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MASTER THESIS

"EVALUATION OF THE EFFECTIVENESS OF VPN TRAFFIC OBFUSCATION METHODS"

Computer Sciences, 45483

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LIST OF USED ABBREVIATIONS

AI - Artificial Intelligence

DPI - Deep Packet Inspection

GFW - Great Firewall of China

HTTPS - Hypertext Transfer Protocol Secure

IP - Internet Protocol

ISP - Internet Service Provider

LSB - Least Significant Bits

ML - Machine Learning

NAT - Network Address Translation

SSH - Secure Shell

SSL - Secure Sockets Layer

TCB - TCP Control Block

TCP - Transmission Control Protocol

TCP - Transmission Control Protocol

TLS - Transport Security Layer

UDP - User Datagram Protocol

VM - Virtual Machine

VPN - Virtual Private Network

INTRODUCTION

In an time when digital communication plays a fairly important role in modern socienty, ensuring the confidentiality and integrity of network communications has become crucial. The arrival of virtual private networks (VPNs) as a way of securing and privatizing digital communications on the publicly used Internet has been a significant development in this direction. Because of the ever growing popularity of virtual private networks, government agencies and corporate network administrators have ever so increased their efforts to identify and block these encrypted connections. The result has been, what one may call, an arms race between organizations seeking to monitor, control, or censor Internet traffic and VPN service providers competing for the privacy of their users. The implementation of VPN obfuscation, an advanced collection of technologies capable of disguising VPN traffic as routine Internet operations, is central to this dispute. This obfuscation allows free access to the global digital landscape.

Initially, VPNs were implemented as just a way to establish secure network connections across the insecure infrastructure of the public Internet. However, the use of VPN technology eventually grown ouside of the scope of corporate applications. Privacy oriented users are increasingly adopting virtual private networks for their own benefit, due to the potential for enhanced privacy, circumvention of surveillance, circumvention of content location based restrictions, and protection against cyber threats. In response, efforts to undermine the effectiveness of virtual private networks have increased. These initiatives include corporate firewall policies, government censorship initiatives such as China's Great Firewall, and anti-VPN measures implemented by content providers (El-Maghraby et al. 2017).

The gradual and yet noticable proliferation of anti-VPN initiatives has sparked the emergence of a complex area of cybersecurity that uses data packet signatures to distinguish VPN connections. In response, the VPN obfuscation movement has developed a number of countermeasures. As a recent example, we have the Geneva algorithm which employs genetic algorithms to generate dynamic, packet- manipulation-based evasion strategies, providing a new take on Deep Packet Inspection (DPI) evasion (Bock et al. 2019).

Steganography can also be utilized in VPN obfuscation. This method provides a way around DPI systems by embedding VPN traffic inside regular data streams. Steganography enables regular web traffic, like audio or video streams, to conceal VPN packets, making it difficult for DPI tools to discern between encrypted and regular traffic (Kundur & Ahsan 2003). The effectiveness and subtlety of this method are assessed, offering insights into its limitations and useful applications in different network environments.

Another way of obfuscating VPN traffic is through the application of port switching. To avoid detection, a VPN server is configured to use non-standard ports, which can assist in getting around simple DPI systems that keep an eye on popular VPN ports.

Another way of providing VPN obfuscation is the integration of encrypted proxy tunneling software like Shadowsocks and Stunnel. It can be used to make VPN traffic look like HTTPS traffic (Clowwindy et al. n.d.).

All of these methods, excluding port switching, bring with them a trade-off of in connection speed and throughput, though of varying degrees.

The thesis begins with an overview of VPN technology and then describes the various use cases for VPNs as well as the fundamental principles underlying their operation. It then describes the techniques used to detect VPN traffic. The following is a comprehensive examination of various obfuscation methods and their adaptation to evolving VPN traffic detection strategies. The goal of this analysis is to provide insight into VPN detection methodologies and obfuscation techniques through experimentation, literature analysis, qualitative assessment, and technical proficiency in the process developing a methodology by which one can consider selecting an obfuscation method in real-life scenarios. The bulk of the experimentation was conducted utilizing a virtual networking topology with the prime VPN being OpenVPN and ndpi being used as the DPI system. The questions this thesis aims to answer are as follows:

- Which of the selected VPN obfuscatory methods are capable evading detection of the nDPI deep-packet inspection system within the provided virtual network topology?
- How effective these methods are in terms of selected evaluation criteria?
- Which method to choose in a real-life scenario?

