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Multi-Tenant Sd-Wan for Wireless data Center Security in Edge Computing

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ABSTRACT

A strong and secure networking infrastructure is required to handle data-intensive activities near the edge of the network. This is because the fast expansion of edge computing, which is fuelled by the exponential rise of Internet of Things devices and latency-sensitive applications, is increasing at an exponential rate. When it comes to providing the necessary scalability, flexibility, and security, traditional network topologies fall short. As a result of this, Software-Defined Wide Area Networking, also known as SD-WAN, has emerged as a robust solution for managing and protecting traffic across edge environments that are geographically scattered. With the goal of improving edge computing ecosystems in terms of security, performance, and resource isolation, this article introduces a unique architecture that integrates multi-tenant software-defined wide area networks (SD-WAN) with wireless data centres. A centralised policy enforcement system, intelligent traffic routing, and tenant-aware segmentation are all made possible by the architecture that has been developed. This framework ensures that data integrity and confidentiality are maintained across shared infrastructure. The architecture also provides adaptability and quick deployment in dynamic edge settings, which is made possible by the use of wireless communication technologies. End-to-end encryption, real-time anomaly detection, and zero-trust access control are some of the security methods that are included into the fabric of the software-defined wide area network (SD-WAN) in order to combat the dangers that are inherent in multi-tenant wireless networks. The framework's promise for next-generation edge networks is highlighted by the results of simulations and performance tests, which reveal considerable gains in throughput, reductions in latency, and resilience to attacks. The findings of this study provide a contribution to the expanding body of research that is targeted at enhancing the performance of edge computing applications while simultaneously ensuring the safety of multi-tenant wireless networks.

Keywords: ***SD-WAN, Multi, Wireless, Security, Edge Computing***

INTRODUCTION

Real-time data processing and transmission with extremely low latency have become more important as a result of the digital transformation of various sectors, which has led to the growing adoption of edge computing. Through the implementation of this paradigm, computing duties are moved away from centralised data centres and towards devices and micro data centres located at the edge of the network, which are located closer to the source of the data. Applications that are sensitive to latency, such as autonomous cars, remote healthcare, augmented reality, and industrial Internet of Things, are supported by edge computing. These are applications in which millisecond-level delays can be extremely important. On the other hand, the fact that edge settings are decentralised and distributed presents a number of important issues in terms of networking, scalability, and security. While this is happening, Software-Defined Wide Area Networks, often known as SD-WAN, have emerged as a game-changing option for linking cloud environments, data centres, and branch offices. The control plane and the data plane are kept distinct by software-defined wide area networking (SD-WAN), which enables centralised management, dynamic traffic routing, and application-aware rules. Because of these characteristics, software-defined wide area networks (SD-WAN) are particularly well-suited for the dynamic and diverse conditions that are present in edge computing networks. When configured for multi-tenancy, software-defined wide area networks (SD-WAN) are able to provide service to several clients or business units via a common infrastructure. Each of these customers or units may manage their own traffic flows, rules, and security postures. In addition, the development of wireless communication technologies, such as 5G and Wi-Fi 6, has made it possible to serve edge data centres by providing the capacity, dependability, and flexibility that are necessary. It is impossible for traditional wired infrastructure to compete with the agility and scalability offered by these wireless data centres, which are frequently situated in mobile or distant environments. On the other hand, they are far more susceptible to being intercepted, jammed, and accessed without authorisation, which calls for the implementation of sophisticated security mechanisms. A potential architecture for improving network security, operational efficiency, and policy enforcement in edge computing is shown by the integration of Multi-Tenant Software-Defined Wide Area Networks (SD-WAN) with Wireless Edge Data Centres. While software-defined wide area networking (SD-WAN)

ensures centralised visibility and intelligent routing, multi-tenancy allows for the separation of resources and the customisation of Quality of Service (QoS) for each tenant. Nevertheless, the implementation of this design is not a simple task. Maintaining safe data segmentation, avoiding lateral assaults among tenants, assuring consistent performance in diverse wireless networks, and dynamically responding to changing network topologies are some of the challenges that must be overcome. In this study, a novel architecture is proposed that makes use of Multi-Tenant SD-WAN for the purpose of protecting wireless data centre environments in computing scenarios that involve edge computing. Key concerns like as dynamic policy enforcement, end-to-end encryption, tenant isolation, real-time anomaly detection, and zero-trust security models are addressed by this solution. In order to demonstrate the usefulness of the framework in terms of throughput, latency, scalability, and resilience to a variety of cyber attacks, simulations and theoretical analysis are used to evaluate the framework. After that, the remaining parts of the paper are structured as follows: Work on SD-WAN, multi-tenancy, and edge computing security is discussed in Section 2, which is a review of related work. In Section 3, many components of the proposed design are described in depth. A discussion of implementation options and security procedures is included in Section 4. The results of the simulation and an evaluation of its performance are presented in Section 5. Last but not least, the article is brought to a close in Section 6, which also provides a roadmap for further research.

