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Implementation of SD-WAN with Intelligent Traffic Steering and Load Balancing Based on SLA Metrics

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Traditional Wide Area Network (WAN) architectures, largely dependent on static routing and MPLS links, are increasingly unable to meet the performance and flexibility demands of modern cloud-based and real-time applications. These limitations often result in inefficient bandwidth utilization, poor application performance, and limited adaptability to changing network conditions. Software-Defined Wide Area Networking (SD-WAN) addresses these challenges by enabling centralized control and dynamic traffic management.

This paper presents the implementation of an SD-WAN architecture with intelligent traffic steering and load balancing based on Service Level Agreement (SLA) metrics such as latency, jitter, and packet loss. The proposed system is developed in a simulated environment using a FortiGate device with multiple WAN links. Real-time monitoring of link performance allows dynamic path selection to ensure optimal traffic flow.

The results demonstrate improved bandwidth utilization, reduced latency, and seamless failover during link failures. The study highlights the effectiveness of SLA-driven decision-making in enhancing network performance and reliability, establishing SD-WAN as a practical and efficient solution for modern enterprise networking.

Keywords: SD-WAN, Load Balancing, Intelligent Traffic

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1. Introduction

With the rapid growth of cloud computing, remote work, and bandwidth-intensive applications, traditional Wide Area Networks (WANs) are no longer sufficient to meet modern enterprise requirements. Legacy WAN architectures primarily depend on Multiprotocol Label Switching (MPLS), which, although reliable, is expensive and lacks flexibility in handling dynamic traffic patterns.

Software-Defined Wide Area Networking (SD-WAN) addresses these limitations by introducing centralized control, application-aware routing, and real-time performance monitoring. It enables organizations to utilize multiple internet links efficiently, improving both performance and cost optimization.

In this research, an SD-WAN environment is implemented using a FortiGate firewall with dual WAN links. The system is designed to monitor network conditions and dynamically route traffic based on predefined Service Level Agreements (SLAs).

Despite these advancements, traditional WAN environments still face several critical challenges, including inefficient utilization of backup links, lack of real-time traffic optimization, and delayed failover mechanisms. These limitations result in increased latency, packet loss, and reduced application performance, particularly for real-time services. Therefore, there is a need for an intelligent network solution capable of dynamically adapting to changing network conditions while ensuring optimal performance and reliability.

2. Literature Review

The increasing demand for scalable, flexible, and cost-effective networking solutions has driven the adoption of Software-Defined Wide Area Networking (SD-WAN) over traditional WAN architectures. Conventional WAN technologies, particularly MPLS-based networks, are often constrained by high operational costs and limited adaptability to dynamic traffic patterns.

Rajagopalan provides an early overview of SD-WAN, highlighting its centralized control, application-aware routing, and ability to improve bandwidth utilization across distributed networks [1]. The separation of control and data planes further enables programmability and simplifies network management, forming the foundation for modern WAN optimization.

Load balancing remains a critical factor in enhancing network performance, especially in distributed and cloud-based environments. Traditional load balancing approaches often fail to adapt to real-time network conditions. To address this, Zedan et al. proposed a hybrid load balancing model combining active monitoring with a hill-climbing algorithm, demonstrating improved response time and reduced processing cost compared to conventional techniques [2]. Similarly, dynamic resource allocation and intelligent task scheduling have been identified as key strategies for minimizing SLA violations and improving system efficiency in cloud environments [2], [6]. These concepts directly align with SD-WAN's ability to dynamically steer traffic based on network conditions.

Service Level Agreement (SLA) monitoring and optimization have evolved significantly with the integration of intelligent systems. Traditional SLA mechanisms rely on static thresholds, which are inadequate for modern, highly dynamic networks. Jayasinghe introduced an AI-based SLA monitoring framework that leverages machine learning to predict potential performance degradation and automate resource allocation [3]. Complementing this approach, Talana et al. proposed a semantic framework for automating SLA interpretation using ontology-based models, improving interoperability and accuracy in service delivery [4]. Together, these studies demonstrate a shift from reactive to proactive and intelligent SLA management, which is essential for SD-WAN environments.

