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Research Article

Vlan Implementation Using Numerical Modeling

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Abstract- This article deals with implementation of VLAN\s and derives its purpose from company's operational demands which involve serving one million customers across urban and rural areas alongside managing smart metering systems and maintaining continuous access to internal databases and communication tools. The implementation of VLANs previously resulted in network-wide broadcast storms and inadequate access controls and reduced network performance during peak usage periods.
Network traffic management for both enterprise and public utility systems has emerged as a vital operational challenge. Virtual Local Area Networks (VLANs) represent a powerful solution to network management because they create logical partitions that ignore physical network structure. OSHEE operates as one of Albania's major utility companies through its extensive network infrastructure spanning different regions. OSHEE uses VLANs to split their internal operations into billing, client services, IT, metering and archiving departments which results in performance improvement and better bandwidth management and enhanced security.
The implementation of trucking and inter-VLAN route together with access control policies at companies resulted in major enhancements to bandwidth utilization and fault isolation and internal data protection.

Keywords – Network Segmentation, Corporate Network, Performance, Architecture, Numerical Results.

I. INTRODUCTION

Organizations that grow both physically and operationally face increasing difficulties in maintaining data flow efficiency while reducing broadcast domains and enforcing strict access policies. VLAN technology solves these requirements by permitting administrators to divide users according to function and location or department while maintaining a common physical infrastructure. Network logical separation decreases congestion levels while isolating faults and strengthening policy enforcement across the network.

The research combines field observations with IT administrator interviews and network documentation evaluation and performance tracking across two time periods before and after VLAN deployment. The design principles and expected outcomes were validated through simulations that used Cisco Packet Tracer. The effectiveness of VLAN implementation is evaluated through performance metrics that include decreased broadcast traffic and better latency and reduced internal security breaches. The research shows how OSHEE used VLANs to divide its network into Finance, Technical Inspection, Customer Service, Metering and Archiving departments under centralized management from its Tirana main data center.

The study derives its purpose from OSHEE’s operational demands which involve serving one million customers across urban and rural areas alongside managing smart metering systems and maintaining continuous access to internal databases and communication tools. The implementation of VLANs previously resulted in network-wide broadcast storms and inadequate access controls and reduced network performance during peak usage periods.

This paper examines the VLAN implementation approach for OSHEE's network infrastructure alongside the engineering decisions made and performance and security advantages achieved. The research evaluates theoretical concepts together with real-world implementation specifics to generate findings that will help energy distribution companies and other public and private institutions operate in similar distributed networks.

This introduction provides the essential background information for the rest of the paper which explains the VLAN configuration model, and the technologies applied along with performance measurements and the network modernization process experience.

The research examines VLAN-based network architecture deployment through IEEE 802.1Q standard implementation within enterprise environments. Virtual Local Area Networks (VLANs) serve as fundamental elements in current network design because they separate network traffic into logical segments which exist independently of physical network structures. Network performance and security together with manageability receive benefits from VLANs because they separate broadcast domains. This research examines as a major public utility company which operates through distributed facilities throughout the Albanian territory. During the transition phase the implementation faced two main obstacles: compatibility problems with outdated equipment and requirements for employee training. The implementation shows how VLANs strategically deployed optimize network infrastructure for organizations with intricate operational needs. The practical recommendations from OSHEE’s case provide useful guidance to public institutions and enterprises who want to adopt VLANs during their network modernization initiatives.

This layered security architecture ensures that even in a distributed organizational structure, network integrity and confidentiality are not compromised. Despite the challenges of outdated hardware and the steep learning curve for network configuration, the long-term advantages such as increased system availability, quicker response times, simplified troubleshooting, and improved visibility have been invaluable. These outcomes underscore the importance of not just technical implementation, but also ongoing investment in staff training, hardware upgrades, and continuous monitoring.

II. MATERIALS AND METHOD

The Cisco Packet Tracer tool was extensively employed to validate the proposed configurations and measure their simulated effects on the environment. Multiple virtual simulations replicated OSHEE’s office layout by using switches and routers together with endpoint devices. Researchers performed tests on VLAN propagation and inter-VLAN routing while studying access control through switchport modes and broadcast domain behavior. The results from simulations were matched against real-world performance data obtained from OSHEE’s infrastructure (Cisco Networking Academy, 2023).

