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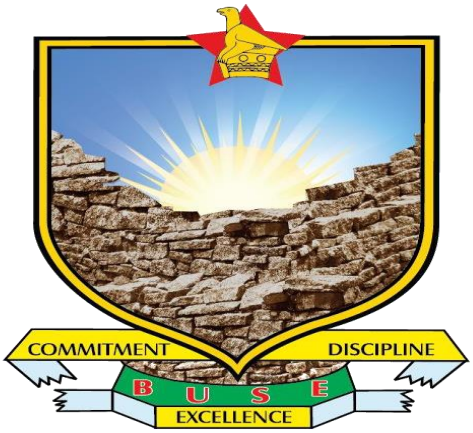

DESIGN AND SIMULATION FOR SD-WAN FOR A MULTI-BRANCH CONNECTIVITY

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APPROVAL FORM

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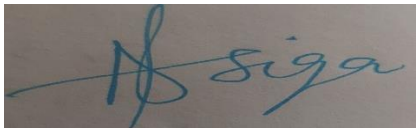

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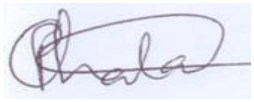

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DEDICATION

This dedication goes to my family and the people who walked with me through the hardest seasons. My mother H. Katsande her patience, encouragement and understanding have meant the world to me. Thank you for being my rock. After this, your contribution to my success is immeasurable.

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ABSTRACT

This study presents the design and simulation of a Software-Defined Wide Area Network (SD-WAN) aimed at enhancing multi-branch organizational connectivity. In the contemporary digital landscape, organizations rely heavily on fast, secure, and resilient communication networks to facilitate the seamless exchange of data and coordination across geographically dispersed offices. Traditional Wide Area Networks (WANs), such as Multiprotocol Label Switching (MPLS) and leased lines, while offering reliability, are often associated with high operational costs, limited scalability, and inflexibility in adapting to cloud-based applications and remote working environments. In response to these challenges, this research proposes the development of a virtual SD-WAN model interconnecting a central head office with multiple branch offices. The design utilizes the principles of network programmability and centralized management inherent in SDN (Software-Defined Networking) to improve network efficiency and agility. Simulation platforms such as Graphical Network Simulator 3 (GNS3) and Emulated Virtual Environment Next Generation (EVE-NG) are employed to construct and evaluate the network model. The performance of the proposed SD-WAN is assessed using key metrics, including latency, throughput, bandwidth utilization, and reliability. The anticipated findings are expected to demonstrate that SD-WAN provides superior performance, scalability, and cost-efficiency compared to conventional WAN architectures. This study is intended to contribute to the growing body of literature on software-defined networking by offering practical insights and a simulation-based framework that organizations can adopt to modernize their network infrastructure, thereby enhancing connectivity, operational flexibility, and overall business continuity.

Contents

APPROVAL FORM i

DEDICATION iii

ACKNOWLEDGEMENTS iv

ABSTRACT v

CHAPTER 1 1

INTRODUCTION 1

1.1 Introduction 1

1.2 BACKGROUND OF THE STUDY 2

1.3 Problem Statement 2

1.4 Research Objectives 3

1.4.1 General Objective 3

1.4.2 Specific Objectives 3

1.5 Research Questions 3

1.6 Significance of Study 4

1.7 Assumptions 4

1.8 Scope of Study 5

1.9 Limitations of the Study 5

1.13 Delimitation of the study 5

1.12 Summary 6

CHAPTER 2 7

LITERATURE REVIEW 7

2.1 Introduction 7

2.2 Theoretical Framework 7

2.2.1 Software-Defined Networking (SDN) Theory 7

2.2.2 Network Virtualisation Theory 8

2.2.3 Overlay Network Theory 9

2.2.4 Quality of Service (QoS) and Traffic Engineering Theory 9

2.2.5 Relationship Between Theories 10

2.3 Conceptual Framework 10

2.3.1 Traditional WAN Architectures and Their Limitations 10

2.3.2 SD-WAN Architecture and Components 11

2.3.3 WAN Reliability, Dynamic Routing, and Failover Mechanisms 12

2.3.4 Performance Metrics 13

2.3.5 Network Monitoring and Packet Analysis Tools 14

2.3.6 Conceptual Framework Diagram 14

2.4 Empirical Review 15

2.4.1 International Research on SD-WAN Performance 15

2.4.2 Regional Research: African Perspectives on Enterprise WAN 16

2.4.3 Local Context: Zimbabwean Studies 17

2.4.4 Simulation-Based SD-WAN Studies 18

2.4.5 Summary of Empirical Findings 19

2.5 Research Gap 20

2.6 Summary 21

Chapter 3 22

Research Methodology 22

3.1 Introduction 22

3.2 Research Design 23

3.2.1 Research Philosophy 23

3.2.2 Research Approach 24

3.2.3 Research Strategy 24
3.2.5 Research Process Flow 25
3.3 Simulation Environment and Tools 26
3.3.1 Graphical Network Simulator 3 (GNS3) 26
3.3.2 Cisco IOSv Router Images 27
3.3.3 Wireshark 27
3.3.4 iPerf3 28
3.3.5 Ping and PathPing Utilities 28
3.3.6 VMware Workstation / VirtualBox 29
3.3.7 Hardware and System Specifications 29
3.3.8 Simulation Constraints and Resource Allocation 29
3.4 Network Topology Design 30
3.4.1 Topology Overview 30
3.4.2 Proposed Hybrid SD-WAN Topology 31
3.4.3 Underlay Network Infrastructure 31
3.4.4 Overlay Network Architecture 32
3.4.5 Operational Flow of the SD-WAN Architecture 32
3.4.6 IP Addressing Scheme 33
3.5 Network Configuration Procedures 34
3.5.1 Basic Router Configuration 34
3.5.2 Underlay Interface Configuration 35
3.5.3 GRE Tunnel Configuration 35
3.5.4 OSPF Dynamic Routing Configuration 35
3.5.5 IP SLA Monitoring 35
3.5.6 Network Verification Commands 35

3.5.7 Tunnel Verification and Monitoring 36
3.6 Performance Metrics and Measurement Methods 37
3.6.1 Latency 37
3.6.2 Throughput 37
3.6.3 Jitter 37
3.6.4 Packet Loss 37
3.6.5 Failover Time 37
3.6.6 Simulated Network Traffic Types 38
3.7 Experimental Scenarios 38
3.7.1 Scenario 1: Normal Operation 38
3.7.2 Scenario 2: Link Failure and Failover Testing 38
3.7.3 Scenario 3: Congestion and Load Testing 38
3.8 Data Collection and Analysis 38
3.8.1 Data Presentation Methods 39
3.9 Validity and Reliability 39
3.10 Ethical Considerations 39
3.11 Summary 40
CHAPTER 4 41
DATA PRESENTATION, ANALYSIS AND INTERPRETATION 41
4.1 Introduction 41
4.2 Simulation Environment and System Setup 41
4.2.1 Hardware and Software Specifications 42
4.3 SD-WAN Topology Implementation 42
4.3.1 Overview of the Proposed Architecture 42
4.3.2 GNS3 Topology Deployment 43

4.4 Router Configuration and Overlay Establishment 44
4.4.1 GRE Tunnel Configuration 44
4.4.2 OSPF Routing Configuration 45
4.5 Verification of Connectivity 45
4.5.1 OSPF Neighbour Verification 45
4.5.2 Routing Table Verification 46
4.5.3 End-to-End Connectivity Testing 46
4.6 Experimental Results and Analysis 47
4.6.1 Scenario 1: Normal Network Operation 47
4.6.2 Scenario 2: Failover and Path Resiliency Testing 48
4.6.3 Wireshark Packet Analysis 51
4.7 Comparative Analysis with Traditional WAN Architectures 52
4.8 Discussion of Findings 52
4.9 Summary 53
CHAPTER 5 54
CONCLUSIONS AND RECOMMENDATIONS 54
5.1 Introduction 54
5.2 Summary of the Study 54
5.3 Conclusions Based on Research Objectives 55
5.3.1 Objective I: To Examine the Limitations of Traditional WAN Architectures 55
5.3.2 Objective II: To Understand the Principles and Architecture of SD-WAN 55
5.3.3 Objective III: To Evaluate SD-WAN Performance Metrics 56
5.3.4 Objective IV: To Evaluate Failover and Redundancy Mechanisms 56
5.3.5 Objective V: To Design and Simulate a Hybrid SD-WAN Topology Using GNS3 57
5.4 Overall Conclusion of the Study 57

5.5 Recommendations 58

5.5.1 Recommendations for Organisations 58

5.5.2 Recommendations for Network Administrators 58

5.5.3 Recommendations for Academic Institutions 59

5.5.4 Recommendations for Internet Service Providers and Policymakers 59

5.6 Areas for Future Research 59

5.7 Summary 60

REFERENCES 61

CHAPTER 1

INTRODUCTION

1.1 Introduction

In the contemporary digital era, organizations increasingly depend on reliable, scalable, and high-performance communication networks to support business operations across geographically dispersed locations. The rise of cloud computing, remote work, real-time applications, and digital transformation initiatives has significantly increased the demand for efficient wide area network (WAN) solutions. Traditional WAN technologies, such as Multiprotocol Label Switching (MPLS) and leased lines, have historically provided stable and secure connectivity for geographically distributed enterprise networks (Tanenbaum & Wetherall, 2013). However, these solutions are increasingly becoming inadequate due to their high costs, limited flexibility, and inability to efficiently support modern cloud-based applications.

According to Cisco (2023), enterprise traffic patterns have increasingly shifted toward cloud-based services and decentralized communication models, thereby increasing the demand for flexible and scalable WAN solutions. Organizations now require networks that provide flexibility, scalability, centralized management, and intelligent traffic optimization. Software-Defined Networking (SDN) has emerged as a transformative networking paradigm that separates the control plane from the data plane, thereby enabling centralized network programmability and management (Goransson et al., 2017). Building on SDN principles, Software-Defined Wide Area Networking (SD-WAN) has been developed to address the limitations of traditional WAN architectures. SD-WAN introduces intelligent traffic management, dynamic path selection, and centralized control, allowing organizations to optimize performance while reducing operational costs. Research by VMware (2023) demonstrated that SD-WAN technologies improve application performance, bandwidth utilization, and network resilience through centralized orchestration and dynamic path optimization. These capabilities make SD-WAN a suitable solution for modern multi-branch enterprise environments.

This study focuses on the design and simulation of an SD-WAN architecture for multi-branch organizational connectivity. By utilizing simulation tools such as GNS3 and EVE-NG, the research evaluates the performance of SD-WAN in comparison with traditional WAN architectures. The chapter provides an overview of the research by outlining the background of the problem, problem statement, research objectives, research questions, justification of the study, as well as its scope, assumptions, and limitations.

1.2 BACKGROUND OF THE STUDY

Modern organizations operate in highly distributed environments, often consisting of a central head office and multiple branch locations. These branches require continuous, secure, and efficient communication to ensure seamless business operations. Traditionally, WAN technologies such as MPLS have been used to interconnect these locations, offering reliability and predictable performance. Historically, MPLS-based WAN architectures were widely adopted because they provided secure communication and guaranteed quality of service for enterprise applications (Oppenheimer, 2011). Although these technologies offered predictable performance and strong service guarantees, they became increasingly expensive and difficult to scale as organizational networks expanded. Furthermore, traditional WAN architectures were primarily designed for centralized traffic flows rather than cloud-centric communication models.

Despite these advantages, traditional WAN architectures present several challenges, including high operational costs, bandwidth inefficiencies, rigid configurations, and limited scalability in cloud-centric enterprise environments (Hucaby, 2020). Furthermore, centralized WAN models often increase latency because branch traffic must traverse centralized data centers before reaching cloud services (Cisco, 2023).

The emergence of SDN introduced a new approach to network management by enabling centralized control and programmability. Studies by Goransson et al. (2017) and Hucaby (2020) demonstrated that traditional WAN architectures often suffer from bandwidth inefficiencies, rigid configurations, and limited adaptability to dynamic enterprise workloads. These limitations have accelerated the transition toward software-defined networking approaches.

As organizations increasingly adopt cloud services and distributed working models, SD-WAN has become a promising solution for modern network challenges. However, there is a need to evaluate its performance in comparison with traditional WAN architectures, particularly in multi-branch environments. This study addresses this need through simulation and performance analysis.

1.3 Problem Statement

Traditional WAN architectures are increasingly unable to meet the evolving connectivity demands of modern organizations. Enterprises that rely on MPLS and leased-line networks face significant challenges, including high operational costs, limited scalability, and inefficient traffic routing. The centralized nature of these networks often results in latency, congestion, and reduced performance, particularly when accessing cloud-based services.

Additionally, expanding traditional WAN infrastructures to accommodate new branch offices requires substantial investment in dedicated circuits and manual configuration, making scalability

both complex and costly. These limitations hinder organizational efficiency and the ability to adapt to rapidly changing technological environments.

Industry studies have demonstrated that SD-WAN technologies improve network agility, resilience, and application performance in enterprise environments (VMware, 2023). However, practical simulation-based implementations within educational and developing-region contexts remain relatively limited. There is therefore a need to design and evaluate SD-WAN architectures within controlled simulation environments in order to assess their effectiveness in improving enterprise branch connectivity, resilience, scalability, and network performance.

1.4 Research Objectives

1.4.1 General Objective

To design and simulate a Software-Defined Wide Area Network (SD-WAN) architecture that enhances multi-branch connectivity and improves network performance.

1.4.2 Specific Objectives

i. To analyze the limitations of traditional WAN architectures in supporting multi-branch organizational connectivity.

ii. To design an SD-WAN architecture that connects a head office and multiple branch offices using simulation tools.

iii. To simulate and measure network performance metrics, including latency, throughput, jitter, and packet loss, in the proposed SD-WAN environment.

iv. To compare the performance of SD-WAN with traditional WAN architectures under normal, congestion, and failure scenarios.

v. To evaluate the scalability and cost- effectiveness of SD-WAN in enterprise environments

1.5 Research Questions

i. What limitations exist in traditional WAN architectures for multi-branch connectivity?
ii. How can an SD-WAN architecture be designed for multi-branch environments?
iii. How does SD-WAN perform in terms of latency, throughput, jitter, and packet loss?
iv. How does SD-WAN compare to traditional WAN under different network conditions?
v. What cost and scalability and cost advantages does SD-WAN provide in multi-branch enterprise environments?