1. LITERATURE

For the purposes of gaining insight into the topic of VPN obfuscation an extensive dive and analysis was conducted into the topic of VPNs, DPI and protocol obfuscation. Many related sources and research publications were found, though it may be noted that none of the research results found were of a similar nature to my own topic. Much of the research, was of a more focused nature, typically centering around a more narrow topic. None of them took a comparative approach to the VPN obfuscation methods. In addition, they approached the topic from a different perspective. The perspective of general data hiding, not taking VPNs into consideration, some examples being Bock et al. (2019), Kundur & Ahsan (2003) and Wang et al. (2020) where there is no explicit mention of VPNs. In addition, many research publications were aimed towards the opposite, with the goal of developing progressively new ways of detecting VPN traffic instead of hiding it, examples of thing being Chen & Lin (2021), Ghatikar & Sai (2022) and Naidu & Jha (2023).

1.1. Search Strategy

The process of finding source of literature was incremental and partially iterative in its nature. At first, a list of topic specific terms and keywords was compiled: Deep packet inspection, network traffic analysis, censorship circumvention. With these keywords, a number of initial sources were found, those most prominently included: Bock et al. (2019), Wang et al. (2014) and El-Maghraby et al. (2017).

Based on the found literature sources, a more clear understanding of the topic and its terminology was garnered. Accordingly, an extended list terms and keyword was compiled which now included: steganography, packet fragmentation, traffic manipulation, network security, Obfsproxy. This process was then again repeated until an adequate understanding of the topic was achieved.

1.2. Literature Repository Selection

In order to find the literature a number of digital libraries were utilized based on the degree of relevance in relation to the topics of computer science, networking and software engineering. The most prominent of those repositoiries being:

- Research Gate
- IEEE Xplore
- ArXiv

- ACM Digital Library
- Springer Link
- Dergi Park

In some exceptional cases, more unoffical sources were used, for example, jouralist articles or website documentation. This applied for cases like Clowwindy et al. (n.d.) and Network Solutions LLC (2021) where the most reliable source of information for how Shadowsocks and OpenVPN work came from website documentation.

1.3. Exclusion criteria

For the systematic review of literature relating to VPN obfuscation, Deep Packet Inspection, and protocol obfuscation, certain exclusion criterias were employed to ensure the relevance and validity of the chosen sources. These criteria were used in filtering out literature that did not directly contribute to the understanding of the topic or meet the requirements. The used exclusion criteria are as so:

- **Non-Academic Sources:** Sources lacking peer-review or not published in recognized academic journals or conferences were excluded to the utmost degree. This includes blog posts, non-reviewed whitepapers, and informal publications. Though still, some non-academic sources were used when absolutely needed.
- **Irrelevant Topics:** Literature that did not directly address VPNs, VPN obfuscation, DPI, or protocol obfuscation was excluded. This encompasses studies focused solely on broader topics of corporate network security or general VPN usage. Though, to be clear, papers that provide in some way a detailed technical explanation on how protocols, VPNs or DPI were, in certain cases, were included.
- **Language Constraints:** Sources not available in English were excluded.
- **Duplicate Studies:** In cases where multiple publications reporting the same information or research, only the most comprehensive or recent version was included.
- **Geographical Irrelevance:** Studies focusing on region specific VPN usage or censorship practices, which are not applicable or relevant to the broader context of global VPN obfuscation, were excluded.
- **Technical Inapplicability:** Research that focuses on obsolete or rarely used VPN protocols or technologies was excluded, to concentrate on methods and findings relevant to current practices.

These exclusion criteria were applied to make sure the collection of literature was focused and relevant. The criteria were developed to strike a balance between inclusiveness and specificity, therefore providing a comprehensive overview of the current state of research in VPN obfuscation, DPI, and protocol obfuscation.

1.4. Found literature

As mentioned before, a number of sources relating to VPNs, protocol obfuscation and DPI were successfully found. Though all of these sources differ in their goal from this thesis. None of them perform a wide comparative review and analysis for VPN obfuscation methods. The found literature is used as a source of information, from which a comprehensive overview of VPN obfuscation is synthesized

1.4.1. VPN related literature

The found literature addressing VPNs is quite diverse. Covering various topics from technical implementation to traffic identification and obfuscation. Here is a general overview of the key literature in this area:

- **OpenVPN Traffic Identification:** Pang et al. (2013) in their work titled ”OpenVPN Traffic Identification Using Traffic Fingerprints and Statistical Characteristics” provides a good general overview on how OpenVPN traffic could be identified. This information is critical towards understanding the characteristics of VPN traffic and how DPI can go about detecting it.

