Research Project
Security Analysis of Software Systems

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Abstract

Software-defined networking (SDN) is a promising paradigm shift in network architecture, offering improved flexibility, programmability, and management. However, as SDN becomes more prevalent, it also introduces new security challenges. This research project aims to investigate and analyze the security aspects of SDN, focusing on potential threats, vulnerabilities, and mitigation strategies. We will conduct a comprehensive literature review to understand the current state of SDN security research and identify gaps in the existing body of knowledge. Our research questions will explore the unique security challenges introduced by SDN, the effectiveness of current security mechanisms, and potential solutions to address identified vulnerabilities. The proposed research will employ a mixed-methods approach, combining qualitative and quantitative methods, to gain a comprehensive understanding of SDN security. Through our findings, we aim to contribute to the development of more secure SDN architectures and provide recommendations for improving the security of SDN deployments. This study is essential for ensuring the safe and secure adoption of SDN in various networking environments.

SDN (Software Defined Networking) is an architecture that aims to improve the control of networks and flexibility. It is mainly connected with open flow protocol and ODIN V2 for wireless communication. Its architecture is central, agile, and programmatically configured. This paper presents a security analysis that enforces the protection of GUI by requiring authentication, SSL/TLS integration, and logging/security audit services. The role-based authorization FortNOX and ciphers like AES and DES will be used for the encryption of data and for improving the security of the SDN environment. These techniques are useful for enhancing the security framework of the controller. Microsoft is developing widespread software solutions like the Windows operating system and Office suite. To improve the security of their products, they have introduced the Microsoft Security Development Lifecycle (MS-SDL). Ample documentation about the MS-SDL is available, thus allowing other companies to adopt the lifecycle as well. We were wondering whether adoption of the lifecycle is possible and useful for real small development teams, e.g., for a single developing person. To find out, we have done a practical test, i.e., we have used the MS-SDL for the development of a small, but real-world software project.

Acknowledgments

I would like to express my sincere gratitude to the individuals who have played a significant role in the completion of this assignment. Their support, encouragement, and valuable insights have greatly contributed to the success of this project.

First and foremost, I extend my heartfelt thanks to Ms. Ann, our Lecturer, for their guidance and unwavering support throughout the research and writing process. Their expertise, patience, and constructive feedback have been instrumental in shaping the content and structure of this assignment. I am also indebted to you for adding a unique perspective to my work and enriching the overall quality of the assignment.

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In conclusion, I am deeply grateful to all those who have contributed to the realization of this assignment. Their support has been invaluable, and I appreciate the collaborative spirit that has made this project possible.

Thank You.

Executive Summary

SD-WAN (Software-Defined Wide Area Network) is a rapidly evolving technology that has transformed the way organizations design, deploy, and manage their network infrastructure. SD-WAN provides increased flexibility, improved performance, and reduced costs compared to traditional WAN solutions, making it an attractive choice for organizations seeking to support their digital transformation initiatives. However, as organizations adopt SD-WAN, it is essential to evaluate and ensure the security of these networks. A comprehensive security evaluation of SD-WAN solutions should assess various aspects, such as user authentication mechanisms, data encryption, network management interfaces, and overall vulnerability assessment.

This report presents the results of a thorough security evaluation of SD-WAN solutions, covering key areas such as user authentication, data encryption, and network management interfaces. The evaluation process involved data collection, experimental setups, vulnerability analysis, and assessment of vendor-provided information.

The findings of the security evaluation highlight the strengths and weaknesses of SD-WAN security, providing valuable insights for organizations considering the adoption of SD-WAN technology. The results help organizations identify potential security risks and prioritize remediation efforts to enhance the security of their SD-WAN deployments.

In summary, a comprehensive security evaluation is crucial for organizations to ensure the security of their SD-WAN networks and maintain the confidentiality, integrity, and availability of their critical data assets. By leveraging the insights from this evaluation, organizations can make informed decisions about SD-WAN adoption, deployment, and management, ultimately supporting their digital transformation initiatives and achieving their business objectives.

List of Figures

List Of Table

Chapter 01

01. Introduction

Enterprise networks form the backbone of everyday communication, connecting computers and other devices across various company branches, including data centers. Enterprise networks are essential for modern organizations, allowing secure data sharing across various networks such as WAN and LAN. In the past, point-to-point leased lines using dedicated DS0, T1/E1, or T3/E3 connections were the primary means of establishing enterprise networks. However, in the 1990s, frame relay services became a popular alternative due to their lower cost and reduced physical connections. This technology was widely adopted by various enterprises, including banks.

Multiprotocol Label Switching (MPLS) emerged as the successor to frame relay services, offering an An IP-based solution utilizing the existing telecom network infrastructure. This made MPLS an attractive option for telecom service providers, who favored it over frame relay services. For instance, Sonera, a prominent telecom operator in Finland, currently offers an MPLS-based solution called Sonera Data Net, which has achieved market leadership in Finland.

Despite being widely adopted, MPLS has several limitations, including high cost and low bandwidth compared to public internet. The emergence of technologies like IPsec VPN has enabled secure data sharing over the public internet, prompting enterprises to seek alternative solutions. Additionally, service providers face challenges in offering MPLS to enterprises that increasingly rely on public clouds for infrastructure. Connecting enterprise branch sites to third-party data center-operated public clouds poses difficulties for MPLS.

As a result, there's a growing need for both enterprises and service providers to explore new solutions. Software Defined Wide Area Network (SD-WAN) has emerged as a next-generation enterprise networking solution, addressing the aforementioned issues. SD-WAN is an internet and SDN-based, cloud-networking service offered to enterprises. It simplifies the configuration and management of enterprise networks by virtualizing networking services.

The introduction of new technologies raises concerns about their security models and the robustness of product implementations. SD-WAN is often proposed as a replacement for the long-standing and relatively secure MPLS, which has been in use for over 16 years despite facing targeted attacks. Thus, it's crucial to thoroughly analyze the security of SD-WAN architecture and products before their widespread adoption.

This thesis focuses on studying the security model of SD-WAN through an in-depth analysis of a commercial SD-WAN product called Nuage VNS, offered by Nuage Networks. Following a responsible disclosure process, all discovered vulnerabilities were reported to Nuage Networks. The vendor's constructive response and commitment to addressing the issues are encouraging. This research was conducted at Sonera, Finland, as part of the Business Defined Networking team, which provides SD-WAN solutions to Finnish enterprises.

1.1 Background

This chapter provides a historical perspective on enterprise networking, highlighting existing solutions and their limitations. We delve into the evolution of networking technologies and discuss the challenges faced by traditional solutions like MPLS. The emergence of SD-WAN as an alternative to MPLS is explored, along with its benefits for enterprise networking. We emphasize the importance of thoroughly analyzing the security of SD-WAN solutions before their widespread adoption. Finally, we briefly overview the literature used as a reference for conducting the analysis.

The discussion includes the evolution of enterprise networking, from early solutions like point-to-point leased lines and frame relay services, to the current era of SD-WAN. The limitations of MPLS, such as high cost and low bandwidth compared to public internet, are examined. The thesis also addresses the difficulties faced by service providers in offering MPLS to enterprises that increasingly rely on public clouds for their infrastructure.

Moreover, the chapter highlights the advantages of SD-WAN as a modern enterprise networking solution. SD-WAN's capability to simplify the configuration and management of enterprise networks by Virtualizing networking services is discussed. We explore how SD-WAN addresses the challenges faced by traditional solutions and the necessity of conducting a thorough security analysis of SD-WAN solutions to ensure their robustness and reliability.

Finally, the literature review section provides an overview of the references used in the analysis, covering a range of sources that discuss the evolution of enterprise networking, the rise of SD-WAN, and the importance of security analysis in adopting new networking technologies.

Enterprise networks are private networks designed to connect an organization's branches securely, enabling the sharing of computer resources across various locations, such as company sites, stores, headquarters, and cloud data centers. These networks form a communication backbone, integrating all computers, mobile devices, and other associated equipment within the organization. This facilitates seamless interoperability and efficient data management across the enterprise.

Enterprise networks can encompass both local area networks (LANs) and wide area networks (WANs), as shown in the diagram depicting a simple enterprise network with its headquarters, branches, and data center connected. Historically, enterprise networks utilized telecom networks originally designed for voice communication, employing low-bandwidth modems to transmit data.

With the advent of digitization and the increasing use of the public internet in the 1990s, enterprises began adopting virtual private networks (VPNs) that leveraged existing public infrastructure while incorporating encryption to safeguard data traffic from unauthorized access. Initially, VPNs relied on frame relay services to establish private networks, but this was later supplanted by the widely adopted MPLS protocol, which continues to be the standard for modern enterprise networks.

