



Vasco Regal Sousa

Multiple Client Wireguard Based Private and  
Secure Overlay Network

# DOCUMENTO PROVISÓRIO

“An idiot admires complexity,  
a genius admires simplicity.”

— Terry A. Davis



**o júri / the jury**

presidente / president

**ABC**

Professor Catedrático da Universidade de Aveiro (por delegação da Reitora da Universidade de Aveiro)

vogais / examiners committee

**DEF**

Professor Catedrático da Universidade de Aveiro (orientador)

**GHI**

Professor associado da Universidade J (co-orientador)

**KLM**

Professor Catedrático da Universidade N



**agradecimentos /  
acknowledgements**

Ágradecimento especial aos meus gatos

Desejo também pedir desculpa a todos que tiveram de suportar o meu desinteresse pelas tarefas mundanas do dia-a-dia



## **Abstract**

An overlay network is a group of computational nodes that communicate with each other through a virtual or logic channel, built on top of another network. Although there are already numerous services and protocols implementing this mechanic, scalability and administration agility are among the most desired characteristics of such a network topology. Hence, this document presents a centralized solution for the creation and control of secure overlay networks for multiple nodes - from client management to operation auditing, based on Wireguard, an open-source protocol for encrypted communication. In the University of Aveiro, namely the autonomous robot ecosystem residing in the IRIS lab, supporting such a networking architecture would prove to be particularly interesting, both for development and project organization.





# Contents

|  |            |
|--|------------|
| <b>Contents</b>  | <b>i</b>   |
| <b>List of Figures</b>                                     | <b>iii</b> |
| <b>List of Tables</b>                                      | <b>v</b>   |
| <b>1 Introduction</b>                                      | <b>1</b>   |
| 1.1 Motivation . . . . .                                   | 1          |
| 1.2 Objectives . . . . .                                   | 1          |
| 1.3 Document Structure . . . . .                           | 2          |
| <b>2 State of the Art</b>                                  | <b>3</b>   |
| 2.1 Encrypted Peer to Peer Communications / VPNs . . . . . | 3          |
| The problem with NAT . . . . .                             | 3          |
| 2.1.1 IPSec . . . . .                                      | 4          |
| Transport and Tunnel modes . . . . .                       | 4          |
| Authentication Header . . . . .                            | 5          |
| Encapsulating Security Payload . . . . .                   | 5          |
| 2.1.2 OpenVPN . . . . .                                    | 5          |
| TUN and TAP interfaces . . . . .                           | 5          |
| OpenVPN flow . . . . .                                     | 6          |
| 2.1.3 Wireguard . . . . .                                  | 6          |
| Routing . . . . .  | 6          |
| Cipher Suite . . . . .                                     | 6          |
| Security . . . . .   | 7          |
| Basic Wireguard Configuration . . . . .                    | 7          |
| 2.1.4 Performance Comparison . . . . .                     | 7          |
| 2.2 Control Platforms . . . . .                            | 8          |
| 2.2.1 OOR Map Server Implementation . . . . .              | 9          |
| 2.2.2 Tailscale . . . . .                                  | 9          |
| Overcoming network constraints . . . . .                   | 10         |
| Headscale . . . . .  | 10         |
| 2.3 University of Aveiro Network . . . . .                 | 11         |

|          |   |           |
|----------|---|-----------|
| <b>3</b> | <b>Methodology</b>                      | <b>12</b> |
| 3.1      | Prototype Development . . . . .         | 12        |
| 3.2      | Deployment . . . . .                    | 13        |
| 3.3      | Automation . . . . .                    | 13        |
| <b>4</b> | <b>Prototype Development</b>            | <b>15</b> |
| 4.1      | Development Environment . . . . .       | 15        |
|          | Virtual Machines . . . . .              | 15        |
|          | Access Point . . . . .                  | 15        |
| 4.2      | Headscale Instance Deployment . . . . . | 16        |
| 4.3      | Client Configuration . . . . .          | 17        |
| 4.4      | Authentication . . . . .                | 17        |
| 4.5      | Communication with ROS . . . . .        | 17        |
| <b>5</b> | <b>Production Deployment</b>            | <b>18</b> |
| <b>6</b> | <b>Automation</b>                       | <b>19</b> |
| <b>7</b> | <b>Validation and Results</b>           | <b>20</b> |
| <b>8</b> | <b>Conclusion</b>                       | <b>21</b> |
|          | <b>Bibliography</b>                     | <b>23</b> |

# List of Figures

|     |   |    |
|-----|---|----|
| 2.1 | Basic Wireguard Communication Between Two Peers . . . . . | 8  |
| 3.1 | Development Enviornment Architecture . . . . .            | 13 |
| 3.2 | Development planning proposal . . . . .                   | 14 |



# List of Tables

|     |  |    |
|-----|--|----|
| 2.1 | Nodes to be configured with a Wireguard tunnel . . . . . | 8  |
| 4.1 | Development Virtual Machines specification . . . . .     | 16 |
| 4.2 | Services running in the Headscale instance . . . . .     | 16 |



# Chapter 1

## Introduction

### 1.1 Motivation

Network security has become a topic of growing interest in any information system. Companies strive to ensure their communications follow principles of integrity and confidentiality while minimizing attack vectors that could compromise services and data. With such goals in mind, network topologies are subjected to policies that apply rules and conditions to inbound and outbound traffic. One such mechanism is the use of Virtual Private Networks (VPNs).

Traditional VPN services consist in the process of establishment of a secure, encrypted channel between a client and a network, through an insecure communication medium.