Recent research has also focused on improving SD-WAN performance through congestion control and traffic optimization techniques. Nasir and Abdullah proposed a bucket-based packet aggregation algorithm to reduce processing overhead and improve throughput in high-traffic SD-WAN environments [5]. While their approach effectively addresses congestion at the data plane level, other studies emphasize the importance of architectural and monitoring enhancements.

Emmanuel presented an SD-WAN architecture that integrates real-time traffic monitoring and dynamic load balancing, identifying key performance metrics such as latency, packet loss, and bandwidth utilization as critical evaluation parameters [6]. These findings highlight the need for a holistic approach that combines algorithmic efficiency with architectural improvements.

Practical implementations further validate the effectiveness of SD-WAN in real-world scenarios. Rahim and Akbi demonstrated that SLA-based bandwidth optimization using FortiGate NGFW enables dynamic traffic distribution across multiple links, resulting in improved bandwidth utilization, reduced jitter, and enhanced network stability [7]. Their study also emphasizes the importance of integrating security mechanisms such as firewall policies within SD-WAN deployments to ensure both performance and data protection. Such implementations reinforce the practical viability of SLA-driven traffic steering mechanisms.

Traffic engineering (TE) has also been widely explored as a means of optimizing network performance. Zheng et al. proposed an online optimization framework that jointly considers traffic engineering and network update costs to improve long-term efficiency [8]. Unlike traditional TE approaches that focus solely on short-term optimization, this method reduces routing instability and operational overhead. In addition, network emulation techniques have been used to evaluate performance under controlled conditions. Elbouanani et al. demonstrated that distributed network emulation can effectively identify delay-related issues and infrastructure limitations in virtualized environments [9]. These methodologies provide valuable insights for validating SD-WAN solutions before deployment.

Overall, the literature indicates that SD-WAN represents a significant advancement in network design by integrating centralized control, intelligent traffic management, and real-time performance monitoring. While existing studies have addressed individual aspects such as load balancing, SLA optimization, congestion control, and traffic engineering [2]–[5], [7]–[9], there remains a gap in developing integrated frameworks that combine these features into a unified solution.

The present study builds upon these contributions by implementing SLA-driven traffic steering and load balancing within a simulated SD-WAN environment, aiming to enhance network efficiency, reliability, and adaptability.

3. Methodology

The methodology adopted in this study follows a structured and implementation-oriented approach to design, configure, and evaluate an SD-WAN architecture. The process is divided into clearly defined steps to ensure reproducibility and alignment with real-world deployment practices

Step 1: Network Topology Design

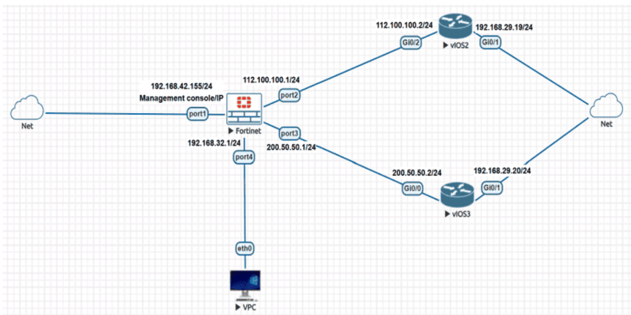


Figure 1 illustrates the proposed network topology used in this study, where two WAN links are connected to a firewall and traffic is routed dynamically.

The initial step involves designing a network topology that simulates an enterprise WAN environment. The topology consists of a FortiGate firewall connected to two WAN links representing different Internet Service Providers (ISPs), along with a local LAN network. Each WAN link is assigned a separate IP subnet and connected to upstream routers to emulate internet connectivity. The LAN segment represents internal users generating different types of traffic. This design ensures that the system can evaluate traffic behavior under multiple paths and varying network conditions.

The network is configured using a structured IP addressing scheme to differentiate between LAN and WAN segments. The LAN interface is assigned the subnet **192.168.32.0/24**, representing internal users, while the management interface operates on **192.168.42.0/24**. Two WAN links are configured using **112.100.100.0/24** and **200.50.50.0/24**, each connected to separate upstream routers acting as independent ISPs.

The default gateway for outbound traffic is configured dynamically through the SD-WAN zone, allowing intelligent path selection between the two WAN links. This addressing scheme ensures proper segregation of traffic and enables efficient routing, monitoring, and failover operations within the network.

