

**COMPARATIVE ANALYSIS OF DIFFERENT NETWORK DESIGNS,
CONNECTIONS, AND PERFORMANCE MEASUREMENT USING
OPTIMIZED NETWORK ENGINEERING TOOLS (OPNET) MODELER**

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THE UNIVERSITY OF ZAMBIA

LUSAKA

2024

As the candidate's supervisor, I have approved this research for submission.

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DECLARATION

I declare that this research represents solely my contributions. In instances where collaboration with other individuals occurred or materials from fellow researchers have been utilized, appropriate citations and acknowledgments are diligently provided.

This submission pertains to the pursuit of a Master of Engineering in ICT at the University of Zambia. I confirm that this work has not been presented for consideration in pursuit of any other Master's Degree or examination at any other academic institution.

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CERTIFICATE OF APPROVAL

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Internal Examiner 1	Signature	Date
Internal Examiner 2	Signature	Date
Internal Examiner 3	Signature	Date
Chairperson Board of Examiner	Signature	Date

DEDICATION

I wholeheartedly dedicate this research to my esteemed supervisor, Dr. Simon Tembo. His invaluable guidance, wisdom, and unwavering support have been the bedrock of this research endeavor, and I am profoundly grateful for his mentorship.

Additionally, I extend my dedication to my cherished family, especially my wife, Twaambo, whose constant encouragement, understanding, and unwavering patience during the demanding phases of this research have been my steadfast motivation.

To my incredible sons, Twalumba and Mwebewangu, your boundless love and infectious joy have been a constant source of inspiration, infusing every pursuit of knowledge with profound reward and meaning.

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ABSTRACT

The study conducted at the Technical and Vocational Teachers' College (TVTC) aimed to optimize its Local Area Networks (LANs) following a survey via a Google Forms questionnaire, which identified problem gaps. This led to stating a research problem statement and prompted a network redesign and upgrade. A comprehensive comparative analysis of various network designs, connections, and performance measurements was conducted using the Optimized Network Engineering Tool (OPNET) Modeler. The study aimed to discern factors influencing network performance and Quality of Service (QoS), with the goal of designing networks for optimal functionality and recommending superior configurations.

Utilizing OPNET simulation software, scenarios were crafted to address connectivity challenges at TVTC, revealing significant bottlenecks across diverse network designs and connections. Higher link capacities demonstrated lower HTTP response times, while lower capacities struggled with simultaneous traffic, resulting in delays. First In, First Out (FIFO) exhibited the highest data traffic drop, whereas Weighted Fair Queuing (WFQ) showcased the lowest drop rate. LAN delay increased with user volume, and WFQ proved most effective for video traffic, while Priority Queuing (PQ) excelled in handling Voice Traffic.

Building upon this analysis, recommendations are provided to enhance network performance and QoS. Prioritizing investments in high-bandwidth infrastructure and adopting efficient queuing mechanisms like WFQ are crucial. Regular assessment and adjustment of network configurations, along with the implementation of Quality of Service (QoS) strategies tailored for video and voice traffic, are essential for maintaining service quality.

This study makes a substantial contribution to network engineering knowledge, benefiting IT professionals, organizations, and educational institutions by providing actionable insights and best practices. It promotes informed decision-making, encourages standardization across sectors, and lays the groundwork for future advancements in network optimization. By offering practical solutions to modern challenges, it advances our understanding of network dynamics and serves as a foundation for ongoing innovation and improvement in network engineering practices.

Keywords: Computer Network metrics, OPNET simulator, LAN Network, Computer network designs, Computer network connections, Propagation delay, Network performance, and Quality of service (QoS).

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LIST OF ABBREVIATIONS/ACRONYMS

OPNET	- Optimized Network Engineering Tools (OPNET) Modeler
ICT	- Information and Communication Technology
TVTC	- Technical and Vocational Teachers' College
ISP	- Internet Service Provider
POP	- Point of Presence
LAN	- Local Area Network
QoS	- Quality of Service
NDLC	- Network Life Cycle Models
PPDIOO	- Prepare, Plan, Design, Implement, Operate, and Optimize
PBM	- Plan, Build, Manage
HTTP	- Hypertext Transfer Protocol
Email	- Electronic Mail
FTP	- File Transfer Protocol
SNMP	- Simple Network Management Protocol
CISCO	- Cisco Systems, Inc.
Cat5	- Category 5
Cat6A	- Category 6A
10GBaseT	- 10 Gigabit Ethernet over Twisted Pair (a networking standard)
PCs	- Personal Computers
VoIP	- Voice over Internet Protocol
bps	- bits per second
Bps	- Bytes per second
KBps	- Kilobytes per second
MBps	- Megabytes per second
GBps	- Gigabytes per second
ms	- milliseconds
EMI	- Electromagnetic Interference
SMF	- Single Mode Fiber
MMF	- Multimode Fiber

RJ	- Registered Jack
UTP	- Unshielded Twisted Pair
STP	- Shielded Twisted Pair
NS2	- Network Simulator 2
NS3	- Network Simulator 3
JSIM	- Java-based Simulation Environment
OMNeT++	- Objective Modular Network Testbed in C++
QualNet	- A commercial network simulation software for evaluating the performance of networking protocols and systems.
GUI	- Graphical User
WYSIWYG	- What You See Is What You Get

CHAPTER 1

INTRODUCTION AND BACKGROUND

1.0 Introduction

In today's digital landscape, seamless connectivity is not just a luxury but a necessity for efficient data communication. Despite the continuous advancements in networking technology, many network designs still grapple with critical bottlenecks, leading to various connectivity challenges that significantly hamper data transmission. Recognizing this, Technical and Vocational Teachers' College (TVTC) embarked on a survey using Google Forms questionnaires to pinpoint problem areas and establish a researchable problem statement.

The survey revealed a staggering 90% dissatisfaction among users regarding the network performance. Thus, this research aims to delve deeply into the intricacies of computer network designs and connections, with a specific focus on addressing persistent bottlenecks within the TVTC Local Area Network (LAN).

The primary objectives of this study are to design a network that optimizes performance and Quality of Service (QoS), evaluate link connections and their impact on network performance, and recommend and implement the most effective network designs and connectivity solutions. Leveraging the OPNET simulation software tool, this research will simulate various scenarios, ranging from the Internet Service Provider (ISP) Point of Presence (POP) to the LAN within the college premises.

Through empirical evidence and analysis, this research seeks to identify the most efficient network configurations, scrutinizing metrics such as throughput, response server time, traffic congestion, and latency.

1.1 Background to the study

In today's fast-paced and interconnected world, network performance management and monitoring have become vital for businesses of all sizes[1]. By actively monitoring and measuring network performance, businesses can optimize their network's efficiency and maximize productivity[2]. For instance, Pratik Timalsena's exploration of "Understanding Network Performance Bottlenecks" underlines the pivotal role of networks in delivering services to users. Timalsena emphasizes that a

content delivery network's core function hinges on its ability to consistently deliver content at predictable and acceptable performance levels[3].

In a related study, Adil Nazir Malik and Faisal Mehmood investigated the "Modeling and simulation of Computer Network in Bahria University Islamabad using OPNET". Their analysis encompassed critical facets such as traffic load, delay, data rate, LAN and WLAN characteristics, ping reports, and network efficiency, shedding light on the intricacies of network design within the university's infrastructure[4]

Similarly, A.A. Atayero, A.S. Alatishe, and J.O. Iruemi conducted a study on the "Modeling and Simulation of a University LAN in OPNET Modeler Environment." This research emphasized efficient resource sharing and information access among network users, highlighting the significance of robust network designs in facilitating seamless connectivity[5].

The importance of this research lies in its aim to address persistent network bottlenecks observed not only within the Technical and Vocational Teachers' College (TVTC) network but also in similar networks facing challenges in meeting end-users' performance demands. By probing into the nuances of LAN network performance and addressing underlying issues affecting efficiency, this research aims to offer substantial solutions to augment the body of knowledge about network optimization.

Despite substantial investments in technology upgrades, many networks continue to grapple with bottlenecks such as congested links, impacting factors like speed, page response time, and latency. A fundamental aspect of network enhancement involves a comprehensive understanding of different network designs' capabilities in minimizing costs while meeting data communication requirements effectively[3].

This study undertook a comparative analysis of network designs, connections, and their impact on performance using OPNET Modeler. It sought to discern the factors distinguishing one network's performance from another despite similarities in hardware and software configurations. By scrutinizing the network architecture from the ISP Point of Presence (PoP) to the entire Local Area Network (LAN), this research unearthed the critical elements influencing network performance.

Utilizing diverse network architectures, this research measured performance using various network applications such as HTTP, Email, and FTP, which aimed to deduce

the optimal network design. The specific objectives entailed designing a network configuration that optimizes performance, evaluating connectivity's effects on network performance, and implementing the most effective network designs and connections to achieve superior network performance.

1.2 Problem statement

Recognizing the pressing need for improvement, Technical and Vocational Teachers' College (TVTC) undertook a comprehensive survey utilizing Google Forms questionnaires (see **Appendix D**) to identify and define critical problem areas.

The survey findings revealed an alarming dissatisfaction among users regarding the network performance at TVTC. The institution's computer LAN wired network has been besieged by persistent issues such as poor connectivity, subpar performance, and unsatisfactory Quality of Service (QoS). Users articulated several concerns, including:

- i) Inconsistent application response times,
- ii) Elevated internet latency,
- iii) Sluggish and sporadic internet connectivity in specific zones, resulting in diminished productivity for certain staff members,
- iv) Numerous network failure points causing prolonged troubleshooting periods.

In response to these formidable challenges, this research endeavours to conduct a comparative analysis of diverse network designs, connections, and performance metrics to effectively mitigate these issues. The accompanying diagram below illustrates the areas flagged by users as experiencing inadequate network services, depicted by the red links.

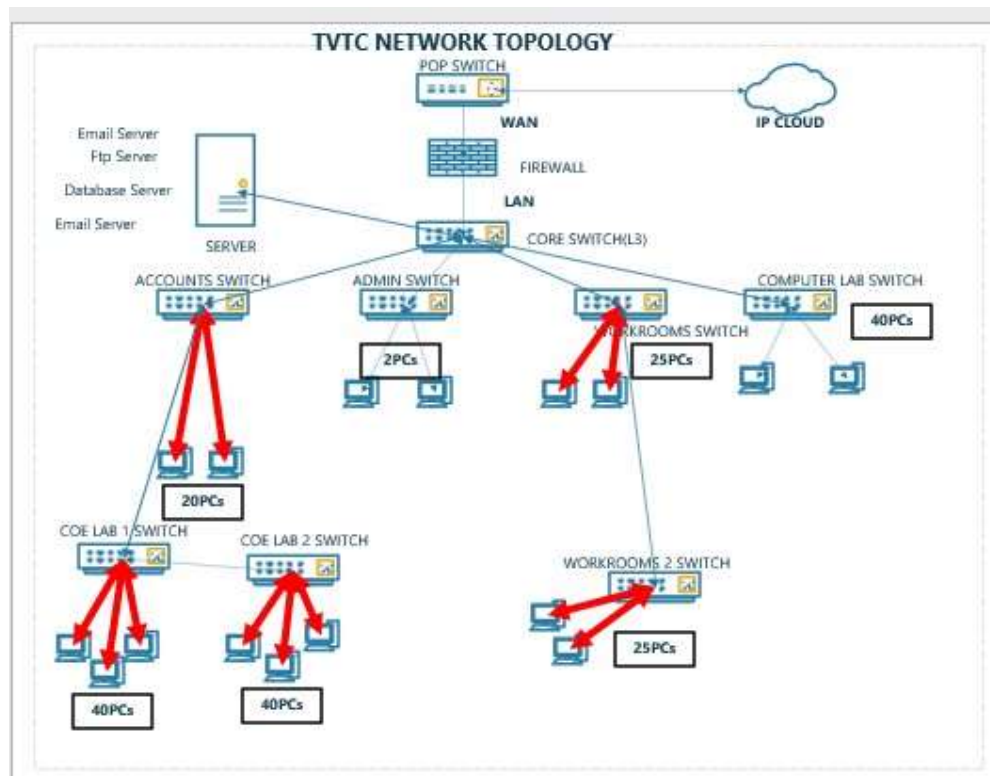


Figure 1. 1: Diagram showing network problem areas.

Source: Researchers Design - April (2024)

Note: COE in the diagram above stands for Center of Excellence

1.3 Aim

To conduct a comparative analysis of various network designs, connections, and performance measurements using the Optimized Network Engineering Tool (OPNET) Modeler to provide substantial insights, formulate strategic approaches, and offer recommendations for enhancing the TVTC network design and connectivity.

1.4 Objectives of the Study

The main objective of this project was to carry out a comparative analysis of different network designs, connections, and performance measurements using OPNET Modeler. The coverage area was from the Internet Service Provider (ISP) Point of Presence (POP) to an entire Local Area Network (LAN). The specific objectives are:

- i) Design a network design which gives the best network performance and QoS

- ii) Evaluate link connections, connectivity, and effect on network performance
- iii) Recommend and implement the best network designs, link connections, and connectivity which yields the best network performance and QoS.

1.5 Research Question(s)

The study attempted to answer key evaluation questions mirroring the objectives outlined above:

- i) How does network design (POP to entire LAN) affect network performance and QoS?
- ii) What effective network link connections and connectivity gives optimised network performance and QoS?
- iii) Which network design, link connections, and connectivity yield the best network performance and QoS?

1.6 Conceptual Framework

A conceptual framework can be defined as a visual representation in research that helps to illustrate the expected relationship between cause and effect. It is also called a conceptual model or research model. That means that different variables and the assumed relationships between those variables are included in the model and reflect the expectations[6].

This framework is a tool that is used before a study. This makes a conceptual framework an analytical tool. It is used to make conceptual distinctions and bring together different ideas. Strong conceptual frameworks lead to an actual realisation of the intended objective[7]. This research was, therefore, conducted by a conceptual framework.

In Figure 1.2 below, the input represents the data and factors that were fed into the research process. The process involved simulation and analysis to transform the input into meaningful output, which included performance data, recommendations, conclusions, and potential policy implications. The framework helped illustrate how the research aimed to address the research problem and achieve its objectives.

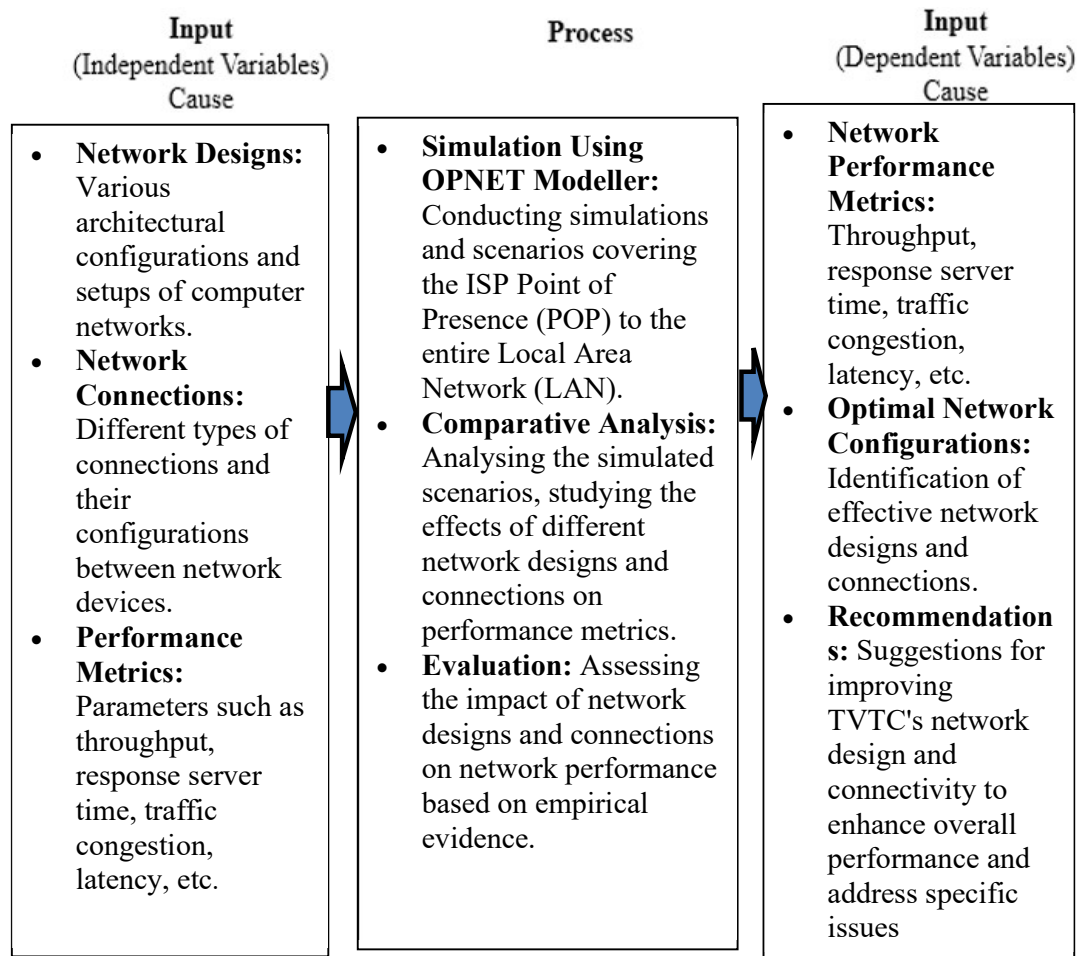


Figure 1. 2: Conceptual Framework

Source: Researchers Design - April (2022)

In Figure 1.2 above, input included the existing network infrastructure data, information about different network design strategies, and details about connectivity strategies. These inputs provided the foundation for my research. The process was the core of my research, where we used OPNET Simulation to model TVTC's network, simulate various strategies, measure performance metrics, and conduct a comparative analysis.

The Output consists of the results and findings from the research, such as performance data (latency, throughput, packet loss, reliability), recommendations for improving network performance, conclusions, policy and strategy implications, and suggestions for future research.

1.7 Significance of the Study

Network design is a critical feature of any enterprise-grade network. The way a network is designed impacts network monitoring capabilities and overall system performance, making it as important a factor as the infrastructure itself[8]. The research assisted in devising optimal network designs and connections to address issues of poor network performance at TVTC in specific sections. This was achieved by utilizing statistical results obtained from OPNET simulations.

Furthermore, the research contributed to the development of mitigation measures aimed at reducing disruptions in the educational processes for both students and staff members. It also alleviated productivity losses among staff and mitigated unnecessary costs incurred through production loss. Additionally, it made a substantial contribution to the body of knowledge regarding best practices in computer network designs, connections, and performance, thereby advancing the understanding of network designs and connections and providing valuable insights for further research in the field.

Contributions:

- Researchers:

- Advances the understanding of network designs and connections, providing valuable insights for further research in the field.
- Contributes to the body of knowledge regarding best practices in network engineering and performance measurement.

- Learning Institutions:

- Offers educational institutions the opportunity to implement optimized network designs, improving overall connectivity for students and staff.
- Provides a practical case study for academic purposes, enhancing the curriculum in information technology and network engineering.

- Industries:

- Benefits industries by promoting more efficient and reliable communication networks, potentially reducing downtime and enhancing productivity.
- Offers insights into the latest network engineering tools and methodologies, aiding in the adoption of cutting-edge technologies.

- Organizations:

- Enables organizations to optimize their network infrastructure, leading to improved operational efficiency and better service delivery.
- Reduces the risk of network-related disruptions, ensuring smoother day-to-day operations.

This means that other researchers in similar lines of research will also benefit. Last but not least, obtaining a master's degree in engineering in Information and Communication Technology (MEngICT) is an academic requirement for the researcher upon the successful completion of the research as a partial fulfillment.