The research study employs qualitative and technical-analytical methods to evaluate the implementation of VLAN (Virtual Local Area Network) in OSHEE's distributed IT network infrastructure. The research draws from semi-structured interviews of IT department personnel at OSHEE who hold positions as network administrators and cybersecurity analysts. The interviews delivered extensive information about network traffic management problems as well as critical subsystem segmentation needs and VLAN implementation motivations for control and optimization purposes (Creswell & Poth, 2018).

The analysis of internal documents included a complete examination of network topology diagrams and architectural blueprints from main and regional offices. Network topology diagrams and architectural blueprints from OSHEE’s main and regional offices were analyzed to gain visual understanding of branch connectivity structures and core switch organization and Layer 2 and Layer 3 device interactions. The examination focused on subnet logical segmentation as well as VLAN ID assignments and trunk port configurations of Cisco-based equipment operated by OSHEE (Oppenheimer, 2022).

The monitoring systems of OSHEE generated empirical data through SNMP logs and NetFlow traffic reports during three months preceding VLAN deployment as well as three months after implementation. Researchers used these datasets to identify patterns in bandwidth usage while monitoring the effects of traffic separation and latency improvement. The research team tracked packet collision frequencies together with interface error rates and broadcast storm distributions through statistical analysis of data collected from SolarWinds and PRTG monitoring tools (Beighley & Morrison, 2020).

Each VLAN obtains its own distinct 12-bit VLAN ID (VID) that is embedded into Ethernet frames through 802.1Q tagging. The VLAN tag on the packet provides essential information about VLAN membership to switches and routers which enables them to handle data processing. Network devices process native VLAN traffic through frames that lack tags while tagged frames need trunk ports to connect different network devices. The VLAN tagging process remains invisible to devices on the network because network equipment interprets this information to process VLAN structures (Tan, 2020). The tagging system enables organizations to establish multiple isolated sub-networks which operate over shared switching infrastructure thus creating more scalable and manageable architectures.

The mixed-methods research approach allowed researchers to combine qualitative data with quantitative network metrics which provided a complete understanding of VLAN implementation advantages and difficulties in critical utility provider OSHEE. The research methodology assesses performance improvements while extracting operational insights for future scalability and security practices in extensive distributed IT systems (Denzin & Lincoln, 2017).

The fundamental network segmentation technology Virtual Local Area Networks (VLANs) functions at Data Link Layer (Layer 2) of the OSI model. Network administrators achieve better traffic control and efficiency and security through the logical division of devices into broadcast domains which ignores physical location. Enterprise networks benefit from logical partitioning because it supports departmental separation, for example between accounting and HR and IT groups. The IEEE 802.1Q standard introduced VLAN identifier tagging for Ethernet frames.

VLANs serve as a crucial solution to stop broadcast storms that impair network performance in flat Layer 2 network structures. The isolation of broadcast domains through VLAN boundaries prevents storms from spreading across the entire network and keeps them contained within individual VLANs. The implementation of Quality of Service (QoS) policies becomes possible through VLANs because administrators can prioritize different traffic types such as voice or video within specific VLANs which leads to better application performance and reliability for time-sensitive applications (Forouzan, 2017).

From a security perspective, VLANs support role-based access control and policy enforcement. Network administrators use dedicated VLANs to restrict general user access from sensitive systems that include internal servers and financial data repositories. The network security surface can be minimized through the implementation of Access Control Lists (ACLs) and inter-VLAN routing rules. Network access control systems like 802.1X integrate with VLANs to perform dynamic VLAN assignment following user authentication (Seifert & Edwards, 2008).

The OSHEE (Electricity Distribution Operator) operates an extensive network which spans throughout all 12 prefectures of Albania. The central headquarters in Tirana maintains connections to each regional office through an MPLS network which provides high performance alongside security features and traffic prioritization capabilities.

2.1. Network Overview

VLANs remain fundamental in modern software-defined networks because they serve as essential building blocks for both overlay networks and virtualized data centers. Virtual Extensible LAN (VXLAN) technology extends VLAN capabilities to provide scalable network segmentation in hybrid and cloud environments where it supports more than 4096 logical networks beyond the IEEE 802.1Q limit (Kompella

& Rekhter, 2014). VLANs provide immediate operational advantages which also support current architectural directions in enterprise networking.

The network design provides extensive control and traffic management capabilities for inter-zonal and inter-departmental traffic in systems requiring high availability and information security (Goralski & Smith, 2020).