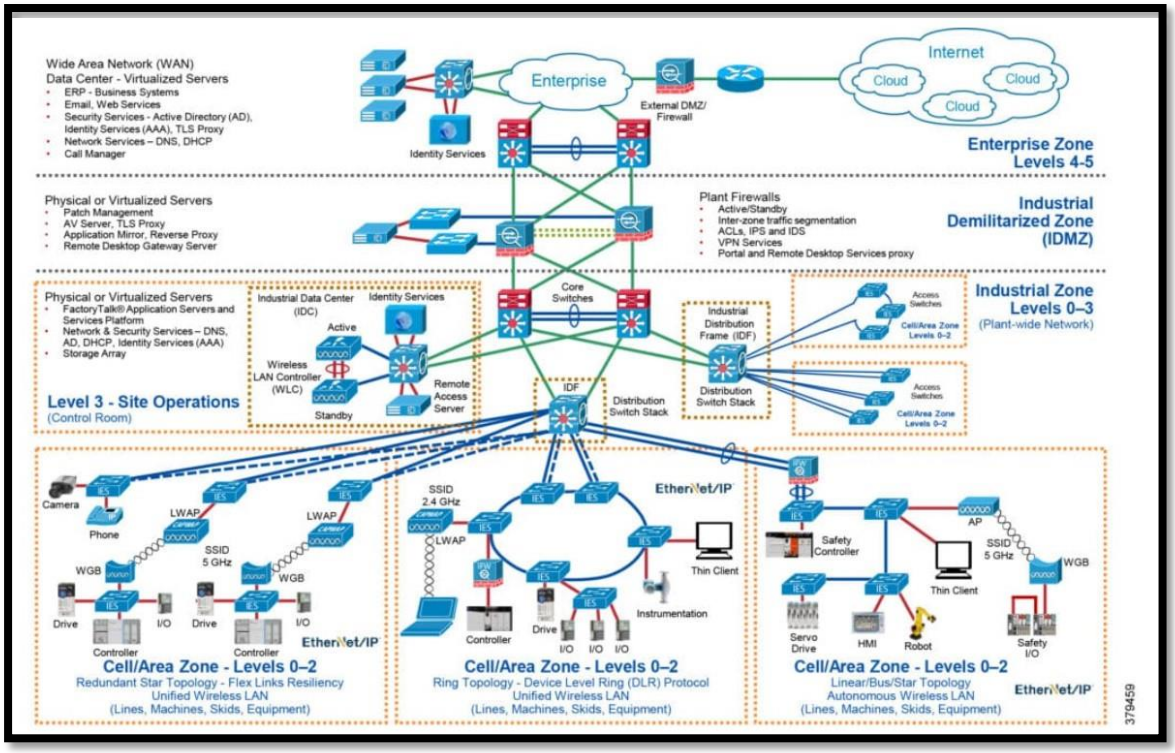

Figure 1: Enterprise Network

From the mid-2000s, enterprise networks began adopting the MPLS (Multiprotocol Label Switching) protocol for their private networks. MPLS enhances data speed and overall network performance. In traditional networking, routers determine the path for data packets based on the information contained in the network layer header of each packet. This process involves analyzing the IP header to decide the next hop for the packet, operating at layer 3 of the network.

With MPLS, the routing decision is made based on pre-assigned labels rather than the IP header. These labels are added to data packets by the ingress router as they are forwarded into the operator's network. MPLS-enabled routers quickly process packets by examining the labels and forwarding them to the next router according to predetermined rules. This label-based forwarding mechanism eliminates the need for

time-consuming analysis of the IP header at each hop. The MPLS header, which contains the labels, is added in front of the IP header.

A sample MPLS network, showcasing customer edge routers, illustrates how the protocol optimizes data flow and enhances network performance. This example demonstrates the efficiency and versatility of MPLS in enterprise networking scenarios, improving overall connectivity and communication within the organization. The origins of MPLS trace back to Ipsilon Networks' proposal of a flow management protocol, which operated solely over Asynchronous Transfer Mode (ATM). Later, Cisco introduced tag switching, a more versatile approach that wasn't restricted to ATM alone. Cisco eventually renamed it to label switching and presented it to the Internet Engineering Task Force (IETF) for standardization. With contributions from various vendors, MPLS evolved to support multiple networking protocols like T1/E1, ATM, Frame Relay, and DSL. Due to its compatibility with various protocols, it was named multiprotocol switching (MPLS).

MPLS offers numerous advantages compared to per-packet routing, including high-speed data transmission, scalability, and the ability to function over various underlying protocols. These factors have led to the widespread adoption of MPLS-based solutions in enterprise networks. Service providers, such as Sonera in Finland, offer MPLS-based solutions like Data Net to their customers. Sonera's data net is a market-leading example of an MPLS-based service in Finland, showcasing the protocol's reliability and effectiveness in enterprise networking environments.

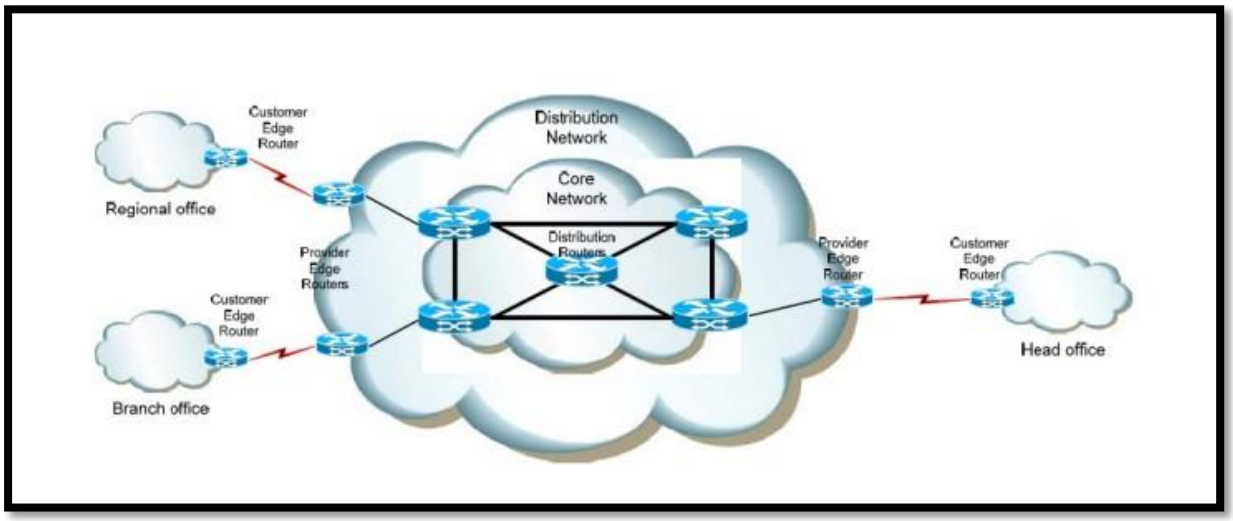

Figure 2: MPLS Network

The text discusses the evolution of network services, highlighting the replacement of Frame Relay service by MPLS in the early 2000s. MPLS was developed as an IP-based solution that leverages telecommunications network infrastructure and is preferred by network service providers over Frame

Relay. However, MPLS has its own limitations in terms of cost and capacity, making it expensive compared to the open internet and having limited bandwidth.

The development of technologies like IPsec VPN has enabled secure sharing of business data over the internet, leading organizations to seek alternatives to MPLS. Moreover, the shift towards public clouds for business infrastructure has made it challenging for MPLS to connect enterprise branch locations to external data centers housing these public clouds. This shift has resulted in a decline in MPLS-related revenue for network service providers.

In light of these changes, both enterprises and service providers are faced with the need to find a new solution. This situation presents opportunities for research and innovation in network services, focusing on developing cost-effective and scalable solutions that can effectively connect enterprise locations with public clouds and support the evolving business needs. Potential areas of research could include the development of new network architectures, optimization of existing technologies, and exploring synergies between different network services to create hybrid solutions.

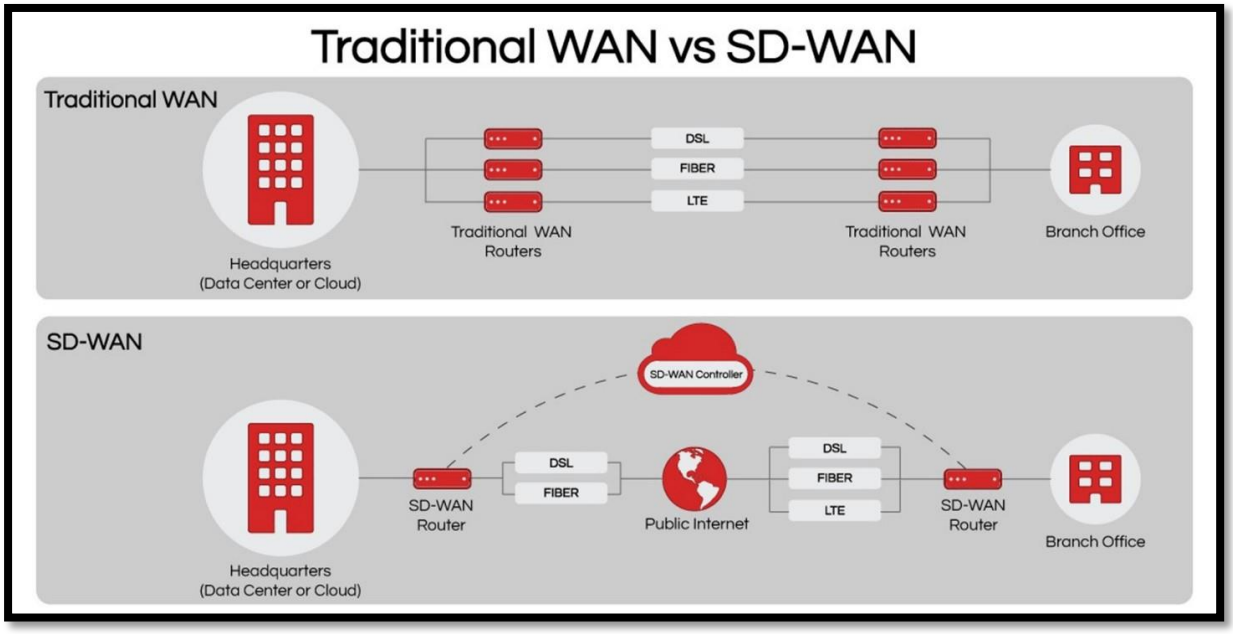

Figure 3: Traditional WAN vs. SD-WAN

The text discusses the background and development of SD-WAN technology, which emerged in response to the increasing demand for agility, flexibility, and scalability in wide-area networks (WANs). SD-WAN is derived from Software-Defined Networks (SDN) and employs a methodology based on software drivers and API, allowing communication with physical hardware infrastructure, and facilitating administration and device setup.

