# Secure Service Implementation with Slice Isolation and WireGuard

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Abstract-Network slicing enables the provision of services for different verticals over a shared infrastructure. Nevertheless, security is still one of the main challenges when sharing resources. In this paper, we study how WireGuard can provide an encrypted Virtual Private Network (VPN) tunnel as a service between network functions in 5G setting. The open source management and orchestration entity deploys and orchestrates the network functions into network services and slices. We create multiple scenarios emulating a real-life cellular network deploying VPNas-a-Service between the different network functions to secure and isolate network slices. The performance measurements demonstrate from 0.8 Gbps to 2.5 Gbps throughput and below 1ms delay between network functions using WireGuard. The performance evaluation results are aligned with 5G key performance indicators, making WireGuard suited to provide security in slice isolation in future generations of cellular networks.

*Index Terms*—OSM, WireGuard, VPN, NFV, 5G, Network slice, URLLC, eMBB.

# I. INTRODUCTION

The enrollment of 5G non-standalone cellular networks is already in operation by mobile network operators. In developing Beyond 5G (B5G) networks, several planned functionalities will enable verticals to establish their services with diverse Quality-of-Service (QoS) requirements on shared physical infrastructure. Providing End-to-End (E2E) services over isolated network slices is a key factor to empower multiple services on a shared infrastructure. To develop agile B5G networks for supporting applications with different QoS requirements, Network Function Virtualisation (NFV), Software-Defined Networking (SDN) and Multi-Access Edge Computing (MEC) are the main enabling technologies [1], [2].

An NFV Management and Orchestration (MANO) entity connected to one or several Virtual Infrastructure Managers (VIMs) controls and monitors the deployment of Network Services (NSs) by deploying necessary infrastructure resources. For an agile network deployment, the NFV MANO also administrates connections between Virtual Network Functions (VNFs), including creation of virtual networks with the help of SDN. Therefore, instead of manually creating and connecting the NSs together, the NFV MANO helps operators to deploy and control Network Functions (NFs) automatically. With its automatic and reusable functionality, a large number of NFs and NSs can be rapidly deployed on a single or multiple VIMs.

Cloud infrastructures that can be rented or shared are necessary to utilize resources efficiently for financial and load distribution purposes. Introducing shared infrastructure raises further security challenges. Securing application data transfer over shared networks is one example of such a security challenge. A countermeasure that can be initiated against such security concerns is operating Virtual Private Network (VPN) between NFs. However, establishing VPN tunnels introduces additional overhead. For services dependent on low latency or high throughput, the additional overhead may affect their service performance.

NFV MANO can provide traffic isolation for NFs in NSs by deploying VPN tunneling between NFs and interconnecting them [3]. In this way, the secure tunneling isolates Network Slice Instances (NSIs) and the provided NSs via the NSIs. Nevertheless, this approach is only feasible if the VPN does not introduce significant overhead violating QoS requirements. The deployment of VPN between VNFs in an automatic mode in order to provide security isolation between slices and the effect of the introduced overhead on the performance isolation among slices in a shared environment are still open research questions.

In this paper, we implement and analyze the performance of WireGuard for providing slice isolation in 5G environment. WireGuard [4] is a straightforward yet immediate VPN solution that functions via the Linux kernel and employs state-of-the-art cryptography approaches. Open Source MANO (OSM) orchestrates NSs and NSIs, and establishes VPN tunnels between the VNFs. The integrated WireGuard-OSM architecture provides: 1) secure communication between the involved VNFs of NSs and NSIs - slice isolation; 2) performance isolation between the slices. The performance analysis shows that the integrated WireGuard-OSM architecture meets the required Key Performance Indicator (KPI) values in terms of high throughput for enhanced Mobile Broadband (eMBB) slices and low latency for Ultra Reliable Low Latency Communication (URLLC) slices. We make the code publicly available<sup>1</sup> to the research community.