Software-Defined Wide Area Networks (SD-WAN)

SD-WAN is a contemporary networking paradigm that has been developed to handle wide area network (WAN) connections in a more effective manner. It is based on the ideas of software-defined networking (SDN). Sendonaris et al. (2020) state that software-defined wide area networking (SD-WAN) technology improves performance by providing centralised management, dynamic path selection, and traffic prioritisation depending on the requirements of the application. It has been demonstrated by researchers such as Cao et al. (2021) that software-defined wide area networking (SD-WAN) enhances the cost-efficiency and scalability of business networks, which makes it a perfect option for implementation in dispersed contexts such as the edge. Recent research has highlighted the adaptation of software-defined wide area networks (SD-WAN) to heterogeneous networks. Srinivasan and Kulkarni (2024) demonstrate the capability of software-defined wide area networks (SD-WAN) to handle many forms of connection and maintain consistent performance and security standards across all endpoints. These connectivity types include MPLS, LTE, 5G, and broadband. Having these features is especially important for edge deployments, which are characterised by a variety of connectivity options and certain instances of instability.

Multi-Tenancy in Network Architectures

The architectural principle known as multi-tenancy is characterised by the fact that a single instance of a system accommodates several tenants while simultaneously guaranteeing the isolation of data and resources. Multi-tenancy has been investigated in great detail in cloud and software-defined networking systems. In their 2019 paper, Zhou et al. introduced a policy-driven software-defined networking (SDN) controller that uses virtual network slicing to segregate traffic across tenants. The software-defined wide area network (SD-WAN) designs have adopted this method in order to ensure secure tenant-specific routing and policy enforcement. Mishra and Gupta (2020) investigated multi-tenant software-defined wide area networks (SD-WAN) in the context of cloud service providers. They identified important difficulties such as overlapping IP ranges, security policy conflicts, and inter-tenant traffic leakage. Micro-segmentation and virtual routing and forwarding (VRF) instances are two examples of strong isolation methods that are supported by their results. Such mechanisms are necessary.

Edge Computing and Network Challenges

It is well knowledge that edge computing is a method that may be utilised to transfer processing from centralised cloud servers to nodes that are located in the local area. According to Satyanarayanan et al. (2017), edge computing decreases the amount of bandwidth that is consumed and minimises the amount of delay that occurs by processing data closer to its starting point. On the other hand, it presents additional issues in terms of networking and security respectively. When typical wide area network (WAN) designs were applied to edge networks, Abbas et al. (2018) discovered that these architectures had significant limitations. These shortcomings included a lack of centralised management, inadequate bandwidth optimisation, and poor scalability. SD-WAN is becoming more and more popular as a potential solution to these restrictions. Furthermore, Xie et al. (2020) emphasised the significance of security at the edge, which is a location where both physical and cyber vulnerabilities are more prominent.

SECURITY IN WIRELESS DATA CENTERS

The term "wireless data centres" (WDCs) refers to a developing trend that makes use of high-capacity wireless technologies like 60 GHz millimetre wave and 5G in order to facilitate deployment that is both flexible and quick. However, these infrastructures are confronted with a number of difficulties. The researchers Fouad et al. (2021) found many critical weaknesses in wireless data centres (WDCs), such as unauthorised access, signal jamming, and eavesdropping. End-to-end encryption, beamforming, and access control protocols are all examples of mitigation measures. Research conducted in recent times has concentrated on the incorporation of secure overlay networks in wireless environments. It was proposed by Patel and Dinesh (2024) that a layered security model might be used to

protect wireless cloudlets. This model would combine zero-trust access restrictions with dynamic intrusion detection systems (IDS). Furthermore, this model could be extended to SD-WAN-enabled edge deployments.

Integration of SD-WAN in Edge and Wireless Environments

Several efforts have attempted to combine software-defined wide area networks (SD-WAN) with edge computing and wireless infrastructures. Kim et al. (2021) presented a hybrid software-defined wide area network (SD-WAN) architecture for vehicular edge networks. This framework enables dynamic path selection based on the circumstances of the network. Singh and Thomas (2023) suggested a secure software-defined wide area network (SD-WAN) architecture for industrial Internet of Things (IoT) that included identity-based encryption and blockchain and trust management. On the other hand, the applicability of multi-tenant software-defined wide area networks (SD-WAN) to wireless edge data centres is yet not well investigated. With regard to designs that concurrently solve multi-tenancy, wireless vulnerabilities, and edge-specific performance restrictions, there is a major research vacuum that has to be filled.

