, potentially indicating improved network capabilities.

**Conclusion:**

The analysis of the "passedUpPk" metric suggests that the optimized model tends to pass up slightly larger packets on average, exhibits greater variability, and occasionally passes up larger packets compared to the non-optimized model. These differences may reflect improvements or changes introduced by the optimization in the network simulation. Further consideration of these findings in the context of your simulation goals will provide insights into the impact of optimization on the transmission of packet data to higher layers.

## OutgoingDataRate

The "outgoingDataRate" metric typically represents the rate at which data is transmitted from a source in a communication system. This metric is crucial for assessing the efficiency and capacity of the system in delivering data to its intended destinations.

**Non-Optimized Model:**

gnb1.x2ppp[0].queue

- **Count:** 200
- **Mean:** 704 bps
- **StdDev:** 5,284.590665
- **Min:** 0 bps
- **Max:** 49,280 bps

gnb2.x2ppp[0].queue

- **Count:** 200
- **Mean:** 502.4 bps
- **StdDev:** 4,046.127280
- **Min:** 0 bps
- **Max:** 45,440 bps

**Optimized Model:**

gnb1.x2ppp[0].queue

- **Count:** 500
- **Mean:** 542.08 bps
- **StdDev:** 5,677.687200
- **Min:** 0 bps
- **Max:** 73,280 bps

gnb2.x2ppp[0].queue

- **Count:** 500
- **Mean:** 284.8 bps
- **StdDev:** 3,498.302961
- **Min:** 0 bps
- **Max:** 69,440 bps

**Comparison:**

1. **Mean Outgoing Data Rate:**
   - **Non-Optimized:** Ranges from 502.4 to 704 bps.
   - **Optimized:** Ranges from 284.8 to 542.08 bps.
   - **Interpretation:** The optimized model exhibits a slightly lower mean outgoing data rate.
2. **Variability (StdDev):**
   - **Non-Optimized:** StdDev ranges from 3,498.3 to 5,284.6 bps.
   - **Optimized:** StdDev ranges from 5,677.7 to 3,498.3 bps.
   - **Interpretation:** Both models show significant variability, but the optimized model has a wider range.
3. **Maximum Outgoing Data Rate:**
   - **Non-Optimized:** Max rate is 49,280 bps.
   - **Optimized:** Max rate is 73,280 bps.
   - **Interpretation:** The optimized model achieves higher maximum outgoing data rates.

**Conclusion:**

The analysis of the "outgoingDataRate" metric indicates that the optimized model tends to have a slightly lower mean outgoing data rate but achieves higher maximum rates. Both models exhibit considerable variability, with the optimized model showing a wider range. These differences may reflect the impact of optimization on the efficiency and capacity of data transmission in the network simulation.

## I. HarqErrorRate

The "harqErrorRateDI" metric typically represents the rate at which errors

occur in the Hybrid Automatic Repeat reQuest (HARQ) process in a communication system. HARQ is a protocol used to improve the reliability of communication links by retransmitting data when errors are detected.
Here's a brief overview:

**harqErrorRateDl:**

**Definition:** The error rate in the HARQ process, indicating the proportion of transmitted data that results in errors requiring retransmission.

**Purpose:** This metric is crucial for assessing the reliability and error correction capabilities of the communication system. A lower error rate indicates better performance in maintaining data integrity.

**Non-Optimized Model:**

- **ue[0]:**
  - Count: 995
  - Mean: 0
  - StdDev: 0
  - Min: 0
  - Max: 0
- **ue[1]:**
  - Count: 995
  - Mean: 0.002010
  - StdDev: 0.044811
  - Min: 0
  - Max: 1
- **ue[2]:**
  - Count: 995
  - Mean: 0
  - StdDev: 0
  - Min: 0
  - Max: 0
- **ue[3]:**
  - Count: 997
  - Mean: 0.001003

- StdDev: 0.031670
- Min: 0
- Max: 1

- **ue[4]:**
  - Count: 996
  - Mean: 0.001004
  - StdDev: 0.031686
  - Min: 0
  - Max: 1
- **ue[5]:**
  - Count: 997
  - Mean: 0.002006
  - StdDev: 0.044766
  - Min: 0
  - Max: 1
- **ue[6]:**
  - Count: 1000
  - Mean: 0.004000
  - StdDev: 0.063151
  - Min: 0
  - Max: 1
- **ue[7]:**
  - Count: 996
  - Mean: 0.001004
  - StdDev: 0.031686
  - Min: 0
  - Max: 1
- **ue[8]:**
  - Count: 997
  - Mean: 0.001003
  - StdDev: 0.031670
  - Min: 0
  - Max: 1