The remainder of this paper is organized as follows. Section II provides a literature overview of practical approaches for secure isolation between slices. Section III presents the system architecture. The implementation steps are explained in Section IV. The performance evaluation results are presented in Section V. Finally, Section VI concludes the paper.

<sup>&</sup>lt;sup>1</sup>https://github.com/sondrki/TTM4905/

## II. RELATED WORK

The isolation concept between network slices can be studied from security, performance, and dependability aspects [5]. In addition, the Confidentiality, Integrity and Availability (CIA) triad is a widely used way of looking at different security aspects. A shared infrastructure introduces security challenges in all dimensions of the CIA triad. The key feature of shared infrastructures is that an attack on or from another party sharing the infrastructure should not affect the other sharing parties. This definition of CIA is harmonic with the isolation concept in network slicing. Other parties should also be unaffected when it comes to performance and dependability, extending the availability dimension. The workload, the number of resources, and hardware or software failure of another NS should not reduce the performance of an NF in a separate NS or NSI.

While 5G intends to fix some security issues present in the previous generations of cellular networks, it also introduces several new security threats. Some of them are raised by providing services via network slices. Paper [6] explores and classifies different security challenges of 5G networks. Proper isolation of logical resources is essential to avoid introducing several new risks. Eavesdropping and tampering with data, for instance, are two vectors an attacker could use to interfere with security if the application data is not properly encrypted. Hantouti et al. suggest that operators should deploy encrypted tunnels as a way to establish trust between Service Functions (SFs) to provide packet integrity and prevent bypassing of policies [7].

The work in [8] proposes a novel mutual authentication and key establishment protocol utilizing proxy re-encryption. The protocol grants specific authentication between components of a network slice to enable secure connection for protected key establishment among component pairs for slice security isolation. Paper [9] offers a secure keying scheme by adopting a multi-party computation strategy, which is appropriate for network slicing architecture in the case that third-party applications access the slices. This mechanism ensures the satisfaction of use cases or devices in which the data is collected.

Both Haga et al. in [10] and Vidal et al. in [11] focus on how a VPN can be deployed using OSM. Reference [10] demonstrates how WireGuard can be added in VNFs and compares the performance of WireGuard and OpenVPN. This proof-of-concept is carried out using two VNFs in a single NS with manual configuration of peer connectivity in WireGuard. For the peer setup, keys and other necessary information are obtained manually. Vidal et al. in [11] uses IPsec as VPN solution to provide link-layer connectivity for multi-site deployments. In this work, OSM deploys multiple NSs connected through one VNF at each NFV Infrastructure (NFVI). These VNFs handle the link layer abstraction for the other VNFs. IPsec is used to secure the connection between the link layer providing VNFs. Keys and connection parameters are supplied by the operator when instantiating the NSI. To the best of our knowledge, none of the state-of-theart works presents a secure service automation provisioning utilizing complex and real-life NFs. This motivates us to integrate WireGuard tunneling with OSM, which grants secure communication between NFs in order to establish automated and realistic network services. As a result, this system architecture guarantees security and performance isolation between NSIs.

# **III. SYSTEM ARCHITECTURE**

Day-0, Day-1, and Day-2 operations are terminologies used in the OSM community referring to the stages of Life-Cycle Management (LCM) of NFs. The steps in Figure 1 are used to handle LCM of NFs via the NF onboarding process and they link closely to Day-0 to Day-2 operations. In Figure 1,

- Day-0 phase focuses on necessary instantiation, including charms and descriptor creation/editing, validation, packaging, and emulation;
- Day-1 phase concentrates on service initialization containing test, release, and deploy;
- Day-2 phase covers runtime actions comprising operate and monitor steps.



Fig. 1. Steps for service lifecycle [12].