1.8 Motivation for the Research

It's imperative that TVTC LAN users should be satisfied at the end of the day with the quality of IT network services provided by having consistence application response times for both staff and students, fast internet speed, less downtimes, and other network performance issues. Business networks must also be able to adjust to changing traffic loads to maintain consistent application response times. It is no longer practical to construct networks by connecting many standalone components without careful planning and design. Computers and information networks are critical to the success of businesses, both large and small. They connect people, support applications and services, and provide access to the resources that keep the businesses running. To meet the daily requirements of businesses, networks themselves are becoming quite complex. Therefore, was a need to redesign the network to meet the user demands[9]. Currently, internet connectivity (interconnections of network) is at the centre stage of everything. With several research and developments going on now in Africa and the world at large, network performance must be at its best to not impede the progress of research and development going on[10]. Network design is a crucial aspect of any enterprise-grade network. The way a network is designed impacts the network monitoring capabilities and the overall system performance, making it as important a factor as the infrastructure itself [8].

1.9 Application of the Research

Network analysis was conducted at an inter-organizational, organizational, or departmental level[11]. The network design phase is typically executed by specialist network designers, IT administrators, engineers, or other IT professionals before the

full implementation of the network infrastructure. Network design is a complex process that involves evaluating and scoping the network to be implemented. The design process is usually depicted in the form of a network diagram, serving as the blueprint for the physical implementation of the network[8]. The network design typically includes the cabling structure, a logical map of the network to be implemented, the number and type of network devices, the location of network devices, the IP addressing structure, and the network security architecture[12]. The outcomes of this research have practical implications. By scrutinizing various network designs and connections, the research aimed to offer recommendations and best practices to enhance the efficiency, reliability, and security of network infrastructures. Professionals involved in network design and implementation can utilize these insights to create robust, scalable, and secure networks tailored to their specific organizational needs[13][14].

1.10 Scope of the study

This study was restricted to the analysis of various network designs, LAN link connections, and the measurement of network performance using selected performance metrics. The assessment was conducted using the OPNET simulation tool. However, due to time constraints, the focus was limited to the area extending from the ISP POP to the entirety of the Technical and Vocational Teachers' Training College (TVTC) LAN.

1.11 Operational Definitions

Jitter: Absolute value of delay difference between selected packets[15].

Computer Network: A computer network is a group of computers linked to each other that enables the computer to communicate with another computer and share its resources, data, and applications[16],[17],[18].

OPNET: It is a network simulator is a tool to simulate the behavior and performance of any type of network[19],[20],[21]

Device Monitoring: Refers to monitoring the use of network resources or network devices using SNMP monitoring protocol. For example, to monitor the state of a firewall or determine the CPU usage or bandwidth usage of an interface. In that case, we usually take measurements from a specific location in the network, such as the counter of an interface, a CPU, etc. [22].

Network Performance Monitoring: This is end-to-end network monitoring of the end-user experience. It differs from traditional monitoring because performance is monitored from the end user[22].

Latency: In a network, latency refers to the measure of time it takes for data to reach its destination across a network. You usually measure network latency as a round trip delay, in milliseconds (ms), taking into account the time it takes for the data to get to its destination and then back again to its source[15], [23], [24].

Packet Loss: Number of video packets not reaching the preferred destination[15].

Throughput: amount of video data that can be transferred to the preferred destination (video server) per unit time (usually bits/second [15])

Packet Duplication: Refers to when data packets are duplicated somewhere in the network and are then received twice at their destination. Many times, if the source of the data believes that a data packet would not be transmitted correctly because of a packet loss, it may retransmit that packet. The destination source may have already gotten the first packet and will receive a second duplicate packet[22].

Packet Reordering: This occurs when data packets arrive at their destination in the wrong order. This can happen for various reasons, such as multi-path routing, route fluttering, and wrong QoS queue configuration[22].

Bandwidth: The maximum amount of data transmitted over an internet connection in a given amount of time or data rate supported by a network connection or interface[18],[25].

1.12 Ethical Considerations

In adherence to ethical principles, this research aligns with the guidelines stipulated in the UNZA Research Student Handbook, ensuring strict compliance with established protocols. Upholding a high standard of ethical conduct, the researcher was committed to safeguarding the rights of all involved parties throughout the research process. The key Ethical Commitments Include:

- i) **Adherence to Guidelines:** This research meticulously followed the ethical guidelines outlined in the UNZA Research Student Handbook, ensuring that every step complied with prescribed norms and standards.
- ii) **User Rights Protection:** A primary focus lay in safeguarding the rights, privacy, and confidentiality of all participants involved in or affected by the study. Measures were put in place to obtain informed consent and protect sensitive information throughout the research journey.
- iii) **Enhanced Research Authenticity:** Emphasis was placed on ensuring the authenticity and reliability of research findings. All data collection, analysis, and reporting processes-maintained transparency and accuracy, contributing to the credibility of the study outcomes.
- iv) **Commitment to Academic Integrity:** Upholding the highest standards of academic integrity, this research attributed sources accurately, avoided plagiarism, and maintained honesty and fairness in all scholarly endeavors.

This commitment to ethical conduct not only aligns with institutional guidelines but also reflects dedicated, responsible, and principled research practices.

1.13 Plan of Development (Organization of the Study)

The research was organized into distinct segments to provide a structured flow, namely: Introduction; Literature Review; Research Methodology; Results and Discussions; and Conclusion and Recommendations. The detailed outline is as follows:

Chapter One: This is the first part of the research. The chapter looks at the introduction for the research, the background of the study, the problem statement, the aim of the study, the research objectives, the research questions, the conceptual framework, the significance of the study, motivation of the research, application of the research, the scope of the project, the research operational definitions, and last but not the least ethical consideration. The chapter was used as input to the subsequent chapters.

Chapter Two: This section focuses on the literature review, where other related works in the market and additional information related to the research topic are

reviewed to gain a broader understanding of the research and insight into the gaps that needed to be addressed.

Chapter Three: This chapter looks at the selected research approach to gather, evaluate, and translate data for the research. Furthermore, it looks at the research design which helped plan to answer research questions, the research methodology used, the review of the research tools, the criteria for selecting a specific tool on the market to carry out the research simulations, and design models used to carry out the research.

Chapter Four: This segment constitutes the essence of the research, presenting the implementation of the lab, data collection/viewing, and analysis of results derived from OPNET simulation and Microsoft Excel Spreadsheet analysis. This involved the utilization of tables and graphical representation.

Chapter Five: This part provides the research conclusion and recommendations grounded in the simulations, experimental results, and discussions. Additionally, potential future work is proposed as a final consideration.

1.14 Summary

The chapter gave a general overview of the comparative analysis of different network designs, connections, and performance measurement using Optimized Network Engineering Tools (OPNET) Modeler. It looked at some network bottlenecks and their negative impacts on the overall performance of today's networks. Some of the performance matrices of concern are latency, packet delay, slow internet speeds, LAN resource request delays, etc. The research eradicated some of the problems to help in the optimization of the general network performance.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

In this section, a review of relevant theories was be conducted, accompanied by an extensive exploration of existing systems related to the research topic. This meant undertaking a comprehensive market survey. The review encompassed an analysis of various computer network designs, simulations, and models, providing context for past and present trends in computer architecture, connectivity, and performance.

Drawing from a rich array of sources including the internet, scholarly articles, electronic books, specialized journals, and pertinent databases, this literature review aimed to synthesize insights and knowledge essential for understanding the landscape surrounding the research domain. By scrutinizing these resources, a nuanced perspective was crafted, shedding light on the evolution and current state of computer systems, networks, and their interplay within contemporary environments.

2.1 Network Design using Graph Theory

This sub-section gives a brief explanation of one of the theories that supports the research topic:

2.1.1 Network Design using Graph Theory

In our contemporary world, networks pervade every facet of existence, seamlessly facilitating communication and transportation, extending from the expanse of the internet to intricate transportation systems. Crafting and optimizing a network to meet specific objectives, whether geared towards maximizing efficiency, minimizing costs, or ensuring robustness, constitute the essential components of network design. The application of graph theory provides a robust mathematical framework for the description and analysis of networks, furnishing an extensive toolkit for effective network design[26], [27].

Graphs, defined as mathematical structures composed of vertices (or nodes) interconnected by edges, constitute the foundational elements in representing networks. Graph theory, a specialized branch of mathematics, systematically examines the properties of these mathematical structures[28][29]. The broader field dedicated to

the mathematical study of networks is aptly named graph theory. The surge in computer networks, the internet, and social networks has accentuated the pivotal role of graph theory in network design[30]. Its application not only expedites the swift creation of networks but also maximizes their functionality, offering a powerful suite of tools for comprehensive network design and optimization[31]. Below is a sample of Graph theory diagram.

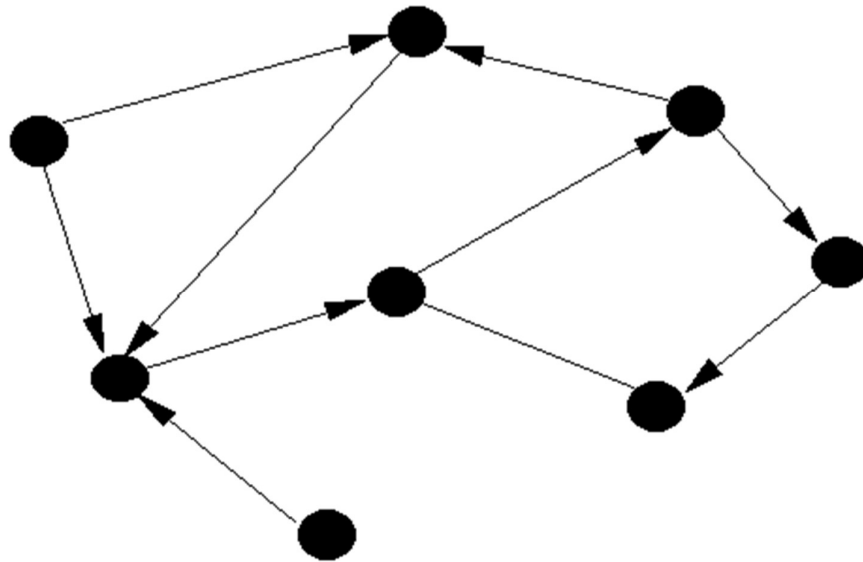


Figure 2. 1: Sample Graph Theory diagram [25]

2.1.1.1 Graph Theory and Network Design: Network Connectedness

Graph theory serves as a valuable tool for analyzing the interconnectedness of a network. By representing the network as a graph, various characteristics can be explored, including the degree distribution of nodes, the clustering coefficient, and the shortest path between nodes[32].

The concept of the shortest path is a fundamental aspect of graph theory, addressing the determination of the most efficient route between any two nodes in the network. This is particularly crucial for optimizing data routing within the network and plays a vital role in network architecture[33].

The clustering coefficient, another key concept in graph theory, quantifies the proximity of connected nodes in a network. Understanding this metric is essential for network design as it aids in identifying bottlenecks and enhancing communication efficiency among nodes[34], [35].

Graph theory also offers insights into a network's robustness. By simulating the removal of nodes or edges in the graph representation, the impact of network failures on connectedness can be assessed. This analysis enables the design of more resilient networks capable of withstanding failures and disruptions[36].

2.1.1.2 Network Design:

Network design involves determining the topology, which encompasses the arrangement of nodes and the connections linking them. Graph theory serves as a valuable tool in this process, allowing for the analysis of network connections and the improvement of overall performance to construct robust networks[33], [34].

2.1.1.3 Network Topology:

Network topology, whether physical or logical, pertains to the arrangement of nodes and other devices in a network. It delineates the connections between nodes and the direction of data flow within the network. Various types of network topology exist, such as Star, Bus, Tree, Hybrid, Mesh, and Ring, each with its distinct set of advantages and disadvantages[37],[38], [39].

2.2 Local Area Network (LAN)

A Local Area Network (LAN) constitutes a cluster of computers or network devices interlinked within a confined area, typically facilitated through Ethernet or Wi-Fi connectivity[40]. According to a CISCO study, a LAN embodies a network assembly housed within a singular physical location, be it an office, building, or residential space[41]. The scale of a LAN can vary significantly, spanning from modest home networks serving a single user to expansive enterprise networks supporting thousands of users and devices within office complexes or educational institutions[42], [43]. For visual reference, a sample LAN diagram is presented below.



Figure 2. 2: Local Area Network Diagram

Source: [43]

2.3 Network Life Cycle Models

Before delving into network design intricacies, it is essential to comprehend the network life cycle models. These models provide a framework elucidating the placement and relevance of network design within the broader lifespan of a network's components and overall structure. Notably, various models exist, including Cisco's PPDIOO (Prepare, Plan, Design, Implement, Operate, and Optimize) model [44], [45], Cisco's PBM (Plan, Build, Manage) model [44][45], [46], and the Network Development Life Cycle (NDLC) [44], [45], [47].

Regardless of the specific model chosen, the fundamental stages of information gathering, design, implementation, and enhancement remain consistent, embodying a cyclical nature. The crucial insight lies in comprehending the network life cycle and delineating the role of network design within it. Among these models, Cisco's PPDIOO model stands as one of the most widely recognized and utilized frameworks [46].

2.4 LAN Network Designs

Network design embodies the strategic layout of an organization's network infrastructure [48], [49]. Defined as the meticulous planning and architectural structuring of a communication network, this process commences with a thorough assessment of business and technical requisites, extending until the pre-implementation phase. Network design encompasses multifaceted elements such as network analysis, IP addressing, hardware selection, and meticulous implementation

blueprints. While executing network design in simpler setups like small offices or domestic networks might be straightforward, in sprawling enterprise networks, the process often becomes intricate, involving multiple stakeholders[49], [50].

In alignment with this perspective, it emphasizes that the efficacy of a computer system's design hinges significantly on the quality of the network infrastructure. Suboptimal network infrastructure can lead to inefficient system performance due to network congestion. The primary thrust of network infrastructure design is to alleviate congestion and augment performance, primarily through network segmentation[22]. This involves three pivotal areas: ethernet network infrastructure design, segmentation strategies (partitioning large networks into more manageable segments), and judicious selection of network solutions[51],[48], [50]. Although the latter may not directly address the internal issue at hand.

Delving deeper into ethernet network infrastructure design, comprehension of ethernet topology assumes significance. Ethernet networks typically employ physical bus or star topologies, where the logical topology operates as a bus, broadcasting all messages across network devices through cabling. Familiarity with LAN cable selection as the transmission media for Ethernet networks is paramount [9].

Segmentation, a core aspect of network infrastructure, entails breaking down networks into smaller, more manageable segments. Achieving this often involves introducing additional switches and cables strategically within the network, effectively alleviating congestion if appropriately executed with suitable cabling[52].

Expanding on this, both “N able Solutions ULC and N able Technologies Ltd” underscore the essential requisites for a comprehensive network infrastructure design. This includes meticulous network mapping, cabling structure and layout, device specifics, IP addressing schemas, and a robust network security architecture[53]. They emphasize that network design, a crucial phase in a company's IT infrastructure rollout, necessitates a holistic understanding of how various network devices, from routers to desktops and printers, interconnect to optimize network performance. This strategic design endeavor, typically handled by network designers, IT managers, administrators, and related personnel, enhances operational efficiency[53].

Echoing these sentiments, Lazapoint, a network solutions entity, highlights the criticality of a high-performing core network infrastructure for fostering employee productivity[54]. This aligns precisely with the situation requiring attention at TVTC.

To provide visual context, below are sample Local Area Network (LAN) designs sourced from diverse organizational networks on the internet.

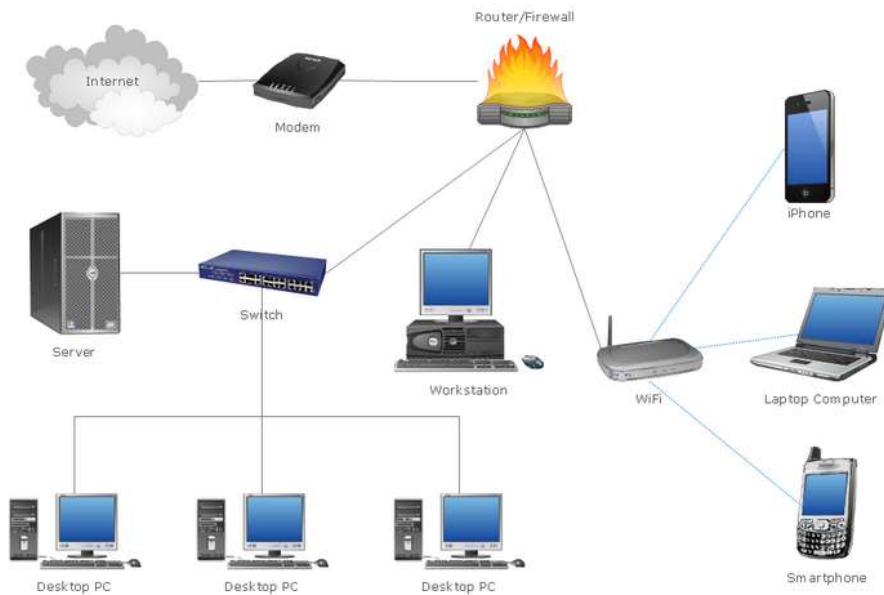


Figure 2. 3: Sample Network diagram design

Source:[55]

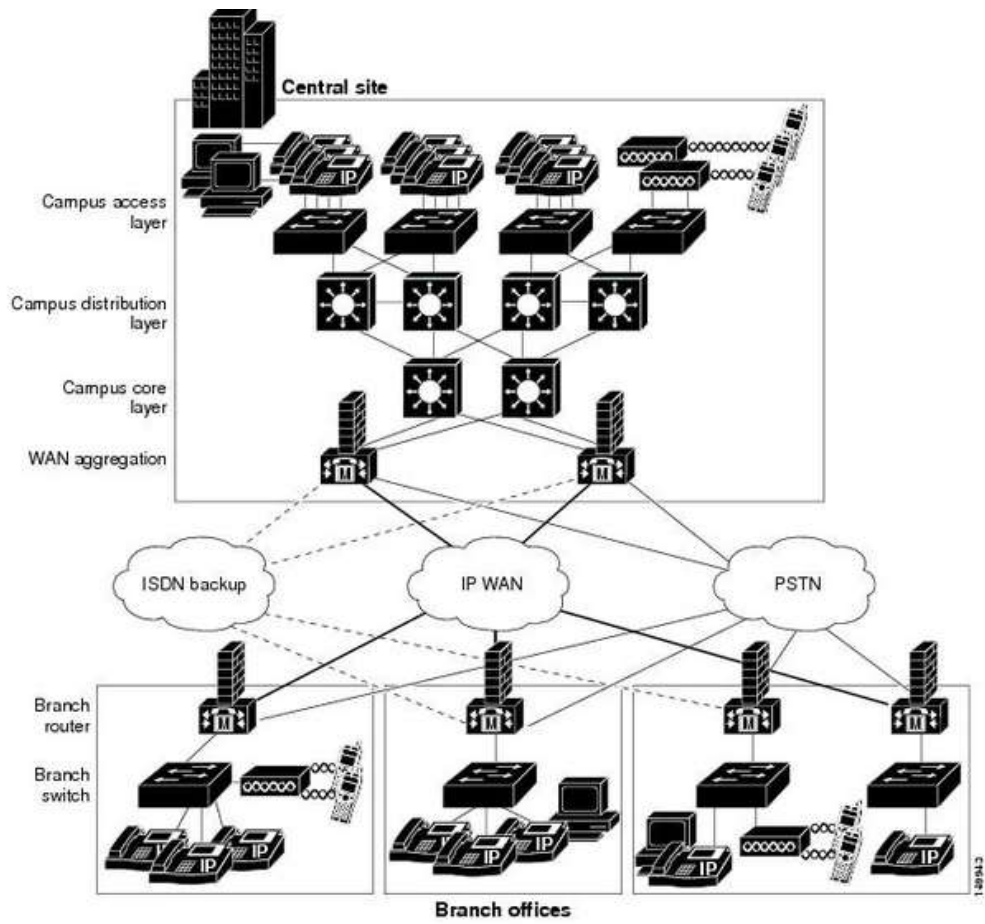


Figure 2. 4: Sample Network diagram design

Source:[56]

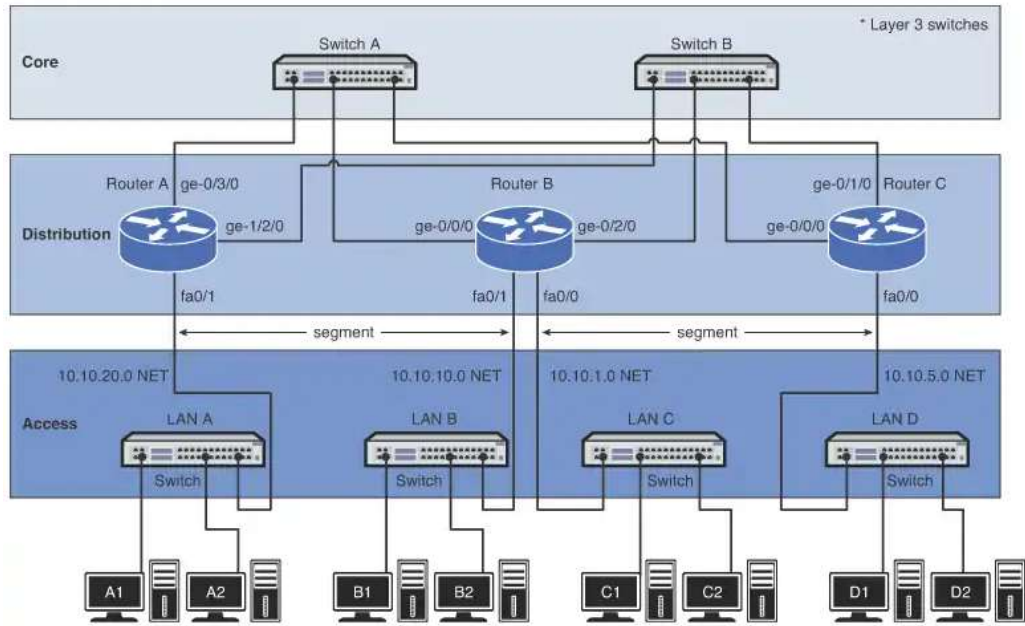


Figure 2. 5: Sample Network diagram design

Source:[57]

2.5 Considerations for designing computer networks.

There are considerations to be taken note of when designing a network such as Copper vs fiber, logical topologies, IP addressing, VLANs, bandwidth, and network. However, that's far from an exhaustive list. There is a lot that goes into designing a network, and it can be easy to overlook things [58],[59],[60].