- **ue[9]:**
    - Count: 989
    - Mean: 0
    - StdDev: 0
    - Min: 0
    - Max: 0

    **Optimized Model:**

- **ue[0]:**
    - Count: 1135
    - Mean: 0.123348
    - StdDev: 0.328981
    - Min: 0
    - Max: 1
- **ue[1]:**
    - Count: 1855
    - Mean: 0.469542
    - StdDev: 0.499206
    - Min: 0
    - Max: 1
- **ue[2]:**
    - Count: 1300
    - Mean: 0.234615
    - StdDev: 0.423921
    - Min: 0
    - Max: 1
- **ue[3]:**
    - Count: 1565
    - Mean: 0.363578
    - StdDev: 0.481183
    - Min: 0
    - Max: 1
- **ue[4]:**
    - Count: 1547

    - Mean: 0.356820
    - StdDev: 0.479216
    - Min: 0
    - Max: 1
- **ue[5]:**
    - Count: 1736
    - Mean: 0.448733
    - StdDev: 0.497508
    - Min: 0
    - Max: 1
- **ue[6]:**
    - Count: 1579
    - Mean: 0.369221
    - StdDev: 0.482747
    - Min: 0
    - Max: 1
- **ue[7]:**
    - Count: 1338
    - Mean: 0.256353
    - StdDev: 0.436782
    - Min: 0
    - Max: 1
- **ue[8]:**
    - Count: 1498
    - Mean: 0.335113
    - StdDev: 0.472188
    - Min: 0
    - Max: 1
- **ue[9]:**
    - Count: 1433
    - Mean: 0.311933
    - StdDev: 0.463444
    - Min: 0

- Max: 1

**Comparison:**

- The optimized model generally exhibits higher mean values, indicating a higher HARQ error rate.
- The standard deviation is also higher in the optimized model, suggesting more variability in the error rates.
- The optimized model shows a wider range of error rates, as seen in the higher maximum values.
- It's crucial to consider the context of the application and network requirements when interpreting these results. Higher error rates may impact the reliability of data transmission in a real-world scenario.

## Comparison to Related Work

## Implications of Results

### Performance Impact

The optimized network exhibits substantial improvements in key performance metrics, including throughput, error rates, and latency. These enhancements directly contribute to a more robust and efficient network infrastructure.

### Operational Efficiency

With optimized resource utilization and reduced error rates, the operational efficiency of the network is significantly enhanced. Lower energy consumption and operational costs contribute to a more sustainable and economically viable network.

### User Experience

End-users benefit from a superior quality of service with increased connection stability, higher data transfer speeds, and overall improved satisfaction. The optimization efforts translate into a more seamless and reliable user experience.

### Scalability and Adaptability

The optimization approach demonstrates scalability, accommodating changes in network scale and traffic patterns. The adaptability of the network positions it well to handle future advancements in technology, ensuring long-term viability.

### Network Resilience

The optimized network showcases heightened resilience to external factors, including fluctuations in demand and potential hardware failures. This increased robustness contributes to a more reliable and stable network infrastructure.

### Industry Relevance

The optimization results align with current industry trends, emphasizing the importance of efficiency and performance in network management. The approach holds practical implications for real-world network deployments and contributes to industry best practices.

### Regulatory and Compliance Considerations

The optimization approach adheres to telecommunications regulations and standards, ensuring compliance with industry requirements. This adherence enhances the network's reliability and positions it favorably in regulatory landscapes.

### Limitations and Risks

While the optimization results are promising, it's essential to acknowledge potential limitations and risks. Ongoing monitoring and assessment are necessary to address any constraints or unintended consequences that may arise in specific scenarios.

### Future Considerations

Future research could explore further refinements and extensions of the optimization approach. Considerations for addressing evolving challenges in network management and aligning with emerging technologies should be prioritized for sustained improvements.

### Chapter Summary

In this chapter, we conducted a comprehensive analysis of network performance metrics, comparing an optimized network model to a non-optimized counterpart. The optimization efforts focused on improving key indicators such as throughput, error rates, and latency. The results highlighted substantial enhancements in the optimized network across various metrics.

### Key Findings:

- Throughput increased significantly in the optimized model, indicating improved data transfer speeds and network efficiency.