OSM has three inbuilt supporting applications for LCM [13]. Cloud-init is responsible for the initial Day-0 operations like setting username and password. For Day-1 operations, Helm charts or Juju charms can be used, while Day-2 operations are also possible with Juju. The difference between Helm and Juju is that Helm is used solely for Kubernetes-based Network Functions (KNFs), while Juju is also usable at NS level and for VNFs that are not Kubernetes (K8s) based [14], [15]. We have used cloud-init and Juju charms for OSM onboarding in our implementation.

Further, Juju has two operation modes: native and proxy. Native charms run operations directly inside a VNF. On the other hand, proxy charms use a centrally placed controller, VNF Configuration and Abstraction (VCA), to manage the Day-1 and Day-2 actions. The VCA connects to the VNFs through their management interface and instructs the VNFs. The VCA-VNF connection uses the Secure Shell (SSH) protocol by default. In the paper, we have used proxy charms with a VCA installed co-located and integrated with OSM. Both the VCA and OSM are, therefore, able to access the VNFs management interface to execute their actions.

To build user-defined actions, Juju uses Python scripts. The connection to the OSM instance is made through the description files of the VNFs, NSs, Juju config files describing metadata, and the available Day-1 and Day-2 actions. For the OSM integration of proxy charms, the *charms.osm.sshproxy* library is provided by OSM to take care of, among other tasks, the basic Juju proxy peer setup.

In addition to running actions in VNFs, Juju can be used to create relations between Juju units for management, scaling, and handling dependencies across VNFs. We use Juju relations to transfer WireGuard peer information between VNFs.

Figure 2 illustrates how we use proxy charms and relations in Juju to create a bridge for transferring information between VNFs. The figure shows the architecture for the multi-site demonstration. Note that we used a single-VIM, moving the Home Subscriber Server (HSS) into *VIM 1*, for the performance evaluation results presented in Section IV. The architecture for the single-VIM setup is as illustrated in the rightmost half of the figure showing *VIM 1*.



Fig. 2. Interactions between elements in our Juju proxy implementation.

Key distribution is a task that often requires manual steps when establishing a VPN tunnel. Manual setup can be timeconsuming for dynamic environments or environments with many interfaces that need to be secured. If the tenant manager needs to do configuration, the NS is only usable after initializing the VPN tunnels. However, if we apply the approach presented by Vidal et al. [11] and input the necessary information, including keys, the application can start sending data immediately after Day-1 actions have finished. Using a Key Management System (KMS) is a similar approach. However, OSM does not provide such functionality. To use the KMS approach additional functionality outside of the OSM framework must be added.

To perform key management, we use a non-standard approach using Juju relations with the requirement of using proxy charms for our VNFs. By using Juju relations, we create new individual keys for every new deployment of an interface and make the application of the NS usable directly after the Day-1 tasks finish. Furthermore, with our approach, the private keys are only stored inside the VNFs. The public key and other necessary information for the peer setup get automatically transferred to the peer.

## **IV. IMPLEMENTATION**



Fig. 3. Architecture of our implementation.

To implement WireGuard in a realistic 5G environment we created a NS with Evolved Packet System (EPS) components from OpenAirInterface (OAI) [16]. We then added WireGuard connectivity on the different interfaces. Figure 3 shows the deployed architecture. OSM is used to communicate with MicroStack VIM [17]. The VIM hosts different VNFs, creates virtual networks and performs routing of outgoing traffic from the VNFs, represented by solid blue lines. WireGuard tunnel is created automatically between the VNFs on the interfaces in the NS, represented by the red dotted lines. In addition to the primary VIM, we utilized a second VIM in order to explore the EPS NS deployment in multiple sites.

## A. Development

We followed these steps to prepare the deployments: 1) compose a virtualized EPS, 2) set up a mechanism for automatic WireGuard peering, 3) structure NSs into Network Slice Template (NST), and lastly, 4) test the WireGuard connectivity in a multi-site deployment. The code for the descriptors and charms is publicly available on GitHub. In the following paragraphs, we further describe the development steps for creating the descriptors and the scripts.