- **SSL VPN Advanteges:** The benefits of SSL based VPNs is discussed in-depth by Sun (2011) and this work highlights certain features and benefits of SSL VPNs, which are critical for secure and remote access.

- **General VPN overview:** a basic definition and understanding of VPNs is provided by Ferguson & Huston (1998) helping to establish a baseline border between data obfuscation and VPN obfuscation.

- **Tor and VPNs:** The intersection of Tor and VPNs is discussed in the chapter ”Tor Relays, Bridges, and Obfsproxy” by Loshin (2013). The chapter provides a fairly well-rounded understanding of how Tor and VPNs can be used together for enhanced anonymity and privacy.

1.4.2. DPI related literature

DPI is an important part of corporate networking and traffic analysis and several sources have been found that provide an insightful overview of this technology. Here are some of the key highlight in terms of found literature:

- **Deep Packet Inspection Survey:** In the paper by El-Maghraby et al. (2017) ”A survey on deep packet inspection”, a comprehensive look is provided for DPI technologies, expositing fundamental facts about DPI such as on what OSI layer they operate and what mechanism are used to inspect packet contents, such as regular expression.
- **DPI and Traffic Manipulation:** Yoo & Ahmed (2019) in ”Control Logic Injection Attacks on Industrial Control Systems” and Wang et al. (2017) in ”Your State is Not Mine: A Closer Look at Evading Stateful Internet Censorship”, study DPI in terms of traffic manipulation and evasion methods. These papers provide insights into how DPI can be circumvented or exploited, which is important for understanding its limitations and possible vulnerabilities.
- **DPI and Machine Learning:** Trivedi & Patel (2016) postulate the integration of machine learning into DPI systems and present an new approach for DPI systems enhanced by machine learning which potentially describes the future of DPI and how they will further evolve.
- **DPI and SSL Inspection:** Chakraborty et al. (2022) assess the DPI system of network traffic, including anomaly detection. This study is important for understanding how DPI is adapting to modern encrypted traffic.

These chosen studies give a broad look at DPI, looking at its scientific roots, its uses in different areas, and new problems that are coming up. To fully understand DPI in the bigger picture of VPN obfuscation and protocol obfuscation, which are the main ideas of this thesis, one needs to understand these aspects.

1.4.3. Protocol obfuscation related literature

Protocol obfuscation refers to the process of using various methods and techniques to hide the true identity of the protocol being used for communication between network devices. This is most important area of study pertaining to my thesis and as such many different sources and papers were found for it:

- **Geneva: Evolving Censorship Evasion Strategies:** Bock et al. (2019) provide an modern and innovative new method for automated DPI evasion by utilizing genetic algorithms for developing a unique strategy that could be used to bypass any DPI system in place.

- **Practical Internet Steganography:** Kundur & Ahsan (2003) presents steganography as a means of obfuscating communication protocols, an important aspect of circumventing DPI. The paper itself talks about utilizing redundant IP header fields for carrying the conent data.

- **SymTCP: Automated Discrepancy Discovery:** Wang et al. (2020) discuss a method for evading DPI through the discovery and use of discrepancies/inconsistencies in TCP implementations. Mainly, this study helps in understanding how protocol behaviors can be manipulated to evade detection.

- **Hiding Data in the OSI Network Model:** Handel & Sandford (1996) discuss the idea of data hiding at various layers of the OSI model and their corresponding protocols which in some cases have field headers that are unnecessary in certain situations. This research provides foundational knowledge on the versatility of obfuscation techniques across different network layers.

All together, these studies give a full picture of protocol deception methods and how they are used. They show how protocol obfuscation is changing because DPI and filtering technologies are getting better. This thesis needs to put these methods in the bigger picture of VPN obfuscation, so understanding how they work is very important.

2. BACKGROUND

2.1. Virtual Private Networks

2.1.1. Definition and Purpose of VPNs

A VPN is a fairly complicated communication system that enables safe and private connections within a public network infrastructure, such as the internet by using secure protocols and encryption. Its purpose is to facilitate the secure and private transmission of data over a shared network, restricting access to only authorized users within a certain community of interest.(Ferguson & Huston 1998) VPNs ensure anonymity by utilizing techniques such as tunneling and encryption. This allows for the creation of a virtual network that makes use of the existing infrastructure of the public network, while maintaining high levels of security and privacy. A VPN serves the purpose of facilitating safe and confidential communication, which is particularly crucial for the transmission of sensitive data and distant connectivity to private networks.