The University of Aveiro (UA)'s Intelligent Robotics and Systems Laboratory (IRIS-Lab) conducts research projects using autonomous mobile robots, which communicate through a Wi-Fi network. Currently, this network is confined to the premises of the IRIS-Lab, preventing the robots from operating in the remaining UA's buildings. Although the UA's Wi-Fi infrastructure covers most of its edifices, which can be used by the robots, due to security mechanisms, this network proves to be highly restrictive, not allowing Peer to Peer (P2P) communications through the Robot Operating System (ROS) [19] middleware without additional network equipment. Also, these constraints keep developers from being able to interact with the robots through their personal machines, which, if otherwise possible, would be of great interest.

### 1.2 Objectives

The main goal of this dissertation is to implement a private overlay network manager to be used exclusively by UA's clients. The concept of a manager entails both the definition of a network's client universe (which nodes should be allowed to connect to a certain network) and its respective identification and authentication mechanisms.

In the IRIS-Lab scenario, the management platform should provide operations to achieve communication between a team of robots, regardless of their physical location within the campus. Moreover, the authentication and connection to a desired overlay network by the robots must be a seamless operation, requiring little to no manual configuration.

Finally, all traffic must be encrypted and properly authenticated, to ensure the privacy of the communication.

## 1.3 Document Structure

This document presents an implementation proposal for such an overlay network manager. Hence, it is structured in two main chapters, the state of the art and the methodology. The former describes an exploration of the background and current state of the art, providing an analysis not only of potential tools, protocols, and frameworks suitable for the scope of the dissertation but also of published research conducted covering similar topics and scenarios. The latter establishes the work methodology to be taken for the development and results gathering process.



## Chapter 2

# State of the Art

“Observation is a dying art”

— Stanley Kubrick

### 2.1 Encrypted Peer to Peer Communications / VPNs

VPNs have become a mature technology, with widespread usage on the Internet. With such a range of products offering VPN capabilities, this section aims to analyze some of its most notable providers, focusing on the processes involved on their respective data planes, which refers to the subsection of network communications responsible for carrying data between devices. This implies not only the robustness of its authentication methods, encryption suite and protocol security but also its features regarding concepts such as mobility - how the service behaves when clients change their physical locations and Internet Protocol (IP) addresses - and overcoming constraints associated with networks using Network Address Translator (NAT) mechanisms and secured with firewall rules. Finally, since operations taken in the data plane are necessarily associated with computational overheads, namely traffic encryption and session management, overall performance is also perceived as a valued dimension.

VPNs can be classified according to their topology in two main categories: client-to-site and site-to-site. A client-to-site VPN is characterized by connections from a single user (client) to a private network (site), while site-to-site VPNs offer a secured connection between two private networks. Thus, in site-to-site networks, users are not required to individually configure VPN clients. The tunnel in this type of VPN is made available to the entire network.

For the scope of the scenario at hand, where robots (the clients) require access to a private network, there's an emphasis on client-to-site use cases.

This section aims to explore some of the most popular and widely used VPN protocols, regarding features, cryptography and performance. The structure of some of the following paragraphs is loosely inspired by similar research and publications, namely [1].

#### The problem with NAT

NAT is a networking mechanism responsible for translating IP addresses in private networks into public addresses when packets sent from a private network are routed to the public Internet. In the context of VPN communications, this process can prove to be a major constraint, not only due to NAT's tampering of IP packets' fields, namely destination and source

addresses, which could potentially compromise its integrity in the eyes of a VPN protocol, but also regarding the dynamically changing public IP addresses which NAT decides to translate private addresses to.

In fact, it is very likely that devices on the internet reside in a network behind both NAT mechanisms and Firewall rules, with no open ports. Also, believing nodes will have a consistent static IP is a very naive assumption, especially when considering mobile devices. NAT Traversal is a networking technique that enables the establishing and maintaining (by keeping NAT holes open) of P2P connections between two peers, no matter what's standing between them, making communication possible without the need for firewall configurations or public-facing open ports. There's no one solution to achieve this functionality. In fact, there are various developments effectively implementing a NAT Traversal solution, such as ICE [10] and STUN [17]. Hence, each VPN service can have its own way of supporting NAT Traversal. Each case is explored separately in its own subsection.

### 2.1.1 IPSec

IPSec refers to an aggregation of layer 3 protocols that work together to create a security extension to the IP protocol by adding packet encryption and authentication. Conceptually, IPSec presents two main dimensions: the protocol defining the transmitted packets' format, when security mechanisms are applied to them, and the protocol defining how parties in a communication negotiate encryption parameters.

Communication in an IPSec connection is managed according to Security Associations (SAs). A SA is an unidirectional set of rules and parameters specifying the necessary information for secure communication to take place [20]. Here, unidirectional means a SA can only be associated with either inbound or outbound traffic, but never with both. Hence, an IPSec bidirectional association implies the establishment of two SAs: one for incoming packets and one for outgoing. SAs specify which security mechanism to use - either Authentication Header (AH) or Encapsulating Security Payload (ESP) - and are identified by a numeric value, the Security Parameter Index (SPI). Although SAs can be manually installed in routers, gateways or machines, it becomes impractical as more clients appear. Internet Key Exchange (IKE) [8] is a negotiation protocol that tackles the problems associated with manual SA installation. In fact, IKE allows the negotiation of SA pairs between any two machines through the use of asymmetric keys or shared secrets.