2.6 Network Design Techniques

When designing networks, there are generally some important steps to be followed or considered. Some literatures have been written on the basics of a network lifecycle model in designing an effective network infrastructure. It's imperative to note that the complexity of networks differ but still with a general framework in place helps to make correct choices[58],[60]. The following steps are to be followed when designing a network.

2.6.1 Identify the requirements

Before any network design, gathering network requirements is an important exercise. Without clearly defining requirements, it leads to the design falling apart which would

lead to having an inefficient performing network. Requirements assist what needs to be done[58], [60], [61].

2.6.2 Assess the current state of the network

The above-mentioned scenario represents a pivotal phase in the network design process, especially relevant to TVTC's existing network infrastructure. Acknowledging the pre-existence of the network and its structured cabling signifies a substantial advantage, as it streamlines the design process. However, while leveraging an existing setup can simplify matters, potential complications may arise if the current cabling, for instance, is Cat5 and the requisite upgrade demands Cat6A to support 10GBaseT. This discrepancy highlights the need for addressing existing infrastructure limitations.

Irrespective of the network's present condition, it is imperative to conduct a comprehensive assessment of its current state before formulating specific recommendations for network design. This preliminary investigation serves as a crucial foundation, enabling a clear understanding of any constraints or deficiencies within the existing setup and guiding subsequent design decisions[58], [60], [61]

2.6.3 Design your network topology

Once the requirements are established and the current state of your network is understood, one can start blocking out the functional components of the network. This is where the physical and logical network design is considered. For physical network design, one should consider things like running fiber and copper cabling, type of switches and ports required, positioning of Wi-Fi access point, and cabling type between network racks just to mention but a few. For logical network design, one should consider IP addressing/subnetting, VLANs, data flows, and topology of the network[58]. The two main network design concepts are hierarchical network layers and top-down vs bottom-up design. A traditional hierarchical network design is based on the idea of three basic network layers. This is the most common[62]. Each layer handles a separate portion of the data flow on a network. The core layer is the backbone of the hierarchy network. The primary transmission and routing of data signals take place at the core layer only. When it comes to the distribution layer, the main responsibility of these switches is to ensure the routing of data to the correct devices in the access layer. However, the distribution layer handles maximum data traffic as

the data packets are pushed through the core layer to the distribution layer[63]. The access layer is the layer for endpoint devices like user PCs, printers, and VoIP phones) as shown in the diagram below.

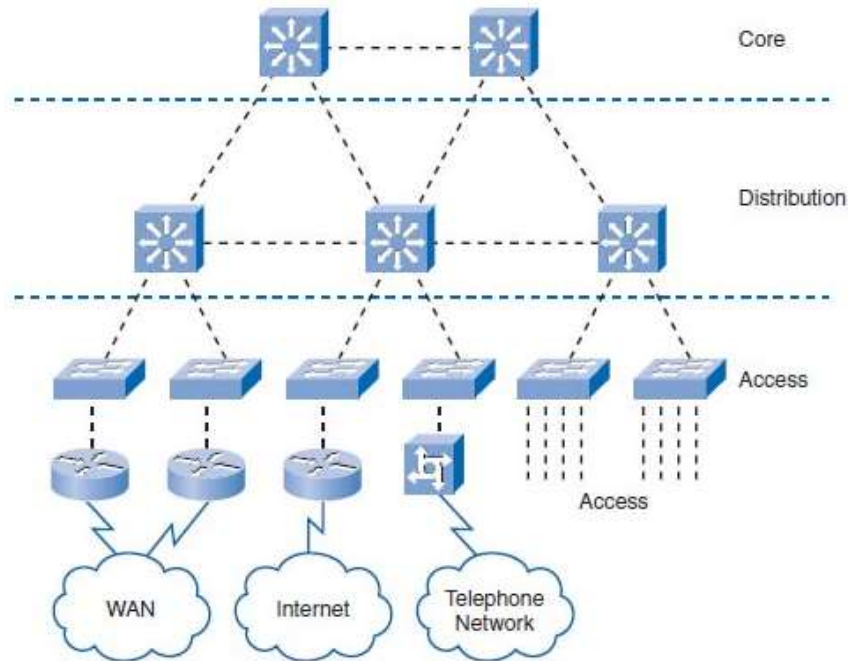


Figure 2. 6: A traditional hierarchical network design

Source:[64]

However, in some cases you may not need all three layers because some networks bypass the distribution layer altogether[58]. The other approaches to network designs are top-down and bottom-up design which are based on the OSI model. Below is a table displaying a summary of the two approaches.

Table 2. 1: Top-down vs Bottom-up network design approach

	TOP-DOWN	BOTTOM-UP
Pros	<ul style="list-style-type: none"> Starts with the needs of the organization Provides a "big picture" to the customer and the designer 	<ul style="list-style-type: none"> Quick Leverages previous experience
Cons	<ul style="list-style-type: none"> Time consuming 	<ul style="list-style-type: none"> Might miss some organizational requirements High probability of failure

Source: [65]

2.6.4 Choose the hardware and software

This involves finding out the hardware and software to be used for the network. This can also be done in parallel with the design the network topology. At this stage, one selects specific cables, switches, applications, servers, etc. to make the design a reality[58].

2.6.5 Plan for implementation and beyond

With your network design and hardware/software selections ready, you can now plan for the implementation and beyond. This involves coming up with a way of deploying, configuring, and testing the network[58].

2.7 Network design best practices

The author underlines the significance of employing five pivotal best practices in network design to ensure optimal network performance, scalability, and improved organizational efficacy[53]. These best practices, crucial during the design phase, encompass:

- i) **Inclusive Design Phase:** Avoiding the omission of the actual design phase ensures a comprehensive blueprint.
- ii) **Future Planning:** Incorporating foresight in design, anticipating future needs for scalability and advancements.
- iii) **Embedded Security:** Integrating robust security measures within the design framework to fortify the network against threats.
- iv) **Continuous Network Monitoring:** Implementing an ongoing monitoring system to track and manage network performance.

In parallel, V500 systems network-related company elaborates on ten essential network design principles, emphasizing their pivotal role in saving substantial resources for organizations. V500 systems echoes the sentiment, emphasizing specific key practices essential for optimal network design:

- i) **Initial Network Sketch:** Commencing with a network sketch to lay the groundwork.
- ii) **Equipment Selection:** Choosing the most suitable equipment aligned with business requirements.
- iii) **Future Planning:** Anticipating network needs over an extended timeframe (e.g., ten years) and instituting adequate security measures.

- iv) **Cabling Consideration:** Acknowledging the importance of both copper and fiber cables.
- v) **Standardization and Redundancy:** Prioritizing standardization and reinforcing network resilience, redundancy, and high availability.
- vi) **Monitoring, Management, and Environment:** Enforcing a robust monitoring and management system while ensuring optimal environmental conditions (cooling, power, etc.)[66].

Another study, detailed by a different researcher, accentuates additional best practices in network design:

- i) **Early integration of Security measures:** Incorporating security measures at an early stage.
- ii) **Top-Down Vs Bottom-Up Approach:** Understanding when to utilize top-down and bottom-up design strategies.
- iii) **Emphasis on standardization:** Advocating for comprehensive standardization across network elements.
- iv) **Growth Planning and Documentation:** Planning for network expansion and maintaining thorough network documentation.

Collectively, these diverse perspectives underscore the critical importance of foresight, security integration, comprehensive planning, and ongoing monitoring as essential pillars in achieving an efficient and resilient network design[66], [67].

2.8 Network performance measurements

Network performance is primarily measured from an end-user perspective (i.e., quality of network services delivered to the user). Broadly, network performance is measured by reviewing the statistics and metrics from the following network components:

- i) **Network bandwidth or capacity** - Available data transfer.
- ii) **Network throughput** - Amount of data successfully transferred over the network in a given time.
- iii) **Network delay, latency, and jitter** - Any network issue causing packet transfer to be slower than usual.
- iv) **Data loss and network errors** - Packets dropped or lost in transmission and delivery[68].

2.8.1 Network performance characteristics

The writer defines the performance of a network as a measure of the service quality of a network as perceived by the user. There are different ways to measure the performance of a network, depending upon the nature and design of the network. The characteristics that measure the performance of a network are;

- i) Bandwidth
- ii) Throughput
- iii) Latency (Delay)
- iv) Bandwidth – Delay Product
- v) Jitter

[68]

2.8.1.1 Bandwidth

Bandwidth determines how rapidly the webserver can upload the requested information [69]. In another study, it is defined as the maximum amount of data transmitted over an internet connection in a given amount of time[68].

The term can be used in two different contexts with two distinctive estimating values. In the case of digital devices, the bandwidth is measured in bits per second(bps) or bytes per second. In the case of analog devices, the bandwidth is measured in cycles per second, or Hertz[68]

2.8.1.2 Throughput

Throughput is defined as the amount of video data that can be transferred to the preferred destination (video server) per unit time (usually bits/second[15]. Other researchers defined throughput as the number of messages successfully transmitted per unit time[68]. It is controlled by available bandwidth, the available signal-to-noise ratio, and hardware limitations. The maximum throughput of a network may be consequently higher than the actual throughput achieved in everyday consumption[68], [70].

Throughput is measured by tabulating the amount of data transferred between multiple locations during a specific period of time, usually resulting in the unit of bits per second(bps), which has evolved to bytes per second (Bps), kilobytes per second

(KBps), megabytes per second (MBps) and gigabytes per second (Gbps). Throughput may be affected by numerous factors, such as the hindrance of the underlying analog physical medium, the available processing power of the system components, and end-user behaviour[70].

2.8.1.3 Latency/Delay

In a network, during the process of data communication, latency (also known as delay) is defined as the total time taken for a complete message to arrive at the destination, starting with the time when the first bit of the message is sent out from the source and ending with the time when the last bit of the message is delivered at the destination. The network connections where small delays occur are called “Low-Latency-Networks” and the network connections which suffer from long delays are known as “High-Latency-Networks[23], [24], [68], [70].

High latency leads to the creation of bottlenecks in any network communication. It stops the data from taking full advantage of the network pipe and conclusively decreases the bandwidth of the communicating network. The effect of the latency on a network’s bandwidth can be temporary or never-ending depending on the source of the delays. Latency is also known as a ping rate and is measured in milliseconds(ms) [69]

2.8.1.4 Jitter

Jitter is absolute value of delay difference between selected packets[15].It’s another performance issue related to delay. In technical terms, jitter is a “packet delay variance”. It can simply mean that jitter is considered as a problem when different packets of data face different delays in a network and the data at the receiver application is time-sensitive, i.e. audio or video data. Jitter is measured in milliseconds(ms). It is defined as an interference in the normal order of sending data packets. For example: if the delay for the first packet is 10 ms, for the second is 35 ms, and for the third is 50 ms, then the real-time destination application that uses the packets experiences jitter[68], [70].

Simply, jitter is any deviation in, or displacement of, the signal pulses in a high-frequency digital signal. The deviation can be in connection with the amplitude, the width of the signal pulse, or the phase timing. The major causes of jitter are electromagnetic interference (EMI) and crosstalk between signals. Jitter can lead to

the flickering of a display screen, affect the capability of a processor in a desktop or server to proceed as expected, introducing clicks or other undesired impacts in audio signals, and loss of transmitted data between network devices[68], [70].

Jitter is negative and causes network congestion and packet loss.

- i) Congestion is like a traffic jam on the highway. In a traffic jam, cars cannot move forward at a reasonable speed. Like the traffic jam, in congestion, all the packets come to a junction at the same time. Nothing can get loaded.
- ii) The second negative effect is packet loss. When packets arrive at unexpected intervals, the receiving system is not able to process the information, which leads to missing information also called “packet loss”. This has negative effects on video viewing. If a video becomes pixelated and is skipping, the network is experiencing jitter. The result of the jitter is packet loss. When you are playing a game online, the effect of packet loss can be that a player begins moving around on the screen randomly. Even worse, the game goes from one scene to the next, skipping over part of the gameplay[68], [70].

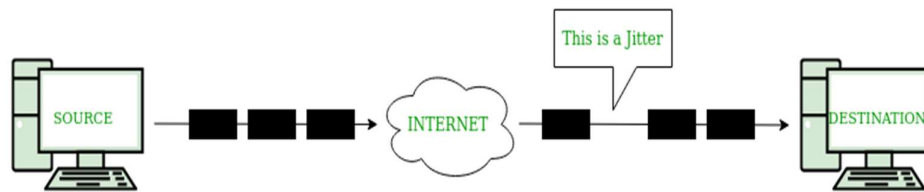


Figure 2. 7: Diagram showing jitter

Source:[70]

In the above image, it can be noticed that the time it takes for packets to be sent is not the same as the time in which they will arrive at the receiver side. One of the packets faces an unexpected delay on its way and is received after the expected time.

A jitter buffer can reduce the effects of jitter, either in a network, on a router or switch, or on a computer. The system at the destination receiving the network packets usually receives them from the buffer and not from the source system directly. Each packet is fed out of the buffer at a regular rate. Another approach to diminish jitter in case of multiple paths for traffic is to selectively route traffic along the most stable paths or to

always pick the path that can come closest to the targeted packet delivery rate[68], [70].

2.8.2 Factors affecting network performance

There are several factors affecting network performance such as network infrastructure, applications in use, network security, general network issues, transfer technology, the number of users sharing a connection or network device, and location as some of the factors. It's concluded that for the network to perform at its best, these key issues are supposed to be addressed because they directly impact network performance KPIs[71],[71].Below are some of the considered issues or factors.

2.8.2.1 Applications

Applications that are not streamlined to suit the capacities of a network or applications that are performing slowly can apply unnecessary stress on a network's bandwidth and reduce user experience. When possible, applications should be designed with the network in mind, as diagnosing these application issues in post-release can be a challenging task[71], [72].

2.6.2.2 Infrastructure and Network Issues

This includes all routers, firewalls, and switches as they can in one way or another other give rise to network traffic performance issues. Measuring these components individually can be a hard nut to crack, but Live Action's network management solution breaks down the complexity to provide insights into the performance of a network's components, to ease the stress and boost the accuracy of the network monitoring and management across IT departments in different enterprises[71], [72].

2.6.2.3 Data transfer technology.

In fixed networks, the main factor affecting the broadband speed is the technology used for data transfer. Fibre-optic and cable networks enable high-speed connections, whereas traditional xDSL connections provided over a telephone network have limited maximum transfer speeds[73].

2.6.2.4 Network centralizer

The speed of the connection also depends on the distance between the terminal device and the network centralizer. The longer the distance from the centralizer, the more it affects the speed of the connection[73].

2.6.2.5 Other devices and users

If several different devices are connected and want to have access to the same network resource at the same time this can cause the connection to slow down or cut out[73].

2.7 LAN cables

A LAN cable is used almost everywhere on this planet. It plugs into Ethernet ports on various network devices to help create home or business networks to share files, information, and data with each other and establish internet connections. This blog will give you a comprehensive guide to help you understand more about a LAN cable[74]. There are three main types of LAN cables:

- i) Coaxial cable
- ii) Copper twisted pair
- iii) Fiber optic cable

Each of the above cables is different and appropriate for various purposes. Below is a brief explanation of each[74].

2.7.1 Fibre Optic Cable

It's a type of Ethernet cable that consists of one or more optic fibers that are used to transmit data. Fiber optic cable transmits data as pulses of light go through tiny tubes of glass. It has a huge transmission capacity of 26000 higher than the twisted pair cable[75]. Below is a sample diagram.

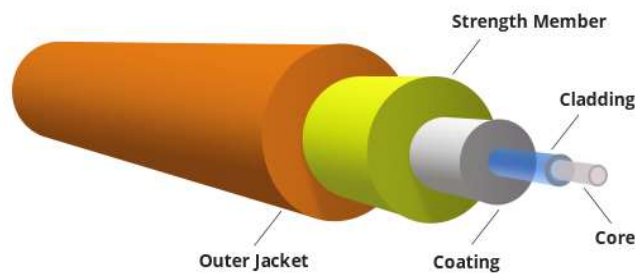


Figure 2. 8: Fibre Optic Cable

Source: [75]

Usually, it comes as a single-mode fiber (SMF) or multimode fiber (MMF). Single-mode optical fiber has a small core and only allows one mode of light to propagate at

a time. While multimode fiber cable comes with a larger core and is designed to carry multiple light rays or modes at the same time. For longer distances, it's better to use SMF than MMF[76].

2.7.2 Twisted Pair Cable

It is used in modern Ethernet networks and in telephone communications. Ethernet network usually uses Rejected Jack (RJ) 45 while telephones (use smaller in size RJ i.e. RJ11, RJ14, and RJ25). It is a kind of wiring in which two conductors of a single circuit are twisted together. A pair of wires forms a circuit that can transmit data. The pairs are twisted together to provide protection against crosstalk, the noise generated by adjacent pairs[76].

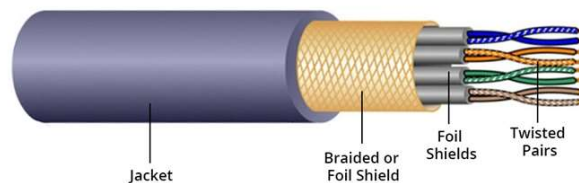


Figure 2. 9: Twisted Pair Cable

Source:[76]

unshielded twisted pair (UTP) and shielded twisted pair (STP) are the two types of twisted pair Ethernet cable. Category5 (Cat5), Category5 (Cat5e), Category6 (Cat6), Category6 (Cat6a) and Category7 (Cat7) are the ones often used. The STP copper cable has a foil-wrapped outside on each pair of wires. It's usually a 150-ohm cable. It has an improved capacity which is able to resist noise than UTP cable regardless of where they are used e.g. in the 10GBASE-T network[76].