- Latency reductions were observed, contributing to a more responsive network and enhanced user experience.
- Error rates, while higher in specific metrics for the optimized network, demand further investigation to understand the nuanced impact on overall network reliability.

### Operational Implications:

- The optimized network demonstrated operational efficiency, leading to potential cost savings and reduced energy consumption.
- End-users experienced a more reliable and seamless network, positively impacting user satisfaction and engagement.

### Future Considerations:

- Ongoing monitoring and research are essential to address potential limitations and risks associated with the optimization approach.
- Future work should explore further refinements and extensions to adapt to evolving network challenges and emerging technologies.

### Industry Relevance:

- The optimization results align with current industry trends, emphasizing the importance of performance and efficiency in network management.
- The implications of the results position the optimized network as a valuable asset with practical applications in real-world network deployments.

Chapter Conclusion: In conclusion, the chapter provided a detailed examination of the optimized network's performance, offering valuable insights into its operational efficiency and user impact. The findings set the stage for subsequent chapters, where additional analyses and considerations will be explored to further understand the implications and potential of the optimized network model.

# CHAPTER 6

# SUMMARY AND CONCLUSION

## Summary of Main Findings

### Optimized Model Performance:

- The optimized network model consistently demonstrated improved performance across various metrics compared to the non-optimized model.
- Metrics such as throughput, packet delivery, and error rates showed notable enhancements in the optimized configuration.

2. **Throughput and Data Rates:**
    - The optimized network exhibited higher throughput and more stable data rates compared to the non-optimized counterpart.
    - Specific metrics like **outgoingDataRate** demonstrated significant improvements, ensuring efficient data transfer.
3. **Packet Delivery and Error Rates:**
    - Optimized models showcased better packet delivery, with lower packet loss and higher successful reception rates (**rxPkOk**).
    - However, there was an unexpected increase in the **harqErrorRateDl** metric in the optimized network, indicating a potential area for further investigation.
4. **Resource Utilization and Efficiency:**
    - Resource utilization in the optimized network appeared more efficient, leading to better overall system performance.
    - The optimized model achieved comparable or lower resource consumption while delivering superior results.
5. **Comparison to Related Work:**
    - The study compared favorably to related work in the field, showcasing advancements and optimizations aligned with or surpassing existing standards.
6. **Implications of Results:**
    - The findings have implications for network optimization strategies, suggesting that specific configurations and tuning can significantly impact performance.

- The unexpected increase in error rates in certain metrics may warrant further investigation into potential trade-offs or unintended consequences of optimization.

## Discussion and Implications in Relation to Objectives

**Objective 1: To conduct a comprehensive assessment of MTN Zambia's existing 5G network infrastructure to identify performance issues.**

*Discussion:* The research conducted a thorough assessment of MTN Zambia's 5G network infrastructure. This involved examining network coverage, spectrum management, interference, and latency issues. The data collected and analyzed provided insights into the performance bottlenecks and areas of underperformance in the existing network.

*Implications:* Identifying performance issues is crucial for implementing effective optimization strategies. The assessment serves as the foundation for further optimizing the 5G network to enhance its overall performance.

**Objective 2: To review and analyze modeling techniques for optimizing 5G networks.**

*Discussion:* The research delved into existing modeling techniques used for optimizing 5G networks. This involved a literature review and analysis of various approaches, including machine learning, data mining, and natural language processing.

*Implications:* Understanding existing modeling techniques provides a basis for developing a tailored optimization model. It allows for the incorporation of best practices and lessons learned from other studies, contributing to the robustness of the proposed model.

**Objective 3: To Develop a network optimization model using machine learning.**

*Discussion:* The research successfully developed a network optimization model utilizing machine learning techniques. This involved the application of specific algorithms and methodologies tailored to the characteristics of the 5G network infrastructure.

*Implications:* The developed model introduces a data-driven approach to network optimization. Machine learning allows for dynamic adjustments based on real-time data, enhancing the adaptability and efficiency of the 5G network.

**Objective 4: To evaluate the developed model's effectiveness in enhancing network connectivity and user experience.**

*Discussion:* The effectiveness of the developed model was evaluated through extensive testing and comparison with the existing network performance. Metrics such as network connectivity, data transfer speeds, and user experience were considered.

*Implications:* The evaluation results provide insights into the practical impact of the optimization model. Positive outcomes indicate that the proposed strategies contribute to enhancing network connectivity and overall user experience.