Step 2: Interface Configuration

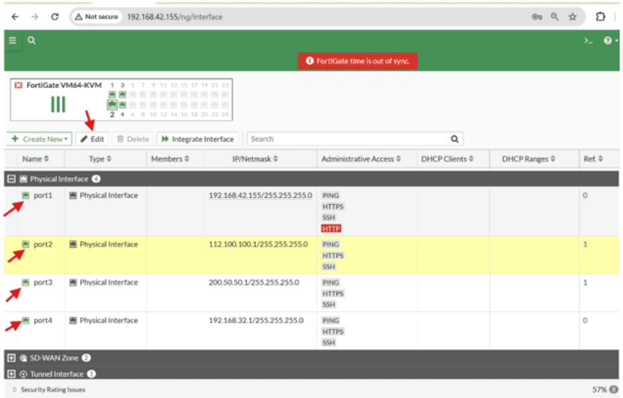
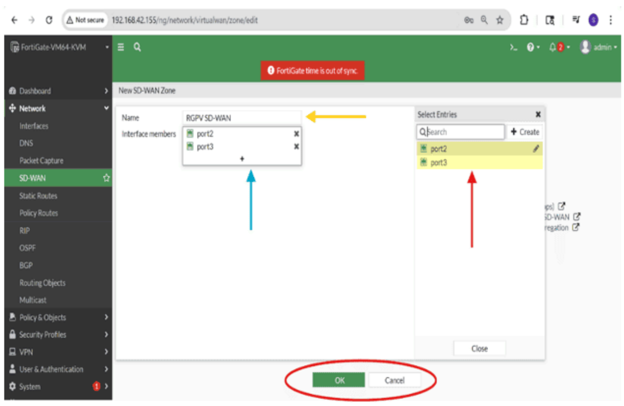


Figure 2 shows the configuration of interfaces including LAN and WAN connections on the FortiGate device.

In this step, all physical interfaces of the firewall are configured with appropriate IP addresses and subnet masks. The WAN interfaces are mapped to external networks, while the LAN interface is configured to serve internal users. Administrative access such as HTTPS, SSH, and ping is enabled where required to facilitate monitoring and management. Proper interface configuration ensures stable communication between network components and forms the foundation for SD-WAN implementation.