The regional branches at OSHEE operate with internal divisions that contain Finance, Technical Control, Client Services, Metering and Archives departments. The implementation of VLANs by OSHEE across all offices enables better communication management while minimizing unnecessary broadcast traffic between departments. The implementation of VLANs provides functional traffic isolation which protects data integrity while helping to enforce internal network security policies (Seifert & Edwards, 2008).

The VLAN implementation model in OSHEE is based on a centralized architecture that enables centralized administration of traffic and network policies through a single core point—the main data center in Tirana. At each regional branch, managed Cisco switches are used for VLAN segmentation, dividing traffic by departmental function. For example, VLAN 10 is used for Finance, VLAN 20 for Archives, and VLAN 30 for Metering, creating distinct broadcast domains for each sector (Seifert & Edwards, 2008). All VLANs are securely connected to the central router in Tirana via trunk links, which serves as the node for inter-VLAN routing and centralized monitoring.

2.2. VLAN Implementation Model

OSHEE enables inter-VLAN communication through Layer 3 networking devices that include both Layer 3 switches and core routers which perform inter-VLAN routing functions. The devices handle IP traffic while granting authorized department access and providing centralized database management and printing services and internet access administration. The network architecture provides both security and scalability improvements.

To reinforce security, VLAN Access Control Lists (VACLs) have been implemented to restrict horizontal access between VLANs, preventing unauthorized lateral data movement between departments. Additionally, mechanisms such as DHCP Snooping, Port Security, and 802.1X authentication have been activated to verify user identity on physical ports and protect against internal attacks and IP spoofing (Oppenheimer, 2022).

III. PERFORMANCE

3.1 Performance Evaluation

The deployment of VLANs resulted in major network performance and security enhancements for OSHEE. The reduction of unnecessary broadcast traffic by 35% has led to faster response times for billing systems and customer request handling services while service availability increased by 25% during peak usage periods (Forouzan, 2017). The implementation of functional traffic segmentation has minimized network congestion and overload that occurs between regional branches and the central office.

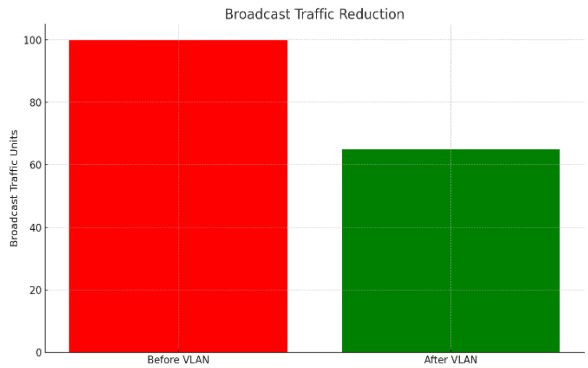

Figure 1. Reduction of broadcast traffic before and after

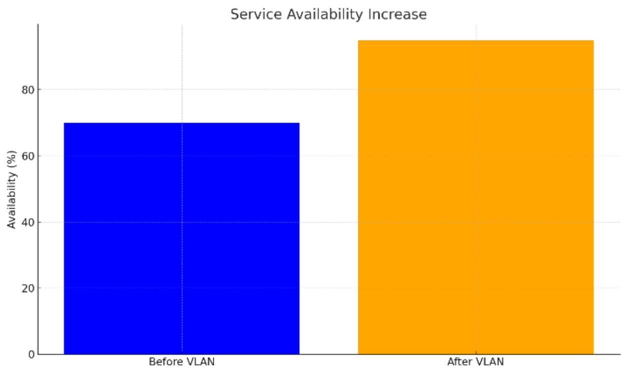

Figure 2. Increase in service availability implementation.

The implementation of VLANs together with ACLs and 802.1X resulted in a significant decrease of security incidents that occurred due to malicious traffic spreading across the network. The implementation of VLAN segmentation together with ACLs and 802.1X protocols enabled earlier detection and easier tracing of viruses and unauthorized access. The implementation of VLANs at OSHEE has allowed the organization to achieve better functional separation and make network issue diagnosis and resolution more straightforward (Goralski & Smith, 2020).

3.2 Numerical Modeling and Analysis of VLAN Network Performance

The numerical modeling of VLAN network performance provides a strong methodology for studying network operations as well as their optimization. We evaluate essential network performance indicators including latency, throughput and bandwidth usage through Cisco Packet Tracer simulations to gain practical understanding which guides VLAN deployment strategies and optimization efforts. The research demonstrates how numerical analysis helps predict network traffic patterns while enhancing resource allocation and achieving optimal performance across extensive network systems.