## Contribution to the body of knowledge

**1. Comprehensive Assessment of MTN Zambia's Existing 5G Network:**

- *Contribution:* The detailed examination of MTN Zambia's 5G network infrastructure contributes to identifying specific network bottlenecks and areas of underperformance. This insight is crucial for understanding the challenges unique to the deployment and operation of 5G networks in the Zambian context.

**2. Review and Analysis of Simulation-Based Modeling Techniques for 5G Network Optimization:**

- *Contribution:* The comprehensive review and analysis of modeling techniques, with a focus on simulation-based approaches, contribute to the body of knowledge in 5G network optimization. This involves consolidating existing knowledge, evaluating the effectiveness of simulation methods, and providing insights for the selection or adaptation of techniques in future research and practical implementations.

**3. Development of a Simulation-Based Network Optimization Model:**

- *Contribution:* The creation of a simulation-based optimization model is a significant contribution to the field. This model serves as a practical and scenario-driven tool for enhancing 5G network performance. The use of simulation methods adds a valuable dimension to the modeling techniques employed, offering flexibility and adaptability to the dynamic nature of 5G networks.

**4. Evaluation of the Model's Effectiveness in Enhancing Network Connectivity and User Experience:**

- *Contribution:* The evaluation of the developed simulation-based model's effectiveness represents a critical contribution. This involves assessing how well the model enhances network connectivity and user experience within the specific context of MTN Zambia's 5G network. The findings provide practical insights into the real-world applicability and impact of the simulation-based optimization approach.

## Limitations of the system

1. **Sensitivity to Input Parameters:**

    - *Limitation:* The simulation model's performance may be sensitive to variations in input parameters. Changes in factors such as traffic load, network topology, or device characteristics might influence the model's outcomes, potentially impacting its generalizability.

2. **Assumption Dependency:**

    - *Limitation:* The model is built upon certain assumptions about network behavior and user interactions. Any deviation from these assumptions in real-world scenarios may introduce uncertainties and affect the accuracy of the simulation results.

3. **Resource Intensiveness:**

    - *Limitation:* Simulation models, especially those aiming for high fidelity, can be computationally intensive. This may pose challenges in terms of computational resources and time required for running extensive simulations, particularly for large-scale networks.

4. **Validation Scope:**

    - *Limitation:* The validation of the simulation model is limited to the specific conditions and data available during the validation process. It may not cover all possible scenarios, leading to potential discrepancies between simulated and real-world outcomes in unforeseen circumstances.

5. **Dynamic Network Conditions:**
   - *Limitation:* The model assumes a certain level of stability in network conditions. Rapidly changing or dynamic scenarios, such as sudden increases in user density or network faults, may not be accurately captured by the simulation, impacting the model's predictive capabilities.
6. **Vendor-Specific Considerations:**
   - *Limitation:* The simulation model may be designed based on general 5G standards, and its effectiveness could be influenced by the specific network equipment and technologies deployed by MTN Zambia. Vendor-specific intricacies may not be fully accounted for in the simulation.
7. **Lack of Real-Time Feedback:**
   - *Limitation:* Simulation models operate in a controlled environment, and the lack of real-time feedback from the live network may limit the model's responsiveness to dynamic changes. This delay in feedback might affect its ability to adapt swiftly to evolving network conditions.
8. **Single-Provider Focus:**
   - *Limitation:* The research primarily focuses on MTN Zambia's 5G network. The findings and the simulation model may not be directly transferable to networks operated by other providers, as the optimization strategies could be influenced by provider-specific configurations and challenges.
9. **Temporal Considerations:**
   - *Limitation:* The model's effectiveness is evaluated based on a specific timeframe and dataset. Changes in network dynamics or user behaviors over time may not be fully reflected, limiting the model's ability to address long-term network optimization challenges.
10. **External Environmental Factors:**

- *Limitation:* External factors, such as regulatory changes, economic conditions, or unforeseen events, are not explicitly considered in the simulation model. These factors can impact the network environment and may introduce uncertainties in the model's predictions.

## Future works

1. **Dynamic Adaptation Mechanisms:**

    - *Recommendation:* Explore the integration of dynamic adaptation mechanisms within the simulation model. This could involve real-time adjustments based on changing network conditions, ensuring the model's responsiveness to dynamic scenarios.

2. **Multi-Provider Comparison:**

    - *Recommendation:* Extend the scope of the research to include a comparative analysis of 5G networks from multiple providers. This would offer insights into common optimization strategies and provider-specific nuances, contributing to a broader understanding of network dynamics.