2.7.3 Coaxial Cable

It is designed to transmit high-frequency signals. The three layers of insulation of the round copper conductor and shielding which it's made of prevent crosstalk from lighting, motors, and other sources of Electromagnetic interference (EMI). It supports longer cable lengths between two devices because of the shield construction[77]

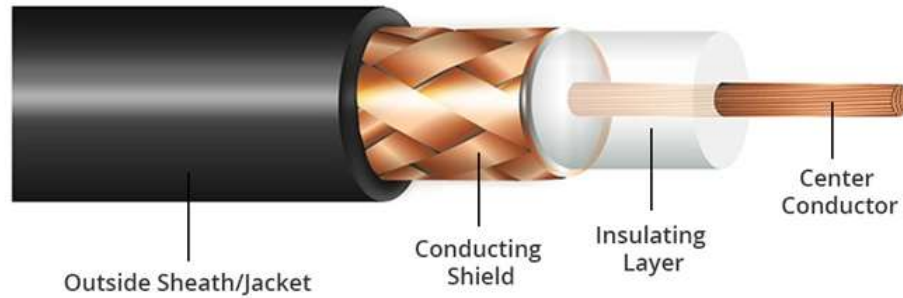


Figure 2. 10: Coaxial Cable

Source: [76]

2.8 Cable Speed, Bandwidth & Distance coverage

Comparisons in terms of speed, Bandwidth, and distance for the three cables are depicted below.

Table 2. 2: Cable Speed, Bandwidth & Distance coverage

Cable Type	Speed	Bandwidth	Distance
Fiber optic cable	10/100/1000 Mbps, 10/40/100/200 Gbps	Up to 4700 MHz	Up to 80km
Twisted pair cable	Up to 10 Gbps	Up to 4700 MHz	Up to 100m
Coaxial cable	—	750 MHz (default)	Up to 500m

Source:[75]

2.9 Related Works

The research landscape surrounding this topic has seen diverse investigations shedding light on various aspects. Several studies have significantly contributed to understanding network performance and optimization.

In one study by Ufuoma Kazeem Okpeki, J.O Egwaile, and F Edeko, a comparative analysis of wired and wireless communication systems using a Local Area Network (LAN) based on IEEE 802.3 and IEEE 802.11 standards was conducted. This focused examination evaluated throughput, delay, bit error, and Signal to Noise Ratio, utilizing the e-library network for Delta State University[78].

Another research initiative led by Atayero A, Alatishe A, and Iruemi J simulated and analyzed Covenant University's LAN to enhance efficiency in resource sharing and information access. Their study revealed insights into how different network configurations, particularly switches and hubs, impacted Ethernet delay and overall network load[79].

Furthermore, a study conducted at the University of Mines and Technology in Ghana used OPNET simulation to address bandwidth management challenges within their LAN [13]. By identifying misuse patterns, including low-priority website access and peer-to-peer applications, and implementing effective bandwidth control policies, they significantly improved network speed and security[80]. Additionally, studies focusing on modeling LAN and wireless LAN (WLAN) compared their efficiencies using simulation. The results highlighted that, without prioritizing mobility, LAN remained the most efficient communication means compared to WLAN[80].

At Delta State University they carried out another research on “Performance and Comparative Analysis of Wired and Wireless Communication Systems using Local Area Network Based on IEEE 802.3 And IEEE 802.11”. The emphasis was on Throughput, Delay, Bit error rate and Signal to Noise Ratio by collecting data. This had to do with the Delta State University e – library network. Based on the networks performance metrics after statistical data analyzed, the wireless network was preferable to the wired network[81].

Other research endeavors explored network design considerations using simulation tools like Opnet™ It Guru Academic Edition Software. They emphasized the impact of faster Ethernet cabling and server distribution on CPU utilization[82].

At Bahria University's NC Campus they carried out a comparative analysis of different network topologies (star, ring, and bus) using OPNET simulator provided valuable insights into network delay, load, and performance variations with varying network sizes and topologies[4].

Moreover, other investigation carried out research on “OPNET Based Performance Analysis and Comparison Among Different Physical Network Topologies”, It looked at the many types of topologies (Star, Bus and Ring) and performance comparisons among the topologies. Part of the compared results indicated that performance decreased when the network size increased and further showed that the bus topology was more effected than two other topologies[83].

Lastly, CIT College's study scrutinized performance metrics like throughput, delay, and security within their well-designed yet problematic network [18]. By using simulation tools like NETSIM, they successfully identified and rectified hardware failures, bandwidth issues, and service quality concerns, significantly enhancing throughput and minimizing delay[84].

These collective studies reflect a rich tapestry of research efforts aimed at understanding, optimizing, and improving network performance in diverse academic and institutional settings.

Below is a summary table of selected recent and similar works in the past 10 years:

No	Title	Authors	Year	Gap
1	Comparison of Network with Cloud Servers using OPNET Modeler[85]	Vijaya Lakshmi Singh, Dr Dinesh Rai	Feb 2017	While the study successfully measured performance metrics, it was limited to evaluating File, HTTP, Email, and Database servers. However, it's essential to note that for this research, the inclusion of Voice and Audio performance analysis is crucial. This is particularly significant due to the rising demand for live web conferencing sessions, which play a pivotal role in facilitating blended teaching-learning approaches and conducting online meetings within the college environment.
2	Comparative Analysis of Network Simulators[86]	Kamal Saluja	Nov-Dec 2015	This study exclusively examined the effectiveness of various tools in conducting simulations, without addressing network performance. Instead, it primarily concentrated on practically enhancing network performance by employing a range of performance metrics
3	Performance Evaluation and Enhancement of	Tareq Al-Khraishi	Jun 2020	The objective was to enhance wireless network performance and conserve bandwidth by implementing VLAN

	VLAN via Wireless Networks using OPNET Modeler[87]			networks. However, the study did not include wired networks and Quality of Service (QoS) for optimizing packet scheduling within the network.
4	Comparative Performance Investigation of EIGRP, OSPF, and Rip Routing Protocol for Campus Area Network using Cisco Packet Tracerand OPNET Modeler[88]	Iffat Ara Badhan, Hoesne Ara Lutfu Halima, Sumon Kumar Debnat and Md. Munirul Islam	Jan 2024,	The focus was on establishing uniform networking configurations across routing protocols such as RIP, OSPF, and EIGRP to evaluate their performance. However, the study did touch on other critical factors, such as connectivity strategies, performance metrics, and methods for improving Quality of Service (QoS), instead of concentrating solely on routing protocols.
5	Opnet Based Performance Analysis and Comparison Among Different Physical Network Topologies[83]	Noor Najeeb Qaqos, Subhi R. M. Zeebaree, Bzar Khidir Hussan	Jul 2018	The study solely examined one aspect of network design and did not address the methods to enhance network connectivity or mechanisms for improving Quality of Service (QoS).

2.10 Comparisons to this study

The exploration of existing literature reveals a gap in comprehensive studies focusing on the comparative analysis of diverse network designs, connections, and performance measurements utilizing OPNET Modeler. While prior research has touched upon network configurations, limited attention has been directed specifically toward dissecting the nuanced impact of varied communication network links and connection arrangements on overall performance.

This study aims to address this gap by delving into the realm of effective network design and optimal network device link connections, targeting enhanced network performance. Leveraging the capabilities of the OPNET tool, the research will

meticulously model simulations to evaluate critical metrics such as throughput, latency, packet loss, capacity utilization, and data speed across diverse setups.

Unlike previous studies that predominantly examined general topologies or isolated performance evaluations of network devices (like hub versus switch), this research will unfold in a real-world context. The objective is to achieve superior network performance across all college network segments.

The study will encompass some distinct network topology scenarios, each featuring varying communication link connections. Through rigorous test runs and simulations, the research aims to fulfill specific study objectives and address pertinent questions regarding the enhancement of network performance in practical settings.

2.11 Summary

The literature review segment extensively investigated various facets related to the study's focus. It encompassed an in-depth analysis of diverse literature, including discussions on LAN fundamentals, Network Life Cycle models, specialized network design techniques, best practices in network design, performance measurement methodologies, and a comprehensive overview of Ethernet LAN cables.

The aim was to provide a holistic understanding of foundational concepts and established practices within the realm of network design. Specifically, these insights were gathered to inform and contextualize the study on the comparative analysis of different network designs, connections, and performance measurements employing OPNET Modeler. By synthesizing existing knowledge in these areas, the literature review served a crucial groundwork for framing the research.

CHAPTER 3

RESEARCH DESIGN AND METHODOLOGY

3.0 Introduction

This chapter delves deeply into the thorough process of methodological selection and the strategic design underpinning this research[89]. It elucidates the pathway through which the study achieved its predefined objectives and laid the groundwork for a robust and comprehensive outcome. At its core, the research design acted as a guiding framework that shaped the approach to addressing the research questions at hand. As highlighted in previous studies, the research design served as the blueprint – a tailored set of methods and techniques curated to facilitate the study's execution[90]. By providing this structured design, the research endeavored to refine the methods pertinent to the subject area, thus fostering a pathway toward successful outcomes.

Within this chapter, emphasis was placed on delineating the research strategy/approach, the intricacies of the research design, the methodology employed, and a comprehensive exploration of the quantitative aspects. Additionally, the discussion encompassed an exploration of the reliability and validity of the data analysis, intricately employing the powerful OPNET simulation tool software.

3.1 Research strategy/ approach

A research approach is the procedure chosen by the researcher to gather, evaluate, and translate data. There are three approaches to research: quantitative, qualitative, and mixed methods[91]. The study employed a hybrid methodology, blending qualitative (survey administration) and quantitative (simulation) approaches to address the research question. Initially, the qualitative approach utilized a questionnaire (administered via Google Form) to elucidate the problem statement. Subsequently, the quantitative method entailed conducting simulations for a comparative analysis of diverse network designs, connections, and performance metrics using OPNET Modeler. A range of input parameters were meticulously defined to accurately represent various aspects of network behaviour. These parameters encompassed bandwidth allocation, prioritization, and scheduling algorithms for QoS mechanisms. Additionally, characteristics of network devices and links, including bandwidth, latency, throughput, packet loss, and network utilization, were specified. Simulation

duration was also determined to ensure adequate data collection and analysis. By meticulously selecting and configuring these input parameters, the researchers facilitated a comprehensive comparative analysis using OPNET Modeler. This approach enabled the acquisition of pertinent data and insights into diverse network configurations, connections, and performance evaluation techniques[92].

3.2 Research design

For the initial stage leading to the problem statement, a set of questions was formulated using Google Forms (**refer to Appendix D**) to assess the feasibility of undertaking the research. In the quantitative phase, within the research design framework, emphasis was placed on how the researcher intended to address the research questions. Various network scenarios were devised, each comprising different network designs and incorporating diverse sets of network cable connections, along with all relevant components.

Relevant network or experimental variables were predefined to facilitate statistical analysis of data for addressing the research questions. Each scenario included switches, servers, computers, and network connection links such as Unshielded Twisted Pair (UTP) and fibre cables. Some scenarios featured UTP connections between switches, while others utilized fibre optic links. Certain scenarios allowed for multiple switches to be interconnected, with a specified number of users per segment.

Before conducting the simulations, all prerequisites for running the OPNET tool simulator were carefully considered to ensure reliable and valid data analysis results, mirroring real-world environment setups accurately.

3.2.1 Population Reviewed through Questionnaire

The population consisted of both staff and students from Technical and Vocational Teachers' College.

3.2.1 Sample Size

The sample was selected from both staff and students of the Technical and Vocational Teachers' College, randomly drawn from different network LAN segments. It comprised 75 staff members and 314 students, chosen based on the researchers' assumption of their relevance to the study. To address user requirements through simulations, the initial phase involved preparing a questionnaire (see Appendix) and

analyzing the results using Google Forms' built-in analysis capabilities. The analysis revealed more negative responses (**refer to Appendix E**), indicating the need for further research and aiding in the formulation of the problem statement.

An important step when designing an empirical study is to justify the sample size that will be collected[93].

Table 3:1 Population and Sample

Target Group	Population	Sample
Staff	105	75
Student	1500	314

3.2.2 Sampling Techniques

All participants were purposively sampled. Staff members were selected for their pivotal roles in the institution's daily operations, which are heavily reliant on network accessibility. Similarly, students were chosen because they rely on the network for diverse academic activities, such as accessing student information systems, engaging in online learning, and conducting research. Purposive sampling ensured the inclusion of individuals crucial to the institution's success, particularly those deeply involved in tasks dependent on the network.

Purposive sampling represents a group of different non-probability sampling techniques. Also known as judgmental, selective or subjective sampling, purposive sampling relies on the judgement of the researcher when it comes to selecting the units (e.g., people, cases/organisations, events, pieces of data) that are to be studied[94].

3.3 Research tools review for simulation

This section extensively explores a range of simulation tools available in the market, serving as crucial aids for network engineers and administrators in modeling and monitoring network designs. The focus here was to conduct a comprehensive survey and market review, shedding light on the diverse spectrum of simulation tools catering to network simulation purposes[95].

Among the prominent tools scrutinized in this review are NS2, NS3, JSIM, OMnet+, and OPNET. Each of these tools boasts distinct features and functionalities, contributing to their unique position in the realm of network simulation[95] [96]. It's important to note the breadth of options available to professionals in this field, each tool offering specific capabilities tailored to various simulation requirements.

To facilitate a comprehensive comparison, the following section presents an in-depth analysis of these simulation tools, encapsulating their key features, strengths, limitations, and suitability for specific network simulation scenarios[95].

3.4 Comparisons between simulation tools.

Table 3. 1: Comparisons between simulation tools.

Features	NS2	NS3	JSIM	OMnet++	OPNET
Language Supported	C++/OTCL	C++,Python	Java, Tcl	C++	C (C++)
GUI support	Poor	Good	Good	Good	Excellent
Time taken to learn	Long	Moderate	Moderate	Moderate	Long
Time takes for download and installation	Moderate time	Long time to download and install all necessary patches and supporting software.	Easy to download and install	Very easy and takes very little time. Easily available	Moderate time
Platform	Linux, Unix, windows, Cygwin	Linux, Unix, windows	windows, Linux, Matlab	Linux,Unix, windows, MAC OS	Linux, solar windows
Network Visualization tool	It supports network visualization tool	It supports network visualization tool	It supports network visualization tool	It supports network visualization tool	It supports network visualization tool

Availability of analysis tool	It has an analysis tool	It has an analysis tool	It has an analysis tool	It has an analysis tool	It has an analysis tool
Crates trace file	It creates a trace file	It creates a trace file	It creates a trace file	It creates a trace file	It creates a trace file
Possibility to design and modify the network scenarios	It is Possible	It is Possible	It is Possible	It is Possible	It is Possible
Design and Implementation Protocols	Supports both wired and wireless simulation of protocols	Supports both wired and wireless simulation of protocols	Supports both wired and wireless simulation of protocols	Supports both wired and wireless simulation of protocols	Supports both wired and wireless simulation of protocols
Interaction with real time system	It is Possible	It is Possible	It is Possible	It is Possible	It is Possible
Fast simulation capabilities	Moderate	Moderate	Poor	Moderate	excellent
Merits	<ul style="list-style-type: none"> -Easy to add new protocols. -A large number of protocols available publicly. 	<ul style="list-style-type: none"> -NS-3 is not an extension of NS-2 it is a new simulator. -NS-3 is open-source -Support for virtualization 	<ul style="list-style-type: none"> -Provides support for energy modelling, with the exception of radio energy consumption – -Support mobile wireless networks and 	<ul style="list-style-type: none"> -Powerful Graphical User Interface (making tracing and debugging easier) -Simulate power Consumption problem 	<ul style="list-style-type: none"> -Opnet communicate with other simulators -Fast discrete event simulation engine -Scalable wireless

			sensor networks. -Component-oriented architecture		simulation support - Integrated, GUI-based debugging and analysis
De-merits	-Supports only two wireless MAC protocols, 802.11, and a single-hop TDMA protocol. -Need to familiar with writing scripting language	-Python bindings do not work on Cygwin. -Only IPv4 is supported.	-Low efficiency of simulation. -The only MAC protocol provided for wireless networks is 802.11. -Unnecessary run-time overhead	-Number of protocols is not large enough. - Compatibility problem (not portable) -OMNeT++ is a bit slow due to its long simulation run and high memory consumption	-It is a commercial product -Memory consuming models -insufficient tutorials

Source:[95]

3.5 Selected tool for the simulation

OPNET stands out among its counterparts due to several inherent advantages. Utilizing a discrete event system technique, OPNET enables the meticulous modeling of system events, meticulously aligning with user-defined scenarios. Its user-friendly Graphical User Interface (GUI) follows a 'What You See Is What You Get' (WYSIWYG) approach, enhancing ease of use when configuring real-system networks. Within OPNET, locating and integrating network devices is simplified

through categorized segmentation, allowing effortless drag-and-drop placements to match required network topologies.

One of its significant strengths lies in the provision of an open interface, facilitating seamless integration of external component libraries. This versatility renders OPNET an invaluable tool for both research and development endeavors. Its robust feature set simplifies the design of real-system networks, offering intuitive options to define applications, protocols, and other critical network features. Notably, OPNET is widely acknowledged and utilized within the research and network analysis domains[97].

In alignment with the objectives of the study, the education version of OPNET simulation tool was selected for its proficiency in network design and its capacity to conduct comprehensive comparative analyses which was well aligned to what I intended to achieve. Leveraging the quantitative nature of the simulation, OPNET Modeler was instrumental in crafting simulated scenarios to precisely evaluate and compare various network configurations and performance metrics. This revision enhanced the description of OPNET's capabilities, emphasizing its relevance to the study's objectives in conducting network comparative analyses.

Below are in addition some of the researched works where OPNET software excelled and aided in making informed choices:

1. Performance evaluation of the wireless tree Wi-Fi video surveillance system

The study employed OPNET Modeler 14.5 to assess system performance, focusing on critical parameters such as throughput, packet loss, jitter, and packet end-to-end delay. Throughput measurements indicated that the wireless tree architecture outperformed both star and wired tree configurations by 100%, demonstrating its superior performance. Moreover, the wireless tree implementation maintained a low packet loss rate of 2.3%. Furthermore, the study evaluated quality-of-service metrics, revealing that the wireless tree scheme met acceptable standards for jitter and packet end-to-end delay values, ensuring reliable video transmission. Constraints and assumptions inherent in the study likely included assumptions about network topology, device configurations, and traffic patterns. For example, the study may have assumed a specific number of cameras, Wireless Access Points (WAPs), and servers in the network layout. Additionally, certain constraints related to hardware limitations or environmental factors may have influenced the simulation results. By referencing this

study, which effectively utilized OPNET for evaluating Wi-Fi video surveillance systems, our research benefits from the relevance and applicability of OPNET software in assessing network performance and informing design decisions within our own research context[15].

2. Performance Study of Mobile IPv6 Using OPNET[98], Evaluating the Performance of Wireless Network using OPNET Modeler

This paper focused on studying Mobile IPv6 (MIPv6) issues using the OPNET IPv6 model, which was crucial for establishing pervasive computing environments. MIPv6 enabled Mobile Nodes (MNs) to maintain reachability while moving within the Internet by associating with a Care-of Address (CoA) alongside their home address. Simulated scenarios in the study included MIPv6 handover with default direction, changing direction of movement, changing speed of movement, and ping pong movement. These scenarios aimed to explore the effects of various parameters such as loads, movement patterns, and multiple Access Points (APs) on MIPv6 handover performance. Key parameters of measurement included handover latency, packet loss, signalling overhead, and network throughput, which were essential for evaluating MIPv6 performance. Constraints and assumptions likely included assumptions about network topology, MN mobility patterns, and AP configurations within the simulated environment[19].