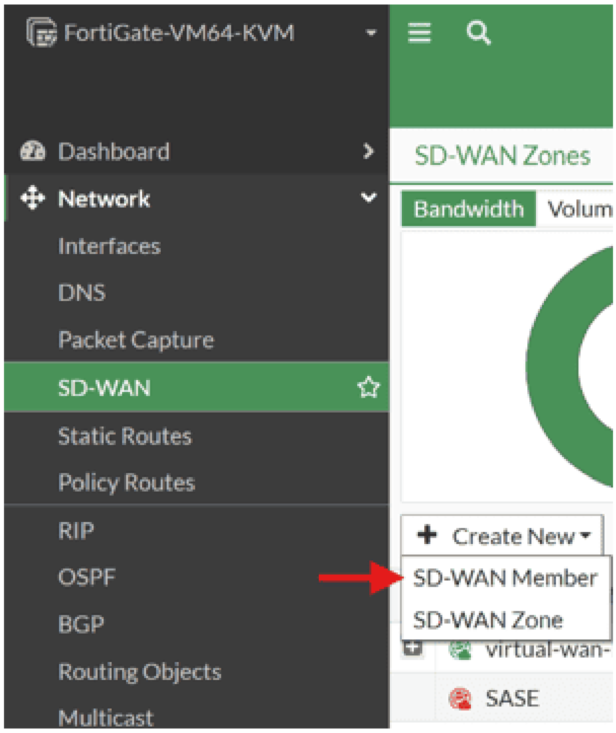
Step 3: SD-WAN Zone Creation



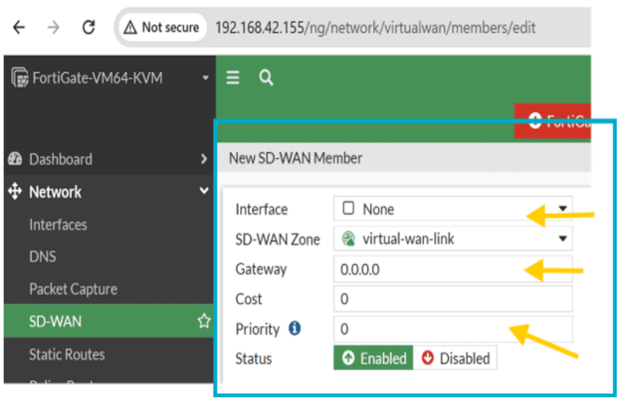
The configured WAN interfaces are grouped into an SD-WAN zone, creating a logical abstraction that allows centralized traffic management.

This step enables the firewall to treat multiple physical links as a single virtual interface. By doing so, the system gains the ability to dynamically select the best available path based on real-time performance metrics. The SD-WAN zone acts as the core component for implementing intelligent traffic steering.

Step 4: SD-WAN Member Configuration

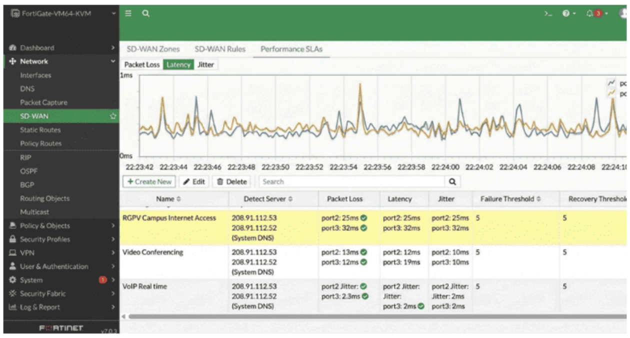


Each WAN interface is added as a member of the SD-WAN zone with parameters such as gateway address, cost, and priority.



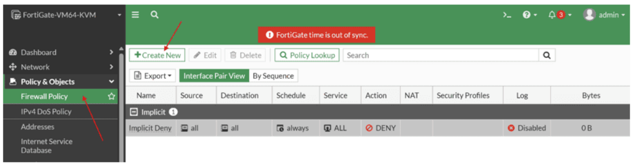
These parameters influence how traffic is distributed across available links. Lower cost or higher priority links may be preferred under normal conditions, while alternate paths are utilized during congestion or failure. This step ensures efficient utilization of network resources and supports load balancing.

Step 5: Performance SLA

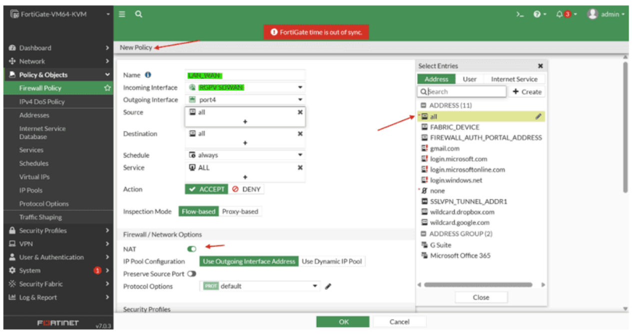


Service Level Agreements (SLAs) are configured to monitor critical performance metrics, including latency, jitter, and packet loss. Specific threshold values are defined to determine acceptable performance levels. The firewall continuously probes external servers to measure these metrics in real time. If a link fails to meet SLA requirements, traffic is automatically redirected to a better-performing path. This step is essential for maintaining Quality of Service (QoS) for different applications.