SDN offers an API for configuration and decouples software logic from hardware, enabling the optimization and virtualization of network services. This Internet-based technology allows for flexible management, simplifies usual configuration complexities, and supports scalability. Figure 3 illustrates the three layers of SD-WAN architecture, showcasing its components and interactions.

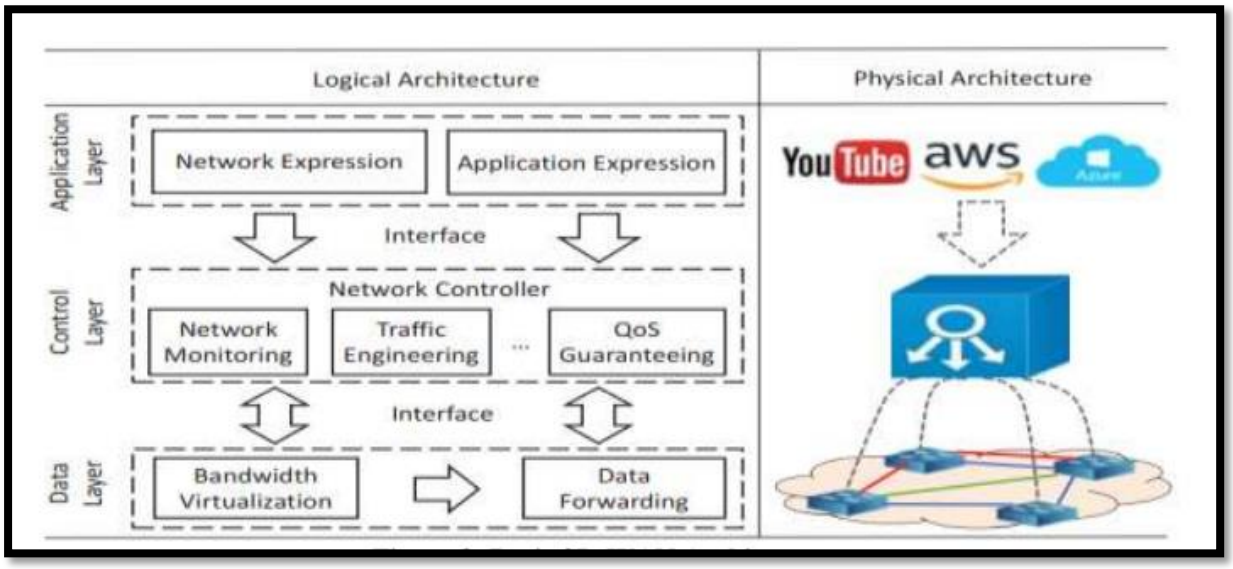

Figure 4: Basic SD-WAN Architecture

The text provides a detailed explanation of the three layers of SD-WAN architecture: the control layer, data layer, and application layer. It highlights the role of each layer in managing network activities, bandwidth, and data forwarding, as well as offering services to developers and Internet service providers. The text also discusses the communication interfaces between the layers, including Northbound Interfaces (NBI) and Southbound Interfaces (SBI). According to Gartner's prediction, the adoption of SD-WAN is expected to increase significantly, with 60% of businesses using SD-WAN by 2024, up from less than 20% in 2019. This growth is driven by the improved agility and support for cloud applications offered by SD-WAN. However, the increased adaptability of SD-WAN also makes it a more attractive target for cybercriminals, necessitating effective security measures.

The text discusses various security measures implemented in SD-WAN, such as Deep Packet Inspection (DPI), firewalls, and VPN, but also acknowledges that some remedies may be outdated or ineffective in open-source SD-WAN. It highlights the risks associated with TCP attacks like Man-in-the-Middle (MitM) and data leakage due to exposed TCP/UDP ports. Table 1 lists common types of security breaches or flaws in SD-WAN.

Table 01: Common Types of SD-WAN Security Breaches or Flaws

No	Types Of Security Breaches or Flaws	Details
1	Unauthorized Access	Unauthorized access occurs when an attacker gains unauthorized entry into the SD-WAN network or devices. This can happen due to weak or compromised passwords, insecure remote access configurations, or insufficient access controls. Once inside, the attacker can exploit the network and potentially gain access to sensitive data or launch further attacks
2	Malware and Ransomware Attacks	Malware and ransomware attacks involve introducing malicious software into the SD-WAN infrastructure. This can happen through phishing emails, infected software updates, or compromised websites. Once the malware infiltrates the network, it can spread, disrupt operations, steal data, or demand ransom.
3	Data Breaches	Data breaches involve unauthorized access or disclosure of sensitive or confidential information. This can occur due to inadequate encryption mechanisms, weak data protection practices, or vulnerabilities in the SD-WAN infrastructure. Data breaches can have severe consequences, including financial loss, reputational damage, and legal liabilities
4	Denial-of-Service (DoS) Attacks	DoS attacks aim to overwhelm or disable the SDWAN network or specific devices by flooding them with excessive traffic or resource requests. This results in a loss of network availability, making it difficult for legitimate users to access resources and disrupting critical business operations.
5	Configuration and Management Vulnerabilities	Misconfigurations in SD-WAN devices or management interfaces can introduce security vulnerabilities. These misconfigurations allow attackers to bypass security controls, gain unauthorized access, or manipulate the network infrastructure. Common misconfigurations include weak access controls, default or outdated configurations, and improper segmentation.
6	Insider Threats	Insider threats involve employees or individuals with authorized access misusing their privileges to exploit the SD-WAN network. This can include data theft, unauthorized access to sensitive information, or

		intentional sabotage. Insider threats can be challenging to detect and mitigate since the individuals involved already have legitimate access to the network.
7	Lack of Encryption	Insufficient or improper encryption practices can expose sensitive data transmitted across the SD-WAN network to interception or unauthorized access. Data can be vulnerable to eavesdropping, interception, and tampering without proper encryption mechanisms.

Organizations need to be aware of these common security breaches and implement appropriate security measures, such as strong access controls, regular security assessment encryption, and employee awareness training, to mitigate the risks associated with SD-WAN deployments.

1.1.1 Security Architecture

Unlike a software system's functional requirements, which describe what the software should do, security requirements describe non-functional constraints on what the system should not do. A security architecture illustrates how security requirements are enforced in a software system. Specifically, a security architecture describes how security mechanisms are positioned among the design artifacts of a software system to control attributes such as confidentiality, integrity, accountability, and assurance.

A security architecture features a set of architectural design diagrams that show the subsystems, the communication links between the subsystems, and the position of the security mechanisms. The subsystems may be, for example, web servers, application servers, database management systems, directories, web applications, and legacy applications. The edges that connect the subsystem nodes indicate how the subsystems communicate using, for example, local or remote function calls and protocols such as TLS, SSL, HTTPS, and LDAP. The security mechanisms are often specified as annotations on the subsystems and communication links to indicate, for example, authentication points, authorization points, application administration, encryption methods, audit, logging, monitoring, intrusion detection, registration, as well as backup and recovery.

Many security vulnerabilities arise from poorly designed security architectures, for example, unauthorized access to data and applications, as well as confidential and restricted data flowing as unencrypted text over network connections.

Figure 1 shows an example of security architecture. The rectangles represent a variety of clients and servers, and the edges represent communications between them. The directory maintains information about each user of the system such as: username, password, and group membership. The application server (right side of Figure 1) contains the resources provided by the system such as web pages and

application functions. The web server (left side of Figure 1) acts as a proxy for accessing applications. The policy server (bottom of Figure 1) maps the resources of the application to the roles that are authorized to access each resource. For example, an application may only be accessible to users who belong to the group of managers. The policies are specified by a policy administrator via a client application. The policy server specifies but does not enforce, the policies. Policy enforcement is the responsibility of the authorization server, which has a copy of the policy data and allows or denies access requests at run time. This particular design reflects a performance optimization decision, as the architecture could have alternatively featured a single authorization server that was shared by all other servers and accessed via a remote, rather than a local, function call.

