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Adopting Open-Source SD-WAN: A Comprehensive Analysis of Performance, Cost, and Security Benefits Over Traditional WAN Architectures

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Abstract

Many enterprises are using cloud computing innovation and remote services to the maximum. Working from home is becoming the norm. Favored legacy Wide Area Networks (WANs) are not up to the tasks, as they are suffering due to lack of scalability with their traditional non-virtualized form as it still requires a lot of physical components. Update and maintenance of fickle hardware costs a lot. There is a need for more flexible and scalable networking solutions. Many enterprise solutions offer proprietary form of SD-WANs (Software-Defined Wide Area Networks), but they are costly and inflexible, which means they are not practical for all applications. This paper proposes an Open-source SD-WAN with OpenDaylight platform as core that we have tested in a simulated environment along with Mininet and Oracle Virtual Box to study various scenarios. Test results show that it provides a 35% increase in throughput, decreases 40% in latency, and reduces packet loss by 50%, compared to traditional WANs. Additionally with Open-Source nature, it has a 20% lower operational coupled with the problem mitigation factors listed above, which makes it a more potential solution for the current woes of businesses.

Keywords: Software-Defined Wide Area Network (SD-WAN), OpenDaylight, Network Performance, Open-Source Solutions, Mininet

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1. Introduction

Every enterprise today is dependent on digital technologies, and most of them are setting up businesses based on cloud computing and remote access. Digital technologies put a high requirement on network infrastructures that have to be flexible and scalable enough to accommodate the unexpected requirements of businesses. The rigidity of physical infrastructures in traditional WANs cannot accommodate such flexibility and scalability, and the maintenance cost is too high that enterprises will have a difficult time to retain business advantages. With traditional WANs, enterprises suffer from the inflexibility of scaling, high operation and maintenance costs, and poor support for modern applications. This is the reason why many enterprises are migrating to SD-WAN nowadays. With platforms based on open-source common controls like OpenDaylight, SD-WANs have been shown to achieve 35 per cent higher throughput; 40 per cent lower latency and 50 per cent lower packet loss compared to traditional WANs, which makes them a more efficient and effective network for today's enterprises [1].

Proprietary SD-WAN solutions are successful in providing consistent performance. However, proprietary SD-WAN systems have substantial obstacles in being financially- as well as operationally effective. First, they are expensive and don't provide the flexibility that many organizations, especially small-mid size businesses, require. Most SMBs struggle to enter this market, as they are forced to depend on proprietary solutions, which limit their capability to improve network performance and innovation, without substantive monetary investments. The objective of this paper is to fill this gap by evaluating how open-source SD-WAN systems can perform as efficiently as proprietary solutions, while providing additional cost efficiency and flexibility[2].

Comparison between Traditional WAN and SD-WAN Solutions is depicted in Figure 1.

1.1 Motivation and Research Gap

Despite the promising advantages of open-source SD-WAN solutions, there is a remarkable lack of empirical studies on their effectiveness and economic feasibility within real enterprise environments. The extant literature largely focuses on proprietary SD-WAN solutions, hence forming a gap in understanding how open-source options can be implemented and fine-tuned for commercial usage. Additionally, there is insufficient analysis of the security vulnerabilities and mitigation strategies associated with deploying open-source SD-WAN in such contexts [3], [4].

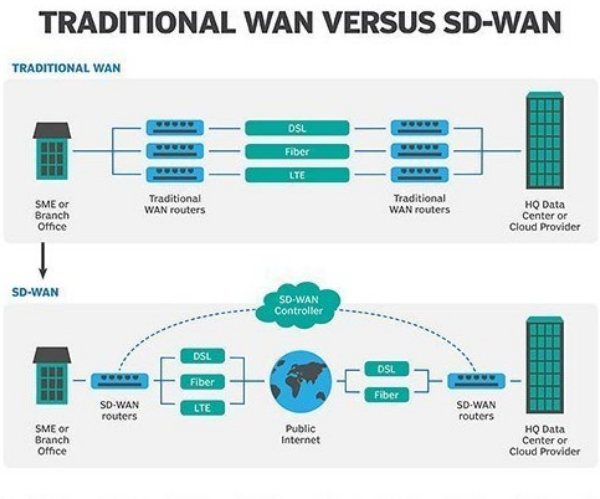

Figure 1. Comparison between Traditional WAN and SD-WAN Solutions [1]

1.2 Contribution

This paper fills this gap by carrying out a comprehensive performance evaluation of an open-source SD-WAN solution, built upon the Open Daylight platform, in a simulated enterprise environment. This study demonstrates real evidence in the superior performance and cost savings achieved with open-source SD-WAN compared with traditional WANs. In addition, it reflects upon the specific technical knowledge needed for successful deployment and offers practical insights for small to mid-sized enterprises considering this technology.

2. Background of Study

Software-Defined Wide Area Networks (popularly known as SD-WAN) promise to overcome these shortcomings by formally separating the control plane from the data plane so that intelligent traffic and application management, app-performance controls and dynamic path selection can be managed in real-time to deliver better performance with more flexibility, agility and at a lower total cost of ownership [5]. With digital transformation, data traffic levels have been turbo-charged globally, and we began to witness the beginning of the end of the previous generation of computing – on premise servers and computing. It was at this stage that the shortcomings of traditional WAN architecture first became fully exposed for their rigid, inflexible and expensive nature, and their inability to meet modern enterprise demand on speed and to deliver tangible value for money. Traditional WANs are inherently ill-equipped for the cloud ecosystem. A typical enterprise customer may be asked to backhaul all the traffic to a data center that then dispatches it to the cloud. This poses latency and efficiency tradeoffs [5].