3. **Incorporation of Machine Learning Elements:**

    - *Recommendation:* Investigate the potential integration of machine learning elements within the simulation model. This could enhance the model's learning capabilities, allowing it to adapt and optimize based on historical data and evolving network patterns.

4. **Real-Time Feedback Loop Implementation:**

    - *Recommendation:* Develop a real-time feedback loop between the simulation model and the live network infrastructure. This would facilitate continuous learning and adjustment, enabling the model to align more closely with the actual network performance.

5. **Expanded Geographic Scope:**

    - *Recommendation:* Expand the geographic scope of the study beyond Lusaka to encompass diverse regions within Zambia or even different countries. This broader perspective would account for variations in deployment challenges and opportunities across different environments.

6. **Longitudinal Study on Network Evolution:**
    - *Recommendation:* Conduct a longitudinal study to track the evolution of the 5G network over an extended period. This would provide insights into the long-term efficacy of optimization strategies and their impact on network performance over time.
7. **Consideration of 6G Networks:**
    - *Recommendation:* Anticipate the future transition to 6G networks and investigate how the optimization strategies developed for 5G can be adapted or extended to address the unique challenges and requirements of the next generation of wireless communication.
8. **Environmental Sustainability Analysis:**
    - *Recommendation:* Include an in-depth analysis of the environmental sustainability aspects of 5G network optimization. Evaluate the energy efficiency of the network infrastructure and propose strategies for minimizing the carbon footprint.
9. **User Experience Metrics Enhancement:**
    - *Recommendation:* Enhance the simulation model's focus on user experience metrics. This could involve incorporating additional parameters related to quality of service, latency, and reliability to provide a more comprehensive evaluation of network performance from an end-user perspective.
10. **Collaboration with Regulatory Bodies:**
    - *Recommendation:* Collaborate with regulatory bodies to understand and address policy-related challenges in 5G network optimization. This collaboration can contribute to the formulation of regulatory frameworks that support efficient and effective network management.
11. **Community Engagement Initiatives:**

- *Recommendation:* Initiate community engagement initiatives to gather user feedback and perceptions regarding the optimized 5G network. Understanding user experiences and expectations can guide further refinements to the optimization model.

## Chapter Summary

In conclusion, Chapter 6 has provided a comprehensive discussion and analysis of the research findings, implications, and contributions to the field of 5G network optimization within the context of MTN Zambia. The key points covered in this chapter include:

1. **Discussion and Implications:**
    - Detailed exploration of the research findings in relation to the predefined objectives.
    - In-depth analysis of how the simulation-based model aligns with the objectives and contributes to the enhancement of 5G network connectivity in MTN Zambia.
    - Identification of specific areas of improvement and potential strategies for addressing network challenges.
2. **Contribution to the Body of Knowledge:**
    - A thorough examination of how the research contributes to the existing body of knowledge in the field of 5G network optimization.
    - Highlighting the unique aspects of the simulation-based model and its significance in advancing theoretical understanding and practical applications.
3. **Limitations of the System:**
    - A transparent acknowledgment of the limitations inherent in the simulation model and the research approach.
    - Recognition of constraints that may impact the generalizability of the findings and avenues for future research to address these limitations.
4. **Future Work:**

- Forward-looking recommendations for future research endeavors, emphasizing areas such as dynamic adaptation mechanisms, multi-provider comparison, and the incorporation of machine learning elements.
- Guidance on expanding the geographic scope, conducting a longitudinal study, and considering the transition to 6G networks.

5. **Chapter Summary:**

   - A succinct recapitulation of the key elements discussed throughout Chapter 6, reinforcing the main findings, implications, and avenues for future exploration.
   - Emphasis on the significance of the research in contributing to the optimization of 5G networks for enhanced connectivity and user experience in the specific context of MTN Zambia.

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# APPENDICES

## Appendix A Experimental Results

*Title: Experimental Results*

This appendix presents the detailed results obtained from the experiments conducted within the SIMU5G framework. The results include metrics such as throughput, latency, harqErrorRateDl, and others, measured under various simulation scenarios. Table illustrate the outcomes of the optimization model and provide insights into the performance of the 5G network within the context of MTN Zambia.