3. Comparative Throughput of WiFi & Ethernet LANs using OPNET MODELER

Researchers conducted a comparative study between wired Ethernet and wireless LAN (Wi-Fi) networks, focusing on various performance parameters such as throughput, collisions, and medium utilization. They noted the sensitivity of wired Ethernet performance to user count and offered load, where higher user numbers and loads lead to increased collisions and reduced overall throughput due to medium wastage. The research aimed to compare LAN throughput using Ethernet and Wi-Fi across three scenarios: 25, 50, and 100 users, utilizing the OPNET-MODELER simulator. Through analysis of simulation results, it was found that Wi-Fi throughput exceeded that of Ethernet when operating at a transmission speed of 10 Mbps, especially with a sufficient number of users supported by the model. However, as the user count surpassed a certain limit, throughput declined for both Ethernet and Wi-Fi due to

propagation delay and overhead collisions. Key parameters of measurement in the study included throughput, collisions, and medium utilization, which are critical for assessing network performance. Constraints and assumptions likely included assumptions about network topology, device configurations, and traffic patterns within the simulated LAN environment. For instance, the study may have assumed specific transmission speeds and packet sizes to facilitate meaningful comparisons between Ethernet and Wi-Fi networks[87].

4. Performance Evaluation of Buffer Size for Access Networks in First Generation Optical Networks

Using OPNET simulations, the study evaluated the performance and energy consumption implications of varying buffer sizes in access networks. By proposing and employing a model, the researchers illustrated that a buffer size capable of holding at least fourteen packets led to reduced router power consumption and enhanced network performance. Constraints and assumptions likely included assumptions about network topology, traffic patterns, and router configurations within the simulated access network environment. The study may have assumed specific network parameters, such as packet arrival rates and transmission speeds, to facilitate accurate simulation results.

5. Performance Evaluation and Compression of IP Packets in a Wireless Local Area Network (WLAN)

The research identified key objectives, including assessing the effectiveness and efficiency of per-interface compression, analyzing the impact of TCP/IP header compression and per-virtual circuit compression on performance and quality of service (QoS), and designing the optimal compression scheme for transmitting IP packets in a WLAN. OPNET simulation software facilitated the evaluation of four IP packet compression schemes: No compression, Per-interface Compression, TCP/IP Header Compression, and Per-virtual Circuit Compression. The results revealed that the Per-interface Compression algorithm outperformed other compression schemes in overall performance. Additionally, the study found that Per-virtual Circuit Compression performed below expectations compared to Per-interface and TCP/IP Header Compression schemes. Constraints and assumptions likely included assumptions about network topology, traffic patterns, and hardware configurations within the simulated WLAN environment. The study may have assumed specific network

parameters, such as transmission rates and packet sizes, to facilitate meaningful comparisons between compression schemes[99].

All the aforementioned sample researches assisted the researcher in selecting OPNET, enabling conducting a comprehensive comparative analyses using OPNET Modeler. This facilitated the gathering of pertinent data and insights into various network designs, connections, and performance measurement techniques.

3.6 Research Methodology Process

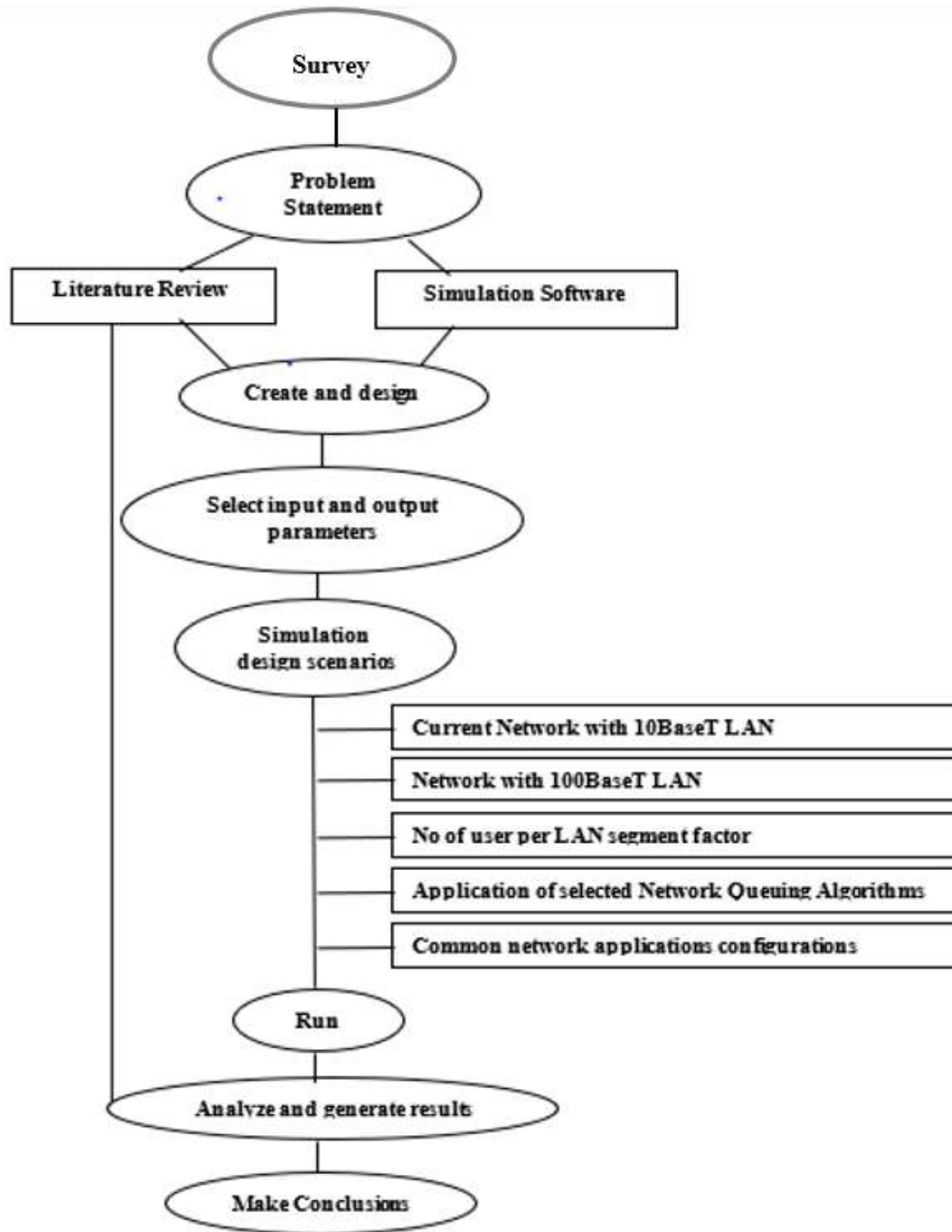


Figure 3. 1: Research Methodology Process

Source: [99]

3.7 Network Topology System Design

The network designs and connections comprised a Point of Presence (POP), switches, transmission media including cables (UTP and Fiber Optic), servers, computers, network applications, and a preferred network architecture.

3.8 Design Model setup in OPNET

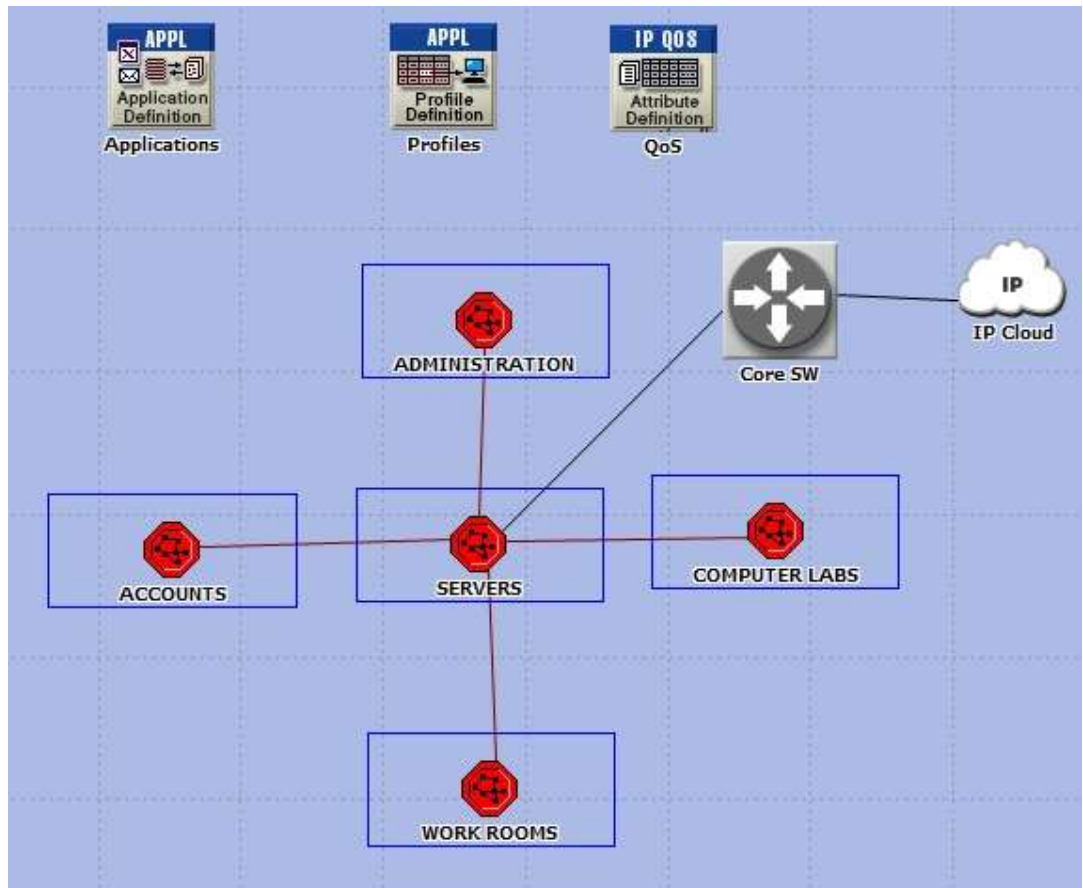


Figure 3. 2: OPNET Design Model

Source: Researcher design December (2024)

The Network Routing Plan in the previous section only goes as far as illustrating the logical illustration of how the full network implementation had been developed. This section, however, consists of modelling the same logical network design plan into a working design model simulation in OPNET.

Table 3.2 below shows the standard network model equipment used for the OPNET simulation for the organization's entire network.

Table 3. 2: The Standard Network Model Equipment used.

Standard Network Model Equipment Used	
Equipment Used	Brief Description
Ethernet Switches	Switches supporting up to 24 Ethernet interfaces
Cisco 4000 Series Routers	Type of routers used e.g., connecting to iCloud
Ethernet Servers	HTTP Server
	FTP Server
	Email Server
	Database Server
	Video Server
	VoIP Server
	WEB Server
Link Connections	10BaseT Duplex Link, 100baseT Duplex Link, PP_DS1, PP_DS3, 10Gbps Ethernet Link
Ethernet Workstations	10BaseT_LAN, 100BaseT_LAN
Ip 32_cloud	Represents internet
Subnets	Administration, Accounts, Work Rooms, Computer Rooms

3.9 Data Collection

There were two modes of data collection: through the questionnaire and via OPNET Modeler. The questionnaire was solely employed in the initial stages to formulate the problem statement, while OPNET was utilized for simulation to address the research questions. In the context of research related to OPNET (Optimized Network Engineering Tools) or network simulation, data collection entails gathering network performance data, simulation results, and other relevant information generated by OPNET simulations. This data is crucial for analyzing network behavior, evaluating performance, and drawing meaningful conclusions from the simulations[99][100]. OPNET was configured and employed as a data collection tool throughout this study.

3.10 Simulation and analysis

The research leveraged the renowned OPNET Modeler 14.5 Release package to conduct simulations and analysis. For producing more accurate graphs, results from OPNET software were exported to Microsoft excel for analysis and produced the required graphs for the research, The primary goal was to determine the most efficient methodologies for both analyzing and presenting the data collected through the OPNET network simulation tool, ensuring a coherent and structured presentation. The simulation primarily emphasized diverse network design and connectivity strategies, evaluating crucial network performance metrics such as packet delay, packet loss, throughput, Quality of Service (QoS), and other associated parameters. Subsequent assessment phases comprehensively covered network performance and QoS metrics, incorporating factors like packet delay, loss, throughput, and various relevant elements. By simulating pertinent scenarios, the study aimed to culminate in a refined, high-performance network model.

3.11 Study Work

The study encompassed a wide range of network designs, exploring different connection types with variations in bandwidth, latency, and reliability to understand their impact on overall network performance. The analysis focused on a comprehensive set of performance metrics, including throughput (data transfer rate), latency (delay in packet transmission), packet loss (data integrity), Quality of Service (QoS) parameters like jitter and reliability, and scalability under varying load conditions.

Various simulated scenarios were created to mimic real-world situations, including heavy data traffic, sudden surges in usage, and network faults, to assess how different designs and connections performed under stress or adverse conditions. Comparisons between simulated results and theoretical models or empirical data from existing networks were conducted to validate the accuracy and reliability of the OPNET simulations.

The study explored practical applications of the findings, acknowledging potential limitations in simulation accuracy, model assumptions, and challenges in replicating real-world complexities to provide a balanced understanding of the study's scope. The proposed steps for creating the scenarios included the following:

- Project Creation.
- OPNET module/object selection
- Topology Design
- Node Configurations
- Traffic Configurations
- Environmental settings
- Duplicate scenarios
- Choose statistics
- Compile the project
- Run Simulations
- View simulation results
- Verify or export for data analysis
- Results interpretation to obtain answers to the research questions

3.12 Reliability and Validity

Validity within any study referred to the extent to which the data-gathering instrument accurately measured what it was intended to measure[101]. Conversely, reliability indicated the consistency of obtaining similar results when the instrument was used in different settings, often termed as internal validity[102]. In the context of this study, ensuring internal validity involved conducting rigorous testing utilizing the OPNET simulator tool.

Specifically, internal validity was established through comprehensive testing procedures conducted within the OPNET simulator tool. This rigorous testing aimed to ensure that the data collected aligned precisely with the intended measurements and that the tool consistently produced reliable outcomes across various simulated scenarios. By emphasizing this internal validity assessment, the study aimed to validate the accuracy and consistency of the OPNET tool's performance in capturing expected measurements under different conditions[102].

3.13 Summary

This chapter delineated the methodology and design adopted for the study, highlighting the strategy, research design, and tools employed for network simulation and analysis. Its focus was on a quantitative approach, utilizing simulations to answer research questions. The study delved into the Comparative analysis of different

network designs, connections, and performance measurements using the Optimized Network Engineering Tools (OPNET) Modeler. Various network scenarios with different designs and connection types were created for simulation purposes. OPNET was used in network modeling and analysis because of its versatility and user-friendliness. In addition, it was very proficient in network design and comparative analyses.

CHAPTER 4

RESULTS AND DISCUSSION

4.0 Introduction

This Chapter forms the core section of the study that outlines the data analysis and discussion of the results obtained from OPNET simulation software tool. In the intricate landscape of network performance evaluation, understanding response time, traffic behaviour, packet delivery, and latency metrics is paramount. Response time, measured in milliseconds, elucidates the server-client interaction, offering a glimpse into server performance and potential congestion. This critical metric, often comprising processing, waiting, transmission, and queuing times, illuminates the underlying server load and network efficiency. This study dives into the nuances of response time analysis using OPNET simulation software, dissecting figures that depict HTTP page response time, IP traffic dropped, packet end-to-end delivery, LAN delay, as well as received traffic for video and voice applications. Through meticulous interpretation, this research unveils insights crucial for gauging network performance, Quality of Service (QoS), and the efficacy of various queuing mechanisms, spotlighting trends and implications crucial for optimizing network infrastructures in real-world applications.

4.1 Results and Discussion

In this subsection we present and discuss results of OPNET simulations obtained using the method that was described in Chapter three (3). The results and discussions section of this report delve into crucial performance metrics analysed through an OPNET simulation. It comprehensively explores Response Time, IP Traffic Dropped, Packet End-to-End Delivery, LAN Delay/Latency, Video Conference Traffic Received, and Voice Traffic Received. Each metric provides valuable insights into network performance, shedding light on aspects like server response, packet drops, queuing mechanisms, end-to-end delivery, LAN segment performance, and the traffic patterns of video and voice data. The analysis showcases trends, variations, and implications for Quality of Service (QoS), enabling a deeper understanding of network behaviour and highlighting the impact of different factors on network performance. All the objectives of the study were met.

4.1.1 Response Time

Response time refers to the amount of time it takes for a server to respond to a client's request. Measured in milliseconds, the timer starts from the moment a client sends out a request and stops when the server sends back its first response. HTTP page response time is an important metric to track and monitor as it gives an insight into server performance. If the server's response time is high, it may indicate that the server is overloaded and having difficulties processing requests[103]. OPNET simulation software also defines HTTP page response time as time required to retrieve the entire page with all the contained inline objects. For a basic understanding, the formula can be represented as:

$$\text{Response Time} = \text{Processing Time} + \text{Waiting Time} + \text{Transmission Time} + \text{Queuing Time} \dots \dots \dots (1)$$

But in some instances where queuing or waiting times are negligible or not explicitly measured, response time changes to Processing Time + Transmission Time

A breakdown of components in the formula are defined below:

- **Processing Time:** The time taken by the system to process the request or perform the necessary computations.
- **Waiting Time:** The time spent waiting in the system's queue before processing starts.
- **Transmission Time:** The time taken to transmit the request and receive the response, especially relevant in network systems.
- **Queuing Time:** The time spent waiting in line (queue) before the request is processed, applicable in systems where requests are queued up due to heavy loads or limited resources.

The labels on the x-axis represent the time taken in seconds, whereas the labels on the y-axis shows HTTP page response time in seconds.

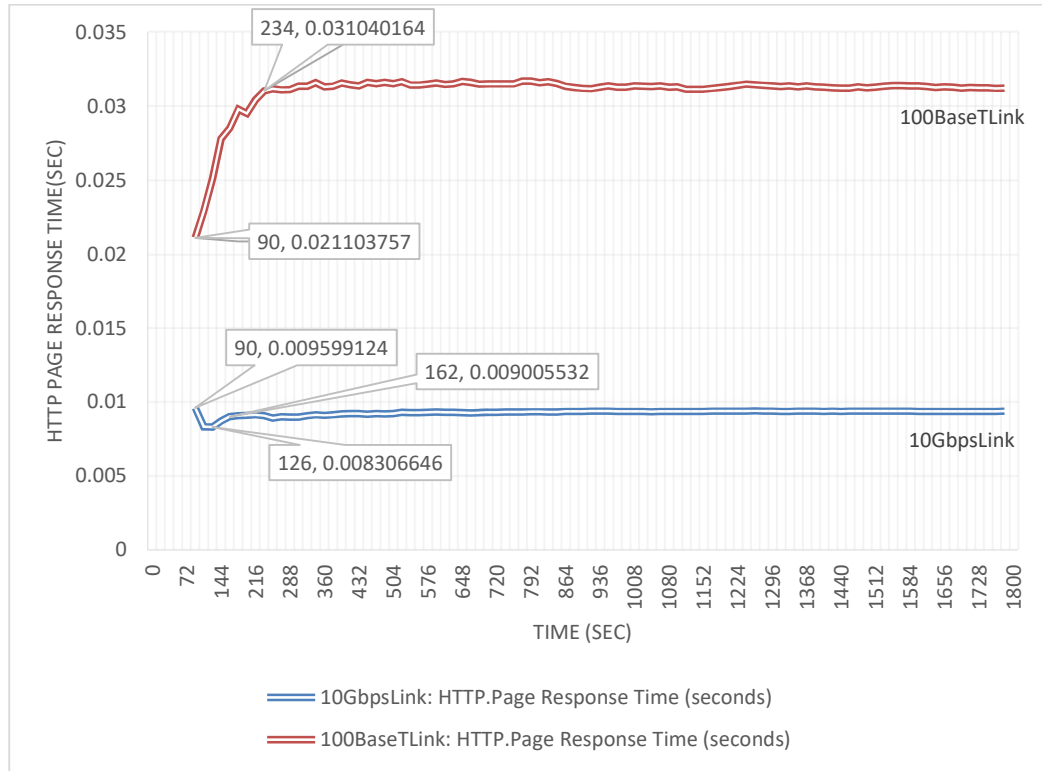


Figure 4. 1: HTTP Page Response time (sec)

Figure 4.1 depicts the HTTP page response time for two different links, 10Gbps and 100BaseT Link, measured in seconds. The x-axis represents time in seconds, while the y-axis represents HTTP page response time in seconds.