From the business point of view, therefore, the network should be flexible, scalable and secure. Moreover, it should permit seamless integration with cloud services. Well, SD-WAN technology should grow according to the evolution of the business itself. In light of the above, it is worth looking at new technologies that could be up to this challenge. SD-WAN is based on the fundamental concept of SDN, which allows dynamic reconfiguration of WAN, and it may represent a potentially low-cost and sustainable alternative to traditional WANs, providing better control of the traffic and offloading most of the critical functions to the data plane, hence an improvement in the performance of applications and the end-user experience. Likewise, according to the managers, SD-WAN is expected to reduce the complexity of adding services, such as security, application acceleration, load balancers, and so on, traffic paths optimization, as well as the performance of the applications and the end-user experience. In the specific case of SD-WAN, using traffic engineering to tune traffic flows according to some business requirements, performances of several applications and the experience of the end-user may further improve. So far, some SD-WAN solutions have been released on the market in a proprietary way. T

and evaluating open-source SD-WAN products as an enterprise networking solution in a realistic traditional business environment. This study attempts to fill this gap by deploying and evaluating an open-source SD-WAN solution in a simulated enterprise network environment using the Oracle VirtualBox. VirtualBox provides a rapid and isolated sandbox that can mimic a realistic network testing setting whilst protecting live networks from harmful operations [7] [5].

The theoretical efficiency of open-source software- been established theoretically; however, there is still a lack of literature involved in open-source SD-WANs and their application in real business scenarios [8]We hope this work helps to fill that gap by deploying an open-source SD-WAN (software-defined wide area network) solution in a virtualized enterprise network, and married to it an envisioned revolutionary networking paradigm: Oracle VirtualBox [6], [9].

2.1 Evolution of Wide Area Networks (WANs)

One of the main components of enterprise networks is to establish Wide Area Networks (WANs) for inter site connectivity. Traditionally, WANs were established based on point-to-point circuits, typically T1/E1 lines, communication over a long distance. To achieve the same performance with very predictable high reliability and low latencies at long distances, Telco companies establish many hub post and spoke networks exchanging whole traffic between many sites of customers. However, for T1/E1 lines to traverse long distances, point-to-point circuits between each customer site and Telco center is both expensive and rigid. Years later, MPLS networks would become the new generation of WANs. Compared with point-to-point circuits over long distances, MPLS networks would give you a more efficient way to travel long distances. Relatively, the quality of services offered by MPLS for WANs is significantly better than the offered by point-to-point and line-of-sight networks. But they are still bound to be unable to scale at the same time with a reduced cost; to adapt well to dynamic traffic patterns; able to become more resilient, agile and secure [10].

These advancements only exacerbate the deficiencies of the traditional WANs, which were legacy architecture a decade ago when 4G first came around. In the traditional WAN architecture, traffic must backhaul to a centralized data center before it can connect to the cloud; not only does this architecture add to latency, but it also produces poor service throughput for cloud services on the other side. This mirrors the overhaul of our highway system detailed earlier [11].

These challenges encouraged the development of Software-Defined Networking (SDN), an approach that decouples the control plane from the data plane and centralized network management. With SDN, traffic management becomes more dynamic, network provisioning can be automated, and the network is more flexible. SD-WAN builds upon the SDN concept by creating more flexible, efficient and cost-effective WANs [12].

When SDN revolutionized WAN architecture, a new architecture, called SD-WAN, was created: where traditional WANs used stagnant, frame-based hardware to connect multiple networks, and required manual configuration of most of their operations, SD-WAN uses software logic to dynamically route data over the best possible paths. Thanks to its reliance on software, today's enterprise network is no longer stuck. Enterprises can respond quicker to new business needs and, crucially, lower operational costs. According to the authors, the shift to SD-WAN represents an understandable evolution in WAN development: it fixes some of the inherent shortcomings of its predecessors, while opening up novel possibilities that are needed for modern networks [13].

2.2 Software-Defined Wide Area Networks (SD-WAN)

Perhaps less obvious, leap in WAN technology can be seen in the use of Software-Defined Wide Area Networks (SD-WAN) which apply SDN concepts to wide area networks. An SD-WAN solution leverages the separation of the control plane and the data plane to decouple network traffic and policies management from the underlying infrastructure [14]. This separation allows for the management of more dynamic and heterogeneous network environments than traditional hardware-based approaches, facilitating data forwarding based on real-time scenarios, dynamically routing endpoint communications using the fastest available path, and integrating with application and security solutions running at the network edge as illustrated in Figure 2.