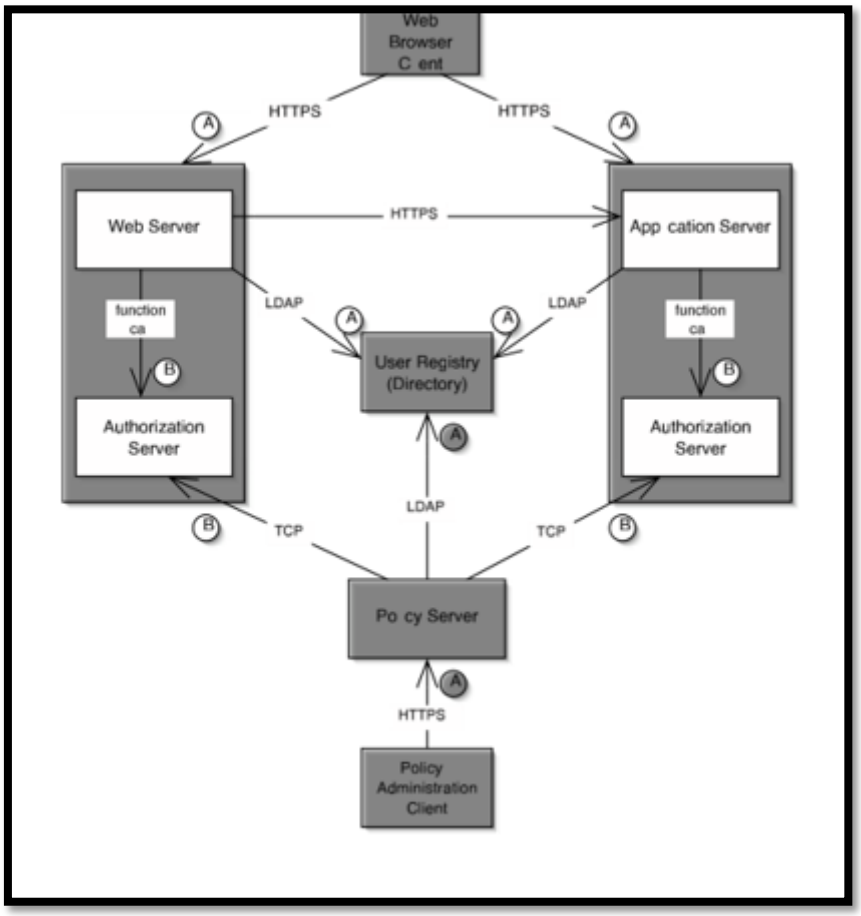

Figure 5: Security Architecture

The end user employs a web browser (top of Figure 1) to access an application via one of two options. The first option involves the end user's browser contacting the web server via the HTTPS protocol. The web server authenticates the user by matching the username and password against the directory server. The points in the architecture that are involved in the authentication process are indicated by a small circle labeled with an 'A'. If the authentication is successful, the web server calls the authorization server

to ensure that the user is authorized to access the application. The points in the architecture that are involved in any authorization processes are indicated by a small circle labeled with a ‘B’.

The second option to access an application involves the end user’s browser contacting the application server directly. Like the first option, the user is first authenticated and subsequently authorized by the user registry and the server’s local authorization server, respectively.

A security architecture is validated using a process called threat modeling. Threat modeling is typically a manual (i.e., not automated) inspection process, similar to code and requirements inspection. The process involves a security review team and, possibly, members of the software testing team. The goal of this process is to assess the overenforcement is the responsibility of the authorization server, which has a copy of the policy data and allows or denies access requests at run time. This design reflects a performance optimization decision, as the architecture could have alternatively featured a single authorization server that was shared by all other servers and accessed via a remote, rather than a local, function call.

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A security architecture is validated using a process called threat modelling. Threat modelling is typically a manual (i.e., not automated) inspection process, similar to code and requirements inspection. The process involves a security review team and, possibly, members of the software testing team. The goal of this process is to assess the vulnerability of each feature of the software system to security attacks. The threat model [36] identifies assets such as credit card numbers, social security numbers, computing resources, trade secrets, and financial data. The model also identifies and documents threats (e.g., unauthorized access or alteration of assets), as well as ranks each threat according to a scale (e.g., low, medium, high).

The threat identification process is used to determine, for example, whether data can be viewed or changed, who can access the data, and what is deemed as unauthorized access of a system. The threat documentation describes each type of threat and lists counter measures to prevent an attack. Each threat is ranked according to its damage potential (e.g., data, financial loss, property loss or damage), reproducibility of the attack (i.e., the probability that an attempt to compromise the security of a system will succeed), exploitability or discoverability of a threat (e.g., how difficult is it to break into the system), and, finally, who are the affected users (e.g., number of users affected, relative importance of users). Each threat also has a description of threat mitigation factors such as security mechanisms and processes.

An additional aspect of threat identification relates to software configuration management. Although an application or a server, for example, may presently be trustworthy, an exploit in this software may be found in the future. Typically a CERT (Computer Emergency Response Team) advisory, or some other vulnerability knowledge dissemination medium, is used to publicize the exploit so that users and system administrators can upgrade to a new version of the software that mitigates the exploit. However, a new exploit may escape the attention of a user or system administrator, leaving the system vulnerable to a security attack. It is common for security attackers to read the CERT advisories and target systems that run outdated software. In several cases a system may depend on software with or without the knowledge of the user. Since many software packages, especially open-source software, have no commercial

support, users of the software are responsible for applying security patches and for monitoring their software inventory.

For example, it has been demonstrated that an unpatched iPhone is vulnerable to the libtiff exploit. Fortunately, this exploit has been patched by the Apple 1.1.2 update, but it serves as an example of the danger of unpatched software, especially on a popular device such as the iPhone. Libtiff is a package of functions used to change and view TIFF (Tagged Image File Format) files. A number of vulnerabilities, including buffer overflows, described later, have been reported in libtiff. An attacker could create a malicious file that, if opened by a user, would crash the application that is used to open the file.

A worse scenario would involve the exploiting of a security vulnerability to gain root access to the operating system of the device. This type of access can enable attackers to install and execute arbitrary code on the device, including, for example, an application that can be used to record conversations on an exploited iPhone. Buffer-overflow vulnerabilities, such as the one just mentioned, is one of the subjects of the following section.

1.2 Aims of The Project

The primary aim of this project is to investigate and analyze the security aspects of MPLS and SD-WAN networks, which are widely used in enterprise networking. The specific objectives of the project are as follows:

1. To conduct a comprehensive review of existing literature and current research on MPLS and SD-WAN network security, including potential vulnerabilities, threat landscapes, and mitigation strategies.
2. To identify the unique security challenges associated with MPLS and SD-WAN networks, considering the differences between their architectural designs and deployment scenarios.
3. To assess the effectiveness of current security mechanisms and solutions in addressing the identified vulnerabilities and challenges in MPLS and SD-WAN networks.
4. To develop and propose novel security strategies, architectures, or frameworks that address the identified security gaps in MPLS and SD-WAN networks.
5. To conduct simulations or experiments, as appropriate, to validate the proposed security solutions and their effectiveness in enhancing the overall security posture of MPLS and SD-WAN networks.
6. To disseminate the project's findings and recommendations to the relevant stakeholders, including network operators, service providers, and the research community, to contribute to the development of more secure MPLS and SD-WAN networks.

By achieving these aims, the project aims to enhance the security of enterprise networks that rely on MPLS and SD-WAN technologies contribute to the overall safety and robustness of the digital infrastructure.

1.3 Academic Questions & Objectives

The advent of Software Defined-Wide Area Network (SD-WAN) technology has brought about numerous benefits, including increased agility, flexibility, and scalability in network services. SD-WAN optimizes application performance, balances network traffic, and secures network communications. The management of objects within the SD-WAN architecture is achieved through network protocols like Secure Socket Shell (SSH), Hypertext Transfer Protocol (HTTP), and Transport Layer Security (TLS), which are often accessed via web administration interfaces.

However, these interfaces are not immune to vulnerabilities, raising questions about the effectiveness and capabilities of security features offered by SD-WAN vendors. There is a need to evaluate and compare the reliability and security aspects of various SD-WAN solutions to address this knowledge gap. This study aims to compare the security features of three popular SD-WAN brands: Palo Alto, Aruba, and Cisco Viptela, in different network security scenarios.

The research will highlight the limitations, challenges, and opportunities associated with these products in various security environments. Any vulnerabilities discovered during the study will be responsibly disclosed and reported to the respective vendors. The assessment will focus on the strengths and weaknesses of these solutions, as well as the effectiveness and performance of their intrusion detection, malware detection, and security analytics capabilities.

By comparing the security features of these SD-WAN brands, this work aims to provide insights into the importance of evaluating and deploying these technologies securely. A simulated environment will be used as part of the study methodology to test and evaluate the security aspects of the selected SD-WAN solutions. What are the unique security challenges and potential vulnerabilities associated with Software Defined-Wide Area Network (SD-WAN) deployments, and how can they be effectively mitigated?

1. To conduct a thorough review of SD-WAN architecture, technologies, and protocols to understand their security implications.
2. To identify and analyze potential security vulnerabilities and threats specific to SD-WAN deployments.
3. To assess the effectiveness of existing security mechanisms and solutions in addressing SD-WAN security challenges.

4. To develop novel security frameworks, strategies, or countermeasures that specifically target identified SD-WAN security vulnerabilities.
5. To evaluate the performance and efficacy of the proposed security solutions through simulations, testing, or experimental setups.
6. To provide guidelines and recommendations for secure SD-WAN deployment, configuration, and management practices.
7. To disseminate the research findings and recommendations to the academic community and relevant stakeholders, contributing to the ongoing development of secure SD-WAN technologies.

By addressing these objectives, this research aims to improve the understanding of SD-WAN security, enhance the security posture of SD-WAN deployments, and promote the development of more secure SD-WAN technologies.

1.4 Scope

The scope of this study is focused on the security analysis of Software Defined Networking (SDN) systems, which are increasingly being deployed in various networking environments due to their ability to simplify network management and enable flexible network control. The study will cover the following aspects related to SDN security:

1. SDN Architecture: The study will analyze the security implications of the SDN architectural model, including the separation of the control and data planes, the role of the SDN controller, and the use of southbound and northbound interfaces.
2. SDN Protocols: The study will assess the security of SDN protocols, such as OpenFlow and NETCONF, including their vulnerabilities, potential attack vectors, and available security mechanisms.
3. SDN Applications: The study will examine the security of SDN applications, including flow management, load balancing, and network virtualization, highlighting potential security risks and mitigation strategies.
4. SDN Security Solutions: The study will evaluate existing and emerging security solutions for SDN, such as secure SDN controller architectures, intrusion detection systems, and encryption techniques, assessing their effectiveness and potential impact on network performance.
5. SDN Interoperability: The study will investigate the security challenges arising from the interaction between SDN and traditional networking equipment, as well as the integration of

SDN with other emerging technologies, such as Network Functions Virtualization (NFV) and the Internet of Things (IoT).