For the 10Gbps link, the graph shows a decrease in HTTP page response time from 0.009599124 to 0.008306646 seconds as the connection is established. However, the processing time increases from 90 to 126 seconds. There's a subsequent increase in response time to 0.009005532 seconds, and processing time increases from 126 to 162 seconds. After 162 seconds, the graph remains almost flat.

For the 100BaseT Link, the HTTP page response time rises from 0.021103757 to 0.031040164 seconds, and the processing time increases from 90 to 234 seconds. After 234 seconds, the graph becomes almost flat.

Interpreting of the HTTP page response time results:

- i) **Performance Measurement:** HTTP page response time is a crucial metric for assessing server performance and network quality of service. It reflects the time taken to retrieve the entire page with all its inline objects.
- ii) **10Gbps Link vs. 100BaseT Link:** The 10Gbps link exhibits lower HTTP response times (0.008306646 seconds) compared to the 100BaseT Link (0.031040164 seconds). This suggests that the 10Gbps link has better network performance and provides a higher quality of service in terms of HTTP response time.
- iii) **Graph Trends:**
 - **Upward Trends:** When the graph rises over time, it indicates an increase in HTTP response time. This could be due to more clients/users attempting to communicate simultaneously, leading to network traffic, potential bottlenecks, and increased latency.
 - **Flat Trends:** A generally flat graph suggests consistent processing without traffic or queue problems. This is indicative of a well-managed server and network, resulting in a stable HTTP response time.
 - **Drops in Graph:** A slight drop during a steady state implies sufficient network capacity, and the server is processing requests without encountering queue errors.

The implications are that for:

- **10Gbps Link:** The lower HTTP response time suggests better network performance, making it more suitable for handling simultaneous communication from multiple clients.
- **100BaseT Link:** The higher response time indicates potential traffic congestion due to the smaller bandwidth, making it less capable of supporting a large volume of traffic simultaneously.

In summary, the 10Gbps link demonstrates superior performance with lower HTTP response times, while the 100BaseT Link shows limitations in handling simultaneous traffic, resulting in higher response times.

4.1.2 IP Traffic Dropped

This refers to a reduction in the amount of data transmitted and received over the network using Internet Protocol (IP). Packet loss, where data packets fail to reach their destination, can lead to performance issues in digital communication. Packet loss occurs when one or more transmitted data packets fail to arrive at their destination. This can cause a noticeable performance issue for all types of digital communication. Packet loss occurs when network congestion, hardware issues, software bugs, and a number of other factors cause dropped packets during data transmission[104].

As defined by the OPNET simulation software in this case, it is the number of IP datagrams dropped by all nodes in the network across all IP interfaces. The reasons for dropping an IP datagram can be caused by insufficient space in the central processor's queue, insufficient space in a slot processor's buffer (only when slot-based processing is enabled), the maximum number of hops exceeded by an IP datagram on non-routing nodes, for destinations that are more than one hop away, a local router interface was not found to be used as the next hop, or the route table lookup failed to yield a route to the destination.

The labels on the x-axis (horizontal) show the time taken in seconds, while the labels on the y-axis (vertical).

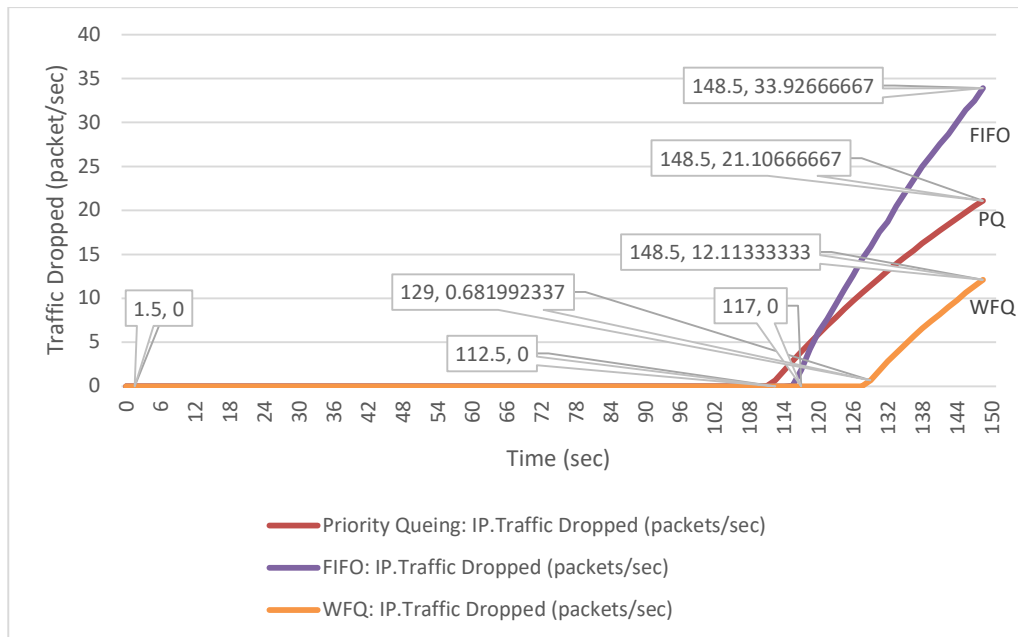


Figure 4. 2: IP Traffic Dropped

Figure 4.2 shows that the PQ graph started to rise when the network connection was established, taking time from 0 to 112.5 seconds, and by then no traffic had dropped. From 112.5 to 148.5 seconds processing time, the "traffic dropped" in packets per second rose to 21.10666667 from 0. For FIFO, the graph started to rise when the network connection was established, which took time from 0 to 117 seconds, and by then no traffic had dropped. From 117 to 148.5 seconds processing time, the "traffic dropped" in packets per second rose to 33.92666667 from 0. For WFQ, the graph started to rise when the network connection was established, which took time from 0 to 129 seconds. From 129 to 148.5 seconds processing time, the traffic dropped in packets per second rose from 0.681992337 to 12.11333333.

Interpreting of the IP Traffic Dropped results:

The findings from the OPNET simulation research indicated that the network experienced IP traffic drops. In the simulation, IP traffic drops were measured by the number of IP datagrams dropped by all nodes in the network across all IP interfaces. Various factors contributed to packet drops, such as insufficient space in the processor's queue, buffer limitations, exceeded hop limits, unavailability of a local router interface, or route table lookup failures.

The simulation results, represented in Figure 4.2, show the IP traffic drop trends for different queuing mechanisms: PQ (Priority Queuing), FIFO (First-In-First-Out), and WFQ (Weighted Fair Queuing). The X-axis represents the processing time, and the Y-axis shows the rate of traffic dropped in packets per second.

Observations from the graph:

i) PQ (Priority Queuing):

- The PQ graph showed no traffic drop initially.
- From 112.5 to 148.5 seconds, the traffic drop increased to 21.10666667 packets per second.

ii) FIFO (First-In-First-Out):

- The FIFO graph had no traffic drop at the beginning.
- From 117 to 148.5 seconds, the traffic drop increased to 33.92666667 packets per second.

iii) **WFQ (Weighted Fair Queuing):**

- The WFQ graph started rising after the network connection was established (0 to 129 seconds).
- From 129 to 148.5 seconds, the traffic drop increased from 0.681992337 to 12.11333333 packets per second.

FIFO had the highest data traffic drop, followed by PQ, and WFQ had the lowest. WFQ's fairness in resource allocation among different flows and its dynamic adjustment of service charges contribute to a more equitable traffic management approach, reducing the likelihood of high-priority traffic dropping lower-priority traffic.

The steepness of the curves in the graph reflects the severity of traffic drops. Steeper curves imply more significant packet drops, which can result from network congestion, insufficient bandwidth, outdated infrastructure, or other factors. Basically, the increased dropped packets as observed caused;

- **Reduced Quality of Service:** Increased dropped packets can lead to degraded performance, especially in real-time applications like video streaming or VoIP, causing disruptions and delays.
- **Network Congestion:** It could indicate that the network infrastructure or configurations might not effectively handle the incoming traffic load, resulting in congestion.
- **Performance Bottlenecks:** Processing delays or insufficient resources (buffer, CPU) could be causing packets to be dropped, impacting overall network performance.

4.1.3 Packet End-To-End Delivery

This is the time difference between video data departure and arrival[15]. Some researchers define it as the time interval between the creation of a packet at the source and its reception at the destination is referred to as packet end-to-end delay. This duration signifies the time taken for a packet to traverse the network. The unit of measurement for this time is seconds. Various types of delays contribute to this overall delay, including processing delay (D_{proc}), queuing delay (D_{queue}), transmission delay (D_{trans}), and propagation delay (D_{prop}). Mathematically, it is represented by

the following equation. The dependability of a network is indicated by a routing protocol with the least amount of latency. This metric holds significance in delay-sensitive applications such as video conferencing, video streaming, and voice transmission.

$$D_{E2EI} = [D_{RDDI} + D_{QUEUEI} + D_{RTDI} + D_{PROCI} + D_{PROPI} + D_{TRANSI}] \dots\dots\dots(2)$$

$$= (R_i - S_i) \dots\dots\dots(3)$$

$$AVE2E =: \frac{1}{N} \sum_{i=1}^m (R_i - S_i) \dots\dots\dots(4)$$

[105]

In another study, it was explained that the end-to-end delay of each packet is the cumulative result of delays experienced at a sequence of intermediate nodes on the way to the destination. Each delay consists of two components: a fixed part, such as transmission delay and propagation delay, and a variable part, including processing delay and queuing delay at the nodes[106].

The packet end-to-end delivery in the OPNET simulation software is referred to the time taken to transmit a video application packet to a destination node's application layer. It captures data from all nodes in the network. The metric is crucial for delay-sensitive applications, such as video conferencing and streaming. The DE2EI equation above mathematically represents this delay, emphasizing the importance of routing protocols with minimal latency for network dependability[105].

The labels on the X-axis represent the time taken in seconds, while the labels on the Y-axis show throughput in bits.

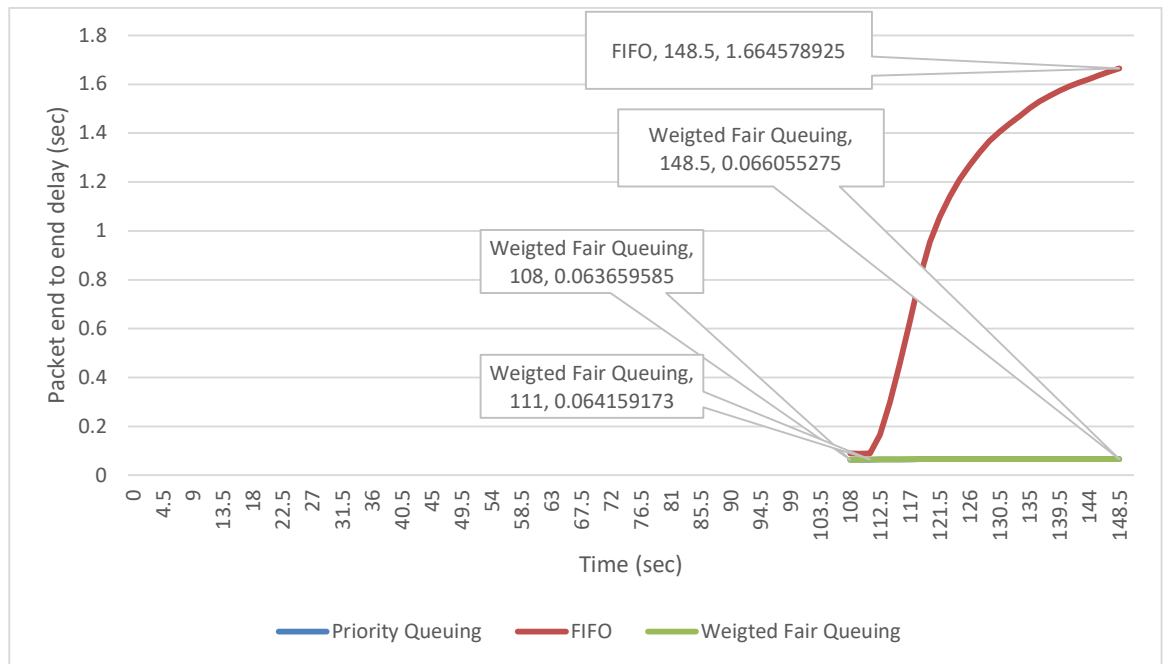


Figure 4. 3 (a): Packet End-To-End Delivery

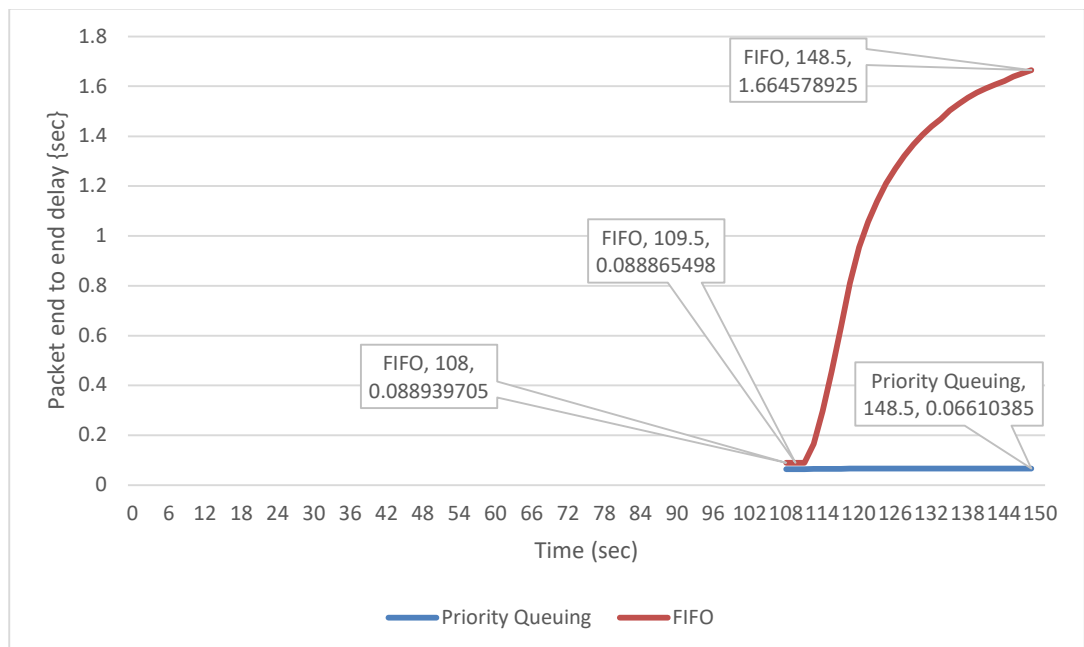


Figure 4. 3 (b): Packet End-To-End Delivery

Figure 4.3(a) and (b) show that all the QoS graphs took 0 to 108 seconds to establish a connection. According to the data, the FIFO graph's packet end-to-end delay in

seconds rose from 0.088939705 to 1.664578925 seconds, while its processing time increased from 108 to 148.5 seconds. The Priority queuing rose slightly from 0.063659585 to 0.06610385 seconds between the processing time of 108 to 148.5 seconds. For the Weighted Fair Queuing graph, the packet end-to-end delay in seconds slightly rose from 0.063659585 to 0.066055275 seconds between a processing time of 108 to 148.5 seconds.

Interpreting of the Packet End-To-End Delivery results:

Figure 4.3(a) presents QoS graphs for different queuing mechanisms (FIFO, Priority Queuing, and Weighted Fair Queuing) over a period of 108 seconds to 148.5 seconds. The analysis identifies key patterns:

i) Rising Curves and Network Load:

The QoS graphs in Figure 4.3(a) and (b) illustrate that all connections took 0 to 108 seconds to establish. When the graphs advance from 108 seconds to 148.5 seconds, a rising curve indicates an increase in network load. This rise in delay suggests that packets experience heightened latency, waiting in queues during congestion. Factors like transmission, propagation, nodal, and queuing delays for flows with lower weights and priority contribute to higher packet end-to-end delays.

ii) Flat Curves and Consistent Performance:

Conversely, a relatively flat curve in the graph signifies consistent end-to-end delay across all network load levels. This suggests consistent performance even as the network load increases, potentially due to some flows having higher weights or high-priority traffic. This indicates a level of stability and predictability in performance under varying network loads.

iii) Comparison of Queuing Mechanisms:

The analysis of different queuing mechanisms reveals insights into their performance:

- **FIFO Queuing:** The graph indicates a substantial increase in packet end-to-end delay, rising from 0.088939705 to 1.664578925 seconds. This queuing mechanism proves less effective in achieving the required network performance and QoS.

- **Priority Queuing:** Despite a slight increase from 0.063659585 to 0.06610385 seconds, priority queuing demonstrates relatively lower delays, making it a favourable option compared to FIFO.
- **Weighted Fair Queuing (WFQ):** Both WFQ and Priority Queuing initially show the lowest delay of 0.063659585 seconds at 108 seconds processing time. However, at 148.5 seconds, WFQ exhibits the lowest delay of 0.066055275 seconds, making it the preferred choice on average. This highlights WFQ's effectiveness in achieving good network performance and QoS by allocating weighted resources to different flows, allowing fine-tuning and control of delays.

4.1.4 LAN Delay/Latency

Delay refers to the time taken for a packet to be processed within a computer network, encompassing processing, queuing, transmission, and propagation delays. Network latency, or simply “latency,” represents the time delay during data transmission over a network. In the context of a local area network (LAN), latency represents the time for a data packet to traverse from its source to its destination within the LAN. Others refer to it as the time delay experienced by data packets while traversing a local area network from source to destination. It primarily includes propagation delay (signal travel time through the medium) and processing delays within network devices. This metric is typically measured in milliseconds (ms) or microseconds (μ s) owing to the inherently low latencies within LANs, attributable to their limited geographical scope[23].

The study conducted a comparison, in seconds, across three (3) LAN segments: The Accounts office with 100 users in the subnet; the Administration office with 10 network users; and the Workrooms offices with 50 users. Figure 4.4 showcases the results obtained from the OPNET simulation. The x-axis denotes processing time in seconds, while the y-axis represents the delay in seconds.