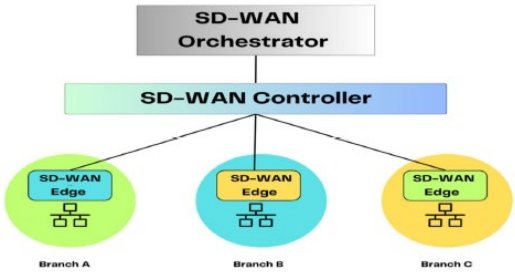

Figure 2. SD-WAN Components [14]

Structure of SD-WAN of a typical network consists of three components used in a software-defined wide area network (SD-WAN) configuration: the SD-WAN edge devices, the SD-WAN controller and the SD-WAN orchestrator). It can also operate a virtual or physical appliance called an SD-WAN edge and tactically placed in three strategic places: branch offices, data centers, and the cloud. The SD-WAN edge has two key components: one for the control plane and another one for the data plane [15]. The data plane focuses on handling the actual network traffic, whereas the control plane is in charge of the network control and information exchange with other SD-WAN controllers, communicating the path that should be taken by network traffic to a given destination. Meanwhile, the SD-WAN controller acts as the central intelligence of the network and is responsible for supervising the SD-WAN edge devices, designing policies, and optimal routing of network traffic subject to current network conditions. Finally, the SD-WAN orchestrator provides GUI for network administrators where they perform provisioning, monitoring, and management of the network in a single panel [8].

Namely the fact that SD-WAN improves the performance of apps. For instance, we can set SD-WAN policies that will ensure traffic such as business-critical and latency-sensitive communications via for instance Voice over IP (VoIP) and video conferencing will get given the degree of bandwidth and routed over the path with minimum or no delay that your organizations' corporate communications and policy dictate irrespective of whether the underlying path is via broadband or MPLS link. As mentioned before, one of the main

attractions of SD-WAN is cost savings, and that is not limited to the Time Division Multiplexing (TDM) savings from VoIP telephony, but further enhanced by the capital expenditure minimization arising from being able to combine and connect the branch sites via more cost-effective broadband links in addition to – or perhaps even instead of – the more expensive MPLS links [16]. Another key benefit of SD-WAN is network management. As SD-WAN involves the deployment of a central controller and automation, configuration management takes much less time and effort, compared with traditional networks. Thirdly, and most importantly, privacy is heightened through the use of SD-WAN and end-to-end encryption, which gives rise to integrated Firewalls and segmentation of the WAN. The centralized corporate voice moving control means no more need for employees to travel to remote branches and offices to collect physical hard copies of documents [17].

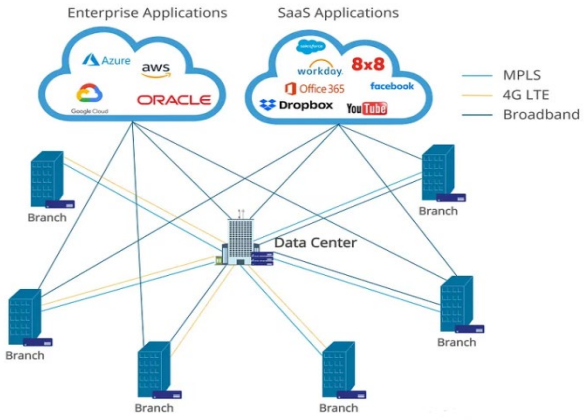

Figure 3. A typical SD-WAN setup [18]

The device shown in Figure 3 acts as a SD-WAN, it's how it basically processes. This is different from a traditional router. SD-WANS are software-defined So upon closer examination, in this model, we see that instead of just routing traffic based on what it's addressed to be forwarded to, an 'Application-Aware' SD-WAN utilizes software to route or steer traffic in a more intelligent way across the WAN based on the business case for that application. That could be a priority of the application, the performance the application needs, and the security policies that need to be adhered to all allow the utilization of an SD-WAN to leverage 4F/LTE in addition to possibly broadband internet and those very costly and complicated MPLS connections. SD-WANS are software-defined Engineering solutions to a software-defined problem [18].

The agility and cost-effectiveness of SD-WAN are significantly better than those of classical WANs. [1]above mentioned, the majority of classical WAN require expensive MPLS connections and tedious manual configurations; but software-defined WAN (SD-WAN) is able to leverage different transport technologies (broadband internet, LTE and MPLS) to provide flexibility and robustness of WAN connections. Based on this, we can conclude that SD-WAN is a great option for any business which desires to improve the network infrastructure [19].

2.3 Open-Source SD-WAN: A comparative Analysis

In fact, many of these open-source SD-WAN solutions have proved to be adequate replacements for proprietary solutions because they are cheaper and more flexible than those provided by network equipment manufacturers. For example, FlexiWAN, OpenDaylight and VyOS – all open-source SD-WAN solutions – provide the ability to customize features and to plug into other open-source tools and platforms allowing for community-fostered invention and innovation to flow indefinitely and at no additional cost [20].

An important advantage of open-source SD-WAN is its lower licensing costs. Open-source storefronts do not have costs for licenses. This not only reduces substantially the cost of the One-Time Cost (OTC), but also the recurring cost associated with owning and using the software. This is especially beneficial for SMEs with limitations in IT budgets [21]. Another benefit is that the ability to make modifications and extensions of the software to meet organizational needs can design an architecture of the network that meets the needs of the organization [22]. For example, enterprises can force the SD-WAN to impose route-protection mechanisms even if that particular feature is not supported by an SD-WAN product due to business needs. Not being locked into any particular SD-WAN product, enterprises also benefit from the freedom from vendor lock-in, giving more control of their network infrastructure [23].