Step 6: Firewall Policy Configuration

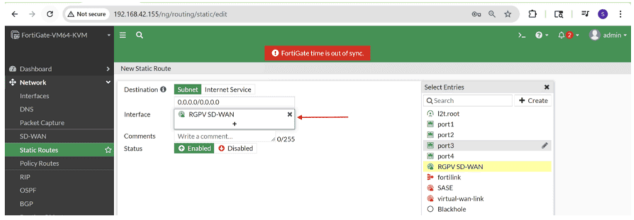


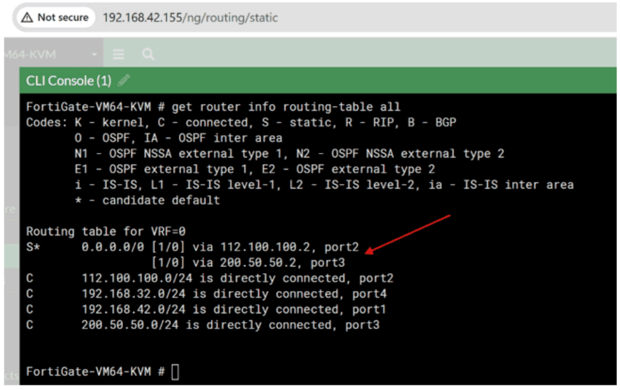
Firewall policies are implemented to allow traffic flow between the LAN and WAN networks. Policies are configured with appropriate source and destination parameters, along with services and schedules.



Network Address Translation (NAT) is enabled to ensure that internal users can access external networks. Security profiles may also be applied to enhance protection against threats. This step ensures secure and controlled communication across the network.

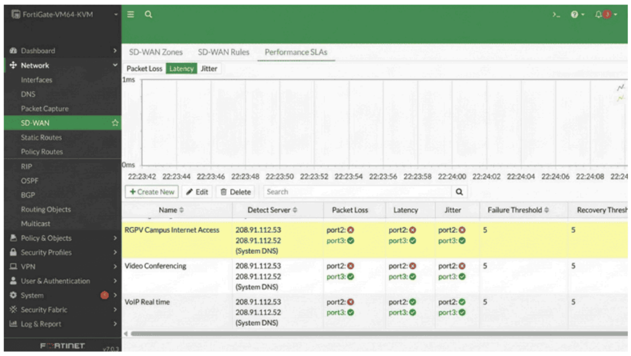
Step 7: Routing Configuration and Verification





Static routing is configured to establish default routes through the SD-WAN zone. Multiple default routes are defined to enable redundancy and failover. The routing table is verified using command-line interface (CLI) commands to confirm that traffic can be routed through both WAN links. Proper routing configuration ensures seamless connectivity and supports dynamic path selection.

Step 8: Traffic Simulation and Monitoring



In the final step, network traffic is generated to simulate real-world usage scenarios such as web browsing, video conferencing, and VoIP communication. The system's behavior is observed under varying conditions, including changes in latency and packet loss. Performance metrics are continuously monitored to evaluate how effectively the SD-WAN solution distributes traffic and maintains service quality. This step provides practical insights into the performance and reliability of the implemented architecture.

4. Results & Analysis

The performance evaluation of the implemented SD-WAN architecture demonstrates significant improvements in network efficiency, reliability, and adaptability when compared to traditional WAN configurations. The system continuously monitored network conditions using Service Level Agreement (SLA) parameters such as latency, jitter, and packet loss, enabling real-time decision-making for traffic routing.

During normal operating conditions, both WAN links actively participated in traffic forwarding, ensuring balanced utilization of available bandwidth. The distribution of traffic across multiple links resulted in reduced congestion and improved throughput. Unlike traditional WAN environments, where backup links often remain idle, the SD-WAN configuration ensured that all available resources were effectively utilized. This behavior highlights the efficiency of dynamic load balancing in optimizing network performance.

As network conditions varied, the system demonstrated intelligent traffic steering by dynamically selecting the most optimal path based on SLA metrics. When one of the WAN links experienced increased latency or fluctuations in jitter, the system automatically redirected traffic to the alternate link without requiring manual intervention. This adaptive behavior ensured that application performance remained consistent, particularly for latency-sensitive services.

The failover capability of the system was evaluated by intentionally disabling one of the WAN links during operation. The SD-WAN architecture successfully detected the link failure in real time and seamlessly shifted traffic to the remaining active link. This transition occurred with minimal disruption, maintaining continuous connectivity and preventing significant packet loss. The rapid response of the system highlights its ability to handle network failures effectively and maintain service availability.

Routing behavior was also analyzed to verify the correctness of the configuration. The presence of multiple default routes through the SD-WAN zone confirmed that the system was capable of supporting redundancy and dynamic path selection. Traffic flow was observed to adjust automatically based on link performance, reinforcing the effectiveness of centralized control in SD-WAN environments.