2.1.2. Types of VPNs

For lone users who must connect to a private network from a distance, **remote access VPNs** are made. It is frequently used by people who work from home and who need safe/secure remote access to company or personal network resources. The user's device's VPN client software creates a secure connection to a VPN server, which then provides access to the private network. With this configuration, data transported over the internet is supposed to be encrypted, protecting its integrity and privacy.

Site-to-Site VPNs, also known as Router-to-Router VPNs, are fairly often used by large enteprises with offices that are dispersed in different places. The goal of these VPNs is to link entire networks together. For example, a company connecting its office network in New York to its office network in London may be able to do so by using a Site-to-Site VPN. This kind of VPN can be further divided into two categories: Extranet-Based (which connects to sites outside the organization, such as partners or vendors) and Intranet-Based (which connects to numerous sites within the same organization). (Rathore et al. 2009)

Personal VPN services are sold to people by outside companies and service providers. These services help people protect their privacy and safety by encrypting their internet data and hiding their IP address from other parties, like ISPs. People often use personal VPNs to get around location based content limits, and to stay anonymous online, and, of course, to keep their data safe when they use public Wi-Fi networks.

A **Mobile VPN** is a VPN that maintains a consistent connection as the user moves and changes network connections, making it very comfortable for professionals who frequently switch between Wi-Fi and cellular data networks. And unlike traditional VPNs, which can drop connections during such transitions, Mobile VPNs ensure uninterrupted connectivity and application session persistence so that, for example, a used logged into a website is not suddenly disconnected. (Alshalan et al. 2016)

Hardware VPNs offer a separate standalone device with dedicated processors to handle VPN operations. This type offers also robust security, naturally high performance, and ease of maintenance, making it fairly suitable for large businesses. Although, they can be more expensive than software-based solutions and could require more technical knowledge and expertise for setup and management. A valid example of this may be a pure hardware implementation of WireGuard on FPGA. (Liu et al. 2023)

Secure Sockets Layer (SSL) VPNs are VPNs that provide safe remote access to an organization's internal network and applications, in a similar fashion to the before mentioned ones, but unlike traditional VPNs that require installing specific client software, SSL VPNs can be used from a standard web browser, providing a more flexible/robust solution for users. They are especially useful for providing access to web applications and services. (Sun 2011)

2.1.3. VPN Protocols and Standards

Different protocols and standards, each with their specific functionality and security mechanisms, could be represented as the core of VPN technology. Understanding VPN protocol obfuscation and Deep Packet Inspection evasion methods requires a solid understanding of these protocols:

- **OpenVPN**: An very configurable and robust protocol. One of the things its known fore are its open-source implementations of security and performance technologies, including the OpenSSL encryption library. OpenVPN is a highly adaptable software that supports a large range of encryption algorithms and can circumvent firewalls. It is an ideal candidate for research into obfuscation and DPI evasion techniques due to its adaptability.

- **IPSec/IKEv2**: with its acclaimed speed and reliability, Internet Protocol Security (IPSec) and Internet Key Exchange version 2 (IKEv2) provide strong security. However, it is less suitable for in-depth obfuscation research because to its intricacy and the need for a third-party client on some platforms. (Matalgah et al. 2002)

- **L2TP/IPSec**: Due to how IPSec and Layer 2 Tunneling Protocol (L2TP) work complementary to each other, many devices use them together. But because L2TP/IPSec depend on fixed ports, it is less suitable for obfuscation research because it is more prone to DPI and simpler to stop.

- **PPTP**: One of the first VPN methods was Point-to-Point Tunneling Protocol (PPTP). PPTP is not recommended for secure communications because it has known security gaps and encryption that is not very strong. This makes it less relevant for current study into obfuscation and DPI evasion.