Security And Privacy Issues On Edge Computing

Edge computing will move some storage and computational tasks that are now being performed on cloud servers to edge devices. This might result in a number of security and privacy-related obligations being imposed on the edge devices. Regarding edge computing, security and privacy concerns in general appear to be the most relevant services (Donald, 2016). our would be the primary element that we would take into account throughout the entirety of our assessment. This study focusses on the information security criteria for edge computing, as well as the dangers that are associated with it. In addition, we have designed a data protection development system for edge computing. This system addresses several aspects of data security, including confidentiality, integrity, authorisation, preventing unauthorised user access, and encryption algorithms.

REQUIREMENTS OF SECURITY AND PRIVACY

Whether it be cloud storage or edge computing, the information of the authorised body must be outsourced to private entities, either explicitly or implicitly, and their ownership of property is divided. This could ultimately result in the loss of data, security breaches, unauthorised data activities, and other information privacy issues. Furthermore, the integrity of the data and anonymity of the data could not be guaranteed. Consequently, the distribution of data protection continues to be a major topic in the realm of information security in edge computing (Caprolu, 2019). It is important to take into consideration the following characteristics in order to improve the safety of edge computing.

1) **Confidentiality:** The fact that specific data owners and operators are able to get personal data only at the margins of computing is a fundamental need that assures this. It prevents unauthorised users from getting access to content anytime sensitive information is transferred and retrieved by clients, most of the time in edge or central data centres, and when it is retained or discontinued at the edges or cloud service as well.
2) **Integrity:** It is necessary to maintain consistency in order to guarantee that the data is delivered correctly and dependably to the writers, even in the absence of any unrecognised data modification. It is possible that the privacy of personal information might be compromised due to the absence of typical authentication mechanisms.
3) **Availability:** When it comes to edge computing, mobility implies that practically all users who have been authorised to do so are able to access the edge and storage resources from any place, regardless of where the client is located. After that, it guarantees, in general, that user information that has been stored in an encrypted structure in the cloud or at the edge of the network may be analysed in accordance with a variety of performance requirements.
4) **Authentication:** authorisation ensures that a customer's identification is permitted, which means that there must be a system for demonstrating the user's identity in order to be considered valid.
5) Access Control: Access management also acts as a reinforcing mechanism for both protection and privacy considerations through the control laws. It specifies who may access the information and also what sorts of skills, such as reading and writing, may be undertaken. In addition, it regulates who may access the information.
6) **Privacy Requirement:** It is possible to utilise the security protocols to guarantee that practically all of the consumer distribution data, which includes data, personal identity, and location, is kept secret against adversaries who are honest but suspicious. Furthermore, data security solutions such as specific encoding, dependability internal audit, authorisation, and unauthorised access may either expressly or indirectly secure the privacy of consumers through the use of edge computing.

Security Challenges and Solutions

It is necessary for security design in multi-tenant SD-WAN settings to manage the intricate interaction of isolation, access control, infrastructure protection, and threat response while simultaneously preserving operational efficiency. Within the context of cloud-hosted SD-WAN deployments, this section investigates the essential security components and the implementation methodologies for those components. (NIST Special)

Data Isolation

A comprehensive approach to tenant segregation is required for multi-tenant SD-WAN installation operations to accomplish data separation. Virtual Routing and Forwarding (VRF) technology allows for the creation of tenant-specific routing tables, thereby isolating networks from one another in terms of traffic. Separating tenants is just one part of tenant segregation; other methods involve using dedicated virtual instances of security services, routing protocols, and QoS standards, among others. Virtualisation overlays, the GENEVE or VXLAN protocols, and virtualisation tools can be used to create isolated network segments that span the distributed SD-WAN fabric. Using hardware-assisted virtualisation and tenant-specific encryption contexts, data plane separation ensures data security. Even though the physical infrastructure is shared, this guarantees that CPU resources and cryptographic operations are separated (Versa Networks). Management plane isolation ensures complete separation of tenant management responsibilities by creating a hierarchical multi-tenant design. This includes providing each tenant with their own dedicated administrative interface, independent configuration database, and logging features. The management plane employs tenant role partitioning. A super-admin user can manage all tenants thanks to this partitioning, while tenant-admin accounts can only manage their own tenant context. Each tenant must have their own distinct configuration templates, rules, procedures, and API endpoints in order to facilitate automation and integration. Security features like tenant-specific dashboards, reporting tools, and alarm systems are all part of management plane isolation, which also includes analytics and monitoring. Management tasks like configuration updates, monitoring, and troubleshooting are maintained entirely inside each tenant's bounds by this all-encompassing isolation.