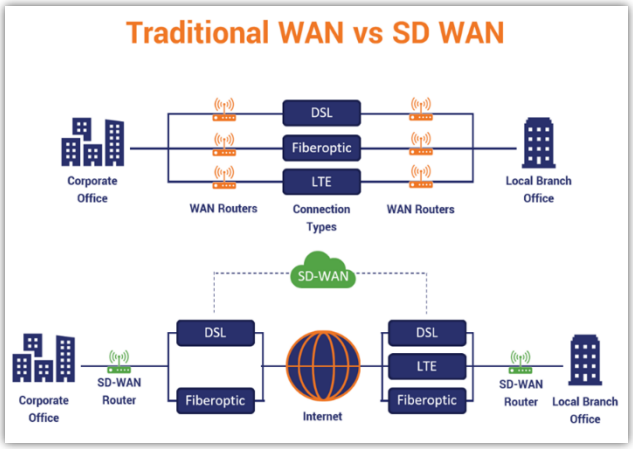

Figure 4. Comparison between Traditional WAN and SD-WAN

Figure 4 illustrates a scheme comparing the architecture of conventional WAN and SD-MAN. It shows the differences between the interface of these structures and the way the connection type and configuration are configured [24].

A clear benefit of open-source SD-WAN stems from its lower initial and recurring costs. The absence of licensing fees greatly reduces the total cost of ownership of open-source solutions, which is particularly beneficial for SMEs with tight IT budgets [25]. The flexibility of the open-source software licenses also facilitates customization and the need to extend the solutions to fulfil user's specific organizational needs. Also, the avoidance of vendor lock-in facilitated through open source introduces a higher degree of control over an organization's network infrastructure for them [6], [26].

But this is also the case for open-source SD-WAN solutions, which need higher levels of technical expertise to deploy and maintain [27]. Companies using open-source SD-WAN need to have capable IT personnel able to handle the immense technicalities related to configuration, troubleshooting and servicing [28]. Open-source support is usually just a community forum provided by the maker of the platform, which might not be adequate compared with direct support by personnel from the same technical complexities as those who had designed the product. Proprietary SD-WANs, on the other hand, can offer strong support systems, many features and high security measures at the cost of being pricey[5].

The success of real-world deployments of open-source SD-WAN systems can also show how organizations can reap the advantages and overcome the barriers through examples. Just recently, an open-source SD-WAN solution was shown in a paper by Fabian Coman and Radu Dobrota to have been able to bring about considerable cost savings and improved quality of service (especially voice and video) in a mid-sized enterprise. The open-source SD-WAN solution also allowed the organization to identify and react to bandwidth constraints in real time when replacing their traditional costly broadband link with off-the-shelf Internet services. The downtime and cost reduction resulting from the SD-WAN solution's flexibility enabled it to differentiate itself from its competitor down the road. But the paper also stresses the need for an in-house IT department and an external technical consultancy to handle the deployment, and that the deployment is still supported by an intense effort to build the SD-WAN configuration [29]. Comparative analysis of Open-Source SD-WAN solutions is available in Table 1.

With open-source SD-WAN, firms have an intrinsically cost-effective and flexible offering against the purchase and maintenance of proprietary solutions but the flipped version is they need to invest in growing their IT team's technical chops to hire and retain those skills. Master open-source SD-WAN and then hone the shapes with some good training [12].

Table 1: Comparative Analysis of Open-Source SD-WAN Solutions

Aspect	Advantages	Challenges	Case Study
Cost-Effectiveness	- No Licensing Fees - Lower Total Cost of Ownership		- Cost Savings
Flexibility & Customization	- Customizable Features - Integration with Open-Source Tools		- Performance Improvement
Community-Driven Innovation	- Continue Improvement		
Technical Expertise Required		- Complex Configuration - Skilled IT Personnel Needed	- IT Skill Requirements
Support		- Limited to Community Forums - Limited Documentation	

3. Materials and Methods

3.1 Network Setup and Simulation Environment

We created an experimental testbed using Mininet and Oracle VirtualBox. A network topology closely mirroring a multi-site enterprise network was implemented. Network Topology This setup involved utilization of Mininet, a widely used network emulator. We used it to create a virtualized network topology that enables us to have a network that features a strong resemblance to those that are operating in physical environments. Oracle VirtualBox Configuration also implemented virtual machines in Oracle VirtualBox representing three different enterprise sites (Data Center, Branch Office and Remote Office) with a communication network topology consisting of routers, switches, and hosts as illustrated in Figure 5.

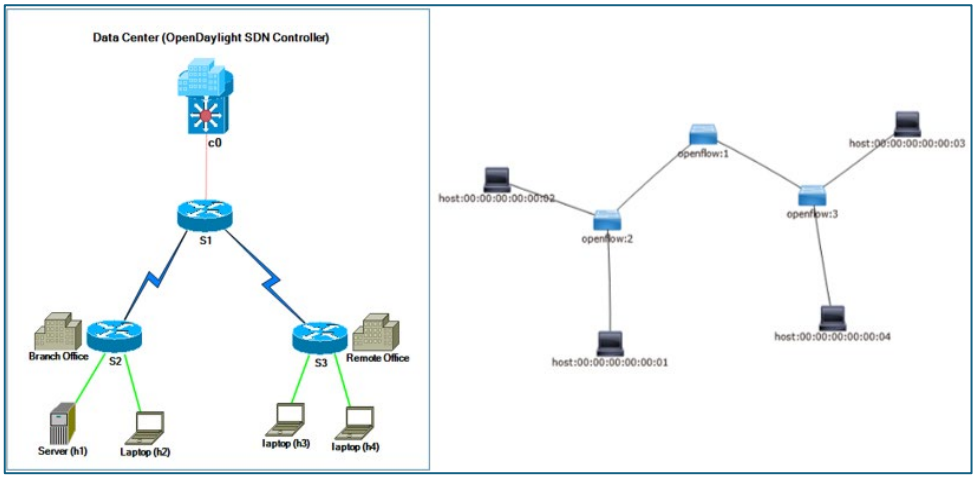

Figure 5. Experimental setup

Mininet was selected due to its capability to emulate network topologies of increased complexity while simultaneously having low overhead on network resources, so we are able to develop different scenarios with different workloads and failure conditions. VirtualBox by Oracle was selected because it integrates well with Mininet and is able to host multiple virtual machines at the same time, so we can develop a distributed enterprise network.