### Transport and Tunnel modes

IPsec supports two distinct modes of functionality: transport and tunnel [20], which differ in the way traffic is dealt with and processed. In the context of VPNs, tunnel mode presents the most desirable characteristics. First, tunnel mode encapsulates the original IP packet, allowing the use of private IP addresses as source or destination. Tunnel mode creates the concept of an "outer" and "inner" IP header. The former contains the addresses of the IPSec peers, while the latter contains the real source and destination addresses. Moreover, this very same encapsulation adds confidentiality to the original addresses.

Transport mode requires fewer computational resources and, consequently, carries less protocol overhead. It does not, however, provide much security compared to tunnel mode, so, in the context of VPNs, tunnel mode's total protection and confidentiality of the encapsulated IP packet carry much more valuable functionalities.

## Authentication Header

AH is a protocol in the IPsec suite providing data origin validation and data integrity consisting in the generation of a checksum via a digest algorithm [9]. Additionally, besides the actual message under integrity check, two other parameters are used under the AH mechanism. First, to ensure the message was sent from a valid origin, AH includes a secret shared key. Then, to ensure replay protection, it also includes a sequence number. This last feature is achieved with the sender incrementing a sequence integer whenever an outgoing message is processed.

AH, as the name suggests, operates by attaching a header to the IP packets, containing the message's SPI, its sequence number, and the Integrity Check Value (ICV) value. This last field is then verified by receivers, which calculate the packet's ICV on their end. The packet is only considered valid if there's a match between the sender and receiver's ICV.

Where this header is inserted depends on the mode in which IPsec is running. In transport mode, the AH appears after the IP header and before any next layer protocol or other IPsec headers. As for tunnel mode, the AH is injected right after the outer IP header.

To calculate the ICV, the AH requires the value of the source and destination addresses, which raises an incompatibility when faced with networks operating with NAT mechanisms [6].

## Encapsulating Security Payload

The ESP protocol also offers authentication, integrity and replay protection mechanisms. It differs from AH by also providing encryption functionalities, where peers in a communication use a shared key for cryptographic operations. Analogous to the previous protocol, the ESP's header location differs in different IPsec modes. In transport mode, the header is inserted right after the IP header of the original packet. Also, in this mode, since the original IP header is not encrypted, endpoint addresses are visible and might be exposed. As for tunnel mode, a new IP header is created, followed by the ESP header.

Tunnel mode ESP is the most commonly used IPsec mode. This setup not only offers original IP address encryption, concealing source and destination addresses, but also supports the addition of padding to packets, diffculting cipher analysis techniques. Moreover, it can be made compatible with NAT and employ NAT-traversal techniques [12], [21].

### 2.1.2 OpenVPN

OpenVPN [22] is yet another open-source VPN provider, known for its portability among the most common operating systems due to its user-space implementation. OpenVPN uses established technologies, such as Secure Sockets Layer (SSL) and asymmetric keys for negotiation and authentication and IPsec's ESP protocol, explored in the previous section, over UDP or TCP for data encryption.

## TUN and TAP interfaces

OpenVPN's virtual interfaces, which process outgoing and incoming packets, have two distinct types: TUN (short for internet TUNnel) and TAP (short for internet TAP). Both devices work quite similarly, as both simulate P2P communications. They differ on the level

of operation, as TAP operates at the Ethernet level. In short, TUN allows the instantiation of IP tunnels, while TAP instantiates Ethernet tunnels.

### **OpenVPN flow**

When a client sends a packet through a TUN interface, it gets redirected to a local OpenVPN server. Here, the server performs an ESP transformation and routes the IP packet to the destination address, through the “real” network interfaces.

Similarly, when receiving a packet, the OpenVPN server will perform decipherment and validation operations on it, and, if the IP packet proves to be valid, it is sent to the TUN interface.

This process is analogous when dealing with TAP devices, differing, as mentioned before, at the protocol level.

### **2.1.3 Wireguard**

Wireguard [4] is an open-source UDP-only layer 3 network tunnel implemented as a kernel virtual network interface. Wireguard offers both a robust cryptographic suite and transparent session management, based on the fundamental principle of secure tunnels: peers in a Wireguard communication are registered as an association between a public key (analogous to the OpenSSH keys mechanism) and a tunnel source IP address.

One of Wireguard’s selling points is its simplicity. In fact, compared to similar protocols, which generally support a wide range of cryptographic suites, Wireguard settles for a singular one. Although one may consider the lack of cipher agility as a disadvantage, this approach minimizes protocol complexity, increasing security robustness by avoiding SSL/TLS vulnerabilities commonly originating from such protocol negotiation.

### **Routing**

Peers in a Wireguard communication maintain a data structure containing their own identification (both the public and private keys) and interface listening port. Then, for each known peer, an entry is present containing an association between a public key and a set of allowed source ips.

This structure is queried both for outgoing and incoming packets. To encrypt packets to be sent, the structure is consulted, and, based on the destination address, the desired peer’s public key is retrieved. As for receiving data, after decryption (with the peer’s own keys), the structure is used to verify the validity of the packet’s source address, which, in other words, means checking if there’s a match between the source address and the allowed addresses present on the routing structure.

Optionally, Wireguard peers can configure one additional field, an internet endpoint, defining the listening address where packets should be sent. If not defined, the incoming packet’s source address is used instead.

### **Cipher Suite**

As aforementioned, Wireguard offers a single cipher suite for encryption and authentication mechanisms in its ecosystem. The peers’ pre-shared keys are Curve25519 points [2], an

implementation of an elliptic-curve-Diffie-Hellman function, characterized by its strong conjectured security level - presenting the same security standards as other algorithms in public key cryptography - while achieving record computational speeds.