- **SSTP**: Secure Socket Tunneling Protocol is well-known for its capacity to circumvent the majority of firewalls. However, because it is Microsoft's proprietary software, it does not have the openness and public inspection that are required for conducting in-depth study on obfuscation. (Kim et al. 2011)

- **WireGuard**: WireGuard, a more recent addition, provides both simplicity and high-speed performance. Although it shows potential, its relative newness has limited its testing in various circumstances, especially in situations involving obfuscation. (Lipp et al. 2019)

Taking these things into account, OpenVPN becomes the main topic of experimentation into hiding VPN protocols and getting around DPI. Because it is open-source, it can be studied and configured in a lot of detail, which is necessary for studying effective obfuscation methods, in addition OpenVPN is widely used and supports many different types of encryption, it is also a good choice for this study.

2.1.4. Security Mechanisms in VPNs and DPI challenges

VPN's build safe, encrypted tunnels that shield users from all kinds of risks, like as censorship, data theft, and spying. However, more sophisticated Deep Packet Inspection (DPI) methods are posing a threat to VPN efficacy. We examine the main VPN security features below, along with how DPI may compromise their efficacy.

Encryption

- **Function**: Encryption is the most important part of VPN security. It changes data into a coded form that can only be read by someone with the right decoding key. AES (Advanced Encryption Standard) and TLS (Transport Layer Security) are two common types of encryption.

- **DPI challenge**: DPI can look at patterns of encrypted data to find VPN use. DPI can't decrypt the data, but it might be able to slow down or stop encrypted traffic, especially if the encryption protocol is well known and easy to spot.

Tunneling Protocols

- **Function**: OpenVPN, L2TP/IPsec, and IKEv2 are standard cases of tunneling protocols that are used for the goal of encapsulating and securely transmitting data over the internet networks. In addition to ensuring that data is kept private and unaltered during the transmission process, they define the manner in which packets are transmitted.
- **DPI challenge**: DPI solutions have the capability to detect and classify network traffic originating from widely used tunneling protocols. DPI can identify and impede VPN traffic by analyzing packet headers and sizes, particularly when conventional ports and protocols are employed.

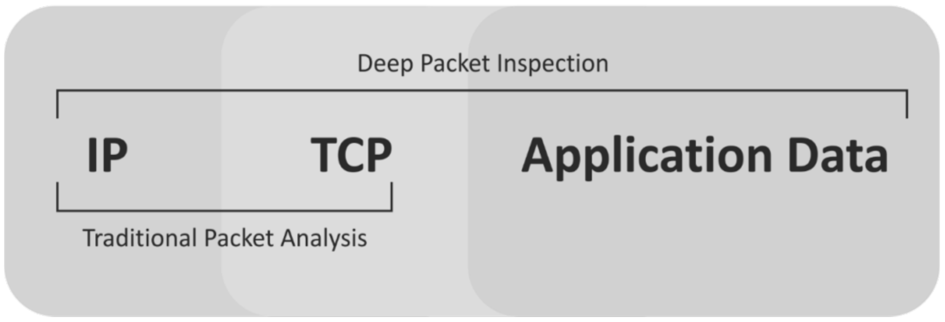
Authentication

- **Function**: VPNs utilize authentication methods to authenticate the identities of users and devices. This procedure frequently includes the use of certificates or credentials to guarantee that only authorized users have access to the VPN.
- **DPI challenge**: DPI doesn't directly affect authentication, but it can prevent users from connecting to VPN servers, which negates the purpose of authentication.

IP Masking

- **Function**: By substituting the IP address of the VPN server for the user's original IP address, VPNs disguise their identity. This aids in preserving anonymity and eschewing limitations based on location.
- **DPI challenge**: It is possible to distinguish between VPN traffic and ordinary traffic using advanced DPI techniques, even when IP masking is in use. This opens the door to the prospect of excluding or restricting VPN traffic depending on its unique properties.

2.2. Deep packet inspection



2.1. Figure. **Inspection area of DPI**

Deep Packet Inspection is a system for network packet filtering. It examines the data part (and often the header) of a packet as it passes an inspection point. As can be seen on Figure 2.1, DPI examines the packet's data payload in depth as opposed to conventional packet filtering, which simply looks at the header section, allowing for more complex packet decision-making. DPI can detect, identify, classify, reroute, or prevent packets containing particular data or code payloads thanks to this sophisticated technique.

Due to its great versatility, DPI technology is employed in many different contexts, such as traffic management, censorship, eavesdropping, and network security. It is an essential tool for internet service providers and regulatory bodies since it can identify and manage apps using the network even in the face of encryption and port-hopping schemes.