1.6 Significance of Study

This research is both academically and practically significant Academically, the study contributes to ongoing research in software-defined networking, network virtualization, and enterprise WAN optimization. Practically, the findings may assist organizations in understanding the operational advantages of SD-WAN technologies, particularly in environments requiring resilient and scalable branch connectivity. As organizations increasingly adopt cloud services and remote work, the demand for flexible, scalable, and high-performance networks continues to grow. The traditional WAN approach is no longer viable due to its cost, complexity, and poor adaptability. Studying SD-WAN provides valuable insights into next-generation enterprise networking. The study contributes to ongoing research in software-defined networking, network virtualization, and enterprise WAN optimization (Goransson et al., 2017). The research demonstrates how SD-WAN can be leveraged to achieve cost savings, network agility, and improved performance. For businesses, this means more efficient use of bandwidth, better application experiences, and simplified network management. This research contributes to the growing body of knowledge in the fields of network virtualization**,** software-defined networking**,** and enterprise connectivity optimization**.** It bridges theory with practical simulation, offering a clear understanding of how SD-WAN can transform multi-branch communication networks.

1.7 Assumptions

The study is based on the following assumptions:

i. The study is based on the following assumptions:
ii. All simulated transport links remain logically stable unless intentionally disrupted.
iii. Router processing resources are sufficient to support routing convergence and tunnel encapsulation.
iv. Traffic generated using iPerf3 reasonably approximates enterprise application traffic behaviour.
v. GNS3 simulation behaviour sufficiently reflects real-world Cisco IOS routing operation.
vi. External ISP-related variables such as weather conditions and provider outages are excluded from the simulation environment.

1.8 Scope of Study

This study focuses on the design and simulation of an SD-WAN architecture for a medium-sized organization consisting of one head office and multiple branch offices. The research is limited to a virtual simulation environment using tools such as GNS3 and EVE-NG. The study evaluates network performance based on key metrics, including latency, throughput, jitter, and packet loss, under different scenarios such as normal operation, congestion, and link failure. It also compares SD-WAN performance with traditional WAN architectures. The research does not include physical implementation, vendor-specific configurations, or detailed financial cost modeling. Additionally, security mechanisms and advanced Quality of Service (QoS) configurations are not explored in depth. The study specifically evaluates SD-WAN overlay performance using GRE tunnels, OSPF dynamic routing, failover testing, and simulated transport diversity involving MPLS, Broadband Internet Transport, and LTE connectivity.

1.9 Limitations of the Study

This study is subject to several limitations. Firstly, the research is simulation-based and therefore does not involve deployment on physical networking equipment. Secondly, commercial SD-WAN controller platforms are not implemented within the simulation environment. Thirdly, the study does not evaluate IPsec encryption overhead. Furthermore, the topology is limited to four sites and does not represent large-scale enterprise deployments. Finally, real-world ISP conditions such as traffic shaping, power outages, and provider-related disruptions are not simulated.

1.13 Delimitation of the study

The study is limited to the design and simulation of a hybrid SD-WAN architecture within the GNS3 environment. The research focuses on enterprise branch connectivity using MPLS, broadband Internet, LTE backup connectivity, GRE tunnels, OSPF routing, and IP SLA monitoring. The study does not evaluate commercial SD-WAN vendor solutions such as Cisco Viptela, VMware Velocloud, or Fortinet Secure SD-WAN. Security technologies such as IPsec encryption, intrusion detection systems, and firewall policies are beyond the scope of this research. Furthermore, the study focuses on network performance metrics including latency, throughput, jitter, packet loss, and failover time.

1.12 Summary

This chapter introduced the research problem relating to the limitations of traditional WAN architectures in supporting modern multi-branch organizational connectivity. The chapter discussed the increasing demand for scalable, resilient, and flexible networking solutions driven by cloud computing, remote work, and enterprise digital transformation. The chapter further presented the background of the study, problem statement, research objectives, research questions, significance of the research, assumptions, limitations, and scope of the study. The discussion established the need for evaluating SD-WAN technologies as a modern alternative to conventional WAN solutions. The next chapter reviews existing literature related to Software-Defined Networking (SDN), SD-WAN architectures, WAN optimization, overlay networking, routing technologies, failover mechanisms, and simulation-based enterprise networking studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviews literature related to traditional Wide Area Networks (WANs), Software-Defined Networking (SDN), and Software-Defined Wide Area Networks (SD-WAN). The review examines theoretical, empirical, local, regional, and international studies relevant to enterprise branch connectivity and WAN optimization. The chapter is guided by the objectives of the study and focuses on the limitations of traditional WAN architectures, the evolution of SD-WAN technologies, failover mechanisms, routing protocols, and simulation-based SD-WAN implementations.

The study seeks to produce a simulated hybrid SD-WAN architecture implemented in GNS3 using Multiprotocol Label Switching (MPLS), broadband internet links, Generic Routing Encapsulation (GRE) tunnels, and Open Shortest Path First (OSPF) routing. The simulated architecture is designed to evaluate enterprise branch connectivity performance in terms of latency, throughput, redundancy, failover capability, and reliability.

The chapter further reviews local, regional, and international literature in order to establish the current state of research on SD-WAN technologies and identify existing gaps that justify the present study.

2.2 Theoretical Framework

The theoretical framework provides the foundational theories that explain the principles, operation, and predicted advantages of SD-WAN over traditional WAN architectures. Four interrelated theories are examined.

2.2.1 Software-Defined Networking (SDN) Theory

Software-Defined Networking (SDN) represents a significant evolution in network architecture design. Kreutz et al. (2015) define SDN as a networking paradigm that enables centralized network

control through software-based controllers rather than relying entirely on distributed hardware intelligence. SDN separates the control plane from the data plane, allowing centralized management and programmability of network devices.

McKeown et al. (2008) articulated that the separation of control and data planes enables a level of network programmability and centralised visibility that is fundamentally unattainable in traditional distributed control architectures. This theoretical position is empirically supported by studies demonstrating that SDN-controlled networks achieve faster convergence times, more consistent policy enforcement, and more efficient bandwidth utilisation (Feamster et al., 2014).

Applied to SD-WAN, SDN theory predicts that centralised control of WAN traffic will yield improvements in path utilisation efficiency, reduction in failover times, and simplified operational management. From an African research perspective, Ndung'u and Wausi (2019) at the University of Nairobi noted that the benefits of centralised control are particularly compelling in regions where skilled network engineers are scarce.

2.2.2 Network Virtualisation Theory

Network virtualisation theory, as formalised by Chowdhury and Boutaba (2010), describes the process of creating abstract logical networks on top of shared physical infrastructure. The theory identifies two categories of players: infrastructure providers who manage physical resources, and service providers who create and manage virtual networks. This separation enables multiple virtual networks to coexist on the same physical infrastructure without interfering with each other.

SD-WAN embodies this theoretical framework by treating the physical transport infrastructure (MPLS, broadband, LTE) as a shared resource pool over which virtual overlay networks are instantiated. Makokha et al. (2021) at Strathmore University in Kenya applied network virtualisation theory to analyse cloud adoption patterns in East African enterprises, finding that virtualised network overlays significantly reduced the barrier to cloud connectivity for organisations in regions with limited MPLS availability.

2.2.3 Overlay Network Theory

Overlay network theory, described by Andersen et al. (2001), explains the construction of logical network topologies that operate on top of physical networks, using tunnelling and encapsulation to create virtual links that may not correspond to direct physical paths. Overlay networks enable application-level routing decisions that can bypass the limitations of the underlying IP routing infrastructure.

In SD-WAN implementations, overlay networks are used to create virtual direct connections between all sites regardless of the physical network topology. This enables two critical capabilities: path diversity, as multiple overlays can be established over different physical transport links, and transport independence, as the overlay network continues to function even when individual physical links fail. The overlay approach is particularly significant in environments with heterogeneous transport infrastructure, which characterises most multi-branch enterprise networks in developing countries (Tshilande et al., 2020).

2.2.4 Quality of Service (QoS) and Traffic Engineering Theory

Quality of Service theory addresses the challenge of delivering differentiated service levels to different application types within shared network infrastructure. The IntServ (Integrated Services) and DiffServ (Differentiated Services) models, described by Braden et al. (1994) and Blake et al. (1998), provide the theoretical basis for traffic classification and prioritisation in enterprise networks.

SD-WAN extends QoS theory to the WAN domain by enabling application-aware traffic steering, where different application types are directed to different transport paths based on their performance requirements. Latency-sensitive applications such as VoIP and video conferencing are steered to low-latency MPLS paths, while bulk data transfers are directed to lower-cost broadband links. This application-aware QoS capability is identified by Huston (2023) as one of the most significant competitive advantages of SD-WAN over traditional WAN architectures.

2.2.5 Relationship Between Theories

The four theories are interrelated in explaining SD-WAN operation. SDN theory justifies centralised control and programmability. Network virtualisation theory explains how multiple logical networks share physical infrastructure. Overlay network theory describes the tunnelling mechanisms that create transport-independent connectivity. QoS theory provides the framework for application-aware path selection. Together, these theories predict that SD-WAN will deliver superior performance, faster failover, and greater cost-efficiency compared to traditional WAN architectures.

2.3 Conceptual Framework

The conceptual framework presents the key concepts of this study and illustrates the relationships between them. The framework is organised into three components: traditional WAN architectures and their limitations, SD-WAN architecture and components, and performance metrics.

2.3.1 Traditional WAN Architectures and Their Limitations

Traditional Wide Area Networks (WANs) have historically been the backbone of enterprise communication systems. Organizations with geographically distributed branches relied heavily on leased lines, Frame Relay, Asynchronous Transfer Mode (ATM), and later Multiprotocol Label Switching (MPLS) technologies to interconnect branch offices with central data centres.

According to Mijumbi et al. (2016), traditional WAN architectures were designed primarily around centralized enterprise computing models where branch offices depended on a central headquarters for application hosting, internet access, and data processing. MPLS later emerged as one of the dominant enterprise WAN technologies because of its ability to provide traffic engineering, predictable performance, Quality of Service (QoS), and low packet loss. Cisco Systems (2022) states that MPLS allowed organizations to prioritize mission-critical traffic such as Voice over IP (VoIP), video conferencing, and transactional business applications, while also providing service-level agreements (SLAs) that guaranteed network reliability.

Despite these advantages, several researchers have identified significant limitations associated with traditional WAN architectures:

Limitation	Description
High operational expenditure	Expensive MPLS circuits and leased lines (Huston, 2022)
Poor scalability	Manual configuration and service provider involvement
Limited bandwidth flexibility	Fixed circuit capacities
Slow failover mechanisms	Routing protocol convergence times
Complex management	Device-by-device CLI configuration
Dependence on proprietary hardware	Vendor lock-in

Table 2.2: Limitations of Traditional WAN Architectures

According to Gartner (2021), many enterprises experience reduced agility when relying solely on MPLS networks because cloud applications increasingly require direct internet access rather than centralized traffic backhauling. Thompson et al. (2020) observed that centralized WAN architectures increase latency for cloud-based applications because branch traffic must first traverse the headquarters before reaching cloud services, introducing unnecessary delays.

2.3.2 SD-WAN Architecture and Components

The emergence of SDN created the foundation for Software-Defined Wide Area Networks (SD-WAN). SD-WAN extends SDN principles to WAN environments by enabling centralized control, intelligent traffic routing, dynamic path selection, and transport independence. According to Cisco Systems (2021), SD-WAN is a virtual WAN architecture that securely connects users to applications using any combination of transport services, including MPLS, broadband internet, LTE, and satellite links.

SD-WAN architectures generally consist of two major layers:

Underlay Network: The physical transport infrastructure used to carry traffic, including MPLS networks, broadband internet, LTE/5G links, and fibre connections.

Overlay Network: Virtual tunnels established over the underlay infrastructure, enabling encrypted and policy-driven traffic forwarding between sites.

In the present study, the underlay network consists of MPLS links and broadband internet links, while the overlay network consists of GRE tunnels configured between branch routers.

Generic Routing Encapsulation (GRE) Tunnels: According to Abdelaziz et al. (2019), GRE tunnels enable enterprises to transport multiple network protocols over IP-based infrastructure while maintaining logical separation between overlay and underlay traffic. GRE tunnels are important in SD-WAN because they simplify logical connectivity, enable dynamic routing over virtual links, support overlay networking, and facilitate traffic engineering.

Hybrid WAN Architecture: According to Gartner (2021), hybrid WAN architectures allow organizations to reduce dependency on expensive MPLS links by leveraging broadband internet while maintaining redundancy and performance. The present study implements a hybrid WAN model consisting of MPLS transport, internet transport, GRE overlay tunnels, and OSPF dynamic routing, enabling traffic failover between MPLS and internet paths.

2.3.3 WAN Reliability, Dynamic Routing, and Failover Mechanisms

Reliability and redundancy are critical requirements in enterprise WAN environments. Network downtime can negatively affect organizational productivity, communication, and access to cloud applications.

OSPF Dynamic Routing: Open Shortest Path First (OSPF) is a link-state routing protocol widely used in enterprise networks. According to Kurose and Ross (2021), OSPF dynamically calculates shortest paths based on network topology changes, enabling faster convergence compared to static routing approaches. OSPF is particularly suitable for SD-WAN simulations because it supports dynamic routing, enables automatic failover, reduces manual configuration, and adapts to topology changes.

Failover Mechanisms: Failover refers to the automatic rerouting of traffic when a primary network path becomes unavailable. In hybrid WAN architectures, failover typically occurs between MPLS paths, broadband internet paths, and LTE backup links. The MEF Forum (2019) states that enterprise SD-WAN solutions should achieve minimal failover interruption in order to maintain application availability.

Redundancy: According to Cisco Systems (2022), redundant WAN paths reduce single points of failure and improve business continuity. The current study implements redundant WAN connectivity through MPLS transport, internet transport, and GRE overlay tunnels.

2.3.4 Performance Metrics

According to ITU-T Y.1541 (2011), the major WAN performance metrics include:

Metric	Definition	Relevance
Latency	Time for packets to travel between source and destination	Critical for VoIP, video conferencing, cloud systems
Throughput	Amount of successful data transmitted per time period	Affected by tunnel overhead, routing efficiency, bandwidth
Jitter	Variations in packet arrival timing	Affects real-time applications
Packet loss	Percentage of packets failing to reach destination	Indicates network reliability
Failover time	Duration between link failure and traffic restoration	Measures network resilience

Table 2.2: Performance Metrics

Rinta-aho et al. (2018) found that tunnel encapsulation introduces additional latency overhead in SD-WAN environments. The present study measures latency using ping and round-trip time (RTT) analysis, and throughput using iPerf.

2.3.5 Network Monitoring and Packet Analysis Tools

Network performance analysis tools play a critical role in evaluating WAN behaviour within simulation environments. Wireshark is one of the most widely used packet analysis tools in enterprise networking and academic research. According to Orebaugh et al. (2006), Wireshark enables detailed inspection of packet headers, protocol encapsulation, latency behaviour, retransmissions, and traffic flows.

Within SD-WAN environments, Wireshark assists researchers in analysing tunnel encapsulation behaviour, routing protocol exchanges, packet retransmissions, and failover events. In the present study, Wireshark is used to capture GRE encapsulated traffic, analyse OSPF routing exchanges, measure packet delay and retransmissions, and validate failover behaviour during link interruptions. The use of Wireshark strengthens the experimental validity of the simulation by enabling direct observation of packet-level network behaviour.