Regarding payload data cryptography, a Wireguard message's plain text is encrypted with the sender's public key and a nonce counter, using ChaCha20Poly1305, a Salsa20 variation [3]. The ChaCha cryptographic family offers robust resistance to cryptanalytic methods [18], without sacrificing its state-of-the-art performance.

Finally, before any encrypted message exchange actually happens, Wireguard enforces a 1-Round Trip Time (RTT) handshake for symmetric key exchange (one for sending, and one for receiving). The messages involved in this handshake process follow a variation of the Noise [16] protocol, which is essentially a state machine controlled by a set of variables maintained by each party in the process.

## Security

On top of its robust cryptographic specification, Wireguard includes in its design a set of mechanisms to further enhance protocol security and integrity.

With such a scope in mind, Wireguard presents itself as a silent protocol. In other words, a Wireguard peer is essentially invisible when communication is attempted by an illegitimate party. Packets coming from an unknown source are just dropped, with no leak of information to the sender.

Additionally, a cookie system is implemented in an attempt to mitigate Distributed Denial Of Service (DDOS) attacks. Since, to determine the authenticity of a handshake message, a Curve25519 multiplication must be computed, an operation requiring considerable CPU usage, a CPU-exhaustion attack vector could be exploited. Cookies are introduced as a response message to handshake initiation. These cookie messages are used as a peer response when under high CPU load, which is then in turn attached to the sender's message, allowing the requested handshake to proceed later.

## Basic Wireguard Configuration

Connecting two peers in a Wireguard communication can be done with minimal configuration. In fact, after the generation of an asymmetric key pair and the setup of a Wireguard interface, it is only required to add the other peer to the routing table with its public key, allowed IPs and, optionally, its internet endpoint (where it can be currently found). After both peers configure each other, the tunnel is established and packets can be transmitted through the Wireguard interface. In a practical scenario, given two peers, *A* and *B*, with pre-generated keys and internet interfaces, presented on table 2.1, the CLI steps to setup a minimal Wireguard communication, as specified in the official Wireguard documentation are presented in figure 2.1.

### 2.1.4 Performance Comparison

The concept of performance in VPN applications entails both protocol overhead on communication throughput and bandwidth usage minimization. These dimensions can be empirically measured, by calculating communication latency / ping time and throughput. The performance claims on [4], where, when comparing Wireguard to its alternatives like OpenVPN and IPsec, present results in favor of Wireguard in both metrics. This conclusion is

|                          | Peer A         | Peer B        |
|--------------------------|----------------|---------------|
| <b>Private Key</b>       | gIb/+...+uF2Y= | aFov...G3l0=  |
| <b>Public Key</b>        | FeQI...jHgE=   | sg0X...7kVA=  |
| <b>Internet Endpoint</b> | 192.168.100.4  | 192.168.100.5 |
| <b>Wireguard Port</b>    | 51820          | 51820         |

Table 2.1: Nodes to be configured with a Wireguard tunnel

|  |  |
|--|--|
| <pre># Peer A - interface setup \$ ip link add wg0 type wireguard \$ ip addr add 10.0.0.1/24 dev wg0 \$ wg set wg0 private-key ./private \$ ip link set wg0 up  # Adding peer B to known peers \$ wg set wg0 peer sg0X...7kVA=     allowed-ips 10.0.0.2/32     endpoint 192.168.100.5:51820 \$</pre> | <pre># Peer B - interface setup \$ ip link add wg0 type wireguard \$ ip addr add 10.0.0.2/24 dev wg0 \$ wg set wg0 private-key ./private \$ ip link set wg0 up  # Adding peer A to known peers \$ wg set wg0 peer FeQI...jHgE=     allowed-ips 10.0.0.1/32     endpoint 192.168.100.4:51820 \$</pre> |
|--|--|

Figure 2.1: Basic Wireguard Communication Between Two Peers

backed by more extensive research [11], [13], where communication is tested in a wide range of different environments and CPU architectures.

Wireguard, due to its kernel implementation (compared to, for example, OpenVPN's user space implementation) and efficient multi-threading usage, contribute greatly to such performance benchmarks. Moreover, its relatively small codebase (around 4000 lines) creates a very auditable, maintainable VPN protocol.

## 2.2 Control Platforms

Although Wireguard proves itself to be a robust, performant and maintainable protocol for encrypted communication, it still presents some complexity regarding administration agility and scalability. New clients added to a standalone Wireguard network imply the manual reconfiguration of every other peer already present, a process with added complexity that is prone to errors, as more nodes join the system. With this in mind, this section explores applications and implementations of control platforms built, or with the potential to be built, on top of Wireguard, aiming to create a seamless peer orchestration and configuration process, minimizing human intervention.

First, it is mandatory to define what a control platform is. The main goal should be to overcome the limitations previously mentioned, by supporting:

- A centralized server storing peers' identification (public key and tunnel IP address).
- Establishment of secure channels between peers and such a centralized server.
- On-demand retrieving of information regarding any peer in its network domain.

### 2.2.1 OOR Map Server Implementation

An implementation with said requirements is proposed in [14]. The core architecture of this solution is composed by a centralized Open Overlay Router (OOR) Map Server, containing peer identification data, which provides devices with on-demand information regarding any other peer in the network to setup a direct connection. From a client perspective, a peer wanting to communicate with another should first establish a secure Wireguard connection to this server and request a connection with a destination node. The server, with the source IP and public key of the requesting client, redirects this data to the destination node, reaching a state where both peers contain all necessary information to begin the Wireguard tunnel.