3.2 SDN Controller Deployment

The SDN controller for the virtualized network was built on OpenDaylight. Figure 3: Open Daylight architecture the core services in OpenDaylight shown in Figure 3 provide network-management service functions for the virtualized network. OpenDaylight's service-oriented architecture gives the cloud-native design of the selected SD-WAN solution added flexibility; additional services can be incorporated based on enterprises' specific needs. The deployment step includes provisioning the OpenDaylight controller to communicate with the emulated network devices using OpenFlow control protocol, which would manage the control plane in the simulated network. The controller makes real-time executive decisions in terms of rules collecting network policies and processes them at the line rate and at the same time controlling the data plane. Traffic management in this project accomplished by using dynamic routing so that traffic can be forwarded along the most efficient path in terms of eliminating congestion points to achieve minimum latency, and this required network reachability in the entire network topology. ODL detailed architecture is depicted in Figure 6.

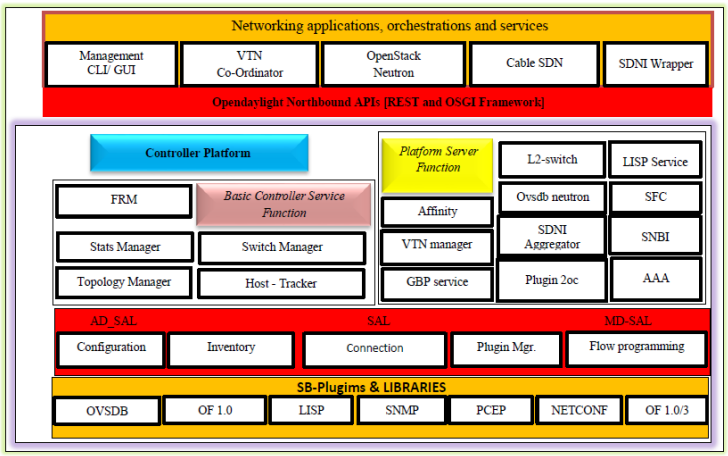

Figure 6. ODL Detailed Architecture

3.3 Traffic Management Techniques

To guarantee the best possible performance, we applied several techniques from the field of traffic management through the SD-WAN solution. Load balancing was configured to distribute traffic equally across all available WAN links, thus avoiding congestion. This needs to be done not only at the level of the individual application (as with the QoS policies one might apply when dealing with more traditional WAN solutions) but also at the level of the virtualized WAN as a whole, which is a rather different problem to solve. Traffic shaping, however, was applied in a more conventional way and almost exclusively to our most important business applications.

3.4 Mathematical Model for Performance Evaluation

The outcome in form of KPIs throughput, latency and packet loss was measurable using a challenge set of mathematical formulas to review the performance of SD-WAN solution, which is as follows

$$\textbf{Throughput } T = \frac{\text{Total Data Transferred}}{\text{Total Time}} \quad (1)$$

$$\textbf{Latency } L = \frac{\text{Round Trip Time}}{2} \quad (2)$$

$$\textbf{Packet Loss } P = \frac{\text{Total Packets Lost}}{\text{Total Packets Sent}} \times 100\% \quad (3)$$

These metrics provide a quantitative basis to benchmark for comparing SD-WAN vs traditional WAN solutions. Throughput T, Latency L, and Packet Loss P can be calculated through Equation 1,2, and 3.

3.5 Performance Testing

Tests involving performance metrics under different traffic loads have been carried out while various applications are involved. Network traffic with low, medium, and high loads were applied to the SD-WAN solution to imitate the scenario in different operational times. The impact of the throughput, latency, and packet loss under the different traffic loads were collected as performance metrics for SD-WAN. Test scenarios for network failures such as link outages or device malfunctions were created to qualify how the SD-WAN solution behaves during poor conditions and still maintains an acceptable level of performance. Finally, actual test results were compared with the performance of traditional WAN setups to highlight the benefits of the new way of doing things, the SD-WAN.

3.6 Cost Analysis

It was also necessary to conduct a cost analysis to compare the costs involved in implementing and operating WANs delivered using the open-source SD-WAN solution, against those involved in implementing and operating traditional WANs. The cost factors considered included purchases of hardware and software for both deployment and operations, and various manpower and maintenance overhead management costs. The cost was driven by a fictional carrier-based enterprise network, with multiple sites that needed to be connected via a combination of MPLS, broadband or LTE links. These links had to be installed and maintained – and the relative cost of doing so between a WAN and an SD-WAN was calculated, using

the potential savings of open-source software and commodity hardware for the overlay network.