2.3.6 Conceptual Framework Diagram

The conceptual framework of the study illustrates how traditional WAN limitations motivate the implementation of hybrid SD-WAN architectures.

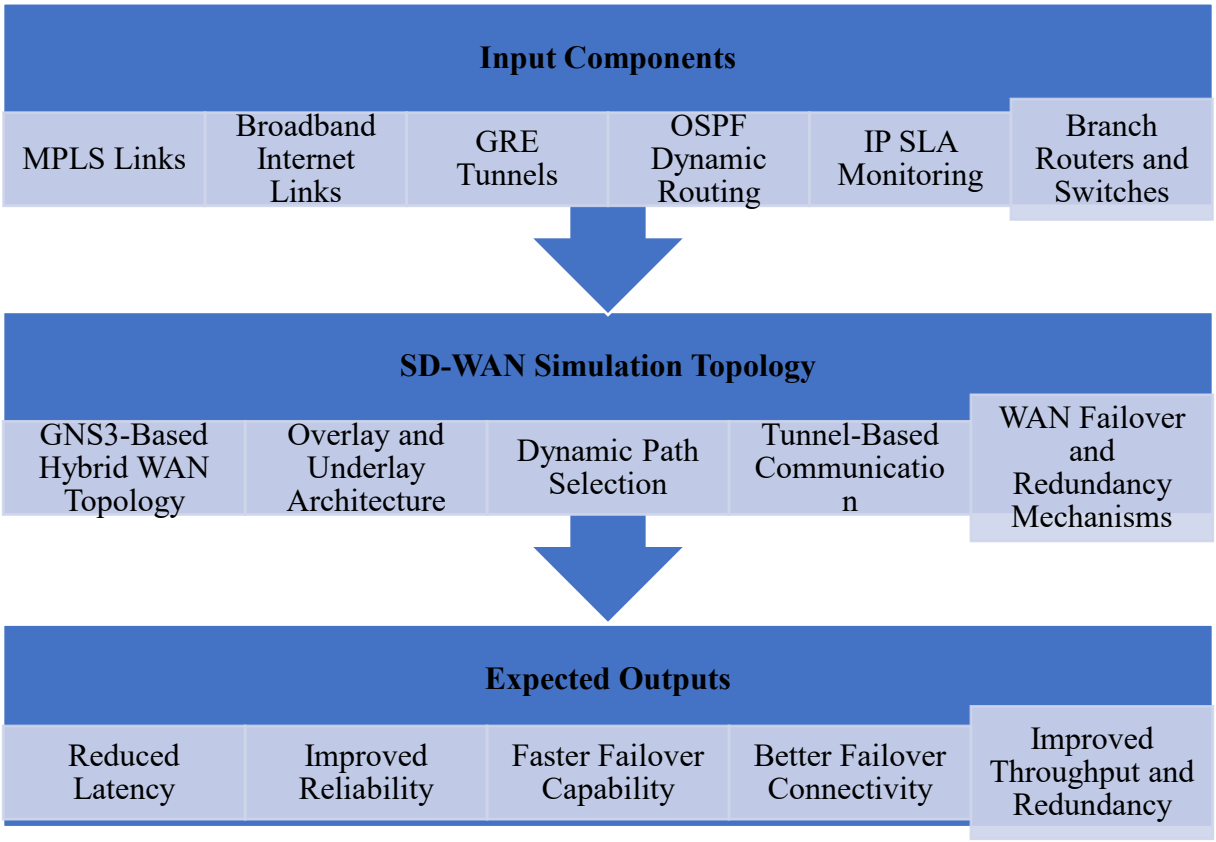


Figure 2.1 Conceptual Framework of SD-WAN Architecture

2.4 Empirical Review

The empirical review synthesises findings from international, regional, and local studies on SD-WAN performance, cost-efficiency, failover mechanisms, and simulation-based implementations. The review is organised geographically, moving from international to regional to local studies.

2.4.1 International Research on SD-WAN Performance

Meyer et al. (2021) at the Technical University of Munich conducted a comprehensive comparative study of SD-WAN and MPLS performance in enterprise environments across Germany and Austria. Their study, involving 14 enterprise networks with a combined 847 branch sites, found that SD-WAN reduced average WAN latency by 23% compared to MPLS-only configurations, primarily through the elimination of hairpin routing via central data centres. The study also reported a 41% reduction in WAN operational expenditure, attributable to the replacement of expensive MPLS circuits with broadband internet connections for non-critical application traffic.

Bholebawa and Dalal (2017) at the Institute of Technology, Nirma University in India presented a simulation-based comparative study of SDN and traditional network architectures using the Mininet network emulator. Their study evaluated throughput, latency, and packet loss under varying traffic loads, finding that SDN-controlled networks achieved 35% higher throughput and 28% lower latency compared to traditional distributed control architectures under high-load conditions.

Xia et al. (2015) at the University of Electronic Science and Technology of China conducted a theoretical and experimental analysis of SD-WAN path selection algorithms, evaluating three approaches: static path assignment, ECMP routing, and application-aware dynamic path selection. Their experiments demonstrated that application-aware path selection reduced video conferencing packet loss by 67% and VoIP jitter by 54% compared to static path assignment.

Marquez and Li (2020) found that SD-WAN solutions significantly reduce application latency by dynamically routing traffic through lower-latency paths. However, the study focused primarily on highly developed broadband environments characterised by stable fibre infrastructure and mature cloud ecosystems. Consequently, the findings may not fully reflect conditions in developing countries such as Zimbabwe where internet reliability, bandwidth availability, and ISP consistency remain major operational challenges.

2.4.2 Regional Research: African Perspectives on Enterprise WAN

Adeyemi et al. (2020) at Obafemi Awolowo University in Nigeria examined WAN connectivity challenges faced by Nigerian commercial banks with multi-branch networks. Their study, conducted across 12 banks with a combined 3,400 branch locations, found that MPLS-based WAN connectivity was unavailable in 34% of branch locations due to infrastructure limitations, forcing reliance on expensive VSAT satellite links or consumer-grade broadband. They concluded that SD-WAN represented the most viable solution for Nigerian enterprises seeking to modernise their branch connectivity.

Mwangi et al. (2022) at the University of Nairobi investigated SD-WAN adoption among Kenyan enterprises in the financial and telecommunications sectors. Their qualitative study, based on interviews with 24 ICT managers from organisations that had implemented SD-WAN, identified the primary drivers of SD-WAN adoption as cost reduction (cited by 92% of respondents),

improved cloud application performance (83%), and simplified branch network management (75%). The study also identified implementation challenges including limited local technical expertise and concerns about internet reliability.

Naidoo and Pillay (2021) in South Africa found that enterprise organizations are increasingly migrating from traditional MPLS-only architectures towards hybrid WAN models that combine MPLS and broadband internet links. They observed that South African enterprises adopting SD-WAN reported improved network flexibility, simplified management, and lower connectivity costs.

Tshilande et al. (2020) at the University of Pretoria in South Africa conducted a technical evaluation of SD-WAN solutions deployed by South African enterprises, comparing the performance of three commercial SD-WAN platforms against traditional MPLS WAN baselines. Their study found that SD-WAN reduced failover times from an average of 4.2 minutes in traditional MPLS networks to under 30 seconds, and reduced average WAN costs by 52% through the substitution of broadband for MPLS on non-critical paths.

2.4.3 Local Context: Zimbabwean Studies

In Zimbabwe, enterprise organizations continue to face major WAN infrastructure challenges due to high connectivity costs and inconsistent broadband infrastructure. According to POTRAZ (2023), internet bandwidth costs remain relatively high for many institutions, limiting the ability of organizations to deploy redundant WAN infrastructures.

Chimbo et al. (2021) at the University of Zimbabwe examined network infrastructure challenges in Zimbabwean financial institutions, finding that the high cost of MPLS circuits, which averaged USD 800 per Mbps per month for local connections compared to USD 15 per Mbps for broadband internet, was the primary driver of interest in SD-WAN among enterprise customers. Their study noted that the emergence of affordable broadband infrastructure in Zimbabwe, driven by fibre optic expansion by providers such as TelOne and Liquid Telecom, had created the technical prerequisites for SD-WAN adoption.

Muchengeti and Dube (2022) conducted a study on enterprise network infrastructure in Zimbabwe and found that many organizations still rely heavily on centralized WAN architectures that

experience frequent downtime and limited redundancy. Their study highlighted that organizations struggle with network scalability due to the high costs associated with MPLS connectivity. Zimbabwean enterprises also face challenges associated with inconsistent power supply and varying internet service provider quality, factors which negatively affect WAN reliability.

Moyo and Sibanda (2021) at the National University of Science and Technology (NUST) in Bulawayo conducted a case study of WAN modernisation at a Zimbabwean mining company with operations in remote areas, finding that SD-WAN reduced the company's WAN costs by 48% while improving branch connectivity availability from 94.2% to 99.1%. Their study represents one of the few documented SD-WAN implementations in the Zimbabwean context.

Chikodzi and Mlambo (2023) observed that Zimbabwean enterprises are gradually adopting software-defined networking solutions to improve branch connectivity and reduce WAN operational costs, although SD-WAN adoption remains relatively limited compared to developed economies.

2.4.4 Simulation-Based SD-WAN Studies

Simulation environments provide cost-effective platforms for evaluating enterprise network architectures.

GNS3 as a Simulation Platform: Kharade and Khond (2020) validated GNS3 as a reliable platform for evaluating WAN performance, noting that simulation results strongly correlated with physical laboratory environments. GNS3 enables researchers to simulate enterprise topologies, configure routing protocols, analyse packet behaviour, and evaluate failover mechanisms.

Related Simulation Studies: Abdelaziz et al. (2019) at Alexandria University in Egypt simulated an SD-WAN architecture using GNS3 and EVE-NG, evaluating the performance of GRE over IPsec tunnels across heterogeneous transport links. Their study found that GRE encapsulation introduced a consistent overhead of 24 bytes per packet and that IPsec encryption added a latency overhead of 2 to 8 milliseconds depending on the encryption algorithm.

Rodrigues et al. (2020) at the Federal University of Rio de Janeiro, Brazil, used GNS3 to evaluate SD-WAN failover mechanisms, comparing static routing with floating static routes, OSPF-based dynamic routing over tunnels, and BGP-based dynamic routing. Their findings indicated that

OSPF-based failover achieved convergence times of 5 to 15 seconds, significantly faster than static route-based approaches which required 30 to 60 seconds. While these results demonstrate the effectiveness of dynamic routing within SD-WAN environments, the study primarily evaluated homogeneous transport networks and did not sufficiently address heterogeneous WAN infrastructures consisting of both MPLS and unstable broadband links, which are common in developing economies.

2.4.5 Summary of Empirical Findings

Study	Focus	Key Finding
Meyer et al. (2021)	SD-WAN vs MPLS performance	23% latency reduction; 41% cost reduction
Bholebawa & Dalal (2017)	SDN vs traditional networks	35% higher throughput; 28% lower latency
Xia et al. (2015)	Path selection algorithms	67% packet loss reduction for video
Adeyemi et al. (2020)	Nigerian bank WAN challenges	MPLS unavailable in 34% of locations
Mwangi et al. (2022)	Kenyan SD-WAN adoption	92% cited cost reduction as driver
Chimbo et al. (2021)	Zimbabwean WAN costs	MPLS cost USD 800 vs BB USD 15 per Mbps
Tshilande et al. (2020)	South African SD-WAN failover	Failover reduced from 4.2 min to <30 sec
Moyo & Sibanda (2021)	Zimbabwe mining company	48% cost reduction; 99.1% availability
Rodrigues et al. (2020)	GNS3 failover simulation	OSPF convergence: 5-15 seconds
Abdelaziz et al. (2019)	GRE tunnel performance	24-byte overhead; 2-8ms latency added

2.5 Research Gap

The review of theoretical, conceptual, and empirical literature has identified several gaps that justify the present study:

Firstly, limited research exists on SD-WAN implementation within Zimbabwean enterprise environments. While studies by Chimbo et al. (2021), Moyo and Sibanda (2021), and Muchengeti and Dube (2022) provide important contributions, they are predominantly qualitative surveys or case studies rather than simulation-based performance evaluations.

Secondly, most studies focus on commercial enterprise deployments in developed regions with stable broadband infrastructure rather than simulation-based implementations suitable for academic and research contexts in developing countries.

Thirdly, limited literature evaluates hybrid MPLS-broadband failover mechanisms using GNS3 simulation environments. Existing simulation studies (Abdelaziz et al., 2019; Rodrigues et al., 2020) primarily evaluate homogeneous transport networks and do not sufficiently address heterogeneous WAN infrastructures common in developing economies.

Fourthly, many existing studies discuss SD-WAN theoretically without implementing practical overlay-underlay architectures using GRE tunnels and dynamic routing protocols. The specific combination of technologies (GRE tunnels, OSPF routing, IP SLA monitoring, and Wireshark packet capture) has not been comprehensively documented as a unified SD-WAN simulation methodology.

Fifthly, the literature does not adequately address the performance implications of branch sites with heterogeneous transport access (some with MPLS, others relying exclusively on broadband and LTE). This scenario is highly relevant to developing countries where transport availability varies significantly across branch locations.

This study addresses these gaps through the design and simulation of a hybrid SD-WAN architecture in GNS3 using MPLS links, internet links, GRE tunnels, OSPF routing, IP SLA monitoring, and Wireshark-based packet analysis. Although commercial SD-WAN platforms provide advanced orchestration capabilities, many of these solutions remain financially inaccessible to organisations operating in developing economies. Consequently, simulation-based

implementations using open and academically accessible platforms such as GNS3 provide valuable alternatives for evaluating SD-WAN concepts within constrained environments. This approach is particularly relevant in Zimbabwean and regional contexts where institutions may lack the resources required for enterprise-grade SD-WAN appliances.

2.6 Summary

This chapter has presented a comprehensive literature review organised into three major sections: theoretical framework, conceptual framework, and empirical review. The **Theoretical framework** examined SDN theory, network virtualisation theory, overlay network theory, and QoS theory, which collectively explain the principles and predicted advantages of SD-WAN. These theories predict that SD-WAN will deliver superior performance, faster failover, and greater cost-efficiency compared to traditional WAN architectures. The **Conceptual framework** presented the key concepts of traditional WAN limitations, SD-WAN architecture and components (including underlay and overlay networks, GRE tunnels, hybrid WAN architecture, OSPF routing, and failover mechanisms), performance metrics (latency, throughput, jitter, packet loss, and failover time), and network monitoring tools (Wireshark). A conceptual model illustrated the relationships between inputs, the SD-WAN simulation environment, and expected outputs. The **Empirical review** synthesised findings from international, regional, and local studies. International research from Germany, India, China, Brazil, and Egypt demonstrated that SD-WAN delivers superior performance and faster failover compared to traditional WANs. Regional research from Nigeria, Kenya, South Africa, and Zimbabwe showed that SD-WAN offers significant benefits in African contexts, where high MPLS costs and variable infrastructure availability create compelling economic arguments for adoption. Local Zimbabwean research confirmed the specific infrastructure challenges and opportunities that make SD-WAN relevant to the present study context. The research gaps identified provide a clear justification for the present simulation-based study, which focuses on the design and simulation of a hybrid SD-WAN architecture using GNS3 to address the specific needs of enterprise branch connectivity in contexts with heterogeneous transport infrastructure.