This prototype successfully tackles one of the main limitations of Wireguard, offering a mechanism capable of dynamically configuring peers, without the need to reconfigure every device every time a new client joins the network. Also, it reduces routing table complexity, as peers are not required to keep all other peers' information locally. However, the addition of such a centralized entity also introduces a new attack vector. Effectively, if the private key of the central server, crucial in creating the first secure channel between a peer and the server, is compromised, a man-in-the-middle attack could be mounted, since an attacker could impersonate the centralized server.

Regarding performance, there is, as expected, an overhead compared to native OOR benchmarks, as requests to OOR Map Server are themselves conducted through a Wireguard channel.

### 2.2.2 Tailscale

Tailscale is a VPN service operating with a golang user-space Wireguard variant as its data plane [15]. Traditional VPN services operate under a hub-and-spoke architecture, a model composed of one or more VPN Gateways - devices accepting incoming connections from client nodes and forwarding the traffic to their final destination. Hub-and-spoke architectures carry some limitations. First, it implies increased latency associated with the geographical distance between a client and the nearest hub. Also, regarding scalability and dynamic configuration, adding new clients to the network requires the distribution of its keys to all hubs. With these constraints in mind, Tailscale offers a hybrid model. Tailscale's central entity, referred to as a coordination server, functions as a shared repository of peer information, used by clients to retrieve information regarding other nodes and establish on-demand P2P connections among each other.

This control plane approach differs from traditional hub-and-spoke since the coordination server carries nearly no traffic - it only serves encryption keys and peer information. Tailscale's architecture provides the best of both worlds, benefiting from the advantages of control plane centralization without bottlenecking its data plane performance.

In practical terms, a Tailscale client will store, on the coordination server, its own public key and where it can currently be found. Then, it downloads a list of public keys and addresses that have been stored on the server previously by other clients. With this information, the client node is able to configure its Wireguard interface and start communicating with any other node in its domain.

## Overcoming network constraints

Tailscale also successfully supports procedures to overcome the problems described in the introduction of this section. Regarding stateful firewalls, where, generally, inbound traffic for a given source address on a non-open port is only accepted if the firewall has recently seen an outgoing packet with such *ip:port* as destination (essentially assuming that, if outbound traffic flowed to a destination, the source expects to receive an answer from that same destination), Tailscale keeps, in its coordination server, the *ip:port* of each node in its network. With this information, if both peers send an outgoing packet to each other at approximately the same time (a time delta inferior to the firewall's cache expiration), then the firewalls at each end will be expecting the reception of packets from the opposite peer. Hence, packets can flow bidirectionally and a P2P communication is established. To ensure this synchronism of attempting communication at approximate times, Tailscale uses its coordination server and Designated Encrypted Relay for Packets (DERP) servers (explored further in the following paragraphs) as a side channel.

Although this procedure is quite effective, in networks with NAT mechanisms, where source and destination addresses are tampered with, this process is not as straightforward, since peers don't know the public addresses NAT will translate their private addresses to. The Session Traversal Utilities for NAT (STUN) protocol offers aid in performing NAT-traversal operations [17] and can solve this problem. For a peer to discover and store in the coordination server its own public *ip:port*, it first sends a packet to a STUN server. Upon receiving this packet, the STUN server can see which source address was used (the address NAT translated to) and replies with this value to the peer.

There are, however, some NAT devices that create a completely different public address mapping to each different destination a machine communicates with, which hinders the above address discovery process. Such devices are classified as Endpoint-Dependent Mapping (EDM) (in opposition to Endpoint-Independent Mapping (EIM)) [7].

Networks employing EDM devices and/or really strict firewall rules, such as blocking outgoing UDP entirely, render these traversal techniques useless. To enable P2P communications in such scenarios, Tailscale also provides a network of DERP servers, which are responsible for relaying packets over Hyper-Text Transfer Protocol (HTTP). A Tailscale client is able to forward its encrypted packets to one of such DERP servers. Since a client's private key never actually leaves its node, DERP servers can't decrypt the traffic being relayed, performing only redirection of already encrypted packets. These relay servers are distributed geographically. However, there is the possibility of an increase in latency and loss of bandwidth, which isn't terrible, as the alternative is not being able to establish connections at all.

As such, Tailscale's design provides a set of directives and infrastructure that work together to ensure Wireguard tunnels can be set up between any two peers, regardless of what policies the network between them employs.

## Headscale

While Tailscale's client is open source, its control server isn't. There is, however, an open-source, self-hosted alternative to Tailscale's control server, Headscale. Headscale [5] provides a narrow-scope implementation (with a single Tailscale private network) of the aforementioned control server, which, in the authors' words, is mostly suitable for personal use and small organizations. Nodes running tailscale clients can opt to specify the location of the control



server, which can be the address of a running self-hosted Headscale instance.

## 2.3 University of Aveiro Network

Due to security and privacy concerns, the specification of the UA's network topology is not publicly available nor is it made available for this dissertation. As such, it is perceived as a black box. There are, however, a few reachable conclusions derived from observing its behavior.

First, the network is highly segmented, where clients are grouped according to their roles. In fact, when clients connect to an Access Point (AP) within the campus, they are connected to a Virtual Local Area Network (VLAN) shared by several other clients, in which the private resources are accessible. Then, the present NAT mechanisms in the network are unknown, as are their mappings' Time To Live (TTL), which is an important variable discussed in the previous sections. Finally, the network contains a segment for public services, which can be accessed from anywhere on the Internet. This public point of communication will allow clients from within the campus to connect to the control platform, serving in this domain.

## Chapter 3

# Methodology

Having outlined the relevant technologies for this dissertation’s context, this chapter aims to present a work proposal for the solution implementation. The approach to be taken is segmented in three main stages: Prototype Development, Production Deployment and, finally, Automation.