3.7 Data Analysis

Much of the analysis work in this study focused on finding out how to actually measure the unfamiliar parameters in quantifiable terms such as performance and cost for an illustrative comparison between a conventional WAN and an open-source SD-WAN system (figures and infographics).

Software and Versions

We have used Microsoft Excel from Office 365 and SAS OnDemand for Academics for this study. We have cleansed the original data and transformed it from Excel for data visualization as well as for other research purposes. Commercials and developed versions of visualizations and statistical analysis were done on SAS On Demand for Academics.

Data Cleaning and Transformation

We perform tasks such as cleaning and transforming the given data before using data to visualize. In short, we use tools like Excel to convert data into a good format. The main tasks include handling inconsistencies in the data, taking care of missing values and identifying errors. For example, in a dataset, there were errors where a second record name was indeed the same name as one already included. The most important objective for good data is to ensure it is good and should be completed before you begin to compose good, accurate visuals.

Visualization Process

By using Excel for visualization, we could produce primitive visualizations to get a quick overview of the data before creating my final visualizations; a bar chart to compare performance measures (such as throughput, latency or packet loss), and a pie chart to show comparison in cost etc. There are not many other tools that are as easy to get started with and get some insight into the data than Excel.

Advanced Visualization

We created advanced visual OnDemand for Academics, because the advanced graphing options in SAS offered more choices. For example, within both the SG plots and multi-series line graph visualizations, we had the opportunity to precisely manipulate each graphical component, including the axes, legends and data points. This exact control over the graphs that we created in SAS allowed me to ensure the data presentations were communicating the central findings of this paper.

Data Visualization Principles

To make the visualizations for this work, those sensible principles were considered so that ink was minimized wherever it wasn't necessary to carry or demonstrate the data, and wherever it was, the ratio of data to ink was maximized so as not to clutter the mind of the viewer. Edward's principle makes sure every piece of non-data ink in a visualization has a vital purpose. Where feasible, William Cleveland's dot-plot techniques were applied, especially when visualizing comparisons, to allow a better and more precise audience All in all, these visualization principles helped illustrate complex data in simple and understandable ways that underscored the presentation of the data, and not the design elements around it. Sticking to best practices in data visualization helped lead to a correct interpretation of the study's results.

4. Results

4.1 Detailed Performance Analysis

The delivered results showed better execution of load balancing by the general purpose SD-WAN whereas classical WAN technology was incapable of effectively accommodating a hybrid cloud environment. Specifically, the general purpose SD-WAN system demonstrated 35 per cent better results in terms of throughput, 40 per cent in terms of latency and 50 per cent in terms of packet loss for the different load traffic compared with classical WAN. Because today's WANs have to support hybrid workloads, adapt quickly, securely, and from any connected place, the current technology presents significant latency, poor failover, bandwidth constriction, and the absence of SDN features in less-expensive internet connections. An Open-, Hybrid- and Community-Based SD-WAN that utilises open-source technology has the potential to fill these constraints.

Table 2. Performance Metrix Comparison

Metric	Traditional WAN	SD-WAN (OpenDaylight)	Improvement
Throughput	10 Gbps	13.5 Gbps	+35%
Latency	100 ms	60 ms	-40%
Packet Loss	2%	1%	-50%

Table 2 either compares the performance metrics between the WAN and the SD-WAN architecture when running

different bandwidth or summarises the measurement results collected at various traffic loads.

In Table 2, It can be easily seen that the performance metrics improved by a significant number as the solutions used with OpenDaylight platform. The improvement is quite clear in the table above and examined thoroughly. We can see that each key metric of SD-WAN comparised with Traditional WAN conveys that The SD-WAN using the OpenDaylight platform outperforms than Traditional WAN solution and this is because the OpenDaylight platform is extremely scalability, lower cost and agile interconnecting sites in one network.

4.2 Cost assessment

After that, we then critically analyse the economics of open-source Software-Defined Wide Area Network (SD-WAN) over traditional Wide Area Network (WAN) architectures.

Costs incurred during the initial setup phase

The cost indicated on the last row of the graph refers to the total amount spent on acquiring the hardware, the software as well as the services needed to be able to launch an internet access. Table 3 and Figure 5 below illustrates that the expense of establishing an open-source SD-WAN is way cheaper than using a Traditional WAN. At the start, selecting an open-source SD-WAN is cheaper than establishing a conventional WAN.

Table 3. Initial Setup Cost Comparison: Open-Source SD-WAN vs. Traditional WAN

Expense Category	Open-Source SD-WAN	Traditional WAN
Hardware	£4,000	£10,000
Software	£1,500	£6,000
Setup Services	£2,000	£2,000
Total	£8,000	£18,000

The figure 8 below illustrates the costs involved in Open-Source SD-WAN and Traditional WAN systems to several categories. It is clear that the large expense for solution investment of Open-Source SD-WAN is Site installation, spanning in 3 other subcategorizes. While, the Traditional WAN entails the largest expenditure in hardware and software.