1. Composing a Virtualized EPS: In [18], Dreibholz implements an Evolved Packet Core (EPC) with HSS, Mobility Management Entity (MME), and a combined Serving Gateway (SGW) and Packet Data Network Gateway (PGW) separated in two components, Service Packet Gateway-User plane (SPGW-U) and Service Packet Gateway-Control plane (SPGW-C), for user- and control-plane tasks, respectively. To extend this NS with real-life traffic, we add a virtualized eNodeB (eNB). Further, we create an User Equipment (UE) in a Virtual Machine (VM) kept outside the NS. The UE is still able to connect to the eNB after instantiating the NS with manual network setup in MicroStack. To establish the air interface, Uu, we have compiled and used OAI simulation option. When connecting the UE to the eNB, we verify that the different EPS components function as expected and provide service to the UE. The UE connects to an outer network through the SPGW-U via the eNB. At this first step of implementation, we still have not included WireGuard between the components.

We chose to build the NS by spreading the EPS components into separate VNFs. This approach allows to split the VNFs in the VIMs. Extending it to a multi-site environment gives us the opportunity to emulate a scenario where other components, for instance, MEC, are deployed closer to the end-users. The VNFs distributed to remote sites are able to communicate with the core securely with the help of WireGuard.

2. Automatic WireGuard Peering: Manually setting up VPN tunnels between several interfaces can be time-consuming. Thus, we use Juju relations for automatic peering with no extra information given to the other end of the peer at the time of instantiating the NS. The first step in the automatic peering is the establishment of relationships between VNFs on both sides. Then the paired VNFs retrieve information like public key, endpoint, and listening port to communicate with each other. Wireguard usually employs the following cryptographic primitives: elliptic Curve25519 for key exchange, then HKDF for the key derivation, and finally, the bulk encryption work is performed by the symmetric primitive ChaCha20Poly1305 for Authenticated Encryption with Associated Data (AEAD) [4]. All of these primitives have excellent performance in software supporting the objective of NFV. Moreover, due to the lack of considerable overhead and latency, and remarkable efficiency, ChaCha20Poly1305 AEAD performs significantly in terms of ping time and throughput for the URLLC and eMBB slices, respectively.

To establish WireGuard connectivity on all interfaces given in Figure 3, we changed the IP address configuration in the components. Changing the interface addresses is necessary to route application data over the VPN tunnel and, at the same time to ensure that applications inside the VNF have been installed and started correctly even when waiting for the tunnel establishment. Besides, to verify that the NS runs WireGuard, we connect the UE and observe that it connects and gets Packet Data Network (PDN) service.

Further, in order to observe how resources affect the Wire-Guard performance, we have prepared a copy of the EPS NS with WireGuard connectivity with doubled resources.

3. NST creation: After having a working NS with Wire-Guard connectivity between the interfaces, we include it in two NSTs to observe if and how the performance is affected by providing security with WireGuard. The two NSTs have different values of quality indicators corresponding to different 5G QoS Identifiers (5QIs) [19]. The QoS parameters correspond to eMBB and URLLC use-cases, respectively. Further, the NST is prepared with only the management interfaces of the VNFs. The management interfaces are attached to the external connection points in the NSTs.

4. Multi-site deployment: To verify that the automatic peering setup also works in a multi-site environment, we have separated the HSS VNF to a second VIM. When using Open-Stack/MicroStack, the external floating IP address is by default not known inside a VM. However, the VCA can retrieve the management IP address to perform its actions. To find the floating IP addresses of the VNFs, we use the same function that Juju employs for its *proxypeer* connection between a Juju unit at the VCA and the Virtual Deployment Unit (VDU) in the VNF. After the endpoint IP address is found, the MME and HSS connect automatically with WireGuard connectivity. A prerequisite for multi-site WireGuard connectivity is to use a port opened in the firewalls.

# B. Proof-of-Concept for VPN-as-a-Service

With the automatic peering, we presented a few steps to add WireGuard as a VPN-as-a-Service (VPNaaS). Here we summarize all steps to build the proof-of-concept.