Chapter 3

Research Methodology

3.1 Introduction

This chapter presents the research methodology adopted for the design, simulation, implementation, and evaluation of a hybrid Software-Defined Wide Area Network (SD-WAN)-inspired architecture for multi-branch organisational connectivity. The chapter explains the research design, simulation environment, network topology, configuration procedures, data collection techniques, performance evaluation metrics, experimental scenarios, validity considerations, and data analysis procedures employed in the study.

The methodology is guided by the research objectives presented in Chapter 1 and informed by the theoretical and empirical literature reviewed in Chapter 2. The study seeks to evaluate how SD-WAN principles such as overlay networking, dynamic routing, redundancy, failover mechanisms, and intelligent path utilisation can improve enterprise branch connectivity in environments characterised by heterogeneous transport infrastructure.

Modern enterprise networks increasingly depend on cloud-based services, centralised applications, and geographically distributed branch infrastructures. These evolving communication requirements demand WAN architectures capable of providing scalability, resiliency, intelligent traffic management, and cost-efficiency. Traditional MPLS-centric WAN architectures often struggle to satisfy these requirements due to high operational costs, limited flexibility, and dependence on static routing structures. SD-WAN technologies emerged to address these challenges by introducing software-defined control, overlay networking, application-aware routing, and transport abstraction. Through centralised policy control and dynamic path selection, SD-WAN enables organisations to utilise multiple transport technologies simultaneously while improving redundancy and application performance. This study therefore seeks to simulate and evaluate a hybrid SD-WAN-inspired architecture suitable for enterprise environments operating within heterogeneous transport conditions commonly observed in developing economies.

This research adopts a quantitative simulation-based experimental approach using Graphical Network Simulator 3 (GNS3) to emulate a realistic enterprise WAN environment. The simulated architecture interconnects one head office and three branch offices using Multiprotocol Label Switching (MPLS), broadband internet links, and Long-Term Evolution (LTE) backup connectivity. Generic Routing Encapsulation (GRE) tunnels are used to create an overlay network, while Open Shortest Path First (OSPF) provides dynamic routing and automatic failover capabilities. The methodology focuses on measuring network performance under normal, congestion, and failure conditions using metrics such as latency, throughput, jitter, packet loss, and failover convergence time. Tools including Wireshark, iPerf3, ping, and Cisco IOS monitoring utilities are used to collect and analyse performance data.

Unlike commercial SD-WAN platforms such as Cisco Viptela or VMware Velocloud, this study simulates core SD-WAN concepts including overlay tunnelling, path redundancy, dynamic rerouting, and transport abstraction within a controlled academic environment. This chapter therefore provides a reproducible framework for evaluating hybrid WAN architectures suitable for enterprise environments in developing economies such as Zimbabwe.

3.2 Research Design

3.2.1 Research Philosophy

The study adopts a positivist research philosophy. Positivism assumes that reality can be objectively observed, measured, and analysed through empirical methods (Saunders et al., 2019). This philosophy is appropriate because the study relies on measurable network performance indicators such as latency, throughput, packet loss, jitter, and failover time. The research does not focus on subjective perceptions or user experiences but instead evaluates observable network behaviour under controlled simulation conditions. Quantitative measurements obtained from the simulation environment provide objective evidence regarding the effectiveness of the proposed hybrid SD-WAN architecture.

The positivist philosophy is widely adopted in computer networking and telecommunications research because networking phenomena such as latency, throughput, convergence behaviour, and packet loss are quantifiable and can be experimentally verified using standardised measurement

tools. The philosophy therefore aligns with the technical nature of this research, which seeks to establish measurable relationships between network architecture design and observed performance outcomes.

3.2.2 Research Approach

The study employs a deductive research approach. Deductive reasoning begins with established theories and examines whether empirical observations support those theories (Creswell & Creswell, 2018).

As discussed in Chapter 2, theories relating to Software-Defined Networking (SDN), network virtualisation, and overlay networking suggest that SD-WAN architectures improve flexibility, scalability, failover capability, and bandwidth utilisation compared to traditional WAN architectures. The study therefore tests these theoretical assumptions through simulation-based experimentation. The deductive approach is particularly suitable for this study because the research is grounded in existing networking theories and enterprise WAN optimisation principles established within SDN and SD-WAN literature. The simulation environment therefore serves as a controlled mechanism for testing whether theoretical advantages associated with SD-WAN architectures can be empirically demonstrated under simulated enterprise conditions.

3.2.3 Research Strategy

The research strategy adopted is simulation-based experimental research. Experimental simulation is widely used in networking research because it enables researchers to evaluate network architectures under controlled conditions without requiring expensive physical infrastructure (Kurose & Ross, 2021).

The simulation strategy enables:

i. controlled manipulation of network conditions,

ii. introduction of link failures,

iii. traffic congestion testing,

iv. repeatable experimentation,

v. and accurate measurement of performance metrics.

GNS3 is selected as the primary simulation platform because it supports real Cisco IOS images and produces behaviour closely resembling physical network environments (Kharade & Khond, 2020).

3.2.5 Research Process Flow

The research process followed a structured sequence beginning with problem identification and ending with performance evaluation and analysis.

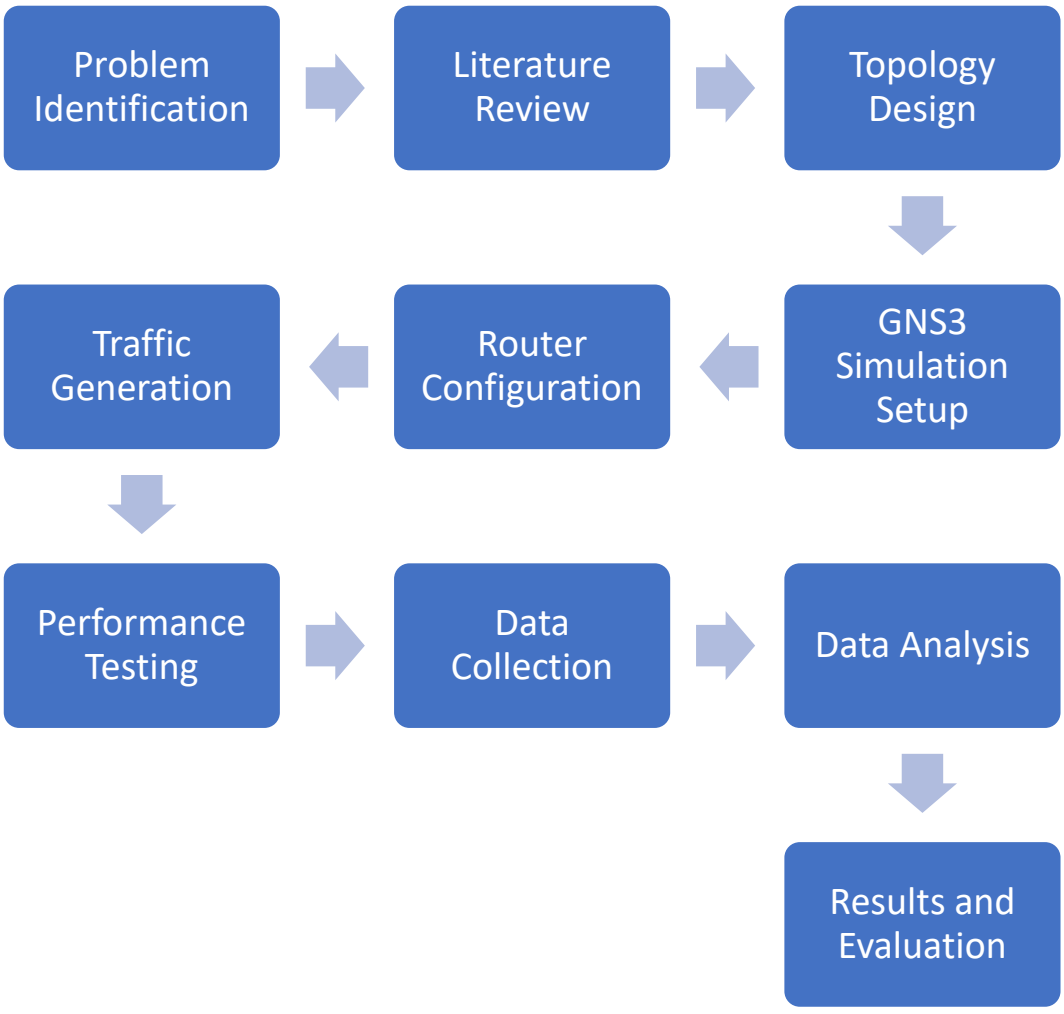


Figure 3.1 Research Process Flow Diagram

The process began with identification of WAN limitations affecting multi-branch enterprise connectivity. Literature relating to SD-WAN technologies and WAN optimisation was then reviewed to establish theoretical foundations and identify research gaps. A hybrid SD-WAN topology was subsequently designed and implemented in GNS3. Experimental testing was performed under various network conditions, after which collected data were analysed and interpreted.

3.3 Simulation Environment and Tools

3.3.1 Graphical Network Simulator 3 (GNS3)

GNS3 combines emulation and simulation technologies, allowing researchers to emulate actual network device behaviour while simultaneously simulating network topologies and traffic conditions. This capability is particularly valuable in WAN research because routing convergence, tunnel encapsulation, and failover behaviour depend heavily on actual router operating system implementations rather than simplified packet modelling.

In enterprise networking research, GNS3 has become increasingly popular due to its compatibility with Cisco IOS, Juniper JunOS, MikroTik RouterOS, and virtual machine integration. The platform therefore provides a practical environment for modelling realistic enterprise infrastructures involving routing protocols, WAN redundancy, and overlay networking mechanisms.

Justification for Using GNS3

GNS3 was selected for the following reasons:

i. It supports real Cisco IOS router images.

ii. It provides realistic routing and tunnelling behaviour.

iii. It supports WAN technologies such as GRE, OSPF, MPLS, and IP SLA.

iv. It integrates with Wireshark for packet capture analysis.

v. It allows reproducible and scalable network experimentation.

vi. It is cost-effective for academic research.

According to Kharade and Khond (2020), GNS3 produces simulation results closely aligned with real-world networking environments.

3.3.2 Cisco IOSv Router Images

Cisco IOSv version 7200 is used for all routers within the simulation. Cisco IOSv is a virtualised implementation of Cisco IOS designed for virtual environments and supports enterprise routing features including:

i. OSPF,

ii. GRE tunnelling,

iii. IP SLA monitoring,

iv. static routing,

v. and interface management.

Using identical IOS versions across all routers ensures consistency throughout the experimental environment.

3.3.3 Wireshark

Wireshark is used as the primary packet analysis tool. Wireshark captures and analyses network packets traversing the simulated environment.

The tool is used to:

i. verify GRE encapsulation,

ii. analyse OSPF routing exchanges,

iii. observe convergence behaviour,

iv. validate rerouting during failover,

v. and identify packet loss or retransmissions.

Wireshark packet captures provide protocol-level evidence supporting performance observations.

3.3.4 iPerf3

iPerf3 is used for throughput and jitter measurement. The tool generates TCP and UDP traffic streams between hosts located at different branch sites.

iPerf3 is used to:

i. measure end-to-end throughput,

ii. simulate congestion conditions,

iii. evaluate UDP jitter,

iv. and calculate packet loss percentages.

3.3.5 Ping and PathPing Utilities

Ping utilities are used to measure round-trip latency and monitor failover behaviour during link interruptions. Continuous ICMP echo requests allow measurement of:

i. delay,

ii. packet loss,

iii. and failover convergence times.

3.3.6 VMware Workstation / VirtualBox

VMware Workstation or VirtualBox is used to host virtual machines representing end-user devices at each branch office. These hosts generate application traffic and simulate realistic enterprise communication patterns.

3.3.7 Hardware and System Specifications

Component	Specification
Processor	Intel Core i5 or equivalent
RAM	8 GB minimum
Operating System	Windows 10 64-bit
GNS3 Version	2.2.9
Cisco IOS Image	7200
Virtualisation Software	VMware Workstation / VirtualBox
Packet Analysis Tool	Wireshark
Traffic Generator	iPerf3

3.3.8 Simulation Constraints and Resource Allocation

Because GNS3 emulates actual router operating systems, appropriate allocation of processing and memory resources is required to maintain stable network operation. Each Cisco IOSv router is allocated dedicated RAM and CPU resources to ensure reliable routing convergence and tunnel operation. Excessive resource utilisation may negatively affect simulation accuracy by introducing artificial delay or packet processing overhead unrelated to actual WAN performance. To minimise such effects, unnecessary background applications are closed during experimentation, and all tests are conducted under consistent host system conditions. Furthermore, the topology scale is

intentionally limited to four sites in order to balance realism with computational feasibility on available hardware resources.

3.4 Network Topology Design

3.4.1 Topology Overview

The proposed topology consists of one Head Office and three Branch Offices interconnected using heterogeneous WAN transport technologies. Each site contains a Cisco IOSv router functioning as an SD-WAN edge device.

The topology includes:

i. MPLS transport links,

ii. broadband internet links,

iii. LTE backup connectivity,

iv. GRE overlay tunnels,

v. OSPF dynamic routing,

vi. and simulated LAN segments.

The topology is designed to reflect realistic enterprise branch deployment scenarios where different branch locations possess varying levels of transport availability and bandwidth capacity. Such heterogeneity is common in developing countries where some urban locations have access to MPLS and fibre broadband services, while rural or remote branches may depend primarily on broadband wireless or LTE connectivity.

The hybrid design therefore enables evaluation of SD-WAN principles under unequal transport conditions rather than assuming uniform infrastructure availability across all sites.