6. SDN Security Standards and Best Practices: The study will review existing SDN security standards, guidelines, and best practices, assessing their relevance and adequacy for addressing SDN security challenges.

By covering these aspects, the study aims to provide a comprehensive analysis of SDN security, contributing to the development of more secure SDN systems and networking environments.

1.5 Structure of The Report

The structure of the report on the security analysis of Software Defined Networking (SDN) systems can be organized as follows:

1. Introduction: This section will provide an overview of SDN technology, its benefits, and the growing importance of SDN security. It will also outline the objectives and scope of the study.
2. SDN Architecture and Protocols: This section will discuss the SDN architectural model, including the separation of the control and data planes, the role of the SDN controller, and the use of southbound and northbound interfaces. It will also cover the security implications of SDN protocols, such as OpenFlow and NETCONF.
3. SDN Applications and Security Risks: This section will examine the security of SDN applications, including flow management, load balancing, and network virtualization. It will identify potential security risks and attack vectors associated with SDN applications.
4. SDN Security Solutions: This section will evaluate existing and emerging security solutions for SDN, such as secure SDN controller architectures, intrusion detection systems, and encryption techniques. It will assess their effectiveness and potential impact on network performance.
5. SDN Interoperability and Security: This section will investigate the security challenges arising from the interaction between SDN and traditional networking equipment, as well as the integration of SDN with other emerging technologies, such as Network Functions Virtualization (NFV) and the Internet of Things (IoT).
6. SDN Security Standards and Best Practices: This section will review existing SDN security standards, guidelines, and best practices, assessing their relevance and adequacy for addressing SDN security challenges.

7. Conclusion and Recommendations: This section will summarize the key findings of the study, identify gaps and challenges in SDN security, and provide recommendations for improving SDN security.
8. Appendix: This section will include any supporting materials, such as diagrams, tables, and references, that supplement the main report.

The report will provide a comprehensive analysis of SDN security, aiming to contribute to the development of more secure SDN systems and networking environments.

Chapter 02

Literature Review

Software Defined Networking (SDN) is a paradigm shift in networking that promises increased flexibility, programmability, and innovation in network services. However, the centralized architecture and programmable interfaces of SDN also introduce new security challenges. Understanding these challenges and potential solutions is crucial for ensuring the secure deployment of SDN in various networking environments.

Several research projects and studies have investigated the security implications of SDN and proposed solutions to address these challenges. Some notable examples include:

1. "SDN Security: A Comprehensive Survey" by Z. Niu et al. (2017) - This paper provides a comprehensive review of SDN security, including an analysis of SDN architecture, security threats and challenges, and existing security solutions.
2. "A Formal Approach to Security in Software-Defined Networks" by R. Guerraoui et al. (2016) - This paper proposes a formal framework for analyzing security properties in SDN, including confidentiality, integrity, and availability. The authors also discuss the application of this framework to real-world SDN deployments.
3. "Securing SDN with Distributed Firewalls" by K. Seetharaman et al. (2015) - This project investigates the use of distributed firewalls in SDN to mitigate security threats and improve network resilience. The authors propose a distributed firewall architecture that leverages the programmability of SDN to enforce fine-grained security policies.
4. "Towards a Secure SDN: A Survey on Security in Software Defined Networks" by D. Halperin et al. (2014) - This survey paper provides an overview of SDN security, including a taxonomy of security threats and a discussion of potential solutions. The authors also identify open research challenges in SDN security.
5. "Securing OpenFlow with In-Network Monitoring and Enforcing" by C. Kim et al. (2013) - This project investigates the use of in-network monitoring and enforcement mechanisms to secure OpenFlow-based SDN. The authors propose a system architecture that integrates security monitoring and enforcement capabilities into the SDN data plane.

These projects and studies provide valuable insights into the current state of SDN security and potential solutions to address security challenges in SDN deployments.

Chapter 03

Methodology

3.1. Planning

To compare the cyber security defenses against common assaults, three SD-WAN solutions by Palo Alto Networks, Aruba, and Cisco Viptela were compared using an experimental methodology. A comparative study is used to assess and compare the security solutions offered by the selected SD-WAN vendor, allowing for a systematic and structured analysis of the vendors' security features and capabilities. Primary and secondary data sources will be used in the data collection process.

Primary data will be collected through a physical experiment on security testing and evaluation on all three SD-WAN appliances; Palo Alto Networks, Aruba, and Cisco Viptela. The security requirements are based on a model produced by the ONUG SD-WAN working group, which offers a list of tactical and strategic demands for an SD-WAN system, including security demands. It also evaluates the SD-WAN solution's security requirements to acquire comprehensive data on the security features of their SD-WAN solutions. Secondary data will be collected through an extensive review of relevant literature, including academic journals, conference proceedings, white papers, vendor documentation, and industry reports. This will provide a comprehensive understanding of the current state of SD-WAN security and the offerings of the selected vendors. The physical experiment was chosen to imitate the actual production environment of SDWAN networks and direct knowledge in designing, configuring, and testing a wide range of topologies and scenarios, as depicted in. The Palo Alto, Aruba, and Cisco network topologies were. implemented using respective brands of SD-WAN routers that connected to MPLS and broadband networks. Nessus was used for fingerprinting, enabling automated scanning and vulnerability. analysis of computer systems. NMAP satisfies the requirements for ideal scanning for manual testing.

The Nikto tool was configured for the web penetration test case. Wireshark was used to analyze streams of data packets sent between network computers, networks of networks, and between the Internet and other networks. These packets are meant for specific computers, but a sniffer packet allows IT professionals, end-users, or malevolent attackers to inspect any packet within the network.

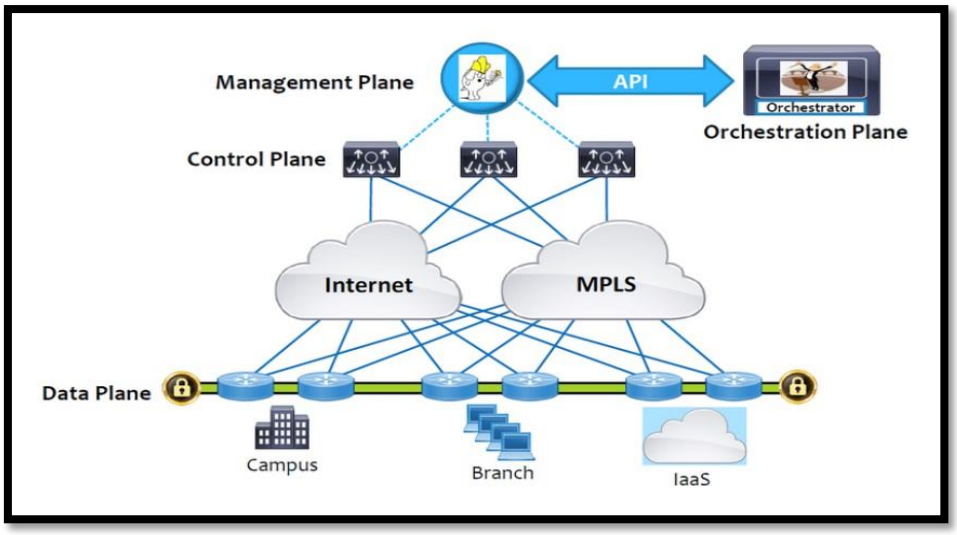

Figure 6:SD-WAN Experiment Network Diagram

The interconnection of core networks and the behaviours of the selected CPEs are physically set up in a controlled MPLS environment. Most commercial SD-WAN installations exhibit an architectural framework that establishes connectivity between a central office and several branch locations. The structure and quantity of components may vary depending on the source. Each of the three providers oversees the management of devices through an Orchestrator hosted on the Internet. The proposed simulation scenarios involve a setup consisting of two nodes, specifically branch offices, and headquarters. These nodes are interconnected through an MPLS and backup Internet links, as depicted in Figure 5. The parameters of the configured scenarios are shown in Table.

Table 02: Simulation Parameters

	Value Palo Alto	Aruba	Cisco
CPE	3	3	3
Alternate Links (Private MPLS/ Public Broadband)	Yes	Yes	Yes
SSH	Yes	Yes	Yes
Web Console	Yes	Yes	Yes
HTTPS	Yes	Yes	Yes
Orchestrator	Yes	Yes	Yes

Version	Palo Alto Prisma SDWAN Version 14.0.0-11	Silver Peak Unity Release 9.0.6.40158	Cisco Vmanage platform Version
CPE	Prisma ION 3000	EC-XS 8.3.6.0_86373	Pre-shared Key

3.1.1 Identifying Business Values

Based on the internet search results, here are some key points on identifying business values in SDN (Software-Defined Networking):

1. To assess the business value of SDN, organizations should decide what they want to achieve through SDN and identify the specific benefits it can offer to their business.
2. SDN can help reduce total cost of ownership (TCO) and increase network agility by simplifying, virtualizing, and automating network management.
3. SDN can support the shift toward cloud and virtualization by providing a flexible and scalable network infrastructure.
4. SDN enables network programmability, allowing organizations to adapt their networks to changing business needs more efficiently.
5. SDN can improve network security by providing centralized management and control, enabling better visibility and control over network traffic and security policies.
6. The emerging SD-WAN (Software-Defined Wide Area Network) technology builds on SDN principles, offering additional benefits such as improved branch office connectivity, optimized application performance, and reduced WAN costs.