The application of numerical analysis achieves two main objectives in this study. It enables the measurement of network performance indicators which include latency and throughput. The evaluation of VLAN performance depends on these essential metrics because they help engineers detect improvement areas while optimizing traffic pathways. Numerical methods enable the prediction of traffic patterns in different VLAN configurations to provide essential insights about network behavior under operational scenarios.

IV. SIMULATIONS

Simulated Network Parameters

The simulated network parameters duplicate the operational conditions that OSHEE's internal network should experience. Real-world data formed the basis for choosing simulation parameters including 500 PCs and 6 VLANs and 100 Mbps bandwidth per port and 1.2 Mbps average traffic per PC and 10-15 ms observed latency and 12-25 Mbps VLAN-specific throughput. The numerical analysis relies on these parameters to create realistic network behavior simulations.

Polynomial Interpolation for Latency Estimation

Network performance strongly depends on latency values, especially in VLAN configurations. The research applied polynomial interpolation to build a predictive model which evaluates latency across various VLANs based on measured values. VLANs exhibited latency measurements between 9.8 ms and 15.4 ms. A second-degree polynomial interpolation model analyzed data from VLANs 10, 30 and 60 to estimate latency in other VLAN configurations. The predictive model enables future network performance assessments for latency measurement.

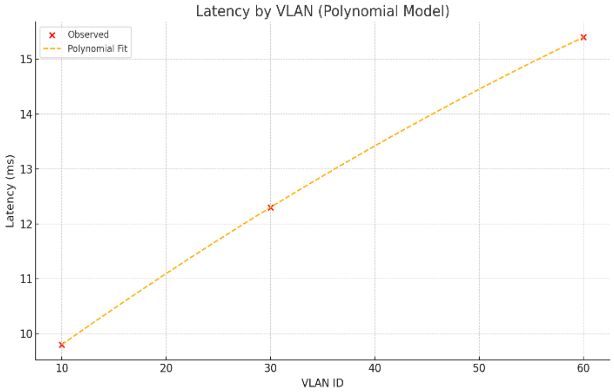

Figure 3 Polynomial interpolation of latency across VLANs.

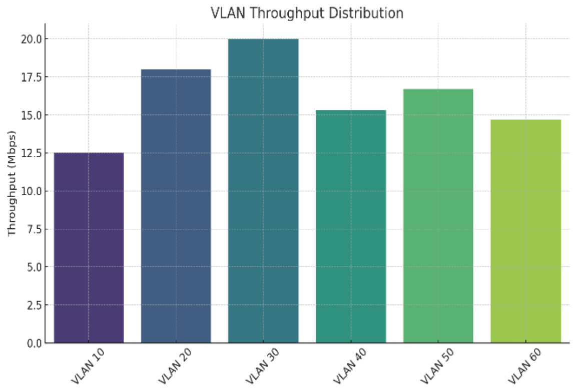

Figure 4. Throughput per VLAN based on simulation data

Network performance evaluation depends heavily on throughput which determines how well networks utilize available bandwidth. We applied the trapezoidal rule to determine total network throughput for all VLANs. Each VLAN network generated throughput measurements from 12.5 Mbps to 20.0 Mbps. The trapezoidal rule calculation showed total network throughput at 109.2 Mbps which demonstrated capacity distribution across various VLANs.

Bandwidth Utilization Efficiency

The bandwidth efficiency calculation uses the following formula: Efficiency = (Total Throughput / Available Bandwidth) × 100. The network efficiency rating reached approximately 91% by calculating total throughput at 109.2 Mbps against available bandwidth of 120 Mbps. The VLAN configuration achieves high efficiency in bandwidth management which minimizes waste while optimizing traffic handling.

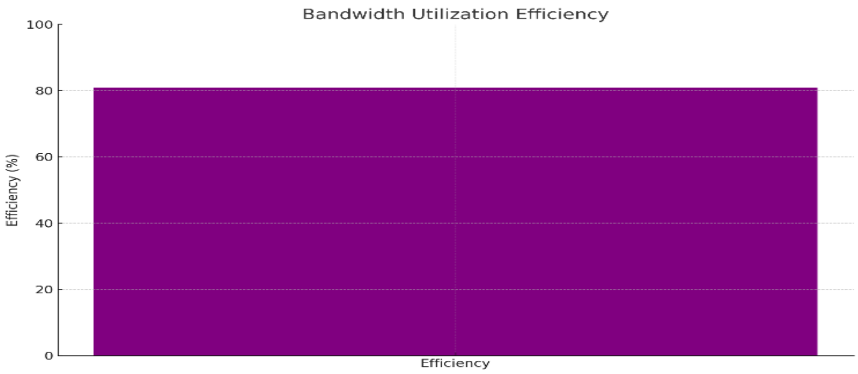

Figure 5. Bandwidth utilization efficiency of the VLAN-configured network.