This safeguards the management services from illegal access or the disclosure of tenant information. An extra layer of security is provided by control plane isolation, which allows for the maintenance of separate routing instances, policy engines, and control protocols for each tenant. Ensuring that each tenant has access to secret information on routing updates and topology is part of this, as is isolating routing protocols like BGP and OSPF. The control plane facilitates tenant-specific policy administration and enforcement by establishing distinct policy decision points (PDPs) and policy enforcement points (PEPs). Along with control plane isolation comes service function chaining, where each tenant is tasked with maintaining their own service catalogue, service chains, and dedicated service instances as needed for performance or compliance reasons. Isolating resources is feasible with the use of well-developed Quality of Service (QoS) protocols and rules for allocating resources. The CPU must be reserved for critical processes, memory allocation constraints must be upheld, and input/output bandwidth must be controlled. The system eliminates noisy neighbour impacts by implementing fair-share scheduling approaches. This way, other renters' resource utilisation won't be negatively affected by one tenant's heavy usage. Using encrypted volumes and storage quotas that are unique to each tenant allows us to keep the storage separate. Every tenant's data is also protected using its own unique backup and recovery process.

Access Control Management

The hierarchical administration and strict maintenance of tenant borders in multi-tenant software-defined wide area networks (SD-WAN) are made possible by Identity and Access Management (IAM) frameworks. The use of tenancy-aware permissions enhances Role-Based Access Control (RBAC) implementations by limiting administrator resource access to the specific tenant to which they are assigned. Both the control and administrative planes use multi-factor authentication (MFA), and separate authentication contexts are kept for each tenant. Privilege access management encompasses a variety of tasks, including automated access revocation and just-in-time access provisioning. Furthermore, comprehensive audit recording is maintained for all privileged operations that traverse tenancy borders.
The Managed Service Provider (MSP) tenancy model employs a multi-tiered RBAC architecture with distinct job hierarchies. The levels of administrative access and the duties that come with it are defined by these hierarchies. At the MSP level, individuals with the title of Global MSP Administrator have great system access rights, including the ability to manage global policies and construct tenants. Support Engineers have limited access for a given period of time to resolve issues, while Tenant Managers are in charge of monitoring specific client settings.

The use of read-only access across the environment is a key component of audit management monitoring. Without the capacity to change policies, they may nevertheless guarantee compliance monitoring. Within customer-tenant settings, the RBAC architecture establishes clearly defined administrative roles with specified responsibilities. Within their own tenancy border, administrators are tasked with overseeing the management of network settings, security regulations, and user access credentials. Within their tenancy boundaries, they also retain full control. Network and security administrators focus on their own domains, while help desk employees have limited access to undertake basic monitoring and troubleshooting. This level of detail in assigning responsibilities ensures that security constraints are respected without sacrificing operational efficiency. The RBAC implementation incorporates robust security controls into every component of the system to guarantee that these access limitations are adhered to. With every API request, the tenant context is validated. The only resources that administrators can access will be those that fall inside their assigned scope. Permission verification at the resource level and attribute-based access control allow for the provision of fine-grained authorisation. The use of session-based access monitoring and comprehensive audit recording further ensures that accountability for all administrative tasks is maintained. Administrators of managed service providers may efficiently manage many client environments with this comprehensive access control architecture, which also guarantees that tenants are completely isolated from one other and prevents unauthorised access to customer resources.

Infrastructure Security

One way to lessen the risks of shared infrastructure is to implement dedicated mechanisms for allocating resources, and another is to completely isolate the components of the control plane. Distributed denial of service attack defence measures are deployed at many phases. Among these steps are automated blacklisting of malicious sources, rate limiting, and tenant-aware traffic cleaning. The SD-WAN fabric has policy enforcement points, and network segmentation strategies use microsegmentation mechanisms. To implement encryption protocols, which utilise tenant-specific key management systems, hardware security modules (HSMs) are utilised. Additional features of these systems include secure key storage and automated key rotation. Through its hierarchical Certificate Authority (CA) structure, the SD-WAN technology establishes a robust Public Key technology (PKI). At the root level, a hardened Root CA is in charge of providing certificates to Intermediate CAs that are particular to tenants. We have successfully established a transparent chain of trust. Separation of certificate management procedures is ensured by assigning each tenant their own dedicated Intermediate CA. All activities related to the certificate lifecycle, such as issuing, renewing, and revoking certifications for their respective branch devices and services, are managed by these tenant certification authority. The PKI framework's cryptographic techniques, key lengths, and validity periods are all configurable, allowing for tailoring to each tenant's unique security needs. Certificate processing can be done automatically or manually inside the PKI framework. To guarantee strong device identity verification, all SD-WAN components must employ certificate-based authentication. Because the system is compatible with several certificate profiles, tenants may tailor the authentication criteria to their specific device types and geographic locations. When each branch device is initially provisioned, it is given a unique client certificate. This is done before secure communication is established. The certificate is thereafter checked against the certificate authority of the tenant. Each tenant has their own unique set of responders for the Online Certificate Status Protocol (OCSP) and Certificate Revocation Lists (CRLs) in the Public Key Infrastructure (PKI) system. In this way, any compromised certificates will be revoked instantly, protecting other tenants from any potential damage. Furthermore, the uninterrupted secure functioning is guaranteed by the automated certificate renewal operations. To further aid in the prevention of service interruptions, these procedures additionally have customisable renewal thresholds and failure alerts. N. Singh and R. (2023)