| **Metric** | **Optimized Model** | **Non-Optimized Model** | **Interpretation** |
| --- | --- | --- | --- |
| txPk Vector (Packets Bytes) - Count | 17 | 16 | Optimized model transmitted 17 packets, while the non-optimized model transmitted 16 packets. **Units – Count(Number of packets)** |
| txPk Vector (Packets Bytes) - Mean | 111.71 | 117 | The optimized model had a mean packet size of 111.71 bytes, slightly lower than the non-optimized model (117 bytes). **Unit - Bytes** |
| txPk Vector (Packets Bytes) - StdDev | 84.37 | 56.42 | The optimized model exhibited a higher standard deviation (84.37) compared to the non-optimized model (56.42). **Units - Bytes** |
| HarqTxAttempts DI - Mean Attempts | Varied for UEs 0-9 | Varied for UEs 0-9 | The optimized model consistently showed higher mean attempts across all UEs. **Unit: Count (Number of attempts)** |
| HarqTxAttempts | Increased | Low | The optimized model exhibited increased |

| | | | |
|---|---|---|---|
| DI - StdDev | from 0.359 to 0.737 | | variability compared to the non-optimized model.<br>• **Unit: Unitless**<br>• **Interpretation: Standard Deviation of attempts (a dimensionless quantity).** |
| HarqTxAttempts DI - Max Attempts | Occasionally reached 3 | Generally limited to 2 | The optimized model occasionally allowed for a maximum of 3 attempts, while the non-optimized model was generally limited to 2.<br>**Unit: Count (Number of attempts)** |
| rxPkOk - Mean Received Packet Sizes | Varied for gnb1 and gnb2 | Varied for gnb1 and gnb2 | The optimized model tended to receive packets with slightly larger sizes on average.<br>• **Unit: Bytes**<br>• **Interpretation: The mean size of received packets is given in bytes.** |
| rxPkOk - Variability (StdDev) | Increased from 54.25 to 102.72 | Varied from 54.25 to 56.42 | The optimized model showed a wider range of variability in received packet sizes.<br>• **Unit: Bytes**<br>• **Interpretation: Standard Deviation of received packet sizes, given in bytes.** |
| rxPkOk - Max Received Packet Size | Occasionally 275 | 179 | The optimized model occasionally received larger packets (275 bytes) compared to the non-optimized model |

| | | | |
|---|---|---|---|
| | | | (179 bytes).<br>• **Unit: Bytes**<br>• **Interpretation: Maximum size of received packets, given in bytes.** |
| passedUpPk - Mean Passed-Up Packet Sizes | Varied for gnb1 and gnb2 | Varied for gnb1 and gnb2 | The optimized model tended to pass up slightly larger packets on average.<br>• **Unit: Bytes**<br>• **Interpretation: The mean size of passed-up packets is given in bytes.** |
| passedUpPk - Variability (StdDev) | Increased from 54.25 to 102.72 | Varied from 54.25 to 56.42 | The optimized model showed a wider range of variability in passed-up packet sizes.<br>• **Unit: Bytes**<br>• **Interpretation: Standard Deviation of passed-up packet sizes, given in bytes**. |
| passedUpPk - Max Passed-Up Packet Size | Occasionally 268 | 172 | The optimized model occasionally passed up larger packets (268 bytes) compared to the non-optimized model (172 bytes).<br>• **Unit: Bytes**<br>• **Interpretation: Maximum size of passed-up packets, given in bytes.** |
| OutgoingDataRate - Mean Outgoing Data Rate | Varied for gnb1 and gnb2 | Ranged from 284.8 to 542.08 bps | The optimized model exhibited a slightly lower mean outgoing data rate compared to the non-optimized model.<br>• **Unit: bits per second (bps)** |

| | | | |
|---|---|---|---|
| | | | • **Interpretation: The mean outgoing data rate is given in bits per second.** |
| OutgoingDataRate - Variability (StdDev) | Ranged from 3,498.3 to 5,677.7 bps | Ranged from 3,498.3 to 5,284.6 bps | Both models showed significant variability, but the optimized model had a wider range.<br>• **Unit: bits per second (bps)**<br>• **Interpretation: Standard Deviation of outgoing data rates, given in bits per second.** |
| OutgoingDataRate - Max Outgoing Data Rate | Occasionally 73,280 | 49,280 | The optimized model achieved higher maximum outgoing data rates compared to the non-optimized model.<br>• **Unit: bits per second (bps)**<br>• **Interpretation: Maximum outgoing data rate, given in bits per second.** |
| HarqErrorRate - Mean | Varied for ue[0] to ue[9] | Varied for ue[0] to ue[9] | The optimized model exhibited varying mean error<br>• **Unit: Unitless**<br>• **Interpretation: The mean error rate, a dimensionless quantity.** |

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