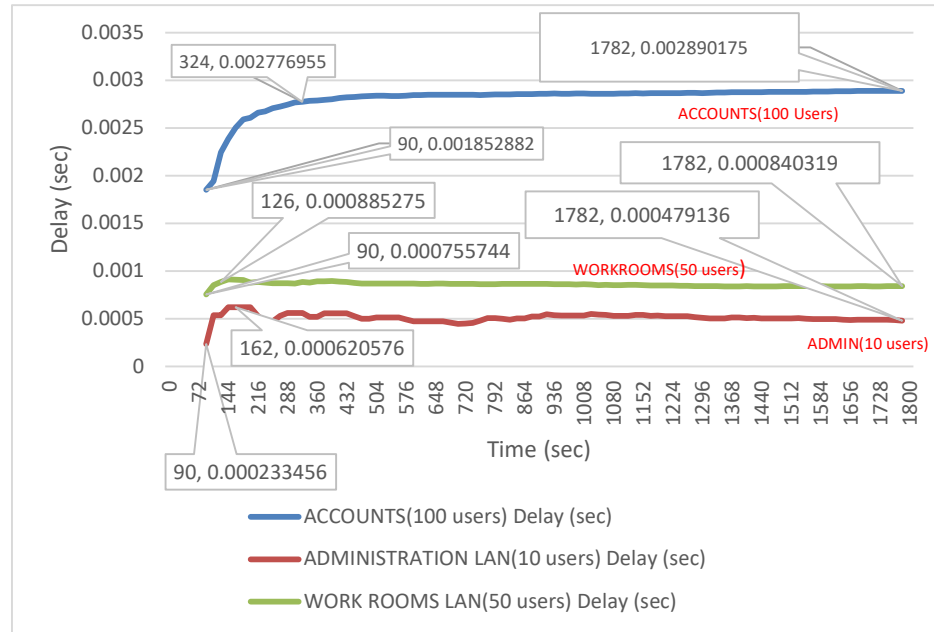


Figure 4. 4: LAN Delay/Latency

Figure 4.4 illustrates that all LAN delay graphs, measured in seconds, took 0 to 90 seconds to establish a connection. For the Administration block with ten (10) users, the average LAN delay increased from 0.000233455532 to 0.000620576033 seconds as maximum delay, while processing time escalated from 90 to 162 seconds. Following 162 to 1782 seconds of processing time, LAN delay gradually decreased to its lowest value of 0.000479135543 at 1782 seconds.

Regarding the Workrooms block with fifty (50) users, the average LAN delay rose from 0.000755743636 to 0.000885275112 seconds, and processing time increased from 90 to 126 seconds. Subsequently, after 126 to 1782 seconds of processing time, LAN delay slightly increased before gradually reducing to a value of 0.000840318716 at 1782 seconds.

In the case of the Accounts block with one hundred (100) users, the average LAN delay increased from 0.001852881895 to 0.002776954801 seconds, and processing time rose from 90 to 342 seconds. From 342 to 1782 seconds of processing time, LAN delay exhibited a slow increment until it reached its highest value of 0.002890174642 at 1782 seconds.

Interpretation of the LAN delay or latency results:

The OPNET simulation research findings delved into the dynamics of LAN delay or latency across different scenarios within a local area network, evaluating its impact on network performance and Quality of Service (QoS). The interpretation of the results are:

i) LAN Delay Measurement:

- LAN delay, characterized by the time taken for data packets to travel from source to destination within the LAN, was assessed across three segments: Accounts office (100 users), Administration office (10 users), and Workrooms offices (50 users).
- The measured delay values ranged from microseconds to a few milliseconds, indicating relatively low latencies typical of LANs due to their limited geographical range.

ii) Variations in LAN Delay with User Load:

- The study illustrated how LAN delay changes concerning the number of users and the resulting traffic load.
- As the number of users increased within each segment, the average LAN delay exhibited specific patterns in response to the workload.

iii) LAN Delay Trends:

- **Administration Block (10 users):** With a gradual increase in processing time from 90 to 162 seconds, LAN delay initially rose but gradually reduced, indicating efficient traffic handling after a temporary bottleneck.
- **Workrooms Block (50 users):** A similar trend occurred, with a slight rise in LAN delay following increased processing time. However, it eventually reduced, showcasing effective traffic management despite increased load.
- **Accounts Block (100 users):** This segment experienced a more significant increase in LAN delay as processing time extended from 90 to 342 seconds, suggesting potential congestion or limitations in handling the increased workload.

Implications of LAN Delay Trends:

- **Increasing Delay:** Indicates potential traffic congestion, leading to longer delays, which could impact real-time applications, causing latency issues and degraded service quality.
- **Decreasing Delay:** Suggests efficient network management, enabling smoother communication and faster response times, especially for real-time applications.
- **Constant Delay:** Reflects stable network performance despite increased user activity, indicating a robust architecture capable of maintaining consistent service quality and predicting response times regardless of user fluctuations. This stability hints at the network's potential for scalability and sustained performance.

Overall, the findings emphasize the critical role of LAN delay as a metric for assessing network performance. They highlight how variations in user load can impact delay, influencing network congestion and the overall user experience, and underscore the importance of efficient traffic management for optimal network performance and QoS maintenance.

4.1.5 Video Conference: Traffic Received (Bytes/Sec)

Traffic received (bytes/sec) denotes the rate at which data is received by a network interface or device, commonly expressed in bytes per second. It quantifies the volume of incoming data directed towards a specific destination, such as a server, computer, or any network-enabled device. This metric is pivotal for monitoring network performance, evaluating bandwidth utilization, and determining data transfer rates, especially in activities like capacity planning, network optimization, or diagnosing network issues. For instance, tracking the influx of data in bytes per second through a network interface aids administrators in comprehending the quantity and speed of data entering a system. In the context of video conferencing, as defined by the OPNET simulation software, "traffic received" signifies the average bytes per second forwarded to all video conferencing applications by the transport layers within the network[107], [108], [109],[110].

The study conducted a comparison of Video traffic received in bytes per second using three (3) QoS scheduling techniques: PQ, WFQ, and FIFO. Figure 4.5 illustrates the results derived from the OPNET simulation. The x-axis (horizontal) represents time in seconds, while the y-axis denotes the Video traffic received in bytes per second.

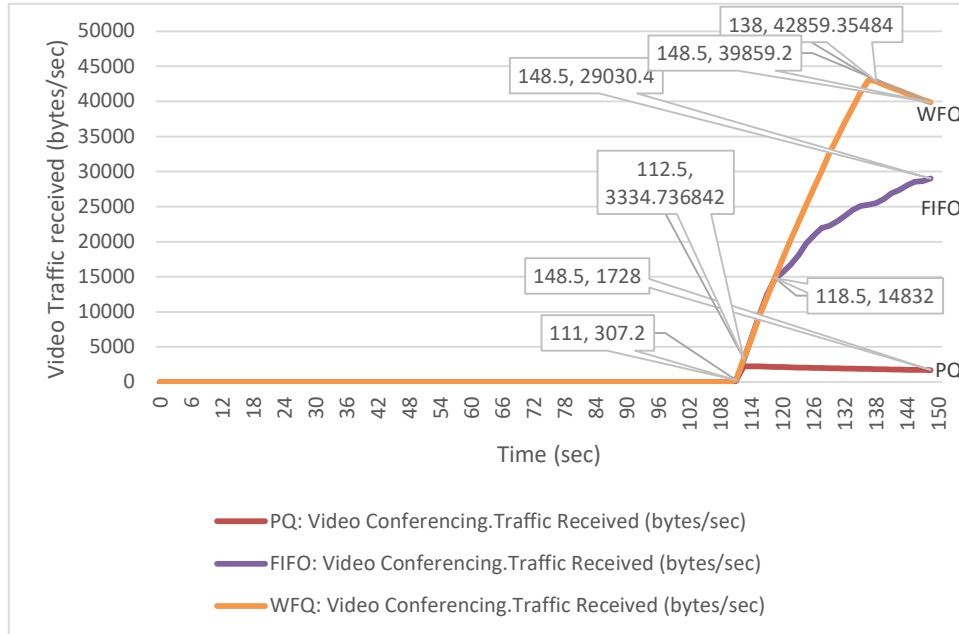


Figure 4. 5: Video Conference: Traffic received (bytes/sec)

Figure 4.5 displays graphs illustrating the video traffic received in bytes per second, indicating an initial rise following the establishment of the network connection, spanning from 0 to 111 seconds. Specific details from the presented data include:

- **WFQ:** Video traffic received increased from 307.2 to 42859.35484 bytes per second between 111 and 138 seconds. Subsequently, it experienced a slight drop from 42859.35484 to 39859.2 bytes per second between 138 and 148.5 seconds.
- **FIFO:** The video traffic received rose from 153.6 to 29030.4 bytes per second within 111 to 148.5 seconds.
- **PQ:** Traffic increased from 307.2 to 3334.736842 bytes per second between 111 and 112.5 seconds, followed by a decrease to 1728 bytes per second between 112.5 and 148.5 seconds.

Interpretation of the Video Conference: Traffic received (bytes/sec) results:

The OPNET simulation research findings delve into the dynamics of Video Conference across different scenarios within a local area network, evaluating its impact on network performance and Quality of Service (QoS):

- i) **Increase in Video Traffic Received:**
 - **FIFO:** Suggests straightforward traffic handling, with surges indicating increased data or queued backlog.
 - **PQ:** Indicates priority changes or elevated high-priority video traffic.
 - **WFQ:** Implies fair resource allocation or increased video traffic weight for bandwidth share.

- ii) **Decrease in Video Traffic Received:**
 - **FIFO:** Might signal reduced data transmission or altered data type proportions.
 - **PQ:** Indicates a lowered priority for video packets, leading to decreased transmission.
 - **WFQ:** Could suggest reduced weight or resource allocation for video traffic.

- iii) **Constant Video Traffic Curve:**
 - **FIFO:** Shows consistent video packet handling without major fluctuations.
 - **PQ:** Indicates stable priority levels despite varying network traffic.
 - **WFQ:** Implies consistent resource allocation for video traffic.

Observations:

WFQ presented the highest video traffic received (42859.35484 bytes per second), followed by FIFO (29030.4 bytes per second) and PQ (3334.736842 bytes per second). Hence, in this context, WFQ showcased superior network performance in terms of video traffic received, a pivotal metric influencing Quality of Service (QoS) and network performance evaluation.

4.1.6 Voice Traffic Received (Bytes/Sec)

Voice traffic received (bytes/sec) refers to the rate at which voice data packets are received by a network interface or device, typically measured in bytes per second. This metric specifically pertains to the amount of data transmitted over a network carrying voice communication, usually facilitated by protocols like VoIP (Voice over Internet Protocol). Unlike traditional data traffic, voice traffic is time-sensitive and demands real-time transmission to ensure clear and uninterrupted communication. When

measuring voice traffic received in bytes per second, it reflects the flow of data associated with voice packets arriving at a destination within a specified time frame[107], [109], [110]. The OPNET simulation software defines Voice traffic received (bytes/sec) as the average number of bytes per second forwarded to all Voice applications by the transport layers within the network. The study compares Voice traffic received in bytes per second across three QoS scheduling techniques: PQ, WFQ, and FIFO. Figure 4.6 illustrates the results obtained from the OPNET simulation, with the x-axis displaying time in seconds and the y-axis representing the Voice traffic received in bytes per second.

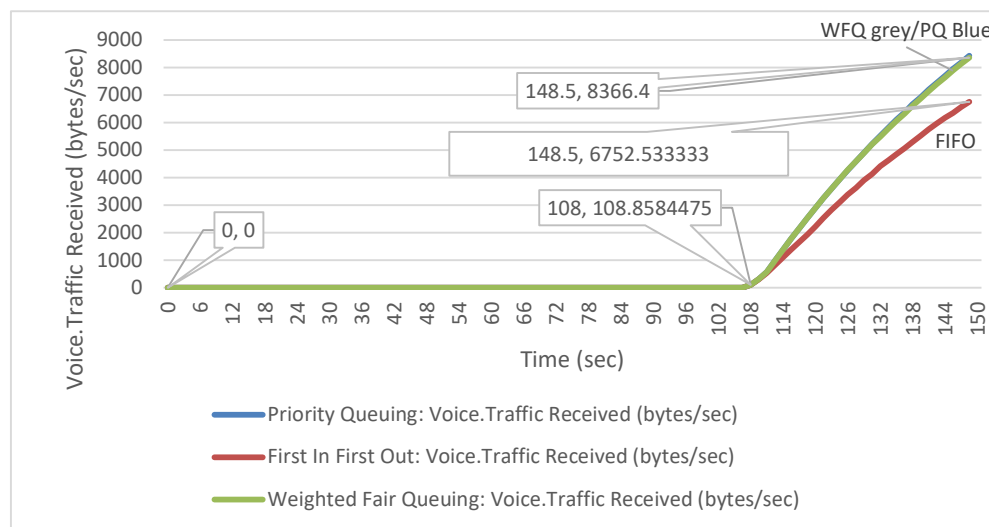


Figure 4. 6: Voice Traffic Received (Bytes/Sec)

Figure 4.6 illustrates that all graphs depicting voice traffic received in bytes per second began their ascent when the network connection was established, taking from 0 to 108 seconds. Both WFQ and PQ exhibited closely similar trends. According to the data, WFQ's voice traffic received in bytes per second rose from 108.8584475 to 8366.4 within 108 to 148.5 seconds. Similarly, FIFO's voice traffic received in bytes per second increased from 100.8219178 to 6752.533333 within the same time frame. PQ's traffic received in bytes per second rose from 108.8584475 to 8430.4 within 108 to 145.5 seconds.

Interpretation of the Voice traffic received (bytes/sec) results:

This research, conducted through OPNET simulation, focuses on Voice Traffic Received (bytes/sec) and its implications on network performance, particularly concerning Quality of Service (QoS). By comparing three QoS scheduling techniques;

PQ, WFQ, and FIFO. Figure 4.6 visually depicts the trends associated with Voice Traffic Received in bytes per second over time.

The findings reveal compelling insights into how these QoS techniques affect Voice Traffic Received:

- i) Notable increases in Voice Traffic Received across different scheduling techniques indicate varying trends: FIFO's rise suggests a surge in voice packet transmission, PQ's increase hints at altered packet priority, and WFQ's uptick signifies potential resource allocation or weight changes favouring voice traffic.
- ii) Conversely, decreases in Voice Traffic Received imply declines in transmission: FIFO's drop may suggest reduced transmission of voice data, while PQ and WFQ reductions might point towards lowered priority or resource allocation for voice traffic.
- iii) Consistent curves in Voice Traffic Received signify stable handling over time: FIFO and PQ show steady flows, while WFQ maintains consistent resource allocation for voice traffic.

Observations from the data highlight PQ's superior performance in Voice Traffic Received, registering the highest volume at 8430.4 bytes per second, closely followed by WFQ at 8366.4 bytes per second. Despite marginal differences, these findings underscore PQ's effectiveness in managing voice traffic, thereby influencing network QoS and performance assessment.

CHAPTER 5

CONCLUSION, RECOMMENDATIONS AND FUTURE WORK

5.0 Introduction

This chapter encapsulates the study's conclusions and offers recommendations derived from the findings concerning the study aim, addressing core research questions to fulfill research objectives, contributions, and proposing opportunities for future research. Utilizing an extensive evaluation of secondary literature and implementing various network designs and connectivity strategies through OPNET simulation tools, scenarios were crafted with well-defined performance metrics as the foundation for drawing conclusions and formulating recommendations.

The data extracted from OPNET simulations underwent thorough analysis and graph creation using Microsoft Excel. Consequently, the structure of this chapter unfolds as follows: an introduction that sets the stage, followed by the conclusion and insights into future endeavors, a set of recommendations, and finally, a succinct summary of the entire chapter.

5.2 Conclusion

The comprehensive analysis of network performance metrics conducted through OPNET simulation software unveils critical insights into network efficiency and Quality of Service (QoS), leading to several key conclusions:

- i) **Response Time Analysis:** The study meticulously examines HTTP page response time, revealing that the 10Gbps link outperforms the 100BaseT Link, indicating better network performance and QoS for the former.
- ii) **IP Traffic Dropped:** The research identifies IP traffic drops across various queuing mechanisms, with FIFO exhibiting the highest data traffic drop, signalling potential issues like reduced QoS, network congestion, and performance bottlenecks.
- iii) **Packet End-To-End Delivery:** Analysis of packet end-to-end delivery underscores the effectiveness of Weighted Fair Queuing (WFQ) in achieving lower delays, highlighting its role in maintaining optimal network performance and QoS.

- iv) LAN Delay/Latency: The evaluation of LAN delay across different user segments emphasizes the critical role of efficient traffic management in maintaining optimal network performance and QoS, especially for delay-sensitive applications.
- v) Video Conference and Voice Traffic Reception: The study reveals the superiority of Weighted Fair Queuing in handling video traffic and Priority Queuing in managing voice traffic, aligning with established principles in QoS and traffic management.

These conclusions significantly contribute to the understanding of network performance optimization and QoS management. They underscore the importance of efficient traffic management and the selection of appropriate queuing mechanisms for ensuring optimal network performance and user experience.

Connecting these findings with existing knowledge in the field of computer networks and network performance evaluation reveals strong correlations:

- Response Time Analysis: Consistent with existing literature, the findings emphasize the importance of response time in evaluating network efficiency and server performance, particularly in relation to bandwidth capabilities.
- IP Traffic Dropped: The observed packet drops align with prior research on factors contributing to packet loss, reinforcing the understanding of congestion-related issues and queuing mechanisms' impact on data traffic.
- Packet End-To-End Delivery: The preference for WFQ is supported by existing studies on queuing algorithms and their effects on delay and throughput, validating its effectiveness in resource allocation and traffic prioritization.
- LAN Delay/Latency: The analysis of LAN delay trends corresponds with established knowledge on network latency determinants, reaffirming the impact of congestion and user load on local area network performance.
- Video Conference and Voice Traffic Received: The conclusions regarding traffic reception align with existing literature on QoS and traffic management, highlighting the importance of prioritizing real-time applications for quality communication experiences.

In summary, these findings not only advance our understanding of network performance but also reinforce established principles, providing actionable insights for optimizing network infrastructures and enhancing QoS based on empirical evidence and theoretical foundations.

5.3 Areas of Future Research

Areas for future research or potential extensions of the current study should aim to broaden the scope and depth of network simulation scenarios to encompass larger real-life network environments. By simulating networks that more closely mirror the complexities and scale of actual deployment scenarios, researchers can validate the robustness of the conclusions drawn from the current study. Additionally, exploring the performance of wireless local area networks (WLANs) alongside wired networks will provide a more comprehensive understanding of network dynamics and facilitate the development of strategies to optimize both types of networks.

Furthermore, future research endeavours could delve into the implementation and evaluation of link aggregation techniques. Link aggregation, also known as port trunking or bonding, involves combining multiple network connections into a single logical link to increase bandwidth, fault tolerance, and load balancing[111],[112]. Investigating the effectiveness of link aggregation in improving network performance and resilience would be valuable for network engineers and administrators seeking to optimize network infrastructure.

Expanding the scope of the study to include wireless networks, in addition to wired networks, would be instrumental in addressing the growing prevalence and importance of wireless technologies in modern network environments. Research could focus on evaluating the performance of wireless technologies such as Wi-Fi and Bluetooth in various deployment scenarios, identifying challenges, and proposing solutions to enhance the reliability, security, and efficiency of wireless communication.

In summary, future research directions should prioritize:

- Simulation of larger real-life network environments to validate current conclusions.
- Investigation of wireless local area networks alongside wired networks for a comprehensive understanding of network dynamics.

- Evaluation of link aggregation techniques to improve network performance and resilience.
- Expansion of the study scope to encompass wireless technologies and address challenges in wireless communication.

5.4 Major contribution to this study

This research presents a pioneering investigation into network performance evaluation using comprehensive simulations with OPNET software, offering a nuanced understanding of response time, packet delivery, and queuing mechanisms. One of the unique contributions of this study lies in its in-depth analysis of various queuing mechanisms and their impact on network performance metrics, shedding light on optimal strategies for improving Quality of Service (QoS) and network efficiency. The findings reveal distinct trends and implications for network optimization, particularly in scenarios involving different types of traffic and network loads.

Notably, the research findings provide actionable recommendations for IT professionals and organizations, leading to tangible enhancements such as reduced latency, increased throughput, and improved reliability. By offering insights into the performance of different network configurations and queuing mechanisms, this study equips decision-makers with the knowledge needed to make informed choices in network design and management.

Moreover, this research serves as invaluable educational material for students and professionals in the IT and network engineering field, fostering a deeper understanding of network dynamics and promoting best practices in infrastructure optimization. By disseminating key findings and methodologies, this study contributes to standardization and knowledge dissemination across various sectors within the IT industry.

Ultimately, this research has the potential to advance the field of network engineering by providing evidence-based insights and practical solutions to common challenges in network performance evaluation and optimization. By bridging the gap between theory and practice, this study benefits the broader IT community by facilitating continuous improvement in network infrastructure and operations.