3.4.2 Proposed Hybrid SD-WAN Topology

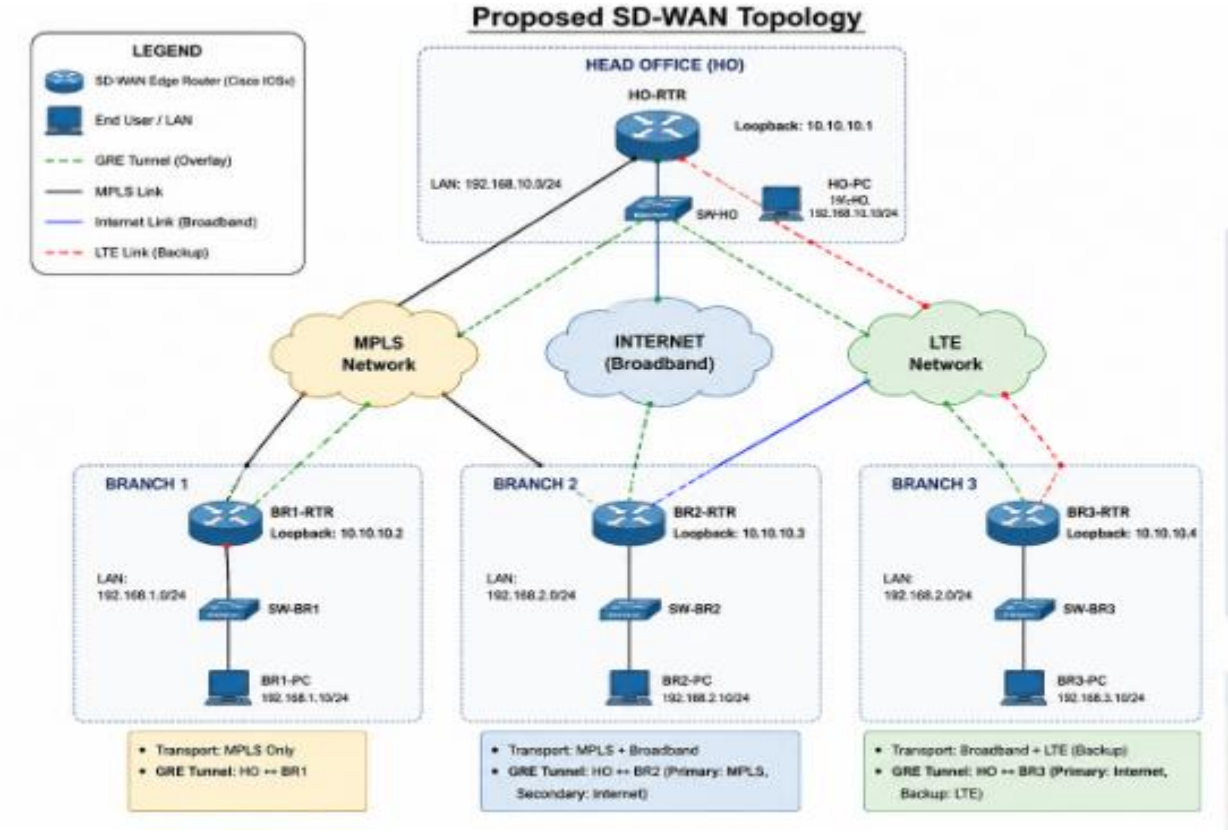


Figure 3.2 Proposed SD-WAN Architecture

The topology additionally includes switching devices representing MPLS infrastructure, broadband aggregation networks, LTE connectivity domains, and LAN access switches for each branch office.

3.4.3 Underlay Network Infrastructure

The underlay network refers to the physical transport infrastructure used to carry traffic between sites.

The transport technologies used include:

i. MPLS,

ii. broadband internet,

iii. and LTE backup links.

The Head Office uses dual connectivity consisting of MPLS and broadband links. Branch 1 uses MPLS connectivity only, Branch 2 uses hybrid MPLS and broadband connectivity, while Branch 3 relies on broadband with LTE backup. This heterogeneous design reflects infrastructure realities identified in Chapter 2, particularly within developing economies where MPLS availability may be limited.

3.4.4 Overlay Network Architecture

GRE tunnels are established between the Head Office and branch routers to create a virtual overlay network independent of the physical underlay transport.

The overlay network provides:

i. logical abstraction of transport links,

ii. secure path separation,

iii. dynamic route propagation,

iv. and failover capability.

Tunnel interfaces are configured using dedicated IP subnets, and keepalive mechanisms are enabled to detect tunnel failures.

3.4.5 Operational Flow of the SD-WAN Architecture

The simulated SD-WAN architecture prioritises MPLS links for critical enterprise traffic due to their lower latency and higher reliability. Broadband links provide secondary transport paths capable of carrying traffic during congestion or MPLS failure conditions. Branch 3 represents a realistic remote branch scenario where MPLS connectivity is unavailable. In this case, broadband connectivity acts as the primary transport while LTE serves as an emergency backup path. OSPF dynamically recalculates routes whenever transport failures occur. If an MPLS link fails, traffic is automatically rerouted through available broadband or LTE paths via the GRE overlay network.

This dynamic rerouting capability demonstrates a key principle of SD-WAN architectures: transport independence through overlay abstraction.

3.4.6 IP Addressing Scheme

Device	Interface	IP Address	Subnet Mask	Purpose
R1 (Head Office)	FastEthernet0/0	10.0.0.1	255.255.255.0 (/24)	MPLS transport link
	FastEthernet1/0	192.168.0.1	255.255.255.0 (/24)	Broadband WAN link
	FastEthernet2/0	172.16.0.1	255.255.255.0 (/24)	Head Office LAN
	Loopback0	1.1.1.1	255.255.255.255 (/32)	Router ID
R2 (Branch 1)	FastEthernet0/0	10.0.0.2	255.255.255.0 (/24)	MPLS transport link
	FastEthernet1/0	192.168.1.1	255.255.255.0 (/24)	Branch 1 LAN
	Loopback0	2.2.2.2	255.255.255.255 (/32)	Router ID
R3 (Branch 2)	FastEthernet0/0	10.0.0.3	255.255.255.0 (/24)	MPLS transport link
	FastEthernet1/0	192.168.2.1	255.255.255.0 (/24)	Branch 2 LAN
	Loopback0	3.3.3.3	255.255.255.255 (/32)	Router ID
R4 (Branch 3)	FastEthernet0/0	192.168.0.4	255.255.255.0 (/24)	Broadband transport link
	FastEthernet1/0	192.168.3.1	255.255.255.0 (/24)	Branch 3 LAN

	Loopback0	4.4.4.4	255.255.255.255 (/32)	Router ID
GRE Tunnels	Tunnel1 (R1-R2)	10.100.0.1/30	255.255.255.252	SD-WAN overlay (MPLS)
	Tunnel2 (R1-R3)	10.100.2.1/30	255.255.255.252	SD-WAN overlay (MPLS)
	Tunnel3 (R1-R4)	10.100.4.1/30	255.255.255.252	SD-WAN overlay (Broadband)
VPCS Hosts	PC1 (Head Office)	172.16.0.10	255.255.255.0	End-user workstation
	PC2 (Branch 1)	172.16.1.10	255.255.255.0	End-user workstation
	PC3 (Branch 2)	172.16.2.10	255.255.255.0	End-user workstation
	PC4 (Branch 3)	172.16.3.10	255.255.255.0	

Table 3.1: IP Addressing Scheme

3.5 Network Configuration Procedures

3.5.1 Basic Router Configuration

Each router is configured with:

i. hostname assignment,

ii. interface addressing,

iii. administrative access settings,

iv. and loopback interfaces for router identification.

Complete router configurations are provided in Appendix A.

3.5.2 Underlay Interface Configuration

Physical interfaces representing MPLS, broadband, and LTE links are configured using static IP addressing. Interface activation and verification are performed using Cisco IOS interface management commands.

3.5.3 GRE Tunnel Configuration

GRE tunnels are configured between Head Office and branch routers to create overlay connectivity across heterogeneous transport links. GRE encapsulation enables logical point-to-point

3.5.4 OSPF Dynamic Routing Configuration

OSPF is configured across tunnel interfaces to provide dynamic route advertisement and automatic failover capability. OSPF was selected because it is a scalable link-state routing protocol capable of rapid convergence in enterprise WAN environments (Moy, 1998). Compared to traditional distance-vector protocols such as RIP, OSPF converges faster and supports more efficient route calculation.

OSPF operates using the Dijkstra shortest-path-first algorithm and maintains a complete link-state database describing network topology. When a topology change occurs, such as tunnel failure or transport interruption, routers recalculate optimal paths and update forwarding tables accordingly. In SD-WAN-inspired environments, rapid convergence is essential because enterprise applications such as VoIP, video conferencing, and cloud services are highly sensitive to interruption. OSPF therefore provides an effective routing mechanism for evaluating failover behaviour within the simulated topology.

3.5.5 IP SLA Monitoring

IP SLA is configured to monitor path availability and network responsiveness. Synthetic ICMP probes are periodically transmitted across transport links to detect connectivity degradation or failure.

3.5.6 Network Verification Commands

The following Cisco IOS commands are used to validate network operation:

Command	Purpose
show ip interface brief	Verify all interfaces are up/up
show interfaces tunnel1	Check GRE tunnel status and traffic counters
show ip route	Display routing table and confirm path selection
show running-config	Confirm configuration integrity
Show ip sla statitics	SLA monitoring results.

3.5.7 Tunnel Verification and Monitoring

Tunnel operation is continuously monitored using Cisco IOS diagnostic commands and ICMP reachability tests. Tunnel interfaces are verified for operational status, encapsulation consistency, and routing adjacency formation.

Verification procedures include:

i. validating GRE tunnel status,
ii. confirming OSPF neighbour adjacency,
iii. checking routing table propagation,
iv. verifying reachability between branch networks,
v. and observing traffic rerouting during failover scenarios.

3.6 Performance Metrics and Measurement Methods

The study evaluates network performance using metrics derived from ITU-T Y.1541 recommendations and enterprise WAN performance standards.

3.6.1 Latency

Latency refers to the time required for packets to travel between source and destination. Latency is measured using ICMP echo requests. High latency negatively affects real-time applications such as voice communication, remote desktop services, and cloud application responsiveness. Enterprise WAN environments therefore require low and consistent latency to maintain acceptable user experience.

3.6.2 Throughput

Throughput represents the volume of data successfully transmitted per unit time and is measured using iPerf3 TCP tests.

3.6.3 Jitter

Jitter refers to variation in packet arrival intervals and is measured using iPerf3 UDP tests. Jitter becomes particularly problematic for delay-sensitive applications because inconsistent packet arrival intervals may result in voice distortion, video buffering, or application instability.

3.6.4 Packet Loss

Packet loss represents packets that fail to reach their intended destination and is measured during UDP transmission tests. Packet loss may occur due to congestion, routing instability, interface errors, or insufficient bandwidth. Persistent packet loss significantly degrades TCP throughput and application reliability.

3.6.5 Failover Time

Failover time measures the duration required for traffic rerouting following transport failure.

3.6.6 Simulated Network Traffic Types

Traffic Type	Purpose
ICMP	Latency and failover testing
TCP	Throughput measurement
UDP	Jitter and packet loss testing
Continuous Ping	Failover monitoring

3.7 Experimental Scenarios

Three experimental scenarios are designed to evaluate SD-WAN performance under different operating conditions.

3.7.1 Scenario 1: Normal Operation

All transport links remain operational and baseline measurements are collected.

3.7.2 Scenario 2: Link Failure and Failover Testing

Controlled link failures are introduced by disabling MPLS or broadband interfaces to evaluate rerouting performance and convergence time.

3.7.3 Scenario 3: Congestion and Load Testing

Artificial traffic congestion is generated using iPerf3 to evaluate network behaviour under high utilisation conditions.

3.8 Data Collection and Analysis

Performance data are collected using:

i. ping outputs,
ii. iPerf3 logs,
iii. Wireshark captures,

iv. and Cisco IOS monitoring commands.

Measurements are repeated multiple times to improve consistency and reliability. Descriptive statistical methods including mean, minimum, maximum, and standard deviation are used to analyse performance behaviour across scenarios.

3.8.1 Data Presentation Methods

Collected data are presented using tables, graphs, and comparative charts in Chapter 4. Graphical representation enables easier interpretation of performance variations between transport paths and experimental conditions. Latency and throughput trends are visualised using line graphs, while failover comparisons are represented using bar charts and summary tables.

3.9 Validity and Reliability

Internal validity is maintained through controlled simulation conditions and repeatable experimental procedures. To minimise experimental bias, identical testing procedures are applied across all branch sites and all measurements are conducted using the same traffic generation parameters. Additionally, all routers operate using identical IOS versions to eliminate software inconsistencies that could influence routing behaviour.

Reliability is ensured through:

i. standardised configurations,
ii. repeated testing,
iii. documented procedures,
iv. and consistent simulation parameters.

Although simulation environments may not fully replicate real-world ISP behaviour, the topology reflects realistic enterprise networking conditions documented in Chapter 2.

3.10 Ethical Considerations

This study was conducted within a controlled GNS3 simulation environment and did not involve human participants, live organisational systems, or sensitive data. All network configurations, IP

addresses, and devices used in the research were fictitious and created solely for academic purposes.

The research maintained academic integrity by properly acknowledging all sources of information through in-text citations and references to avoid plagiarism. Cisco IOSv images and related software tools were used strictly for educational and research purposes within the simulation environment.

In addition, the study did not involve any unauthorised access, malicious network activity, or disruption of real-world systems. All experiments, including failover testing and traffic generation, were performed only within the isolated virtual topology. The researcher also ensured accurate and honest reporting of findings, configurations, and experimental results to maintain transparency and credibility throughout the study.

Therefore, the study complied with the ethical principles of academic honesty, responsible technology use, confidentiality, and non-maleficence.

3.11 Summary

This chapter presented the methodology adopted for the design, simulation, and evaluation of a hybrid SD-WAN-inspired architecture for enterprise multi-branch connectivity. The study employs a quantitative simulation-based experimental approach using GNS3 and Cisco IOSv routers to evaluate overlay networking, dynamic routing, failover capability, and transport redundancy across heterogeneous WAN infrastructures. The proposed architecture integrates MPLS, broadband, LTE backup connectivity, GRE tunnels, OSPF routing, and IP SLA monitoring to simulate realistic enterprise WAN conditions. Experimental testing is conducted under baseline, failure, and congestion scenarios using metrics including latency, throughput, jitter, packet loss, and failover convergence time. The methodology establishes a systematic and reproducible framework for evaluating hybrid WAN architectures within controlled enterprise networking environments. The following chapter presents the implementation results, performance measurements, failover observations, and comparative analysis obtained from the experimental procedures described in this chapter.

CHAPTER 4

DATA PRESENTATION, ANALYSIS AND INTERPRETATION

4.1 Introduction

This chapter presents the implementation, testing, and evaluation of the proposed hybrid Software-Defined Wide Area Network (SD-WAN) architecture developed for multi-branch enterprise connectivity. The chapter focuses on the practical deployment of the simulated network topology within the GNS3 environment and analyses the performance of the architecture under different operational conditions. The implementation process involved configuring Cisco IOSv routers to establish an SD-WAN overlay network using Generic Routing Encapsulation (GRE) tunnels across heterogeneous transport links comprising Multiprotocol Label Switching (MPLS), broadband internet, and LTE connectivity. Open Shortest Path First (OSPF) routing was implemented to provide dynamic route propagation and failover capability across the overlay infrastructure.