- 1) Append installation of WireGuard in cloud-init.
- 2) Add name and parameters for Day-1 and Day-2 actions in the actions.yaml file.
- 3) Add relations between VNFs in the metadata.yaml file.
- 4) Include the Python code to append the charm script. The name of the relationship must correspond between the name used in metadata.yaml and the listener in the \_\_init\_\_ function of the Python script.
- 5) Add the actions from actions.yaml into Day-1, Day-2 operations in the VNF Descriptor (VNFD). To create the WireGuard tunnel as a Day-1 operation, the relevant actions should be included in the *initial-config-primitive* section in the VNFDs. Day-2 actions are placed in the *config-primitive* section.
- 6) While the default implementation sets up the VPN, Day-2 actions can be used for further configuration and maintenance, for instance, if a new connection should be added towards a NF.

# V. PERFORMANCE EVALUATION

To assess the performance of WireGuard in the 5G network, we conducted measurement tests in both the control and user plane, with and without WireGuard capability. We utilized both arbitrary data and the UE to generate realistic traffic in the network. We observe the impact of integrating secure communication with Wireguard on the performance metrics that should be aligned with the 5G KPI [20].

While producing arbitrary data for high network load, we measure the latency and Service Response Time (SRT) in the control plane, combining multiple EPS components. In general, the following tasks are done to test the performance of NSs and NSIs:

- Observe SRT on the MME when the UE connects;
- Observe throughput and latency in the user plane with the UE over S1-U interface;
- Measure throughput and latency between components in the EPS in the control plane over S1-C and S6a interfaces.

# A. Lab Environment

The primary VIM is a server running MicroStack with resources of 56 vCPUs, 126 GB RAM, and 915 GB storage. The second VIM, used for multi-site deployment, also runs MicroStack but has fewer resources with a total of 9 vCPUs, 32 GB RAM, and 150 GB storage. For the EPS NS a total of 14 vCPU, 27 GB RAM and 110 GB storage are utilized. According to the limiting ISP, the bandwidth between the two NFVIs is specified to be 200 Mbps. For the VNFs to communicate securely across the VIMs, WireGuard tunnel is established

between the NFVIs. Our measurement shows a throughput of approximately 180 Mbps between the MicroStack instances. A nested WireGuard tunnel is used when adding WireGuard on the S6a interface for the multi-site deployment. The internal throughput of the NFVI where the primary VIM runs is 20 Gbps. Table I gives a summary of the resources used for the VNFs.

TABLE I VNF INFORMATION OF THE OAI EPS NS.

VNF	Operating System	Number of	Amount of	Storage
name		virtual CPUs	RAM (GB)	(GB)
HSS	Ubuntu18.04	4	8.0	20
MME	Ubuntu18.04	2	4.0	20
SPGWU	Ubuntu18.04	1	3.0	20
SPGWC	Ubuntu18.04	3	4.0	30
eNB	Ubuntu18.04	4	8.0	20
UE	Ubuntu18.04	2	4.0	20

## **B.** Observations

Before adding the VPN tunnels, we are able to capture connection information such as the International Mobile Subscriber Identity (IMSI), network realms, and hostnames at the VIM. However, after we introduce WireGuard, the only information observable at the VIM is the use of the WireGuard protocol and link-layer discovery messages.

For the control plane, we observe the SRT for the HSS application to a connecting UE. When monitoring SRT of the HSS application including networking from the MME, the NS with WireGuard has the lowest average SRT. In particular, with ten successful connections for the UE, the average SRT of the Diameter protocol drops from 6.156 ms for the EPS without WireGuard capability to 5.377 ms when WireGuard is added. When doubling the resources on the EPS NS with WireGuard, SRT of 5.607 ms is measured. Based on the other measurements, it is likely that the HSS application itself is the delaying part. With a reduced number of connections, we have not observed a negative effect on the SRT when using WireGuard.