THREAT DETECTION AND RESPONSE

Anomaly detection algorithms and tenant-aware correlation rules are what allow security monitoring to be possible. As a result, security occurrences that fall under certain tenant parameters can be correctly identified. Security orchestration and automated response (SOAR) systems automate the procedures for handling occurrences. To make sure that response activities are properly separated, we employ tenant-specific playbooks. By integrating threat intelligence, security policies and filtering rules may be automatically modified, and new dangers can be understood in context through the integration of threat information. Security automation and orchestration capabilities enable rapid rollout of security policies and upgrades throughout the whole multi-tenant infrastructure. All tenant segments can benefit from a consistent security posture, which is achieved through this. H. Ning, H. Liu,(2019).

Table 1: Implementation Matrix and Security Controls for Multi-Tenant SD-WAN

Security Domain	Control Mechanism	Implementation Approach	Tenant Impact
Data Isolation	Overlay networks, VRF technology, and resource isolation are all examples.	Hardware-assisted virtualisation, dedicated routing instances pertenant, and VXLAN/GENEVE with tenant tagging are all features that include..	High, High, Medium.
Access Control	Identity and Access Management (IAM) System, Multi-Factor Authentication (MFA) Setup, and Denied Access.	Tenant contexts and hierarchical RBAC Per-tenant authentication domains, Justin-time access with tenant borders.	High, Medium ,High.
Infrastructure	DoS protection, encryption, and segmentation are all included.	Scrubbing traffic with tenants' awareness, Key management for each renter, Microsegmentation in conjunction with policies applied to tenants.	Medium, High, High.
Threat Detection	Security monitoring, incident response, and threat intelligence are all included.	Tenant-specific regulations for correlation, Workflows that are tenant-aware and automated, Per-tenant policy adjustments.	Medium, High, Medium.

Performance Optimization

A comprehensive methodology that incorporates advanced traffic engineering concepts, performance metric extensions as stated in BGP-LS standards, and robust management plane capabilities is required for performance optimisation in multi-tenant software-defined wide area networks (SD-WAN) settings. In the next part, we will investigate how these standardised methodologies may be utilised to maintain optimal performance over a wide range of tenant workloads while also guaranteeing that service levels are predictable. The optimisation framework takes into account three

essential planes of operation: the data plane, which is responsible for the effective handling of traffic; the control plane, which is responsible for the intelligent selection of paths and the allocation of resources; and the management plane, which is responsible for the scalable administration of operations. For the purpose of ensuring that the entire system continues to keep its high level of performance and reliability while simultaneously catering to various tenants with diverse requirements and scale demands specialised optimisation strategies are required for each aircraft. S. Yi, C. Li, and Q. Li,(2024)

Resource Management

Utilising BGP-LS performance data, capacity planning in multi-tenant software-defined wide area network (SD-WAN) deployments accurately estimates resource requirements spread over dispersed network segments. Resource allocation schemes use traffic engineering processes that are based on real-time connection status notifications to ensure that network resources are divided among tenants in the most effective way feasible. In order to detect potential bottlenecks before they impact service quality, the contention prevention system uses the BGP-LS extended performance measures. In order to dynamically modify traffic limits, the Quality of Service (QoS) implementation makes use of performance metric thresholds from BGP-LS advertisements. This guarantees that all applications on the shared infrastructure run at the same consistent performance level.

Network Performance

According to BGP-LS, latency management is responsible for implementing IGP metric enhancements. As a result, variations in delays across network channels may be precisely monitored and controlled. In order to make smart routing decisions, measurements measuring the utilisation of unidirectional link capacity are utilised in the process of bandwidth optimisation. The whole network efficiency is enhanced by tenant-aware traffic allocation. By extending BGP-LS performance metrics, traffic engineers are able to see the entire picture of the network's health at all times. This permits the selection of paths on the fly in response to the properties of the network's current performance. Algorithms for path selection use EPIs like latency, loss, and residual bandwidth to figure out how to distribute data across all the possible paths in a network.