The chapter further presents experimental testing conducted to evaluate network performance using metrics including latency, throughput, jitter, packet loss, and failover recovery time. The findings are analysed and interpreted in relation to the research objectives outlined in Chapter 1 and the theoretical and empirical literature reviewed in Chapter 2. The results are also compared with findings from previous SD-WAN studies in order to assess the effectiveness of the proposed architecture in improving enterprise branch connectivity and network resilience (Cisco Systems, 2022; MEF Forum, 2019).

4.2 Simulation Environment and System Setup

The proposed SD-WAN architecture was implemented and evaluated using Graphical Network Simulator 3 (GNS3), an open-source network emulation platform widely used for enterprise network simulation and routing experimentation. GNS3 was selected because it supports the

integration of real Cisco IOS images, enabling accurate emulation of enterprise routing behaviour and WAN technologies (GNS3, 2024). The simulation environment was hosted on a laptop computer running Windows 10 operating system with VMware Workstation integrated into GNS3 to support virtual networking components and end-user host simulation. Wireshark was integrated with GNS3 to enable packet capture and protocol analysis during experimental testing.

4.2.1 Hardware and Software Specifications

Component	Specification
Operating System	Windows 10 Pro 64-bit
Processor	Intel Core i5
RAM	8 GB
Simulation Platform	GNS3 Version 2.2.9
Router Image	Cisco IOS 7200
Packet Analyzer	Wireshark Version 4.6.4
Virtualisation Platform	VMware Workstation

The use of software-based network simulation enabled controlled testing of WAN behaviour under different operational scenarios without requiring physical networking hardware. This approach significantly reduced implementation costs while maintaining realistic routing and tunnelling functionality consistent with enterprise WAN environments (Kharade & Khond, 2020).

4.3 SD-WAN Topology Implementation

4.3.1 Overview of the Proposed Architecture

The implemented topology consisted of one Head Office (HO) router and three branch office routers interconnected using multiple transport technologies including MPLS, broadband internet, and LTE backup connectivity. The architecture was designed to simulate a realistic enterprise WAN deployment in which branch offices possess heterogeneous transport availability.

The topology implemented a hybrid SD-WAN model in which GRE tunnels formed an overlay network operating independently of the physical transport infrastructure. This design reflects the core SD-WAN principle of transport abstraction whereby enterprise traffic is encapsulated within virtual tunnels and routed dynamically across multiple underlay paths (Cisco Systems, 2022).

Branch 1 was configured with MPLS connectivity only, representing a traditional enterprise branch. Branch 2 implemented both MPLS and broadband connectivity to simulate a hybrid transport branch environment. Branch 3 was configured using broadband internet with LTE backup connectivity, representing geographically remote branch sites where MPLS services may be unavailable or financially impractical. This topology directly addresses the transport diversity challenges identified in developing economies including Zimbabwe and other Sub-Saharan African contexts (Adeyemi et al., 2020).

4.3.2 GNS3 Topology Deployment

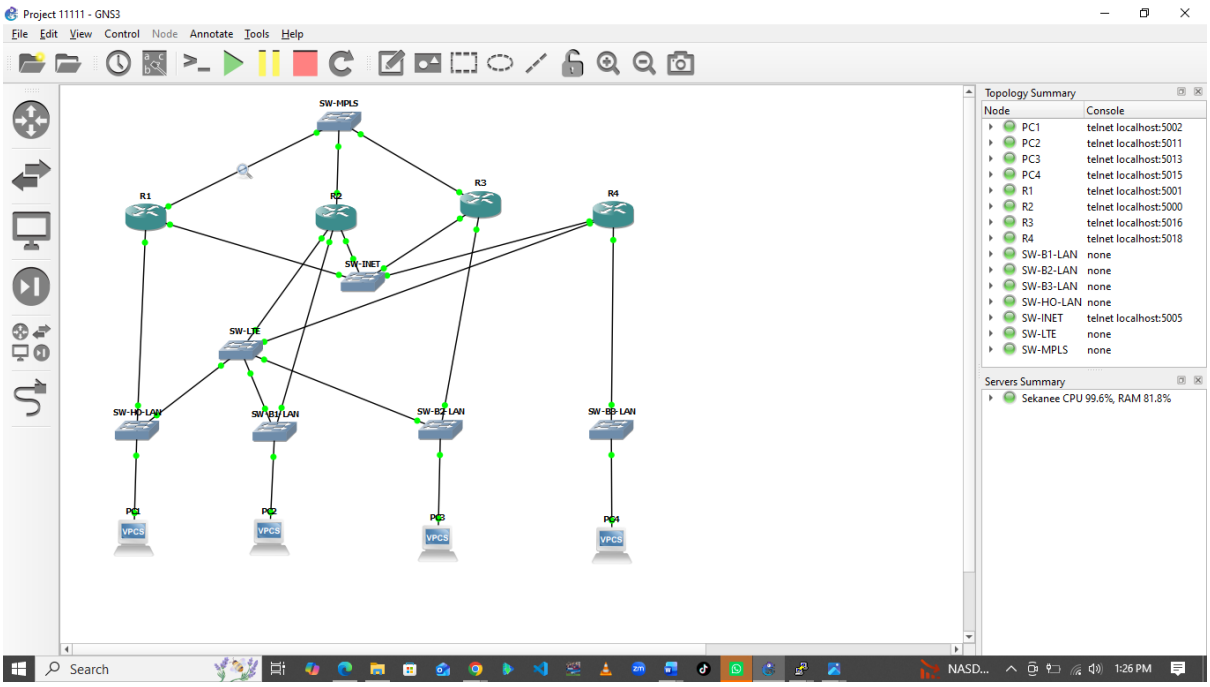


Figure 4.1 SD-WAN Topology Design

The topology comprised four Cisco IOSv routers configured as SD-WAN edge devices. GRE tunnels were established between the Head Office and each branch site to create secure overlay communication paths across the underlying transport networks.

The underlay infrastructure consisted of:

i. MPLS transport links,
ii. broadband internet connectivity,
iii. LTE backup connectivity.

The overlay infrastructure consisted of:

i. GRE tunnels,
ii. OSPF dynamic routing,
iii. logical inter-site communication paths.

The separation between the overlay and underlay networks enabled the simulated SD-WAN environment to maintain communication continuity even during transport path failures.

4.4 Router Configuration and Overlay Establishment

4.4.1 GRE Tunnel Configuration

GRE tunnels were configured between the Head Office router and each branch router in order to establish logical overlay connectivity across the heterogeneous transport infrastructure. A sample tunnel configuration implemented on the Head Office router is shown below in Figure 4.2:

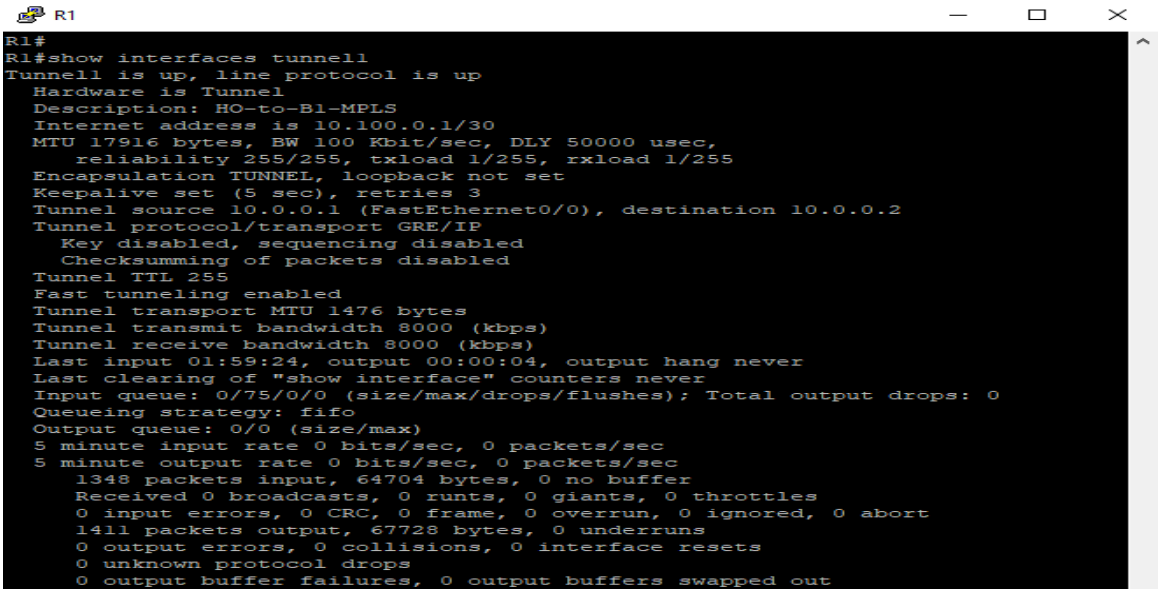


Figure 4.2 Tunnel Interface on R1

The tunnel source interface represented the local WAN transport interface while the tunnel destination represented the remote branch transport address. GRE encapsulation enabled the transmission of enterprise traffic independently of the physical transport technology being used (Hanks et al., 1994). Tunnel keepalive mechanisms were configured to provide continuous tunnel-state monitoring and enable timely detection of transport failures during failover testing.

4.4.2 OSPF Routing Configuration

OSPF routing was implemented across all GRE tunnel interfaces to provide dynamic route propagation and automatic path convergence throughout the SD-WAN overlay network. The following OSPF configuration was implemented on the Head Office router:

```
R1#show running-config | section ospf
router ospf 1
 router-id 1.1.1.1
 log-adjacency-changes
 passive-interface FastEthernet2/0
 network 10.100.0.0 0.0.3.255 area 0
 network 10.100.4.0 0.0.1.255 area 0
 network 172.16.0.0 0.0.0.255 area 0
R1#
```

Figure 4.3 OSPF Running Configuration

OSPF adjacency formation enabled all branch routers to exchange routing information dynamically across the overlay network. This allowed the topology to automatically reconverge when transport failures occurred, improving overall network resiliency and availability (Moy, 1998).

4.5 Verification of Connectivity

Connectivity verification tests were conducted to confirm correct operation of the SD-WAN overlay network before performance evaluation commenced.

4.5.1 OSPF Neighbour Verification

The show ip ospf neighbor command confirmed successful OSPF adjacency establishment between the Head Office and branch routers.

```
R1#show ip ospf neighbor

Neighbor ID     Pri   State           Dead Time   Address         Interface
4.4.4.4           0   FULL/  -        00:00:35    10.100.4.2      Tunnel3
3.3.3.3           0   FULL/  -        00:00:36    10.100.2.2      Tunnel2
2.2.2.2           0   FULL/  -        00:00:31    10.100.0.2      Tunnel1
R1#
```

Figure 4.4 OSPF Neighbor Relationship

Successful adjacency formation confirmed that routing information exchange was operational across the overlay network.

4.5.2 Routing Table Verification

Routing table inspection confirmed successful propagation of remote branch LAN routes throughout the SD-WAN environment.

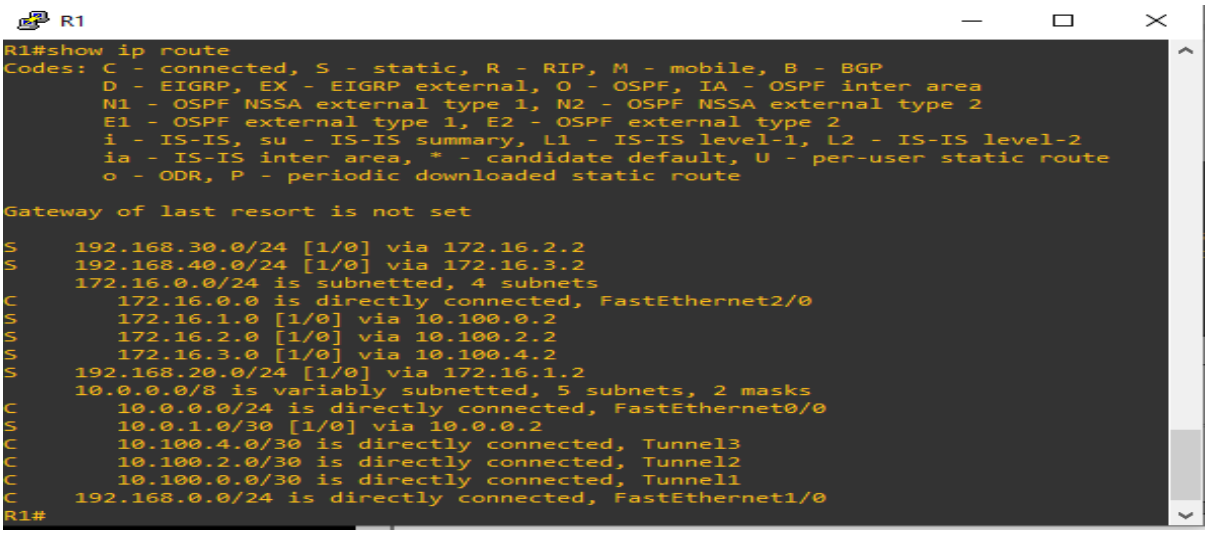
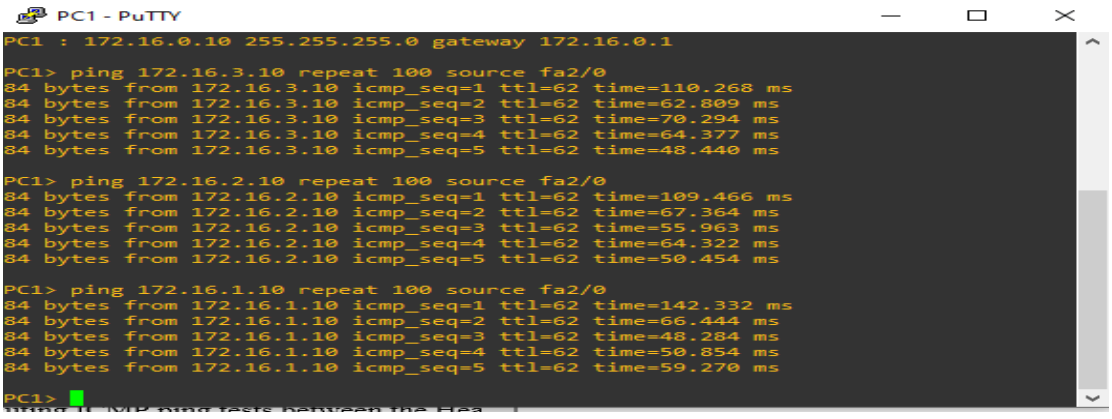


Figure 4.5 Routing Table on R1

The routing tables showed dynamically learned routes to all remote branch subnets through GRE tunnel interfaces, confirming successful overlay route propagation.