### 3.1 Prototype Development

This first phase aims to build a small-scale prototype in a virtual development environment. The prototype should, using Headscale and Tailscale, be able to establish a P2P connection between two sample clients, which couldn’t communicate beforehand. Hence, this phase’s main goals are to (i) create a virtual environment which simulates the scenario being tackled, (ii) establish P2P connections between clients in isolated private networks and (iii) validate the communication through the ROS middleware. Obviously, for goal (i), the simulation of the networking conditions won’t be precise, since, as referenced in section 2.3, details regarding UA’s network mechanisms are vastly unknown. It is possible, however, to create an analogous situation, where clients can’t form P2P communications with each other but can all communicate with an external, public server. Moreover, as stated in previous sections, Tailscale’s protocol effectively deals with most constraints preventing communication. In other words, it is only known clients can’t communicate, the reason they can’t is abstracted by Tailscale.

This virtual environment must be composed of three entities: a public server and two clients in their own private networks. As mentioned in section 2.2.2, Headscale is an open-source implementation of Tailscale’s control server. Thus, the control server in this environment is a self-hosted Headscale instance deployed in the public server. Both clients, which can reach the public server, but not each other, should then authenticate in this control server and configure their Tailscale interfaces and addresses, allowing for a direct communication to take place.

Using virtualization software, this environment could be established with three linux virtual machines with minimum resources, in a single host machine. To achieve the networking requirements, as stated in goal (i), the client machines should be attached to individual private NAT Networks and connected via Wi-Fi to an AP, while the server machine should be attached to a bridge on the host’s ethernet interface. Figure 3.1 depicts this architecture.

Finally, to validate goal (iii), a simple ROS application should be deployed and tested in

the clients, in which communication is done through the Tailscale interfaces.

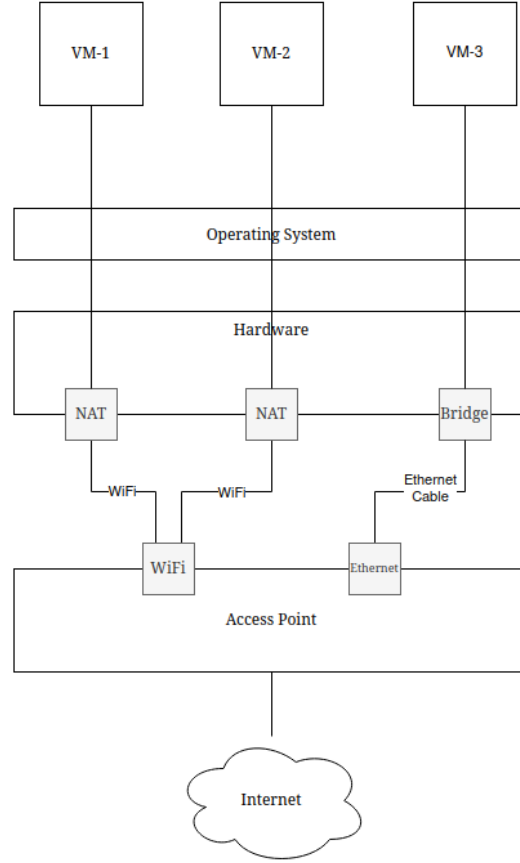


Figure 3.1: Development Enviornment Architecture

## 3.2 Deployment

After achieving and configuring the prototype previously developed, the next phase focuses on the deployment within UA's premises. (i) Deploy headscale server in public domain (ii) Configure robots (iii) validate

## 3.3 Automation

Automation of the processes taken in the previous phases, to make configuration with little to no manual intervention

The tasks encompassing the phases described above can be summed up in a Gantt diagram, presented in figure 3.2. The tasks to be carried out are as follows:

- **Development Environment Design and Requirement Analysis** - Setup of the development environment and minimum requirement analysis (identification of packets, accounts creation and domain definitions)

- **Prototype Development** - Implementation, in the development environment, of a prototype fulfilling the requirements. The end goal is to establish a P2P connection between the two machines that can't communicate.
- **Deployment** - Deployment of the control server in UA's public services domain and configuration of clients in the robots.
- **Validation** - Validation of the deployed solution, ensuring encrypted communication between nodes in different geographical locations within the campus.
- **Automation** - Development of config-based scripts automating client and server configurations.
- **Final Document Writing** - Writing of the final document, presenting the development process and providing analysis of respective results.