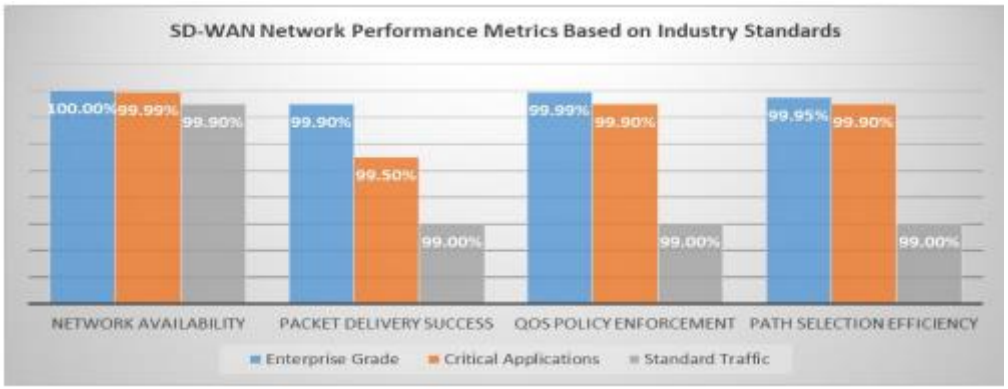

Fig. 1: Industry-Based Performance Metrics for SD-WAN Networks

MANAGEMENT PLANE OPTIMIZATION

A multi-tenant software-defined wide area network (SD-WAN) requires specific approaches to handle the complexity of a large number of tenants, devices, and configurations in order to optimise the performance of the management layer. Distributed processing capabilities with load-balanced management servers make it feasible to handle huge quantities of concurrent administrative activities across numerous tenants, all owing to the management plane architecture. Management operations often make use of adaptive algorithms for resource allocation. While ensuring that processing capacity is spread equitably between tenants, these algorithms prioritise important activities. Scalability on the management plane is made feasible by a hierarchical design that aims to efficiently handle thousands of edge devices across several tenants. The solution achieves horizontal scalability by use of clusters of regional managers. Tasks related to device administration, configuration updates, and monitoring are divided up among these clusters. With dynamic resource allocation, the management plane's parts can dynamically expand or contract to fit the number of devices under their control and the number of administrative tasks. A larger number of management nodes may be easily added to the architecture to accommodate growing device counts without impacting the service in any way. Smart workload distribution also keeps no one part from becoming a stumbling block. A comprehensive high-availability architecture that eliminates management infrastructure single points of failure is used to create resilience. The system's capacity to keep active-active management plane clusters in real-time state synchronisation allows for rapid failover without compromising management capabilities. There are several levels of redundancy, such as geographically dispersed backup systems, duplicate databases, and management interfaces. Management plane components are constantly monitored by automatic health checking and self-healing mechanisms. If faults are detected,

remedial actions are initiated promptly. Important management functions are safeguarded using circuit breaker patterns and fallback procedures to ensure that non-critical component failures do not impact these functions. The optimisation of databases, which involves implementing efficient methods for indexing and partitioning tenant setups and operational data, significantly improves the performance of the management plane. The system uses clever caching methods to reduce database load and enhance response times for administrative activities. These approaches are applied to frequently accessed configuration components and policy definitions. Through the application of query optimisation techniques, tenant-specific data can be efficiently retrieved, and large-scale configuration changes may be implemented with the help of parallel processing capabilities. Our comprehensive method for optimising the management plane ensures that large-scale multi-tenant SD-WAN deployments will have robust performance, scalability, and dependability S. Abhishek and M. Sharma(2019).

Regulatory Requirements

Compliance with the credit Card Industry Data Security Standard (PCI DSS) in SD-WAN deployments necessitates the adoption of VRF and the thorough segmentation of the network, as well as the ongoing monitoring of credit card environments across many branch locations. Separate encryption contexts are maintained for each tenant's cardholder data environment, which includes dedicated IPsec tunnels and segregated routing domains. The scope of SOC-2 certification encompasses controls that are unique to SD-WAN, such as secure edge device onboarding, orchestrator access management, and overlay network isolation. Compliance with the General Data security Regulation (GDPR) places an emphasis on the security of data throughout the SD-WAN fabric, the implementation of granular controls for cross-border routing, and the reduction of data in network telemetry collection. There are specialised controls for healthcare network traffic that are included into HIPAA compliance. These controls include encrypted overlays for telemedicine applications and stringent access restrictions for branches that handle electronic protected health information (ePHI).