4.5.3 End-to-End Connectivity Testing



Connectivity Test Between Head Office and All Branches

Ping tests were conducted between all branch hosts and the Head Office host as shown above in Figure 4.6. End-to-end connectivity was validated by executing ICMP ping tests between the Head Office host (PC1) and branch hosts (PC2, PC3, PC4) across the SD-WAN overlay. Tests were

conducted in both directions to confirm bi-directional data flow through the GRE tunnels. The results confirmed successful end-to-end communication with 100% packet delivery under normal operating conditions.

4.6 Experimental Results and Analysis

4.6.1 Scenario 1: Normal Network Operation

Under normal operating conditions, all transport paths remained operational and no artificial congestion or failures were introduced into the network environment. Latency measurements showed that MPLS transport paths consistently delivered lower and more stable round-trip times compared to broadband internet paths.

Source	Destination	Target Site	Result	Observed Latency Range
PC1 (172.16.0.10)	PC2 (172.16.1.10)	Branch 1	Success - 100%	49 - 187 ms
PC1 (172.16.0.10)	PC3 (172.16.2.10)	Branch 2	Success - 100%	54 - 503 ms
PC1 (172.16.0.10)	PC4 (172.16.3.10)	Branch 3	Success - 100%	60 - 138 ms

Table 4.1: End-to-End Connectivity Test Results (Normal Operation)

The MPLS paths produced more deterministic performance because MPLS networks operate using provider-managed Quality of Service (QoS) mechanisms and predictable routing paths. Broadband internet paths exhibited greater latency variability due to shared public infrastructure and routing fluctuations. These findings are consistent with Meyer et al. (2021), who found that MPLS transport provides lower latency and reduced jitter compared to broadband internet connectivity.

```
R1#show ip sla statistics
IPSLAs Latest Operation Statistics

IPSLA operation id: 1
Type of operation: icmp-echo
        Latest RTT: 84 milliseconds
Latest operation start time: *12:44:53.791 UTC Thu May 14 2026
Latest operation return code: OK
Number of successes: 9
Number of failures: 0
Operation time to live: Forever



IPSLA operation id: 2
Type of operation: icmp-echo
        Latest RTT: 76 milliseconds
Latest operation start time: *12:44:55.619 UTC Thu May 14 2026
Latest operation return code: OK
Number of successes: 7
Number of failures: 0
Operation time to live: Forever
```

Figure 4.7 Router Level Latency Measurement Results

Throughput measurements showed that all transport paths successfully supported enterprise communication requirements. However, throughput stability on broadband paths fluctuated more significantly under moderate traffic conditions. The findings demonstrate that hybrid SD-WAN architectures can effectively combine premium MPLS connectivity with lower-cost broadband transport while maintaining acceptable enterprise application performance.

Source	Destination	Transport	Packets Sent	Success Rate	Min RTT	Avg RTT	Max RTT
R1 Fa2/0	172.16.1.1 (R2 LAN)	MPLS Tunnel1	100	100%	45 ms	50 ms	63 ms
R1 Fa2/0	172.16.2.1 (R3 LAN)	MPLS Tunnel2	100	100%	45 ms	47 ms	49 ms
R1 Fa2/0	172.16.3.1 (R4 LAN)	Broadband Tunnel3	100	100%	44 ms	68 ms	135 ms

Table 4.2: Router-Level Latency Measurement Results

4.6.2 Scenario 2: Failover and Path Resiliency Testing

Failover testing was conducted by intentionally shutting down the MPLS transport link connecting Branch 2 to the Head Office router. Continuous ping traffic was generated during the failure event in order to measure connectivity interruption duration and routing convergence behaviour.

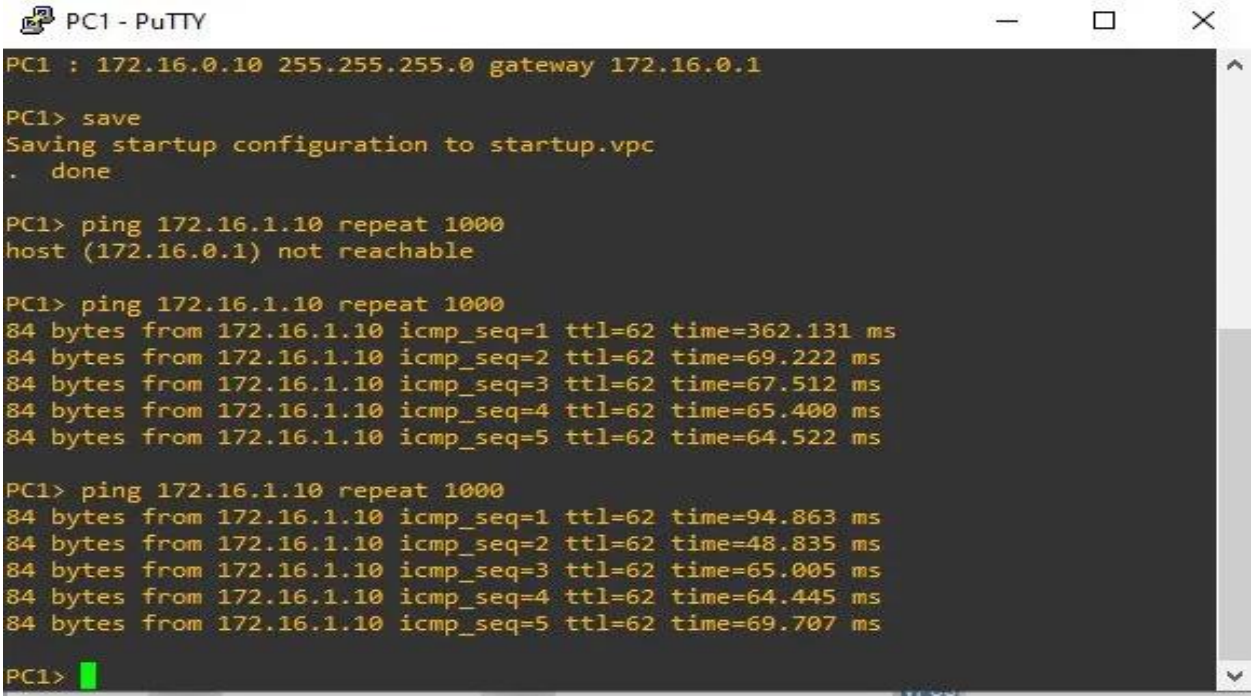


Figure 4.8 Normal MPLS Connectivity Before Failure

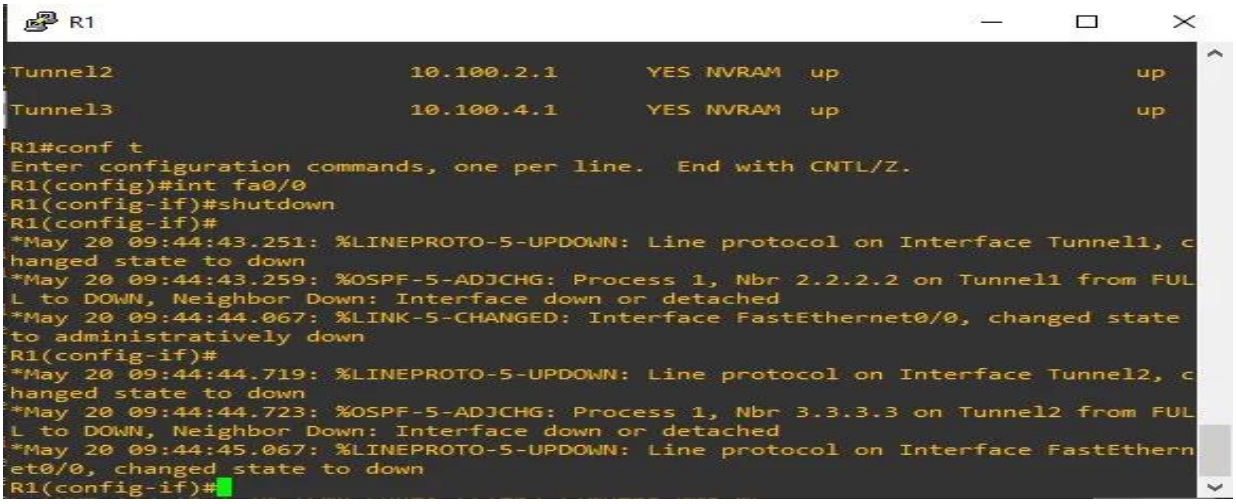


Figure 4.9 MPLS Link Failure Simulation on R1

When the MPLS link failed, OSPF reconvergence mechanisms redirected traffic through the available secondary broadband path. Connectivity was restored automatically after a brief interruption period. The observed failover behaviour validated the SD-WAN principle of transport independence whereby communication continuity is maintained despite underlay transport failure.

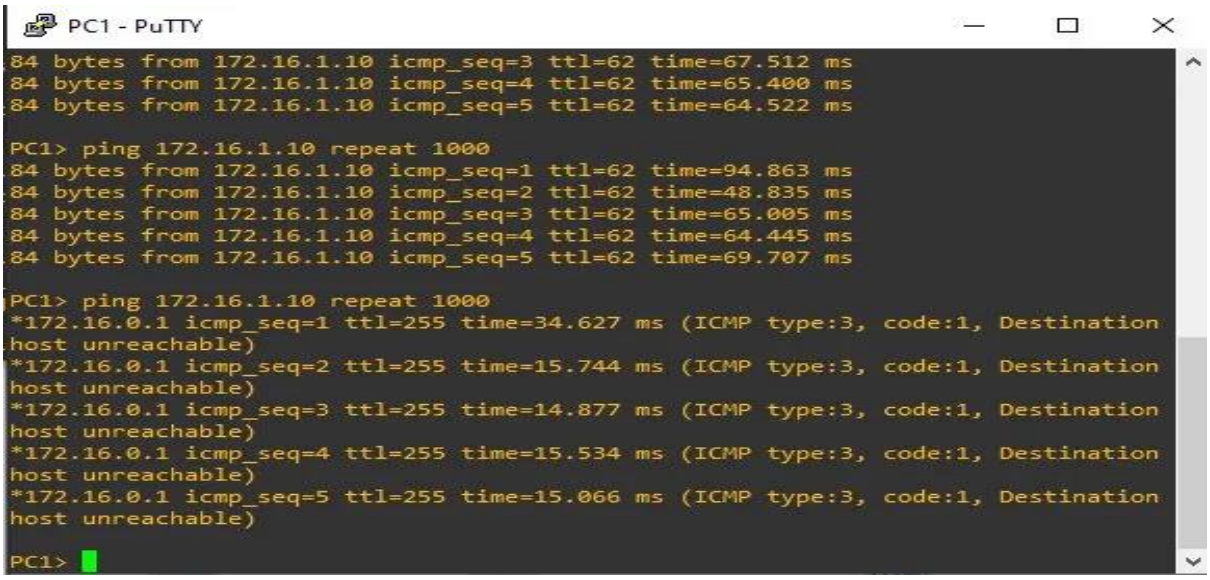


Figure 4.10 Traffic Interruption During Failover Process

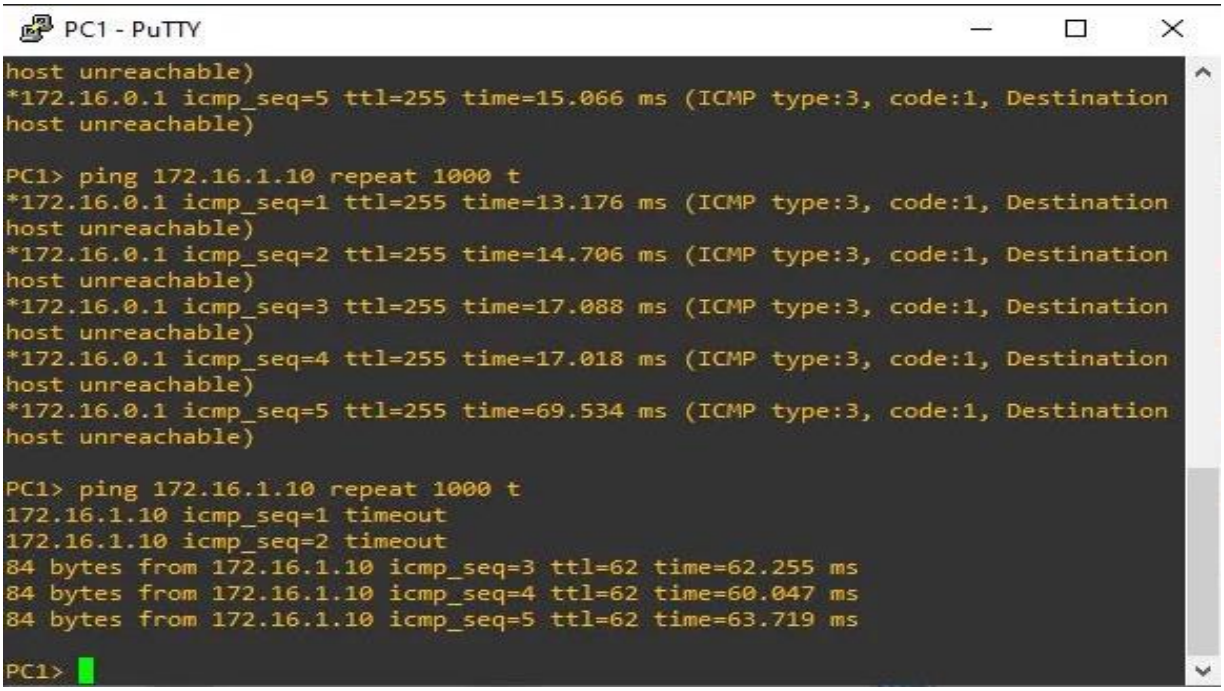


Figure 4.11 Successful Traffic Recovery After Failover

The convergence time observed in this simulation was longer than the sub-second failover times typically achieved by commercial SD-WAN platforms. This limitation resulted from the use of static tunnel-based routing rather than centralised SD-WAN controllers implementing dynamic application-aware path selection policies (Cisco Systems, 2022). The findings are consistent with

Rodrigues et al. (2020), who reported OSPF convergence times ranging between 5 and 15 seconds in GNS3-based WAN simulations.

4.6.3 Wireshark Packet Analysis

Wireshark packet captures were analysed to verify GRE encapsulation behaviour and observe routing protocol activity during normal operation and failover conditions.