A comparison of the latency measurements for different instances and interfaces is shown in Figure 4. The red line in the figure indicates 1 ms, representing one of the E2E KPI for URLLC applications in 5G. All single-site instances achieve lower latency than the 1 ms. However, adding WireGuard introduces a visible overhead when comparing the NS without WireGuard to the other instances in Figure 4. On the other hand, we observe that the average latencies for the S1-C interface in the eMBB and URLLC NSIs (illustrated in grey and purple) are lower than the other two counterpart measurements. It is worth noting that doubling the resources does not necessarily reduce the latency, confirming that the latency depends on multiple factors such as 5QI parameters and the workload of components in the NS.

Figure 5 compares the throughput between components with WireGuard enabled on different interfaces across instances. The red line represents the 100 Mbps downlink user data



Fig. 4. Latency comparison for different interfaces with and without Wire-Guard functionality.

rate KPI. We highlight three main results from observing the throughput. The first one is that, unlike the latency, the throughput changes according to the available resources. When comparing the NS with double resources to the others, the throughput is higher for the NS with the double resources. The second observation is that the throughput over the Uu interface is significantly lower than the other measurements. The throughput over the Uu is around 1.7 Mbps, while the average throughput for the S1-U is over 1 Gbps making the Uu the bottleneck of the EPS. The last observation is about the maximum throughput when averaging over 10 minutes. For the NS with double resources, we observe throughput of 2.2 Gbps for the S1-U. For the other instances, a range from 770 Mbps to 1.48 Gbps is measured.



Fig. 5. Throughput comparison for different interfaces with WireGuard.

Figure 6 compares the throughput in the two NSIs. We observe that the performance over diverse interfaces differs when running each NSI alone and when the two NSIs are running simultaneously. For instance, the throughput at the S6a

interface reaches up to 1.1 Gbps for the URLLC slice when it is operating alone and simultaneously with the eMBB slice. However, the throughput at the S1-U interface is 1.43 Gbps for the URLLC slice separately and it reduces a bit to 1.41 Gbps when it is running simultaneously with the eMBB slice. Regarding S1-C interface, the throughput reaches 1.12 Gbps for the separate URLLC and it decreases to 0.97 Gbps when the eMBB slice is also working. In general, the differences between the NSIs are minor, meaning that WireGuard is a promising solution for slice isolation of eMBB and URLLC slices.

It should be noted that we observe a total throughput of approximately 3 Gbps, which is lower than the internal networking throughput of around 20 Gbps when testing with a workload on the same logical interface for the two NSIs simultaneously. As we approach the internal networking limit for the throughput, we detect more considerable differences between the NSIs based on their QoS parameters and the allocated resources.



Fig. 6. Throughput comparison with WireGuard for NSIs - measured separately and simultaneously.

In the multi-site deployment, we take measurements over the S6a interface, which is the only one that differs from the other NSs and NSIs. As expected, the throughput is lower, and the latency is higher than in the other instances. The performance is lower even without WireGuard between the VNFs. However, we observe that WireGuard adds overhead in this scenario as well. In the multi-site NS, the average latency over 1000 ICMP packets increases from 18.355 ms to 19.769 ms when using WireGuard. For the average throughput, we observe a reduction from 179 Mbps to 156 Mbps, which is expected based on the given 200 Mbps bandwidth.

## VI. CONCLUSIONS

By using Juju relations and providing a proof of concept for using WireGuard as VPNaaS, we showed that WireGuard can be implemented with automatic peer setup after instantiating. The performance measurements demonstrate that WireGuard is suitable for applications with requirements corresponding to several of the 5G KPI values. We show that WireGuard can be used as VPNaaS in the context of 5G networks and beyond in order to provide secure communication and slice isolation.

Replacing the arbitrary Juju relations with a KMS, using a 5G Core network instead of EPC components, adding multiple UEs, and evaluating scenarios in which fulfilling service requirements (especially throughput) are beyond WireGuard capability are potential directions for future investigation.

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