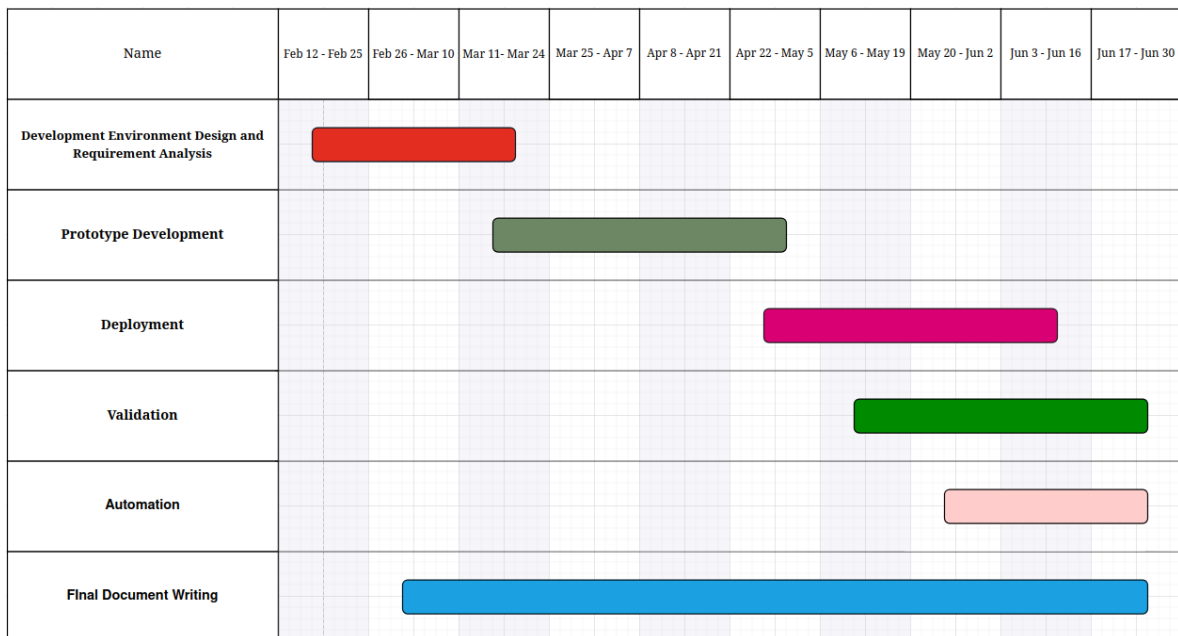


Figure 3.2: Development planning proposal

## Chapter 4

# Prototype Development

This chapter details the configuration of the development environment, as proposed in figure 3.1, and its use for the implementation of a functional prototype. This environment is managed with Oracle Virtual Box. Having defined the goals for this experiment in the aforestated work porposal, this prototype requires the deployment of the Headscale control server, which is hosted in **VM-3**, followed by the configuration, and respective login, of both clients, **VM1** and **VM2**, using the tailscale Command Line Interface (CLI). With the clients configured with Tailscale addresses, these can be used to run tests on containerized ROS applications.

### 4.1 Development Environment

#### Virtual Machines

The three virtual machines composing the environment use *Ubuntu Server 22.04* as their operating system. Due to the nature of the goals to be achieved in this phase, which focus on a very small scope, the machines require very little resources. Regarding networking, **VM3** is attached to a bridge network on the ethernet interface of the host machine. As for **VM1** and **VM2**, each respective network adapter is attached to a NAT, isolating each client on its own private network, unaccessible from the outside. All machines can access the internet through the access point, explored in the following subsection.

Both **VM1** and **VM2** are assigned the same private IP address since they are residing in distinct private networks. For convenience, the Virtual Machines are also configured to allow Secure Shell (SSH) connections, which means port 22 is open on all machines. Moreover, for machines **VM1** and **VM2**, which are confined to their private networks, this was achieved with port forwarding rules, forwarding **VM1**'s port 22 to the host machine's port 2222 and **VM2**'s port 22 to the host machine's port 2223.

Table 4.1 summarizes said specification.

#### Access Point

The access point used in this environment is a N600 Wireless Dual Band Gigabit router. The host machine is connected to the access point via ethernet. With this setup, when one of the client machines wants to communicate with **VM3**, the traffic will be routed from the client to the AP's WiFi interface. Then the router will forward the packet through its ethernet

|                         | <b>VM1</b>          | <b>VM2</b>          | <b>VM3</b>          |
|-------------------------|---------------------|---------------------|---------------------|
| <b>Operating System</b> | Ubuntu Server 22.04 | Ubuntu Server 22.04 | Ubuntu Server 22.04 |
| <b>Memory (Mb)</b>      | 1024                | 1024                | 1024                |
| <b>Storage (Gb)</b>     | 10                  | 10                  | 10                  |
| <b>CPUs</b>             | 1                   | 1                   | 1                   |
| <b>Network Adapter</b>  | NAT                 | NAT                 | Bridged (ethernet)  |
| <b>Address</b>          | 10.0.2.15           | 10.0.2.15           | 192.168.10.214      |

Table 4.1: Development Virtual Machines specification

| <b>Service</b>            | <b>Listen Address</b> | <b>Port</b> | <b>Description</b>   |
|---------------------------|-----------------------|-------------|--|
| Control Server            | 192.168.10.214        | 8080        | Main service implementing Tailscale’s control plane protocol |
| Metrics                   | 127.0.0.1             | 9090        | Exposes the /metrics endpoints, for monitoring               |
| gRPC                      | 127.0.0.1             | 50443       | Allows remote Headscale control via CLI                      |
| STUN Server               | 192.168.10.214        | 3478        | Exposes NAT-Traversal functionalities                        |
| DERP Server<br>(embedded) | 192.168.10.214        | 8080        | Mandatory when not using Tailscale’s own DERPs               |

Table 4.2: Services running in the Headscale instance

interface, reaching the host machine and, consequently, reaching **VM3**, as its network adapter is bridged to the host’s ethernet interface, as described above.

This effectively simulates, within the host machine, a scenario very similar to the one present in the IRIS-Lab’s use case.

## 4.2 Headscale Instance Deployment

Headscale provides an highly configurable open-source implementation of a control server, allowing the configuration of DERP relays and STUN servers, which must also be hosted in this server. At the time of writing, the latest stable Headscale release is *v0.22.3*<sup>1</sup>, which is the version of the software referred to in the rest of this chapter.