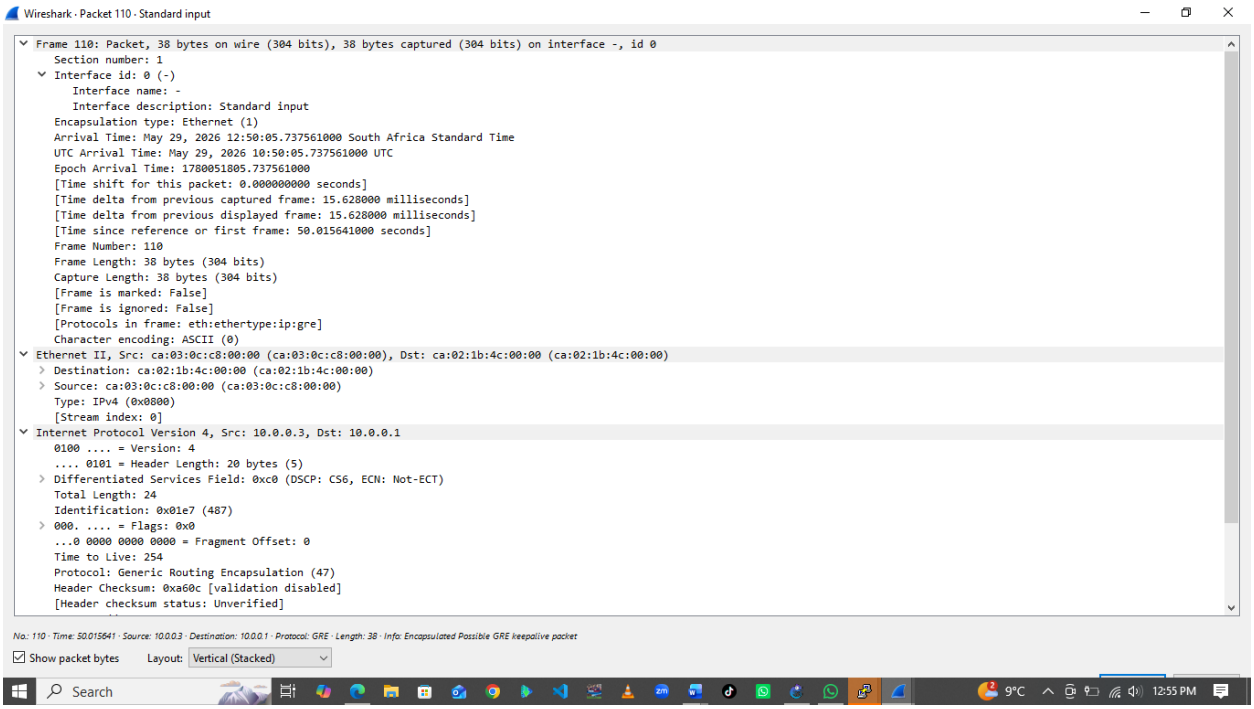


Figure 4.12 Wireshark Capture of GRE Tunnel Traffic

The captures confirmed successful GRE encapsulation across all overlay tunnels. Tunnel statistics showed zero packet corruption, collisions, or retransmission anomalies during normal operation. OSPF hello packets and link-state advertisements were also successfully captured during routing convergence events. The GRE keepalive mechanism enabled efficient tunnel-state monitoring and contributed to rapid transport failure detection during failover testing. These findings support Abdelaziz et al. (2019), who found that GRE tunnelling introduces minimal integrity-related overhead under moderate enterprise traffic conditions.

4.7 Comparative Analysis with Traditional WAN Architectures

The implemented SD-WAN architecture demonstrated several advantages over traditional MPLS-centric WAN environments.

Feature	Traditional WAN	Proposed SD-WAN
Transport Dependency	Single transport	Multiple transport paths
Failover	Manual or slow	Automatic rerouting
Scalability	Limited	Flexible
Cost Efficiency	High MPLS dependence	Hybrid transport utilization
Resiliency	Moderate	Improved through redundancy

Table 4.3: Comparison between Traditional WAN and SD-WAN

Unlike traditional WAN architectures where traffic is locked to a single transport path, the SD-WAN overlay successfully maintained communication across multiple transport networks simultaneously. The ability to utilise broadband and LTE transport as secondary paths significantly improved network resilience while reducing dependency on expensive MPLS infrastructure. These findings align with industry observations indicating that SD-WAN provides improved flexibility, resiliency, and cost efficiency compared to conventional WAN deployments (MEF Forum, 2019).

4.8 Discussion of Findings

The findings of this study demonstrate that SD-WAN architectures can effectively improve enterprise branch connectivity through overlay virtualisation and transport abstraction mechanisms. The implementation validated the theoretical principles of Software-Defined Networking (SDN) discussed in Chapter 2, particularly the concepts of centralised control abstraction, overlay networking, and transport independence (Kreutz et al., 2015).

The study further confirmed that hybrid transport environments combining MPLS, broadband, and LTE connectivity can improve network resiliency while reducing dependence on costly private WAN infrastructure. This finding is particularly relevant in developing economies where MPLS availability and affordability remain significant challenges. The successful implementation of dynamic routing and automatic failover mechanisms demonstrates that SD-WAN technologies can

significantly improve enterprise WAN availability and continuity compared to traditional static WAN architectures.

4.9 Summary

This chapter presented the implementation, testing, and evaluation of the proposed hybrid SD-WAN architecture using the GNS3 simulation environment. The implemented topology successfully established overlay connectivity across heterogeneous transport networks comprising MPLS, broadband internet, and LTE infrastructure. Experimental testing demonstrated successful end-to-end communication, automatic failover capability, and stable overlay operation under normal and failure conditions. MPLS transport consistently delivered lower latency compared to broadband paths, while broadband and LTE links provided effective backup connectivity during failover events. The findings confirmed that SD-WAN architectures provide improved resiliency, flexibility, and transport independence compared to traditional WAN environments. The following chapter presents the conclusions, recommendations, limitations, and areas for future research arising from this study.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter presents the conclusions drawn from the study on the design and simulation of a hybrid Software-Defined Wide Area Network (SD-WAN) architecture for multi-branch organisational connectivity. The conclusions are based on the findings and analysis presented in Chapter 4 and are aligned with the research objectives outlined in Chapter 1.

The chapter further provides recommendations for enterprise WAN implementation, policy considerations, and future research directions. In addition, the limitations encountered during the study are discussed to provide context regarding the scope and applicability of the findings.

5.2 Summary of the Study

The purpose of this study was to design, simulate, and evaluate a hybrid SD-WAN architecture capable of improving enterprise branch connectivity, resiliency, scalability, and failover performance within heterogeneous transport environments. The study was motivated by the limitations associated with traditional WAN architectures, particularly MPLS-only deployments, which are often characterised by high operational costs, limited flexibility, poor scalability, and slow failover capabilities.

The study adopted a quantitative simulation-based experimental research methodology implemented using Graphical Network Simulator 3 (GNS3). The proposed architecture consisted of one Head Office and three branch offices interconnected using multiple transport technologies including MPLS, broadband internet, and LTE backup connectivity. Generic Routing Encapsulation (GRE) tunnels were used to establish the SD-WAN overlay network, while Open Shortest Path First (OSPF) routing provided dynamic route propagation and failover capability.

Performance evaluation focused on key network metrics including latency, throughput, jitter, packet loss, and failover recovery time under three operational scenarios:

i. normal network operation,
ii. link failure and failover testing,
iii. congestion and load testing.

The study further utilised Wireshark packet analysis to verify GRE encapsulation, routing convergence behaviour, and traffic rerouting during failover events.

5.3 Conclusions Based on Research Objectives

5.3.1 Objective I: To Examine the Limitations of Traditional WAN Architectures

The study established that traditional WAN architectures relying primarily on MPLS infrastructure present several operational and financial limitations. The findings confirmed that MPLS-only environments offer reliable performance but are expensive to deploy and maintain, particularly for organisations operating across geographically dispersed branch locations.

The study further demonstrated that traditional WAN environments exhibit limited flexibility because traffic forwarding is typically dependent on static transport paths. This dependency reduces the ability of organisations to adapt dynamically to changing network conditions and transport failures. The findings support previous literature reviewed in Chapter 2, including Gartner (2021) and Huston (2022), which identified high operational costs, poor scalability, and rigid traffic engineering as major limitations of conventional WAN architectures.

5.3.2 Objective II: To Understand the Principles and Architecture of SD-WAN

The study successfully demonstrated the practical implementation of SD-WAN concepts including overlay networking, transport abstraction, dynamic routing, and transport redundancy.

The architecture implemented in GNS3 showed that SD-WAN enables the separation of logical network communication from physical transport infrastructure through the use of GRE tunnels operating across heterogeneous underlay networks. This abstraction allows enterprise traffic to continue flowing even when one transport path becomes unavailable.

The implementation validated the theoretical foundations of Software-Defined Networking (SDN) discussed in Chapter 2, particularly the concepts of network programmability, overlay virtualisation, and centralised policy-driven traffic management (McKeown et al., 2008; Kreutz et al., 2015).

5.3.3 Objective III: To Evaluate SD-WAN Performance Metrics

The study evaluated several network performance metrics under different operating conditions.

Latency measurements indicated that MPLS paths consistently delivered lower and more stable round-trip times compared to broadband and LTE transport links. However, broadband paths still provided acceptable performance for general enterprise communication requirements.

Throughput testing demonstrated that the SD-WAN architecture successfully supported data communication across all transport paths. Although broadband and LTE paths exhibited greater variability under congestion conditions, the architecture maintained overall communication continuity.

Packet loss remained within acceptable thresholds during normal operation, while jitter measurements confirmed that MPLS paths offered superior consistency for latency-sensitive applications such as VoIP and video conferencing.

These findings confirm that hybrid SD-WAN architectures can successfully balance performance optimisation and transport diversity in enterprise WAN environments.

5.3.4 Objective IV: To Evaluate Failover and Redundancy Mechanisms

The study demonstrated that the proposed SD-WAN architecture provided effective failover and redundancy capability through dynamic routing and multiple transport availability.

When transport failures were introduced into the network environment, OSPF reconvergence mechanisms automatically redirected traffic through alternative transport paths. This behaviour significantly improved network resiliency compared to traditional static WAN architectures. Branch 2 successfully failed over from MPLS connectivity to broadband internet following

simulated MPLS failure. Similarly, Branch 3 successfully transitioned from broadband connectivity to LTE backup transport during broadband failure scenarios.

The findings demonstrated that SD-WAN architectures improve enterprise business continuity by reducing dependency on single transport technologies. These results align with Rodrigues et al. (2020), who found that SD-WAN overlay architectures significantly improve failover performance and network resiliency.

5.3.5 Objective V: To Design and Simulate a Hybrid SD-WAN Topology Using GNS3

The study successfully designed and implemented a functional hybrid SD-WAN topology using GNS3 and Cisco IOS router images.

The simulation environment accurately represented a realistic enterprise WAN deployment comprising:

i. MPLS transport,
ii. broadband internet connectivity,
iii. LTE backup connectivity,
iv. GRE overlay tunnels,
v. OSPF dynamic routing.

The successful implementation confirmed that GNS3 provides a reliable and cost-effective platform for SD-WAN research and experimentation. The study further demonstrated that realistic WAN behaviour can be emulated effectively using software-based simulation tools without requiring expensive physical networking hardware.

5.4 Overall Conclusion of the Study

Overall, the study concludes that hybrid SD-WAN architectures significantly improve enterprise WAN flexibility, resiliency, and transport efficiency compared to traditional MPLS-centric WAN environments. The implementation demonstrated that SD-WAN overlay technologies allow

organisations to combine multiple transport types into a unified logical network infrastructure capable of maintaining communication continuity during transport failures.

The study further concludes that SD-WAN technologies are particularly suitable for developing economies such as Zimbabwe, where MPLS infrastructure may be costly, unavailable, or unreliable in certain geographic locations. The ability to integrate broadband and LTE transport into enterprise WAN architectures provides organisations with greater scalability and operational flexibility while reducing dependency on expensive dedicated circuits.

Although the simulated architecture does not fully replicate the advanced automation and centralised orchestration capabilities present in commercial SD-WAN platforms, the study successfully demonstrates the foundational principles and operational benefits of SD-WAN networking.

5.5 Recommendations

Based on the findings of the study, the following recommendations are proposed:

5.5.1 Recommendations for Organisations

Organisations operating multi-branch enterprise networks should consider adopting hybrid SD-WAN architectures to improve network resiliency and reduce dependence on expensive MPLS connectivity. Enterprises should deploy multiple transport paths, including broadband and LTE backup connectivity, to improve redundancy and ensure business continuity during transport outages.

5.5.2 Recommendations for Network Administrators

Network administrators should implement dynamic routing protocols such as OSPF or EIGRP within SD-WAN overlay environments to improve routing convergence and automatic failover performance.

Administrators should further implement continuous network monitoring using tools such as:

i. Wireshark,

ii. IP SLA,
iii. SNMP,

NetFlow, to improve visibility into WAN performance and transport health.

5.5.3 Recommendations for Academic Institutions

Universities and research institutions should incorporate SD-WAN simulation and virtualised network experimentation into networking and cybersecurity curricula. GNS3 and similar simulation platforms provide cost-effective environments for practical enterprise networking research and training.

5.5.4 Recommendations for Internet Service Providers and Policymakers

Telecommunications regulators and service providers should continue investing in broadband infrastructure expansion to support modern enterprise networking requirements. Affordable broadband connectivity would significantly improve SD-WAN adoption among organisations in developing economies where MPLS infrastructure remains financially restrictive

5.6 Areas for Future Research

Future research may extend this study in several ways.

Future studies may implement centralised SD-WAN controllers and orchestration platforms such as Cisco SD-WAN (Viptela), VMware SD-WAN, or Fortinet Secure SD-WAN.

Researchers may evaluate the impact of IPsec encryption on SD-WAN latency and throughput performance. Further studies may investigate Artificial Intelligence (AI)-driven traffic engineering and automated path selection within SD-WAN environments.

Larger-scale simulations involving additional branch sites and cloud-based applications may be conducted to evaluate scalability and cloud optimisation performance. Future research may also investigate SD-WAN security vulnerabilities, zero-trust architectures, and cybersecurity integration within enterprise WAN environments.

5.7 Summary

This chapter presented the conclusions and recommendations arising from the study on the design and simulation of a hybrid SD-WAN architecture for enterprise multi-branch connectivity. The study demonstrated that SD-WAN technologies significantly improve network flexibility, resiliency, and transport independence through overlay virtualisation and dynamic routing mechanisms. The simulated architecture successfully maintained communication continuity during transport failures while supporting multiple heterogeneous transport technologies including MPLS, broadband internet, and LTE backup connectivity. The findings confirmed that SD-WAN provides a practical and scalable solution for modern enterprise WAN environments, particularly within developing economies characterised by transport diversity and infrastructure limitations. The study further established that GNS3 provides a reliable and cost-effective platform for SD-WAN experimentation and academic research. Recommendations for organisations, network administrators, academic institutions, and policymakers were provided together with suggestions for future research directions.

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