2.2.1. DPI in Relation to VPNs

DPI is important when it comes to VPNs. In order to protect privacy and get around censorship or geographical limitations, VPNs usually encrypt data. Nonetheless, DPI can be used to examine encrypted packet metadata, including timing, size, destination, and protocol. This makes it possible to identify VPN activity even when the content is encrypted.

Certain DPI techniques can detect the signatures of the encryption protocols used by VPNs, allowing them to differentiate between conventional and VPN traffic. This capability is essential in situations when the use of VPNs is prohibited or closely watched, like in nations with severe internet censorship.

2.2.2. DPI's Challenges for VPNs

VPN technologies have substantial hurdles due to the efficacy of DPI:

- **Detection and Blocking**: If Advanced DPI detects that a VPN is being used, it has the ability to either block or limit data, making the VPN useless for getting around censorship or geographical restrictions.
- **Avoiding Encryption**: Although DPI is unable to decrypt data, it can identify and potentially block VPN services based on educated estimates about the encrypted traffic's nature.
- **Adaptive Countermeasures**: VPN service providers are compelled to constantly modify and introduce fresh methods to avoid being detected by DPI, resulting in a never-ending game of cat and mouse between VPN providers and DPI-using companies.

2.3. OpenVPN identification

A first impression, may lead one to wonder how DPI systems are capable of differentiating between legitimate encrypted data such as secure HTTPS access to a website and VPN traffic. There are several techniques that DPI can use to identify OpenVPN traffic (Pang et al. 2013):

- **Protocol Signature Identification**: OpenVPN traffic can be recognized by DPI systems by looking for distinctive signatures in the packet headers. This is a conventional method that might work less well for OpenVPN because of its encryption and inconsistent port usage.
- **Heuristic analysis**: In this method, traffic patterns are examined to find traits common to VPN traffic, such as regular timing and packet sizes.
- **IP address and port inspection**: OpenVPN typically uses TCP or UDP port 1194, but it also has the option to use variable ports, which reduces the efficacy of this approach.
- **TLS Handshake Analysis**: VPN traffic, including OpenVPN, can be identified by examining the TLS handshake procedure, paying particular attention to the usage of particular cipher suites or TLS versions.
- **Timing and Packet Size**: DPI can identify consistent timing intervals and packet sizes in OpenVPN traffic.
- **Analysis of Encryption Patterns**: Even though OpenVPN encrypts its traffic, some encryption patterns might still be recognizable.
- **Behavioral Analysis**: VPN usage can be inferred by observing general network behavior, such as persistent, long-lasting connections.

- **Sequence Number and Acknowledgment Number Analysis**: Analyzing these numbers in TCP-based OpenVPN traffic can reveal VPN usage patterns.
- **Opcode Analysis in Packets**: the first 10 packets of a communication can be used as statistical characteristics for early detection of OpenVPN tunnels. By using the five bits of opcode in each packet to classify different types of packets.

These sophisticated methods, which focuses on statistical traits and traffic fingerprints, especially the opcode analysis, are very successful in identifying OpenVPN traffic, with low false positive rates and high accuracy (Pang et al. 2013). In this context, the goal of VPN obfuscation can be described as attepting to bypass detection by trying to render as many as possible of the above mentioned techniques, as ineffectual.

2.4. Packet manipulation

One of the most important tools for the design of hardware implementation for the DPI is the finite state machine. This system design, in certain cases, may be exploited by utilizing packet manipulation techniques like packet fragmentation. (AbuHmed et al. 2008) These attacks are even more relevant in the context of secure network environments, where traditional intrusion detection methods are employed.

In order to avoid detection by DPI systems, the following techniques may be employed:

- **Fragmentation and noise padding**: Harmful data is divided into smaller pieces and mixed in with ”noise” data, which is random or irrelevant data that doesn’t interfere with the payload’s ability to function. The idea is to trick DPI systems into thinking the fragmented packets are harmless, since these systems usually look for patterns in data to identify malicious activity. The attackers can effectively mask the malicious content, preventing it from being identified and prevented, by fragmenting the data and adding noise. DPI systems may find it especially difficult to defeat this strategy since it requires them to precisely reassemble and examine all of the packets in order to find the harmful content that is hidden—a laborious and resource-intensive procedure. (Yoo & Ahmed 2019)
- **TCB Creation Evasion**: The first SYN packet that opens a TCP connection is manipulated in this tactic. A false state is produced in the TCP Control Block (TCB) of the censoring system by changing specific fields in this packet. Actual data packets are able to evade filtering without being noticed because of this manipulation, which makes the censorship monitor think that the link is either nonexistent or has already ended. (Aceto & Pescapé 2015)