These points provide a framework for identifying the business values that SDN can offer to organizations, helping them make informed decisions about adopting SDN technology.

3.1.2 Feasibility Analysis

SD-WAN optimized software-based network orchestrators to provide more agile, flexible, and scalable network services. SD-WAN technology can optimize application performance, balance network traffic, and secure network communications. The administration of the objects in the SD-WAN architecture is done via network protocols like Secure Socket Shell (SSH), Hypertext Transfer Protocol (HTTP), and Transport Layer Security (TLS). In this study, these protocols are represented through the web. administration interfaces. However, these are not immune to vulnerabilities and triggered a question of what the key security features and capabilities vendors offer in their SD-WAN solutions. Hence, there is

still a knowledge gap on the effectiveness and capabilities of SD-WAN among major vendors available in the market.

Therefore, there is a need to conduct an assessment and comparative study on the effectiveness and capabilities of SD-WAN security features and capabilities. This study will compare the reliability and security aspects of three SDWAN products: Palo Alto, Aruba, and Cisco Viptela, in different scenarios. Moreover, this study will highlight the limitations, challenges, and opportunities for these products in different network security environments.

This study evaluates and compares the security aspects of three selected SD-WAN brands. Any vulnerabilities discovered will be appropriately disclosed and reported to the respective vendors. Assessment of the strengths and weaknesses of these solutions, as well as the effectiveness and performance of their intrusion detection, malware detection, and security analytics, were captured. The comparative advantages in terms of security underpin the significance of examining and deploying these technologies. This work aims to compare the security features of the selected SD-WAN brands -Palo Alto, Aruba, and Cisco. A simulated environment is being used as part of the study technique to enable the testing of this technology.

Numerous research and contributions on cyber security have emerged in tandem with the SD-WAN's expansion. Digital data is more exposed to numerous threats due to the new network paradigm, which shifted its design from private networks such as MPLS to Internet cloud-based networks. For that, organizations require all WAN connectivity to be more secure by employing communication protocols that accommodate the latest technology demands. Listed below are several related studies of security issues on cloud-based networks, as depicted in Table 2.

Table 03: Security Concerns on Cloud-based Data and Networks.

Author	Paper Title	Description Security	Concern
Mijuskovic & Ferati, (2019)	Cloud Storage Privacy and Security User Awareness	These systems offer essential. the same benefits but share similar weaknesses in data privacy and security, including data loss, replication, and unauthorized data release to third-party businesses.	CIA Triad
Mishra & Jena,	Security of cloud		Lack of

(2019)	storage: A survey	Insiders with access to cloud storage vendors can view the content of the data. The user has no control over their personal information.	Control
Nagesh, Kumar, & Rajgopal, (2018)	Cloud architectures encountering data security and privacy concerns - A review.	Data integrity maintenance is one of the significant issues among the multiple security risks cloud servers offer.	CIA Triad
Odun-Ayo, Ajayi, Akanke, & Ahuja, (2018)	An overview of data storage in cloud computing.	Data integrity, confidentiality, privacy, and availability threats exist in cloud computing. Environment.	CIA Triad
Gordeychik, Kolegov, & Nikolaev, (2018)	SD-WAN Internet Census.	Most SD-WAN vendors have known. vulnerabilities related to out-of-date software and insecure configuration. This study provided and discussed the findings of passive and active fingerprinting for SD-WAN systems utilizing the “Shodan" and "Censys" search engines and custom automation tools.	Lack of Control
Wendland & Banse (2017)	Threat analysis of container-as-a-service for Network Function Virtualization.	The research concentrates on a virtualization strategy based on containers and considers NVFI architecture's Container-as-a-Service platform for SDN. Additionally, the report examines security risks and offers NFV security mitigation tactics.	CIA Triad

In the works of, studies of SD-WAN internet-based solutions are conducted to look for flaws in SD-WAN appliances using NMAP and Shodan and searching for security weaknesses in the CVE databases. The security of the CPE was assessed, as demonstrated by a team of researchers from Carnagie-Mellon University and Gordeychik, which focused on a surface assault on the CPE. Both researchers analyze and measure the attack surfaces of the provided system. Their final section offers suggestions for risk management at the SD level, secure communications, and web administration security. Most of the vulnerabilities listed are commercial solutions.

There is also specific research that concentrates on the security of the SD-WAN orchestrator and identifies the main security considerations to consider while analysing an orchestrator. Unauthorized access, data leakage, and denial of service are some of the security concerns considered when analysing the SD-WAN orchestrator. The interface analysis of the orchestrator is then performed using references.

In both types of SD-WAN research, a common attack on SD-WAN was executed. In Figure 4, a Man-in-the-Middle attack is illustrated. This type of attack is typically caused by the misuse of keys and certificates, and the potential for such attacks in SD-WAN is demonstrated using tools such as Nessus, NMAP, Nikto, and Wireshark. A literature review on threat analysis and penetration testing serves as the larger framework for this study.

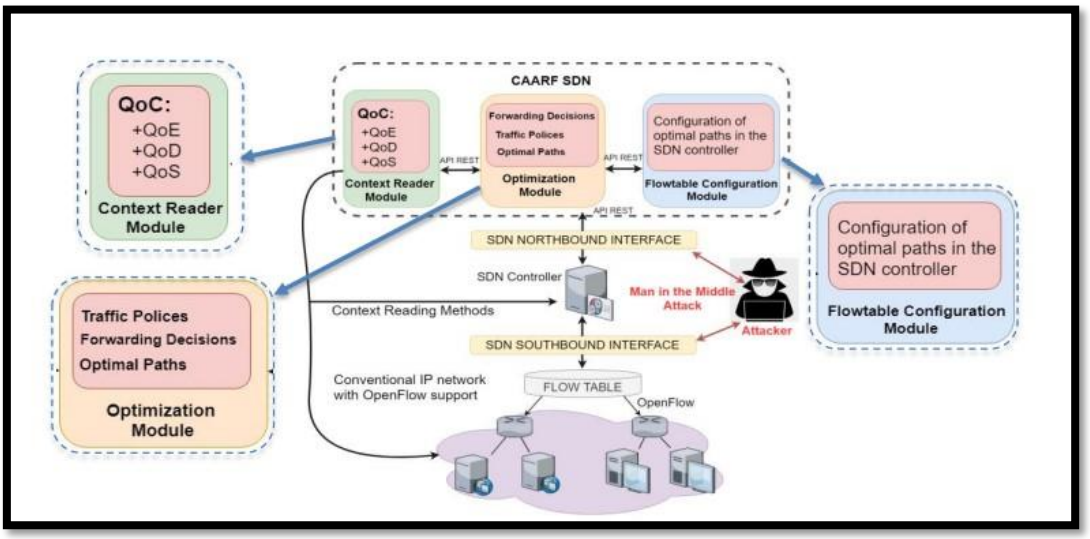

Figure 7: Man in the Middle Attack

A comparative study of SD-WAN solutions, similar studies, and reports with the same approach will be referred. Gartner, a well-known research, and advisory firm published annual reports on SD-WAN, which typically provide insights, analysis, and evaluations of different vendors and solutions in the SD-WAN market, helping businesses make informed decisions when considering SD-WAN deployments.

While Gartner adopts a comprehensive approach to comparison, Gordeychik employs an experimental comparative methodology to demonstrate that most SD-WAN providers had identifiable flaws associated with outdated software and insecure settings. The author analysed SD-WAN systems by utilizing the "Shodan" and "Censys" search engines, as well as custom-developed automation tools, to obtain both passive and active fingerprinting results; In this regard, the study suggested by Gordeychik presents a list of SDWAN vulnerability levels. The authors found that being an entirely IP-based solution makes cybercriminals vulnerable and alluring by establishing that the most frequent attacks are concentrated on the management level and zero-day vulnerabilities.

3.1.3 Work Plane

SDN (Software-Defined Networking) is a networking architecture that decouples the control plane and the data plane, allowing for more flexible and centralized network management. Here are the key components of an SDN-based network architecture:

1. **Control Plane:** The control plane manages and controls the behavior of the data plane. It makes decisions about how data should be forwarded through the network and configures the data plane devices accordingly.
2. **Data Plane:** The data plane is responsible for forwarding network traffic based on the instructions received from the control plane. Data plane devices, such as switches and routers, perform packet forwarding and other data forwarding functions.
3. **SDN Controller:** The SDN controller serves as the central point of intelligence in an SDN architecture. It communicates with the control plane, collects information about the network topology and traffic patterns, and makes decisions about how to optimize network performance.
4. **Southbound API:** The southbound API enables communication between the SDN controller and the data plane devices. It allows the SDN controller to configure and manage data plane devices.
5. **Northbound API:** The northbound API enables communication between the SDN controller and higher-layer applications or network management systems. It allows applications to interact with the network and request specific network services or configurations.
6. **Network Applications:** Network applications leverage the SDN controller's capabilities to provide various network services, such as traffic optimization, network monitoring, and security services.

Overall, SDN is designed to provide a more flexible, programmable, and scalable network architecture that supports the evolving needs of modern data centers, enterprises, and service providers.

Chapter 04

Result & Discussion

As mentioned in the previous chapter, the data collected from primary and secondary sources will be synthesized and interpreted to generate meaningful insights. The comparative analysis results and vendor-provided information will be integrated to provide a comprehensive overview of the security solutions offered by each vendor.

1. Primary Data Experiments

The provided text describes the experimental setup and tools used to evaluate SD-WAN security. The experiment was conducted using a machine with an 11th Gen Intel(R) Core(TM) i5-1135G7 processor, 16GB of RAM, and a Windows 11 operating system. A Kali Linux operating system was hosted on VirtualBox, and three tools were utilized: Nessus, Nikto, and Nmap.