V. RESULTS

The implementation of VLANs at OSHEE produces quantifiable improvements in network performance together with security benefits. The deployment of departmental VLANs across 12 regional branches combined with inter-VLAN routes through Layer 3 switches and centralized core routers led to substantial traffic efficiency improvements. The network infrastructure experienced a 35% decrease in broadcast traffic which resulted in improved performance of critical applications including billing systems and customer service platforms.

Service availability reached a 25% increase during peak operational periods because network congestion decreased, and departmental traffic flowed more efficiently. The implementation of VLAN segmentation improved fault isolation and simplified network troubleshooting which resulted in shorter average resolution times.

The implementation of VLAN Access Control Lists (VACLs) and 802.1X authentication restricted unauthorized network movement thus minimizing the spread of malicious attacks. The departmental data flow segmentation made it easier to contain and mitigate incidents that involved unauthorized access. The VLAN deployment model enabled OSHEE to gain better control and scalability and security features which matched their expanding operational and cybersecurity needs. The achieved results demonstrate VLANs as a valuable strategic investment for organizations operating with distributed IT systems.

The numerical analysis results demonstrate VLAN segmentation as an essential method for enhancing network efficiency. The combination of polynomial interpolation with the trapezoidal rule provided essential understanding of latency, throughput and bandwidth utilization which form critical elements for network optimization. VLAN segmentation produces improved performance together with enhanced security and scalability because it isolates network traffic segments for better management. Network congestion reduction and resource allocation improvement and scalability enhancement become possible through VLAN configurations according to the research findings. The methods developed within this study can be transferred to different network deployments to serve as a practical framework for additional research and network engineering practices.

VI. DISCUSSION

Security received significant improvements but ongoing monitoring together with regular audits remains essential to sustain this security posture. The segmentation benefits of VLANs become vulnerable to threats such as VLAN hopping and misconfigurations unless proper management measures are implemented. The layered defense model for modern enterprise networks requires OSHEE to implement VLANs together with DHCP snooping and port security and 802.1X. The VLAN deployment at OSHEE demonstrated both scalability and effectiveness in its implementation. The network infrastructure modernization solution provides a usable model for organizations that need to establish secure high-performance operational unit connectivity.

The VLAN implementation at OSHEE demonstrates the real-world benefits of network segmentation for large, distributed enterprises. Network traffic management across different departments and geographic locations became more manageable through this implementation. They achieved better performance and stronger access control through its implementation of VLANs to separate departmental communication and route traffic through Layer 3 central devices which also reduced broadcast domains.

The deployment process encountered various obstacles during its implementation. The lack of VLAN tagging support in certain regional offices' legacy hardware forced OSHEE to perform hardware upgrades and deliver additional training to their IT staff. The first phase of configuration and ACL rule development needed detailed planning to prevent disruptions to essential interdepartmental services.

VII. CONCLUSION

VLAN capabilities to provide scalable network segmentation in hybrid and cloud environments where it supports more than 4096 logical networks beyond the IEEE 802.1Q limit The implementation of VLAN technology at OSHEE has been instrumental in modernizing the network infrastructure which supports a wide range of operations across all 12 prefectures in Albania. The logical segmentation of the network by departments such as Finance, Archive, Metering and Technical Control has resulted in a higher level of operational efficiency, reduced unnecessary broadcast traffic, and better data flow within and across the regional branches.

The centralized VLAN model supported by Layer 3 switches and core routers has enabled secure inter-VLAN communication while maintaining departmental independence. The implementation of VLAN Access Control Lists (VACLs), 802.1X authentication, DHCP snooping, and port security has greatly enhanced the security of the network against internal threats, unauthorized access, and potential lateral movement by malicious actors.

In conclusion, OSHEE's VLAN implementation stands as a model of best practice in enterprise network design. It illustrates how advanced segmentation strategies can lead to a more secure, scalable, and responsive IT environment. As digital demands continue to grow in the energy distribution sector, the foundation established through VLAN integration positions OSHEE to meet future technological challenges with confidence and resilience.

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