The instance was configured to run with an embedded DERP server in the default region, which additionally provides STUN functionalities to make NAT traversal possible within the environment. These configurations were achieved through Headscale’s configuration file, a yaml provided in the package. With the service running, **VM-3** is now listening for Tailscale clients to connect and start using the protocol. For development purposes, an Headscale user, **dev**, was registered in the instance and shall be the user the clients will register themselves with. Finally, regarding Tailscale IP assignments, the instance uses the default subnet prefixes, 100.64.0.0/10 for ipv4 and fd7a:115c:a1e0::/48 for ipv6. Registered clients will be assigned IP addresses in these ranges.

Table 4.2 presents the available services and their respective listening configuration produced by the running Headscale instance. Besides the metrics and gRPC services, which are not required by clients to use the Tailscale protocol, are listening privately, on the server’s localhost interface. The remaining services are exposed in the defined ports, reachable by the clients.

<sup>1</sup>Headscale’s official releases, hosted in GitHub. <https://github.com/juanfont/headscale/releases>.

## 4.3 Client Configuration

Initially, clients can't really establish a direct connection in a traditional way. In fact, neither client is assigned a public address which could be used as a communication's endpoint. They can, however, reach the outside internet, which consequently implies the translation of their private addresses into public ones, a process carried by the adapter attached to the host machine's NAT.

Using Tailscale's, CLI, a client is able to authenticate in the Headscale instance previously deployed, which in turn configures its Tailscale interface with a respective Tailscale IP, in the range previously configured in the control server. This will allow a state where P2P WireGuard tunnels can be established freely between the registered clients.

Hence, the Tailscale binaries were installed in each client, using the install shell script provided <sup>2</sup>.

At this point, clients are ready to perform authentication in the control server and start communicating, a process described in the next section.

## 4.4 Authentication

## 4.5 Communication with ROS

---

<sup>2</sup>Tailscale's install script, publicly available online. <https://tailscale.com/install.sh>

## Chapter 5

# Production Deployment



## Chapter 6

# Automation

## Chapter 7

# Validation and Results

## Chapter 8

## Conclusion



# Bibliography

- [1] André Zúquete. *Segurança em Redes Informáticas*. FCA, 2013.
- [2] Daniel J Bernstein. Curve25519: new diffie-hellman speed records. In *Public Key Cryptography-PKC 2006: 9th International Conference on Theory and Practice in Public-Key Cryptography, New York, NY, USA, April 24-26, 2006. Proceedings 9*, 2006.
- [3] Daniel J Bernstein et al. Chacha, a variant of salsa20. In *Workshop record of SASC*, 2008.
- [4] Jason A Donenfeld. Wireguard: next generation kernel network tunnel. In *NDSS*, 2017.
- [5] Juan Font and Kritoffer Dalby. Headscale. <https://headscale.net/>, 2023.
- [6] Sheila Frankel, Karen Kent, Ryan Lewkowski, Angela D Orebaugh, Ronald W Ritchey, and Steven R Sharma. Guide to ipsec vpns:. 2005.
- [7] Cullen Fluffy Jennings and Francois Audet. Network Address Translation (NAT) Behavioral Requirements for Unicast UDP. RFC 4787, 2007.
- [8] Charlie Kaufman, Paul E. Hoffman, Yoav Nir, Pasi Eronen, and Tero Kivinen. Internet Key Exchange Protocol Version 2 (IKEv2). RFC 7296, 2014.
- [9] Stephen Kent. IP Authentication Header. RFC 4302, 2005.
- [10] Ari Keränen, Christer Holmberg, and Jonathan Rosenberg. Interactive Connectivity Establishment (ICE): A Protocol for Network Address Translator (NAT) Traversal. RFC 8445, 2018.
- [11] Steven Mackey, Ivan Mihov, Alex Nosenko, Francisco Vega, and Yuan Cheng. A performance comparison of WireGuard and OpenVPN. In *Proceedings of the Tenth ACM Conference on data and application security and privacy*, 2020.
- [12] Tran Sy Nam, Hoang Van Thuc, and Nguyen Van Long. A High-Throughput Hardware Implementation of NAT Traversal For IPSEC VPN. *International Journal of Communication Networks and Information Security*, 2022.
- [13] Lukas Osswald, Marco Haeberle, and Michael Menth. Performance comparison of vpn solutions. 2020.
- [14] Jordi Paillisse, Alejandro Barcia, Albert Lopez, Alberto Rodriguez-Natal, Fabio Maino, and Albert Cabellos. A control plane for wireguard. In *2021 International Conference on Computer Communications and Networks (ICCCN)*, 2021.

- [15] Avery Pennarun. How tailscale works. <https://tailscale.com/blog/how-tailscale-works/>, 2020.
- [16] Trevor Perrin. The noise protocol framework. 2018.
- [17] Marc Petit-Huguenin, Gonzalo Salgueiro, Jonathan Rosenberg, Dan Wing, Rohan Mahy, and Philip Matthews. Session Traversal Utilities for NAT (STUN). RFC 8489, 2020.
- [18] Gordon Procter. A security analysis of the composition of chacha20 and poly1305. 2014.
- [19] Morgan Quigley, Ken Conley, Brian Gerkey, Josh Faust, Tully Foote, Jeremy Leibs, Rob Wheeler, Andrew Y Ng, et al. Ros: an open-source robot operating system. In *ICRA workshop on open source software*, 2009.
- [20] Karen Seo and Stephen Kent. Security Architecture for the Internet Protocol. RFC 4301, 2005.
- [21] Chaman Singh and KL Bansal. NAT Traversal Capability and Keep-Alive Functionality with IPSec in IKEv2 Implementation, 2012.
- [22] James Yonan. Openvpn. <https://openvpn.net/>.