Overall, the results indicate that the implemented SD-WAN solution provides a robust and efficient alternative to traditional WAN architectures. The integration of SLA-based monitoring, dynamic load balancing, and automatic failover contributes to improved network performance and reliability. These findings validate the effectiveness of SD-WAN in addressing the limitations of legacy WAN systems and demonstrate its suitability for modern enterprise networking environments.

5. Discussion

The results obtained from the implementation clearly demonstrate the effectiveness of SD-WAN in addressing the limitations associated with traditional WAN architectures. The observed improvements in traffic distribution, failover responsiveness, and performance optimization are consistent with the principles discussed in existing literature. However, this study extends those concepts by providing a practical implementation and real-time validation within a simulated environment.

One of the key observations from the results is the effectiveness of SLA-based traffic steering in maintaining consistent network performance. Unlike static routing mechanisms used in legacy WAN systems, the SD-WAN approach dynamically evaluates link conditions and adapts accordingly. This behavior aligns with the findings of previous studies that emphasize the importance of real-time monitoring and adaptive routing. However, while many existing works focus on theoretical models or simulations, this study demonstrates the practical feasibility of implementing such mechanisms using a FortiGate-based environment.

The load balancing capability observed during testing further reinforces the advantages of SD-WAN. Traffic was distributed across both WAN links under normal conditions, ensuring efficient bandwidth utilization and preventing congestion. This behavior is consistent with research on dynamic load balancing in SDN environments, where adaptive algorithms are used to optimize resource usage. The results confirm that similar principles can be effectively applied in WAN environments through SD-WAN.

Another significant aspect of the implementation is the system's ability to handle network failures. The seamless failover observed during testing highlights the robustness of the SD-WAN architecture. Unlike traditional failover mechanisms that rely on routing protocol convergence, SD-WAN enables near-instantaneous switching based on SLA violations. This ensures minimal disruption to ongoing communication and enhances overall network reliability.

From a practical perspective, the study also highlights the importance of centralized control and simplified network management. By abstracting multiple WAN links into a single SD-WAN zone, the complexity of managing individual interfaces is significantly reduced. This not only simplifies configuration but also improves scalability, making the solution suitable for enterprise environments.

While the results are promising, it is important to acknowledge certain limitations. The implementation was carried out in a simulated environment, which may not fully replicate real-world network conditions such as ISP variability and large-scale traffic patterns. Additionally, the study focuses primarily on performance aspects and does not extensively evaluate security features, which are also critical in SD-WAN deployments.

Overall, the discussion establishes a clear connection between theoretical concepts and practical implementation. It demonstrates that SD-WAN is not only a conceptual advancement but also a viable solution capable of improving network performance, reliability, and operational efficiency in modern enterprise environments.

6. Conclusion

This research study presented the design, implementation, and evaluation of an SD-WAN architecture using a FortiGate firewall in a simulated environment. The primary objective was to analyze the effectiveness of intelligent traffic steering and load balancing based on SLA parameters such as latency, jitter, and packet loss.

The results demonstrate that SD-WAN significantly enhances network performance by enabling dynamic path selection and efficient utilization of multiple WAN links. Unlike traditional WAN architectures, which rely on static routing and underutilized backup links, the implemented solution actively distributes traffic across available paths and adapts to changing network conditions in real time.

The system also exhibited strong failover capabilities, ensuring continuous connectivity even in the event of link failure. The integration of SLA-based monitoring allowed the network to maintain consistent performance by proactively identifying and avoiding degraded links. These features collectively contribute to improved reliability and user experience.

In addition to performance improvements, the study highlights the advantages of centralized management and simplified configuration offered by SD-WAN. By abstracting multiple WAN links into a single logical entity, the solution reduces operational complexity and enhances scalability.

In conclusion, the findings validate that SD-WAN is a practical and efficient solution for modern enterprise networks. Its ability to combine intelligent traffic management, load balancing, and failover mechanisms makes it a superior alternative to traditional WAN architectures. Future work may focus on real-world deployment, integration with security frameworks, and the application of advanced techniques such as machine learning for predictive traffic optimization.

Future work may focus on real-world deployment of the proposed architecture and the integration of advanced techniques such as machine learning for predictive traffic analysis and automated network optimization.

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