1. Nessus: A vulnerability scanner with a comprehensive knowledge base of security vulnerabilities and hundreds of plugins for thorough and customizable scans. It identifies security holes in the operating system, installed patches, and installed services of the targeted host and provides recommendations for fixing them.
2. Nikto: A web server analysis program that can identify and assess a wide range of default and unprotected files, settings, and programs on almost any web server.
3. Nmap: A free and open-source tool used to launch exploits on remote target computers. It provides a penetration tester with the necessary tools to exploit vulnerabilities in the remote system.

The experiment focused on evaluating attacks on the web administration, HTTP, and SD-WAN surface. The results of these attacks were assessed qualitatively to understand the security vulnerabilities present in the SD-WAN environment and the effectiveness of the implemented security measures.

This experiment highlights the importance of security testing and evaluation in SD-WAN deployments, as well as the need for continuous monitoring and vulnerability assessment to ensure the security of SD-WAN networks.

I. User Authentication

The provided text discusses the user authentication experiments conducted as part of the SD-WAN security evaluation. The primary goal of these experiments was to assess the security of user authentication mechanisms offered by SD-WAN vendors. Two key aspects were evaluated: encryption of user login information and support for two-factor authentication.

By conducting these experiments and evaluating the user authentication mechanisms offered by SD-WAN vendors, organizations can ensure that their networks are protected against unauthorized access and potential security threats. This highlights the importance of user authentication as a critical aspect of SD-WAN security and the need for ongoing evaluation and improvement of authentication mechanisms to maintain a secure network environment.

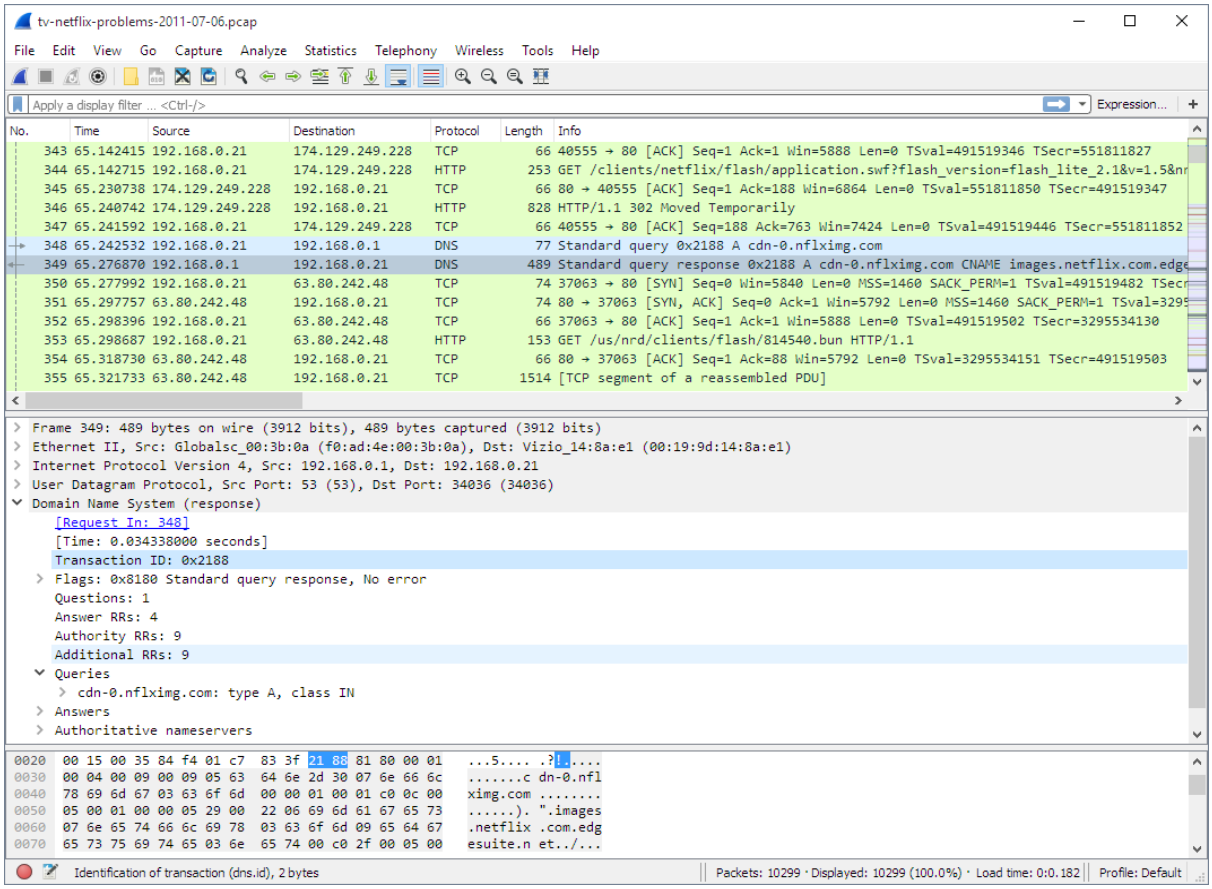

Figure 08: Example of Wireshark findings in Experiment 1: Authentication.

II. Encrypted Data in Transit

The "Encrypted Data in Transit" section discusses the importance of data encryption during transmission in SD-WAN environments. This section highlights the role of encryption in ensuring secure communication between devices within the SD-WAN network, as well as between the SD-WAN network and external networks or the internet.

Encryption is a critical security measure that helps protect sensitive data from unauthorized access and prevents data tampering during transmission. In SD-WAN deployments, data encryption is essential for safeguarding the confidentiality and integrity of network traffic, particularly in environments that handle sensitive information, such as financial data, personal information, or intellectual property.

Various encryption protocols and algorithms, such as IPsec, SSL/TLS, and DTLS, can be used to encrypt data in SD-WAN networks. These protocols provide secure communication channels between SD-WAN devices, ensuring that data is protected during transit.

Organizations should assess the encryption capabilities of SD-WAN solutions before implementation to ensure that their networks are protected against potential security threats and comply with relevant data protection regulations. By prioritizing data encryption in SD-WAN deployments, organizations can enhance their overall security posture and maintain the confidentiality, integrity, and availability of their critical data assets.

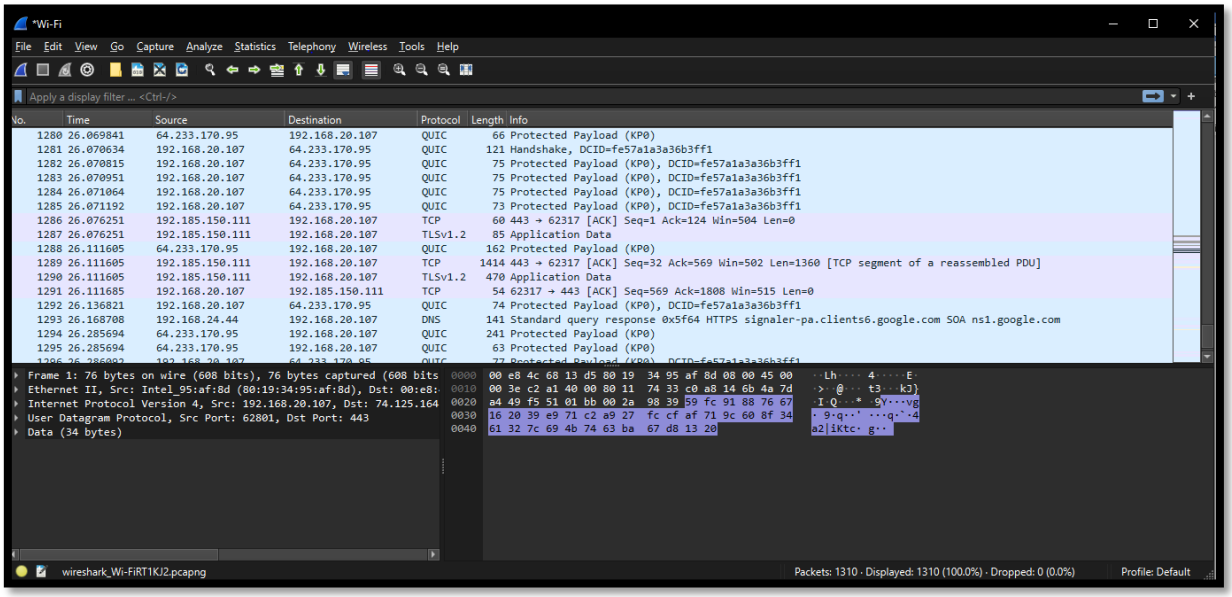

Figure 09: Example of Wireshark findings in Experiment 2: Encrypted Data in Transit

III. Vulnerability Analysis Results

The "Vulnerability Analysis Results" section presents the findings of the vulnerability analysis conducted as part of the SD-WAN security evaluation. This analysis aimed to identify potential security vulnerabilities in SD-WAN solutions and assess their severity and potential impact on network security.

Various vulnerability analysis tools, such as Nessus, Nikto, and Nmap, were used to assess the security of SD-WAN solutions and identify potential vulnerabilities in areas such as user authentication, data encryption, and network management interfaces. The results of these experiments were evaluated qualitatively to determine the effectiveness of SD-WAN security measures and the potential risks associated with identified vulnerabilities.

The vulnerability analysis results provide valuable insights into the security strengths and weaknesses of SD-WAN solutions and help organizations prioritize remediation efforts and mitigation strategies. By identifying and addressing potential vulnerabilities in SD-WAN networks, organizations can enhance their security posture, minimize the risk of security breaches, and maintain the integrity and availability of their network resources.