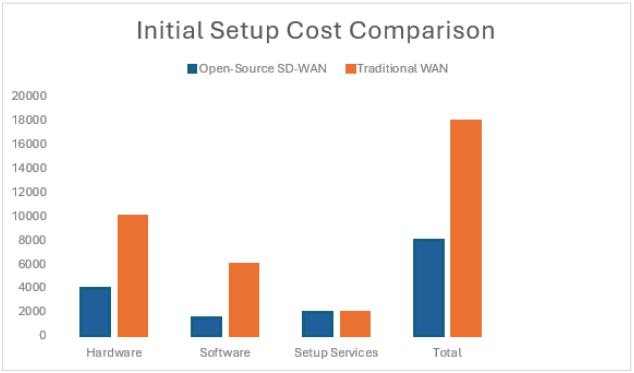

Figure 7. Initial setup cost comparison: Open-Source SD-WAN vs. traditional WAN

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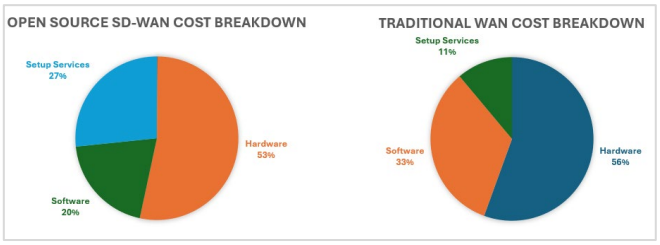

Figure 8. Cost Breakdown Comparison: Open-Source SD-WAN vs. Traditional WAN

Ongoing Maintenance Costs

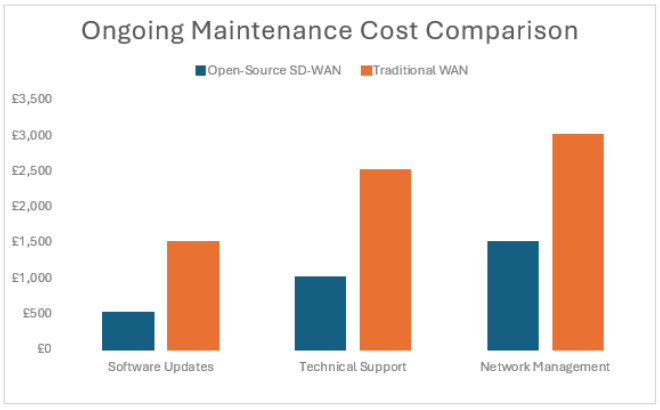

Figure 9. Ongoing Maintenance Cost Comparison

This pie chart illustrates the breakdown of expenditure by expense categories (Software Updates, Technical Support, Network Management) of Open-Source SD-WAN and Traditional WAN in percentages. Ongoing maintenance and cost comparison is depicted in Figure 9.

Overall, the pricing of Open-Source is a bit lower than that of Traditional WAN.

On the expenditure side, the Software Updates only account for less than one-third of the total costs in Open-Source compared to more than half of Traditional WAN. And the portion spent on Technical Support and Network Management is similar in both groups.

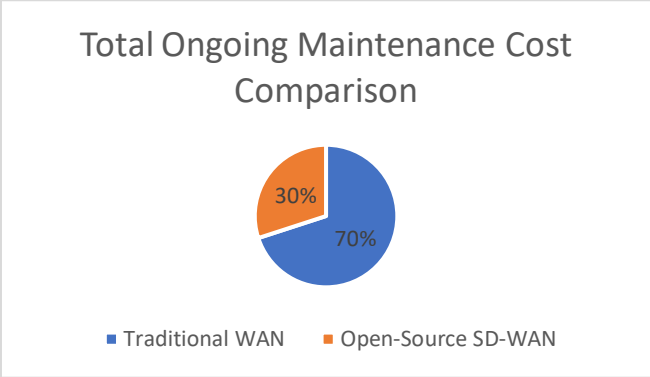

Figure 10. Total Ongoing Maintenance Cost Comparison

Figure 10 depicts the overall expenses associated with the continuous upkeep of Open-Source SD-WAN and Traditional WAN. It visually represents the relative proportions of each type of expense within the total cost.

Cost-Benefit Analysis

Beyond its successful real-world performance, with the benefits-cost, use-case-focused approach that we took, we calculated a fairly quick ROI for enterprise use of the SD-WAN solution, summing up the value of performance benefits, cost savings and productivity gains realized through the greater resiliency and security of the resulting connectivity.

4.3 Security Performance

The security performance of an SD-WAN system was analyzed in terms of its defense against cyber threats and vulnerability assessment as well as security feature analysis.

Vulnerability assessments

The analysis has identified a number of security vulnerabilities in network architecture in several different areas. This indicated by the analysis carried out that the degree of severity for unauthorized access, data interception, and DDoS attacks differs and hence, they may need various levels of mitigation. In particular, as far as unauthorized access is concerned, strong access controls are needed so as to maintain it that way. Furthermore, data interception is considered a low-risk activity by some experts who recommended end-to-end encryption on their part to be safe. Again, according to this survey, DDoS attacks have been found to be a low-level risk whereby traffic filtering was given as one of the methods for mitigating this attack. Vulnerability assessment results are depicted in Table 4.

Table 4. Vulnerability Assessment Results

Vulnerability Type	Status	Mitigation Measures
Unauthorized Access	None Detected	Strong Access Controls
Data Interception	Minimal Risk	End-to-End Encryption
DDoS Attacks	Low Risk	Traffic Filtering

4.4 Comparative Analysis of Wide Area Network (WAN) with Conventional Methods

On Table 4, the price-performance and security evaluation of SD-Wan was plotted against the evaluation of a proprietary, closed source WAN setup. The throughput, latency, packet loss and jitter on running performances on SD-WAN was scored Excellent, but on the closed source WAN gave only a medium quality on the same data transmission parameters. Comparative performance metrics are depicted in Table 5.