- **Data Reassembly Evasion**: This method takes advantage of flaws in the way censorship systems put back together broken TCP segments. When pieces of data are sent purposely out of order or overlapping, it makes it harder for the filtering system to correctly put these pieces back together and analyze them. This means that private information can get through the system that blocks them without being found or stopped. (Khattak et al. 2013)
- **TCB Teardown Evasion**: This method employs deliberately constructed packets, such as RST (reset), RST/ACK (reset acknowledgment), or FIN (finish), to prematurely end the Transmission Control Block in the censoring system. This premature termination results in the censorship system ignoring any subsequent packets from that connection. Nevertheless, the client-server link remains operational, enabling uninterrupted data flow without any intervention from censorship. (Papadogiannaki & Ioannidis 2021)
- **Resync and Desync**: In this approach, particular packets are transmitted in order to initiate a re-synchronization of the censoring system's transmission control block with the specific TCP connection. Following this, an out-of-window sequence packet is transmitted, which ultimately results in the desynchronization of the censorship system from the link that is actually being employed. It is possible for data packets to avoid detection and censorship as a result of this difference. (Wang et al. 2017)

These serve as an example of how packet manipulation methods are capable of bypassing DPI. However, it should be noted that these tactics are, by far, not consistently effective and require a fair amount of manual labor to discover the specific packet sendings order, degree of fragmentation or noise required to bypass the DPI, if at all possible.

2.5. Protocol obfuscation

Protocol obfuscation refers to the strategies used to change or conceal the properties of internet protocols in order to escape detection, censorship, or intervention from third parties. This is especially crucial in situations when internet access is tightly controlled or limited. Obfuscation prevents data packets from being detected by filters or detection systems that depend on established protocol signatures or patterns.

2.5.1. General Methods of Protocol Obfuscation

- **Randomization**: In order to hinder automated systems from identifying patterns, random elements are incorporated into the communication protocol. For example, it may be challenging for Deep Packet Inspection (DPI) to recognize the traffic as being part of a particular protocol when packet sizes or timing change. (Kailanya et al. 2022)

- **Protocol Mimicry**: By transforming the traffic of one protocol into that of another, more widely used protocol (such as HTTPS), users are able to evade filters that target particular types of data. A VPN might make its traffic look like normal HTTPS traffic, for instance. (He & Chen 2016)

- **Header Manipulation**: Systems that use header analysis can't figure out what the data bits are if the header information is changed or encrypted. Changing port numbers or encrypting the whole header are two examples of this. (Munshi 2023)

- **Traffic Pattern Masking**: This technique entails modifying the attributes of traffic, such as its quantity, frequency, or trajectory, in order to conceal its true nature. It can be especially efficient against systems that examine traffic patterns over a period of time. (Iacovazzi & Baiocchi 2014)

2.5.2. Focused methods for practical use

Cosidering the wide range of techniques available, the selection was limited to four specific methods for experimentation:

- **Port Switching**: To get around port-based filtering systems, it's easy but effective to change the port of the VPN server. Numerous DPI systems are set up to either watch or restrict traffic on particular ports that are known to be utilized by VPNs. The VPN traffic can get around these filters by periodically switching the server port. This approach is a sensible option for experimentation because it is simple to use and evaluate. (Crawford 2019)

- **Steganography**: Data concealment is the approach of encoding sensitive information within seemingly innocuous data. It entails hiding the communication within seemingly innocuous data streams, such video or picture streams, within the framework of internet protocols. Systems that aren't built to identify such advanced concealment strategies can be severely harmed by this. To learn how well obfuscation holds up against sophisticated DPI systems, experiments will be conducted with steganography. (Handel & Sandford 1996)

- **Geneva Automated Censorship Evasion**: Geneva is an innovative method that makes use of genetic algorithms to automatically look for new ways to circumvent censorship. Geneva has the capacity to keep one step ahead of censoring systems if it continues to evolve and adapt to the environment with ongoing action. In the subject of protocol obfuscation and censorship evasion, testing Geneva provides a chance to investigate the ways in which automated systems might make a contribution to the field. (Bock et al. 2019)