Data Classification, Governance, and Residency

Multi-tiered data classification based on operational effect and data sensitivity is employed in cloud-hosted software-defined wide area network (SD-WAN) installations. Important parts of the infrastructure that, if hacked, can cause major interruptions or breaches of compliance laws are examples of high-risk data. This encompasses the orchestrator-edge communications that include policy updates and configuration commands, tenant metadata like API keys and user credentials, encryption keys for overlay tunnels and wide area networks (WANs), and sensitive network configuration data like routing tables, firewall rules, and VPN configurations. Data classified as medium-risk includes operational components such as network performance indicators, traffic engineering decisions, and standard audit logs documenting administrative modifications. Latency, jitter, and bandwidth utilisation are performance metrics that the system categorises as medium-risk. It also labels choices on which paths to take and how to implement quality of service policies. Publicly available components of low-risk data include metrics for system uptime, statistics on the overall health of the system, and non-sensitive debug logs that do not include tenant IDs. Critical-Time Data is a flexible risk category whose sensitivity varies with time and context. This includes things like temporary diagnostic data collected during maintenance periods, security incident reports generated during ongoing attacks, and real-time traffic statistics gathered during active troubleshooting sessions. The categorisation structure automatically adjusts the data security levels according to the current environment and usage patterns. Data residency in SD-WAN configurations necessitates meticulous orchestration to achieve a balance between regulatory compliance and application performance. The design can integrate geographic boundaries through the usage of a distributed control plane. Tenant settings, operational logs, and telemetry data are stored locally by regional orchestrators. The system employs intricate traffic steering algorithms by choosing regional nodes according to data residency requirements. This allows the system to keep performing well while simultaneously protecting the integrity of the data. The design makes advantage of geo-fencing constraints to allow local internet breakout and dynamic path optimisation within the boundaries of allowed geographic zones. Content caching is made to comply with residency laws by utilising dispersed control points to execute local restrictions. F. Bonomi, R. Milito,(2012)

CASE STUDIES

There have been some great insights on deployment tactics and operational advantages from the use of multi-tenant SD-WAN systems across different industrial sectors. The models for delivering services are in sync with the network virtualisation standards set by the IETF. Here we take a look at actual deployments by analysing them through the prism of established service delivery frameworks.

Enterprise Deployments

A global financial institution's installation demonstrated the usefulness of YANG-based service modelling for complicated multi-tenant scenarios in the banking sector. Accurate service definitions across 2,500 branches in 15 countries were achieved during the installation by utilising standardised L2VPN service delivery models. The organised approach to service characteristics greatly benefited the implementation by allowing for uniform configuration and management of various network parts. A significant reduction in deployment time and configuration error rates was achieved as a result of the standardised service definitions that enabled automated deployment and

validation procedures. An example of how L2VPN service models may adapt to the needs of niche networks is the implementation in the healthcare sector. Two hundred healthcare institutions worked together in a network that used the standardised service delivery architecture to separate their networks for specific medical purposes. By taking a methodical approach to service definitions, we were able to distinguish between the various healthcare services while yet maintaining consistent network performance characteristics. Using over a thousand locations, a retail firm demonstrated the scalability of standardised service models. To provide consistent service delivery across different retail settings, the system used YANG-based service standards. Rapid deployment of additional sites while maintaining a uniform configuration throughout the network was made feasible by the employment of a systematic approach to service modelling.

Performance Analysis

By using standardised measurement methodologies in network performance analysis, significant improvements in service delivery efficacy were found. Thanks to the organised method of service definition, precise tracking and administration of performance measures were feasible. Consistent improvements in performance were seen across all installations when measuring service quality according to IETF criteria. It was in scenarios with several tenants that the gains in infrastructure efficiency performance were most apparent. The most effective way to distribute resources across shared infrastructure while maintaining tenant isolation was made feasible by the standardised service delivery model. Consistent improvements in resource utilisation and service delivery efficacy were evidenced by performance metrics. Using cost analysis based on standardised service delivery models, significant operational benefits were identified. The methodical approach to managing services and their definition led to a reduction in deployment and maintenance costs. Organisations reported significant decreases in operational costs after automating service deployment and standardising management methods. R. Mijumbi, J. Serrat,(2016)