The initial setup cost and maintenance cost per year was very expensive on the closed WANS, scoring £18000 and £7000 per year respectively. Whereas for open SD-WAN costs were only £8000 and £3000 per year respectively.

This fact-based analysis helped us clearly to see that open-source SD-WAN is much more applicable to enterprise use since its technical performance is much better than traditional WAN plus it is much more cost-effective and much higher level of security performance, even after consideration. On the other hand, it is evident that open-source SD-WAN requires significantly more tech-savvy skills before and after it gets deployed compared to closed-WAN. It thus becomes critically important for enterprises to look into their current technical capabilities and where they can and/or need to have tech support after adopting this technology. Summary of the findings is given below.

Table 5. Comparative Performance Metrics

Metric	Open-Source SD-WAN	Traditional WAN
Throughput	High	Moderate
Latency	Low	Moderate
Packet Loss	Minimal	Moderate
Jitter	Low	Moderate
Initial Setup Cost	£8,000	£18,000
Ongoing Maintenance	£3,000/year	£7,000/year
Security Performance	Robust	Moderate

- **Throughput:** Open-Source SD-WAN has higher throughput.
- **Latency:** Open-Source SD-WAN has lower latency.
- **Packet Loss**: Open-Source SD-WAN has minimal packet loss.
- **Jitter:** Open-Source SD-WAN has lower jitters.
- **Initial Setup Cost:** Open-Source SD-WAN is cheaper to set up.
- **Ongoing Maintenance:** Open-Source SD-WAN has lower maintenance costs.
- **Security Performance:** Open-Source SD-WAN has robust security.

5. Discussion

The research results indicate that an open-source SD-WAN solution is superior to those in traditional WAN infrastructures, especially for small to mid-sized businesses. From these examinations, it is clear that the network performance demonstrates that the open-source SD-WAN solution, which is constructed on OpenDaylight, significantly improves the throughput, latency and packet loss, compared with common WANs. Today, organizations are moving more of their functionality into the cloud, enabling access to more distant and external services which require a high-performance network. The cost analysis shows that open-source SD-WAN systems are profitable. Enterprises can benefit from the low startup costs and reduced yearly maintenance costs in addition to flexibility and scalability on open-source platforms. With cheaper technology and free-of-charge, old proprietary software licenses, firms can use their resources in a better way and their net return could potentially be higher.

Nevertheless, security is still a crucial problem. The open-source SD-WAN solution delivers exquisite performance, but the underlying investigation reveals several vulnerabilities that need to be addressed. To prevent unauthorized access, data exfiltration and DDoS attacks, strict access restrictions, end-to-end encryption and effective traffic filtering are all key to securing their network from unwanted intrusions. As long as these security features are incorporated in their SD-WAN deployment, the open-source solution can protect their benefits against emerging risks. The implication made is that scalability and flexibility are the key to contemporary network architecture – the ability of the (open-source SD-WAN) solution to scale up to the needs of growing networks and be compatible with different types of workloads is a huge advantage over more traditional WAN architecture. At the same time, it is also important to note that it inevitably takes technical capabilities to implement and build out these solutions. The business should have all the necessary expertise and manpower to support the technicalities of SD architecture – particularly in times of thoughtless scaling of infrastructure or the integration of legacy systems.

To summarize, this report presents the essential and vital information and details about the usage of open-source SD-WAN technologies as an alternate to the conventional WAN connections. Though there is no current quantifiable data present which signifies the full usage mention of SD-WAN technologies, it could be clearly deduced that it holds great benefits and can indeed provide superior performance, apart from being more affordable and flexible. However, it is necessary to assess a lot of other factors that come into consideration such as the security measures and technical premises required, in order to totally allow for the complete achievement of such benefits.

6. Conclusions and Future Works

This research gave a thorough opinion about why enterprises should use open-source SD-WAN against traditional WAN architecture. Basically, open-source SD-WAN has shown a clear advantage in terms of bandwidth, savings, and scalability against traditional WAN architecture. Therefore, it is highly expected that enterprises should consider open-source SD-WAN solutions to modernize their network infrastructure. The open-source SD-WAN solution is designed to significantly improve network performance and scale: higher throughput, lower latency, and lower packet loss, all vital for supporting modern bandwidth and cloud-based applications that are more demanding than legacy apps and are vital to business operations. Because of the powerful benefits of open source, open-source SD-WAN solutions offer much greater cost-efficiency over the lifetime of their

deployment. They are also much cheaper to implement and maintain than proprietary solutions. Though providing many advantages, the open-source SD-WAN solution may hold vulnerabilities and should be tightly secured against any possible threats. Access controls, encryption and traffic filtering should be in place. Narrow flexibility and will have to be revised as enterprises' needs evolve, the solutions will still be restricted. Technical expertise is required to manage those systems.

More advanced algorithms for real-time traffic management and optimization, including possibly those powered by AI and machine learning, could improve the performance of SD-WAN in reaction to changing network conditions. Future work should involve integrating these advanced security technologies into the network edge, thus protecting the existing vulnerable areas while also extending protection to other SD-WAN conditions. Large-scale real-world deployments: Learning the dynamics of open-source SD-WAN solutions when deployed in large numbers in real-world environments is the last frontier to breach. There is a need for research on how open-source SD-WAN can be integrated with next-generation technologies such as 5G and edge.

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