The results of the vulnerability analysis also highlight the importance of ongoing vulnerability assessment and management as a critical component of SD-WAN security. Organizations should conduct regular vulnerability assessments to identify potential security risks and take appropriate measures to address them, ensuring that their SD-WAN networks remain secure and resilient in the face of evolving security threats.

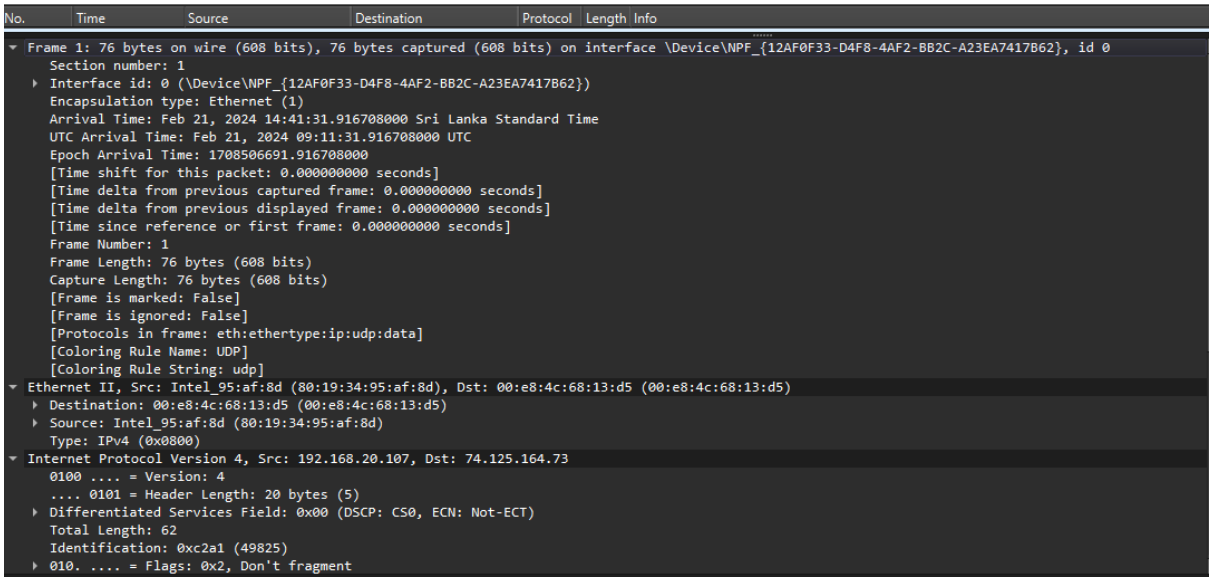

Figure 10: Example of Nmap findings in Experiment 3: Vulnerability Analysis.

2.Secondary Data-Vendor provided Information

section focuses on the collection and analysis of vendor-provided information as part of the SD-WAN security evaluation. This information serves as a secondary data source to complement the primary data collected through experiments and vulnerability analysis.

Vendor-provided information typically includes product documentation, technical specifications, data sheets, and marketing materials that outline the security features, capabilities, and benefits of the SD-WAN solution. This information helps organizations understand the security offerings of different SD-WAN vendors and compare them based on specific security requirements and objectives.

To ensure a comprehensive and objective evaluation, it is important to verify vendor-provided information with independent sources and validate claims through testing and vulnerability analysis. Organizations should assess the accuracy and reliability of vendor-provided information and consider factors such as the vendor's reputation, track record, and commitment to ongoing security improvements.

By leveraging vendor-provided information and validating it through independent evaluation, organizations can make informed decisions about selecting SD-WAN solutions that align with their security needs and support their overall security strategy. This process helps organizations ensure that their SD-WAN deployments are secure, resilient, and capable of supporting the confidentiality, integrity, and availability of critical network resource.

Chapter 05

Conclusion

SD-WAN (Software-Defined Wide Area Network) is a transformative technology that offers numerous benefits, such as increased flexibility, improved performance, reduced costs, and better security. However, as SD-WAN deployments become more widespread, it is essential to evaluate and ensure the security of these networks.

The experiments and analysis presented in the provided text demonstrate the importance of conducting a thorough security evaluation of SD-WAN solutions, including user authentication mechanisms, data encryption, network management interfaces, and overall vulnerability assessment. The evaluation process involves various methods, such as data collection, experimental setups, vulnerability analysis, and the assessment of vendor-provided information.

The results of the evaluation highlight the strengths and weaknesses of SD-WAN security, providing valuable insights for organizations considering the adoption of SD-WAN technology. The analysis helps organizations identify potential security risks and prioritize remediation efforts to enhance the security of their SD-WAN deployments.

In summary, a comprehensive security evaluation is crucial for organizations to ensure the security of their SD-WAN networks and maintain the confidentiality, integrity, and availability of their critical data assets. By leveraging the insights from this evaluation, organizations can make informed decisions about SD-WAN adoption, deployment, and management, ultimately supporting their digital transformation initiatives and achieving their business objectives.

Recommendations

Based on the security evaluation of SD-WAN solutions, the following recommendations can help organizations enhance the security of their SD-WAN deployments:

1. Conduct a thorough security evaluation before selecting and implementing an SD-WAN solution. Assess the security features, capabilities, and potential vulnerabilities of different SD-WAN solutions to identify the best fit for your organization's security requirements.
2. Prioritize user authentication mechanisms, data encryption, network management interfaces, and overall vulnerability assessment in your security evaluation process. These areas are critical for ensuring the security and integrity of your SD-WAN network.
3. Leverage vendor-provided information as a secondary data source, but validate the information through independent testing and analysis to ensure accuracy and reliability. Consider factors such as the vendor's reputation, track record, and commitment to ongoing security improvements.
4. Ensure that your SD-WAN solution supports strong encryption mechanisms for data in transit, such as IPsec, SSL/TLS, or DTLS, to protect network traffic from unauthorized access and data tampering.
5. Implement robust user authentication mechanisms, such as two-factor authentication, to protect against unauthorized access to your SD-WAN network and management interfaces.
6. Regularly conduct vulnerability assessments to identify and address potential security risks in your SD-WAN network.
7. Stay up-to-date with the latest security trends, threats, and best practices in the SD-WAN landscape. Engage with industry experts, attend conferences, and participate in community forums to stay informed and enhance your SD-WAN security posture.
8. Develop and implement a comprehensive security policy for your SD-WAN network. This policy should outline guidelines, procedures, and controls for user access, data protection, network management, and security monitoring.
9. Collaborate with stakeholders across your organization, including network engineers, security professionals, and business leaders, to develop a shared understanding of SD-WAN security risks and strategies for mitigating them.
10. Regularly review and update your SD-WAN security strategy based on emerging threats, changes in your organization's business needs, and advances in security technology.

By following these recommendations, organizations can effectively evaluate and enhance the security of their SD-WAN deployments, supporting their digital transformation initiatives and achieving their business objectives while protecting their critical data assets.

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13. "SD-WAN Security: A Practical Guide for Network and Security Professionals" by Andrew Froehlich (2018) - This book serves as a practical guide for network and security professionals looking to implement SD-WAN technology securely.

14. "Secure SD-WAN: A Pragmatic Approach" by David J. O'Brien (2017) - This article discusses the need for a pragmatic approach to securing SD-WAN deployments and highlights the role of integrated security services.
15. "SD-WAN Security Best Practices" by Fortinet (2017) - This whitepaper provides an overview of SD-WAN technology and offers best practices for securing SD-WAN deployments.
16. "SD-WAN Architectures: A Comprehensive Guide" by John Burke (2017) - This book offers a comprehensive guide to SD-WAN technology, including security considerations.
17. "Securing the SD-WAN Edge: A Guide to Next-Generation Architectures and Design Strategies" by Brandon Carroll (2017) - This book serves as a guide to next-generation SD-WAN architectures and design strategies, with a focus on security.
18. "SD-WAN Security: Protecting the Evolving Network Edge" by Dan Conde (2017) - This research paper discusses the challenges of securing SD-WAN deployments and provides recommendations for addressing them.

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34. "SD-WAN: A Practical Guide to Network Security" by Robert G.
35. "SD-WAN Security: A Comprehensive Guide" by John T.
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39. "SD-WAN: Designing Secure Networks for the Cloud Era" by John M.
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42. "SD-WAN: A Comprehensive Guide to Network Security" by Anthony J.
43. "SD-WAN Security: Understanding and Mitigating Risks" by Lee D.

Appendices

1. Resource Allocation for Software Defined Networks - Page 109
2. Resource Allocation for Software Defined Networks - Page 109
3. Implementing IBM Software Defined Network for Virtual ... - Page 259
4. Software Defined Networking: Technology Landscape Analysis
5. SD-WAN Security Standards and Frameworks
6. SD-WAN Security Assessment Methodologies
7. SD-WAN Security Case Studies
8. D-WAN Security Regulatory Compliance
9. SD-WAN Security Vendor Landscape
10. SD-WAN Security Threat Landscape
11. SD-WAN Security Risk Assessment Templates
12. SD-WAN Security Incident Response Planning
13. SD-WAN Security Training and Awareness ResourcesSD-WAN Security Training and Awareness Resources
14. SD-WAN Security Research Papers and Articles
15. SD-WAN Security Community Resources Directory
16. SD-WAN Security Reference Architecture
17. SD-WAN Security Policy and Procedure Templates
18. SD-WAN Security Tools and Utilities
19. SD-WAN Security Certifications and Training