5.5 Recommendations

To enhance network performance, it is crucial to prioritize investments in high-bandwidth infrastructure, as evidenced by the superior performance of a 10Gbps link over a 100BaseT link. Ensuring that network connections are upgraded and meet the demands of responsive server-client interactions is essential in this regard.

The adoption of Weighted Fair Queuing (WFQ) as the preferred queuing mechanism is recommended, given its effectiveness in managing network resources and minimizing high-priority traffic drops. To optimize overall network performance, it is advised to fine-tune and adjust queuing configurations, focusing on minimizing packet drops and enhancing end-to-end delivery.

Mitigating delays is paramount, and one effective approach is to adopt queuing mechanisms like WFQ, which has demonstrated lower latency in packet end-to-end delivery. Regularly assessing and adjusting queuing strategies, particularly in segments prone to increased user loads, will help maintain optimal latency levels.

An in-depth analysis and optimization of network segments, with special attention to the Accounts block, are necessary to address potential congestion or limitations in handling increased workload. Implementing efficient traffic handling practices observed in successful segments, such as the Administration and Workrooms blocks, across other areas will contribute to consistent performance.

Quality of Service (QoS) strategies play a pivotal role and leveraging insights from QoS scheduling techniques – such as using WFQ for video traffic and Priority Queuing (PQ) for voice traffic – is recommended to uphold a high level of service quality. Regularly assessing and updating QoS strategies based on evolving network requirements and traffic patterns is advised.

Translating gained insights into practical applications by incorporating findings into real-world network infrastructures is key. Continuous monitoring and adaptation of network configurations based on evolving needs and technologies are essential for ongoing improvement. Focusing on continuous optimization of network infrastructures using the knowledge gained from the chapter is critical. Consider periodic simulations or assessments to ensure that the network maintains optimal performance levels over time. By implementing these recommendations, the college or organization can enhance its network performance, improve quality of service, and

ensure the overall efficiency of queuing mechanisms in real-world applications. Regular monitoring and adaptation to changing requirements will be crucial for sustained success.

5.6 Summary

In this comprehensive research study, we undertook a meticulous Comparative Analysis of different Network Designs, Connections, and Performance Measurement using the Optimized Network Engineering Tools (OPNET) Modeler. Through a detailed examination of research results and findings, we derived meaningful conclusions, effectively addressing key research questions and providing valuable insights into network dynamics.

The concluding chapter not only summarizes the current findings but also extends into forward-looking ideas and future work, promising a more comprehensive understanding of network dynamics. These proposed initiatives aim to proactively anticipate and meet the challenges of the evolving network landscape. In essence, this research contributes significant knowledge to the field of network engineering, serving as a foundation for future advancements and offering solutions to address the complexities of modern network challenges.

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APPENDIX A: CERTIFICATE OF PUBLICATION



Scientific & Academic Publishing

International Journal of Networks and Communications

Certificate of Publication

Date: February 22, 2024

Dear Colleague,

Thank you very much for your contribution to Scientific & Academic Publishing.
We are pleased to inform you that your paper has been published online.

Paper ID:	109700242
Paper Title:	Enhancing Network Performance and Quality of Service (QoS) in a Wired Local Area Network (LAN)
Authored by	Kulonga Nzobokela, Simon Tembo, Brilliant Habeenzu

It is published in *International Journal of Networks and Communications* (Volume 13, Number 1, 2024).

We look forward to your continued support.

Thank you again.

Sincerely yours,

Charles Duke

Journal manager

Scientific & Academic Publishing (<http://www.sapub.org/>), USA



APPENDIX B: PUBLISHED JOURNAL/ARTICLE

International Journal of Networks and Communications 2024, 13(1): 1-14
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Enhancing Network Performance and Quality of Service (QoS) in a Wired Local Area Network (LAN)

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Department of Electrical Engineering, University of Zambia, School of Engineering, Zambia

Abstract The study focuses on Enhancing Network Performance and Quality of Service (QoS) in a Wired Local Area Network (LAN). In today's interconnected landscape, the optimization of Local Area Networks (LANs) stands as a pivotal pursuit. The study aims to evaluate and discern the factors that significantly influence network performance and QoS utilizing the Optimized Network Engineering Tool (OPNET) Modeler. The key objectives are to design a network design that gives the best network performance and QoS; to evaluate link connections, connectivity, and effect on network performance, and to recommend and implement the best network designs, link connections, and connectivity that yield the best network performance and QoS. OPNET simulation software tool has been used to simulate the network design scenarios. The results highlighted the impact of link capacity on network performance, revealing that higher capacities led to lower HTTP response times. Conversely, lower capacity links struggled with simultaneous traffic, resulting in delayed responses. In terms of QoS, FIFO exhibited the highest data traffic drop, followed by Priority Queuing (PQ), while Weighted Fair Queuing (WFQ) boasted the lowest drop rate. Additionally, LAN delay increased as user volume accessing the network within the LAN segment grew. WFQ proved most effective in receiving video traffic, followed by First in First Out (FIFO) and PQ. Finally, PQ demonstrated superior handling of Voice Traffic. This analysis provides a holistic understanding of network dynamics, offering guidance to administrators for QoS enhancement, congestion mitigation, and fortification of network infrastructure against future challenges.

Keywords Computer Network, OPNET, QoS, LAN, Queuing Algorithms, and Performance

1. Introduction

In today's interconnected world, where seamless connectivity is paramount, the efficiency and reliability of Local Area Networks (LANs) play a pivotal role. As businesses and individuals rely increasingly on networked systems, the demand for enhanced performance and superior Quality of Service (QoS) within wired LAN environments has never been more critical. This article delves into the strategies, technologies, and methodologies pivotal to bolstering network performance and elevating QoS within a wired LAN infrastructure. Whether optimizing for speed, minimizing latency, or prioritizing data traffic, understanding these mechanisms is central to fostering robust and high-performing LAN ecosystems.

In general, Network performance is the measure of the service quality of a network as experienced by the user. It depends upon the nature and design of the network, and there are several methods for measuring network performance [1] [2] [3] [5]. In this case in a Wired Local

Area Network (LAN). Quality of service (QoS) refers to any technology that manages data traffic to reduce packet loss, latency, and jitter on a network. QoS is typically applied to networks that carry traffic for resource-intensive systems for instance, videoconferencing, video on demand (VOD), and Voice over IP (VoIP) [4].

To come up with a better solution to enhance Network Performance and Quality of Service (QoS) in a Wired Local Area Network (LAN), the study employed Optimized Network Engineering Tool (OPNET) software for computer network design simulations, modeling, and analysis [7] [8] [1]. Furthermore, it helped to Understand how different components within a wired LAN interact and can impact performance by identifying potential bottlenecks, inefficiencies, or areas for improvement by testing different configurations to optimize performance and QoS. The study aimed to design and develop a model that would help in testing the Network Performance and Quality of Service (QoS) in a Wired Local Area Network (LAN) using some network performance metrics and some QoS queuing algorithms. The key specific objectives were to come up with a network design that gives the best network performance and QoS; to evaluate link connections and their effect on network

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APPENDIX C: ETHICS APPROVAL LETTER



THE UNIVERSITY OF ZAMBIA DIRECTORATE OF RESEARCH AND GRADUATE STUDIES

Great East Road Campus | P.O. Box 32379 | Lusaka 10101 | Tel: +260-211-250 258/291 777
Fax: (+260)-211-290 258/253 952 | E-mail: director.drg@unza.zm | Website: www.unza.zm

APPROVAL OF STUDY

IORG No. 0005376
HSSREC IRB No. 00006465
REF NO. NASREC: 2024-FEB-008

21st February, 2024

Mr. Kulonga Makondo Nzobokela
The University of Zambia
P.O. Box 32379
LUSAKA

Dear Mr. Nzobokela

RE: "COMPARATIVE ANALYSIS OF NETWORK DESIGNS, CONNECTIONS, AND PERFORMANCE MEASUREMENT USING OPNET MODELLER".

Reference is made to your protocol dated as captioned above. NASREC resolved to approve this study and your participation as Principal Investigator for a period of one year.

REVIEW TYPE	ORDINARY REVIEW	APPROVAL NO. NASREC-2024-FEB-008
Approval and Expiry Date	Approval Date: 21 st February 2024	Expiry Date: 20 th February, 2025
Protocol Version and Date	Version - Nil	20 th February, 2025
Information Sheet, Consent Forms and Dates	• English.	To be provided
Consent form ID and Date	Version - Nil	To be provided
Recruitment Materials	Nil	Nil
Other Study Documents	Questionnaire.	

Specific conditions will apply to this approval. As Principal Investigator it is your responsibility to ensure that the contents of this letter are adhered to. If these are not adhered to, the approval may be suspended. Should the study be suspended, study sponsors and other regulatory authorities will be informed.

CONDITIONS OF APPROVAL

- No participant may be involved in any study procedure prior to the study approval or after the expiration date.
- All unanticipated or Serious Adverse Events (SAEs) must be reported to NASREC within 5 days.
- All protocol modifications must be approved by NASREC prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator/s or site address.
- All protocol deviations must be reported to NASREC within 5 working days.
- All recruitment materials must be approved by NASREC prior to being used.
- Principal investigators are responsible for initiating Continuing Review proceedings. NASREC will only approve a study for a period of 12 months.
- It is the responsibility of the PI to renew his/her ethics approval through a renewal application to NASREC.
- Where the PI desires to extend the study after expiry of the study period, documents for study extension must be received by NASREC at least 30 days before the expiry date. This is for the purpose of facilitating the review process. Documents received within 30 days after expiry will be labelled "late submissions" and will incur a penalty fee of K500.00. No study shall be renewed whose documents are submitted for renewal 30 days after expiry of the certificate.
- Every 6 (six) months a progress report form supplied by The University of Zambia Natural and Applied Sciences Research Ethics Committee as an IRB must be filled in and submitted to us. There is a penalty of K500.00 for failure to submit the report.
- When closing a project, the PI is responsible for notifying, in writing or using the Research Ethics and Management Online (REMO), both NASREC
- and the National Health Research Authority (NHRA) when ethics certification is no longer required for a project.
- In order to close an approved study, a Closing Report must be submitted in writing or through the REMO system. A Closing Report should be filed when data collection has ended and the study team will no longer be using human participants or animals or secondary data or have any direct or indirect contact with the research participants or animals for the study.
- Filing a closing report (rather than just letting your approval lapse) is important as it assists NASREC in efficiently tracking and reporting on projects. Note that some funding agencies and sponsors require a notice of closure from the IRB which had approved the study and can only be generated after the Closing Report has been filed.
- A reprint of this letter shall be done at a fee.

- All protocol modifications must be approved by NASREC by way of an application for an amendment prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator/s or site address or methodology and methods. Many modifications entail minimal risk adjustments to a protocol and/or consent form and can be made on an Expedited basis (via the IRB Chair). Some examples are: format changes, correcting spelling errors, adding key personnel, minor changes to questionnaires, recruiting and changes, and so forth. Other, more substantive changes, especially those that may alter the risk-benefit ratio, may require Full Board review. In all cases, except where noted above regarding subject safety, any changes to any protocol document or procedure must first be approved by NASREC before they can be implemented.

Should you have any questions regarding anything indicated in this letter, please do not hesitate to get in touch with us at the above indicated address.

On behalf of NASREC, we would like to wish you all the success as you carry out your study.

Yours faithfully,



Dr. E. M. Mwanambo

**VICE-CHAIRPERSON
THE UNIVERSITY OF ZAMBIA NATURAL AND APPLIED SCIENCES RESEARCH
ETHICS COMMITTEE - IRB**

CC: Director, Directorate of Research and Graduate Studies
Assistant Director (Research), Directorate of Research and Graduate Studies
Assistant Registrar (Research), Directorate of Research and Graduate Studies

APPENDIX D: QUESTIONNAIRE

TVTC Network performance and QoS Questionnaire

Dear Participant,

Thank you for taking the time to participate in our research on TVTC Network performance and Quality of Service (QoS). Your input is invaluable in helping us understand and improve the network infrastructure within TVTC.

By collecting data through this questionnaire, we aim to:

1. Assess the current performance of the TVTC network.
2. Identify areas of improvement in network quality and service.
3. Understand user experiences and satisfaction levels with the network.
4. Gather feedback on specific issues or challenges faced while using the network.
5. Inform future decisions and investments regarding network enhancements.

Your honest responses will enable us to address any existing issues effectively and enhance the overall network experience for all users within TVTC.

Thank you for your participation and contribution to this important research endeavour.

Instructions

i) Do not write your name on the questionnaire.

ii) Where you are required to give reasons, please do so accordingly in the spaces provided.

* Indicates required question _____

1. Role *

Mark only one oval.

Student

Staff

2. Location/Office

Mark only one oval.

- Accounts
- Workrooms
- Computer Labs
- Center Of Excellence Lab 1
- Center Of Excellence Lab 2
- Administration
- Workroom 2

3. How long have you been affiliated with the college/institution *

Mark only one oval.

- 1-2 Years
- 3-5 Years
- Above 5 Years

4. How would rate the network performance and Quality of Service (QoS) generally *

Mark only one oval.

- Good
- Moderate
- Bad

5. Have you experienced any instances of poor performance or downtime while using the network? *

Mark only one oval.

- Yes
- No

6. Are there specific times of the day when you notice a decline in network performance? *

Mark only one oval.

Yes

No

7. How satisfied are you with the speed and reliability of the network connection? *

Mark only one oval.

Very satisfied

Satisfied

Not satisfied

8. Do you encounter frequent delays or buffering when accessing online resources or streaming media? *

Mark only one oval.

Yes

No

10. How important is the quality of the network connection to your overall satisfaction with the college/institution? *

Mark only one oval.

- Very Important
 Important
 Not Important

11. How do you foresee the role of technology and networking evolving within the college/institution in the future?

12. Is there anything else you would like to share about your experiences or concerns regarding the quality of service and performance of the network? *

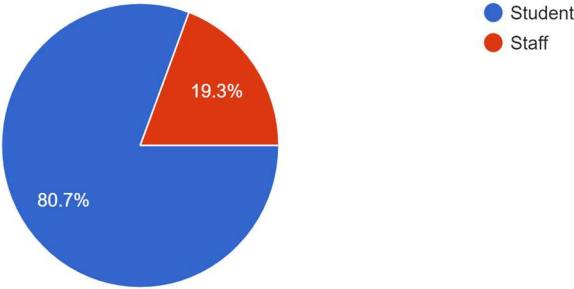
13. What types of activities do you primarily engage in using the network (e.g., research, online classes, administrative tasks, social media)? *

THE END

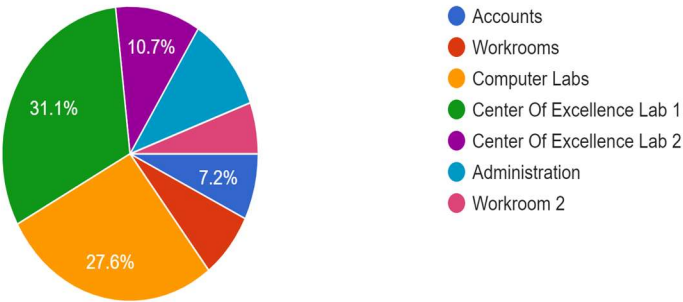
Thank you for your participation

APPENDIX E: QUESTIONNAIRE RESULT

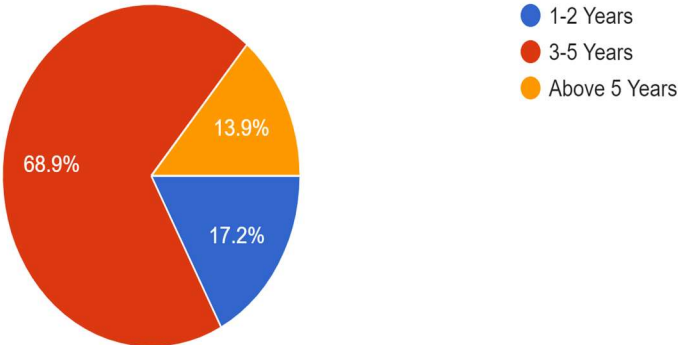
Role
389 responses



Location/Office
373 responses

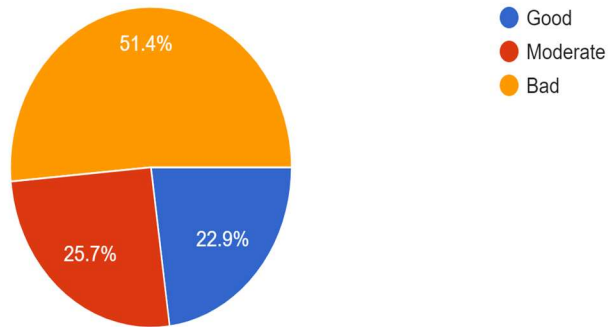


How long have you been affiliated with the college/institution
389 responses



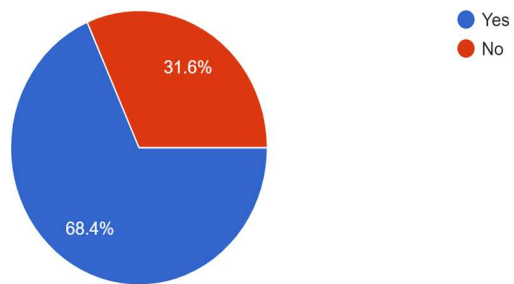
How would rate the network performance and Quality of Service (QoS) generally

389 responses



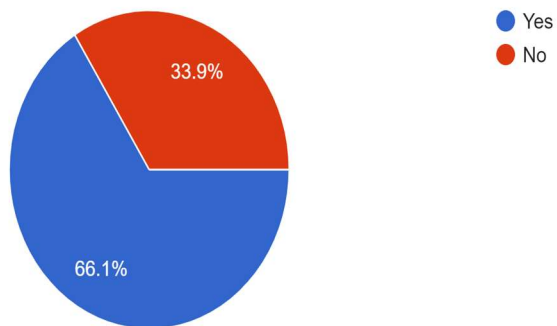
Have you experienced any instances of poor performance or downtime while using the network?

389 responses



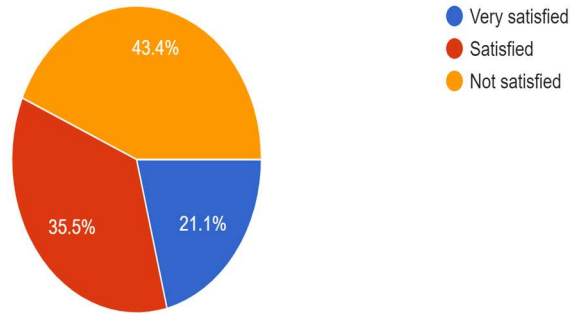
Are there specific times of the day when you notice a decline in network performance?

389 responses



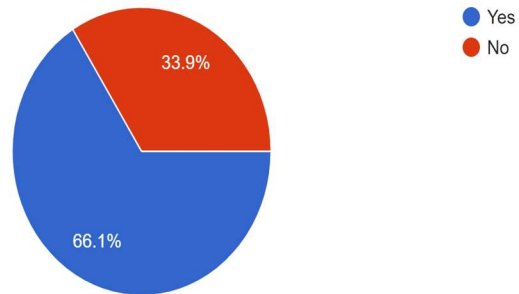
How satisfied are you with the speed and reliability of the network connection?

389 responses



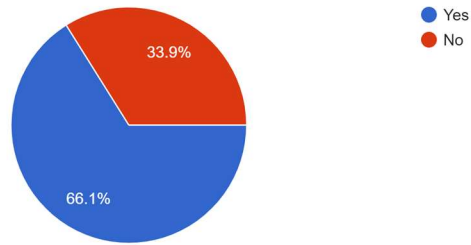
Do you encounter frequent delays or buffering when accessing online resources or streaming media?

389 responses



Have you experienced any issues with dropped connections or sudden disconnections?

389 responses



How important is the quality of the network connection to your overall satisfaction with the college/institution?

389 responses