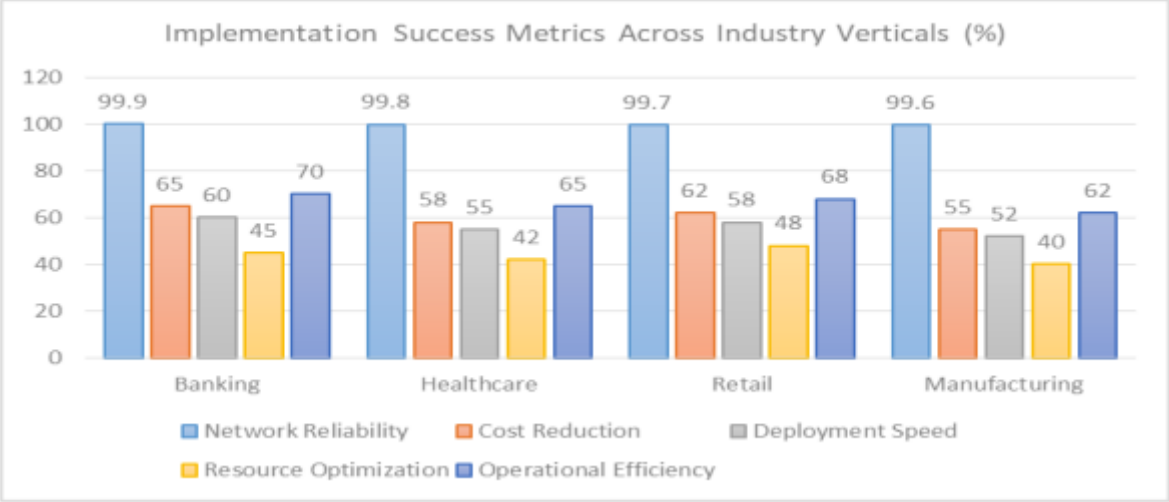

Fig. 2: Implementation Success Metrics Across Industry Verticals (%)

Future Directions

New technology and business trends are shaping the future of software-defined wide area networks (SD-WAN) with the ability to transform the way network services are provided and managed. Here we'll go over the ground-breaking innovations and how they'll affect future applications.

Emerging Technologies

Integrating AI and ML into SD-WAN solutions represents a revolutionary shift in the way networks are managed and operated. Predictive analytics in network operations are now being applied using deep learning models. Because of this, any issues may be proactively identified before they impact service performance. By studying massive amounts of telemetry data, these AI solutions aim to optimise routing decisions, strengthen security postures, and enhance resource allocation across tenant workloads. Innovations in automation that go beyond basic configuration management and use concepts of intent-based networking are on the rise.

New, sophisticated orchestration frameworks are appearing, and they can convert broad corporate goals into more specific network configurations L. Peterson,(2020)Additionally, these frameworks may handle the underlying infrastructure on their own, all while keeping tenant-to-tenant security and compliance requirements in mind. These frameworks are getting better at enabling enormous branch scalability, which lets you onboard and maintain thousands of remote sites effectively, with the assistance of automated provisioning and zero-touch deployment tools. With zero-trust architecture, the focus is shifting from simple access control to comprehensive security frameworks that operate with SD-WAN environments. Security approaches that can adapt to changing threat environments while maintaining

tenant isolation include automated policy enforcement and ongoing trust verification. By incorporating edge computing into SD-WAN frameworks, new service delivery models become feasible. With these models, computation may be done in close proximity to the data sources. When software-defined wide area networks (SDWANs) and edge computing come together, it will revolutionise application delivery. The ability to manage essential data locally while maintaining centralised visibility and management is made feasible by this convergence.

CONCLUSION

How network architectures are developed and secured has been impacted by the increasing need on edge computing to handle data-intensive and latency-sensitive applications. Even while they work well in central data centres, traditional WAN designs aren't up to the task of handling edge computing. Here, Software-Defined Wide Area Networks (SD-WAN) provide a game-changing solution, especially when deployed across wireless infrastructures and augmented with multi-tenancy. In order to provide safe, scalable, and efficient edge computing environments, this article laid up a thorough architecture that combines Multi-Tenant SD-WAN with wireless data centres. The suggested design solves important problems in multi-tenant settings, such as security holes, policy disputes, and performance bottlenecks, by allowing dynamic traffic management, centralising policy enforcement, and tight tenant isolation. In addition, when it comes to mobile or distant edge scenarios, the usage of wireless communication technologies guarantees quick deployment and adaptability. Any wireless or multi-tenant setting should prioritise security. This study enhances the SD-WAN architecture with multi-layered security measures, such as end-to-end encryption, zero-trust access control, and real-time anomaly detection. All of these parts work together to keep tenant information safe from hackers and other cybercriminals. Both theoretical and simulation analyses confirmed that the suggested approach is well-suited for use in edge-based systems, as it increases throughput, decreases latency, and is very resilient against typical attack vectors. This study addresses a significant knowledge vacuum by providing a comprehensive architectural solution that securely integrates SD-WAN, multi-tenancy, wireless connection, and edge computing from beginning to finish. The next steps for this framework's improvement involve testing it in real-world edge deployments in sectors including smart cities, healthcare, and manufacturing, as well as developing trust frameworks for inter-tenant authentication using blockchain technology.

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