- **Encryption Tunneling (utilizing stunnel or shadowsocks)**: This solution involves encrypting the communication, making it impossible for DPI devices to examine the data packets' contents. Tools such as stunnel and shadowsocks are designed to conceal and obscure traffic, offering an extra degree of security. This strategy is especially useful in circumstances where DPI systems are powerful and capable of performing in-depth analysis. The use of these tools for experimentation can provide useful information about the effectiveness of encryption-based obfuscation approaches. (Zhao et al. 2018)

To summarize, the discipline of protocol obfuscation provides a variety of methods to avoid censorship and surveillance. The four selected approaches for experimentation - port switching, steganography, Geneva automatic censorship evasion, and encrypted tunneling - possess distinct advantages and cater to various aspects of obfuscation. Their choice to conduct experiments with these subjects is warranted due to their significance in modern situations when internet censorship and surveillance are becoming more advanced.

2.6. Case Studies

There exist numerous real-life examples of DPI being deployed and used on a significant scale. Some of the most notorious being:

- **The Great Firewall of China (GFW)**: China's Great Firewall is a very well-known real-life applications of DPI technology. Among other censoring tools, it uses advanced DPI techniques to identify and restrict VPN connections. VPN service providers frequently need to improve their techniques on a regular basis to avoid being detected. (Wu et al. 2023)
- **Iran's Internet Censorship**: Especially during political turmoil, Iran's government use DPI to monitor and regulate internet traffic, including the detection and blocking of VPN usage. (Bock et al. 2020)
- **Corporate Network Management**: By keeping an eye out for unauthorised VPN use that might go around corporate security measures, DPI is utilised in a business context to guarantee security and compliance.
- **Russia's Telegram Ban**: Using DPI, Russia attempted to ban the messaging service Telegram. Telegram, however, circumvented this restriction using a variety of strategies, including VPNs, illustrating the continuous conflict between DPI implementation and VPN evasion approaches. (Ermoshina & Musiani 2021)

DPI not only poses a serious threat to VPN technologies but also propels the ongoing development of VPN obfuscation strategies including port switching, network steganography, and sophisticated tunnelling methods like Geneva, Shadowsocks, and Stunnel.

2.7. Early DPI Evasion Methods

Online security and privacy were issues that only a small minority of people worried about in the early days of the internet. But as digital technology developed, so did the techniques for keeping an eye on and filtering online behavior. Deep Packet Inspection started to spread widely and revolutionized the way that institutions and governments could monitor and regulate internet traffic. At first, it was possible to avoid DPI by utilizing networks like Tor or non-standard protocols. However, as DPI technologies advanced, these strategies encountered more difficulties, prompting creative solutions like Tor bridges. (Knapp & Langill 2015)

2.7.1. Rise of DPI and Intial Evasion Tactics

Since Deep packet inspection goes farther than conventional packet filtering by checking the data part (content) of packets as they pass, rather than only the header. Governments and ISPs were able to regulate and control internet traffic with an unparalleled level of precision.

Many people, concerned about their right to privacy and freedom of expression, sought out ways to circumvent DPI as it gained traction. The use of non-standard protocols was one strategy. The original intention of DPI filters was to identify and regulate conventional internet traffic; however, users were able to circumvent these filters by employing less popular or custom-built protocols.

The Tor network was another effective solution against DPI. The Onion Router, or Tor for short, is a system that aims to hide one's online identity. It conceals the user's location and activity from network monitors by rerouting their web traffic through a network of relays. At first, it may like seemed to be a reliable way to avoid DPI—simply connect to Tor and use it. The traffic looked like typical encrypted web traffic.

2.7.2. Advancement of DPI technologies

But things started to change as DPI tools got better. DPI systems got smarter and could look at more protocols and even decrypted traffic trends. They started to notice the signs of Tor activity and the use of non-standard protocols, which made these ways of hiding from surveillance less effective.

Long lists of known IP addresses for Tor relays and entry nodes started to be used. They could stop the Tor network or keep an eye on people who tried to use it with these lists. Advanced DPI systems were also able to recognize Tor's unique traffic patterns, such as its uniform packet sizes and timing. So, using Tor or other obscure methods was no longer a surefire way to get around DPI.(Dingledine & Mathewson 2006)

In response to these developments in DPI, the Tor Project created additional ways to assist users in maintaining their anonymity while still gaining access to the network. The introduction of Tor bridges was one of the those ways.

Tor bridges are alternate Tor network entry points that are not included in the public Tor directory. Because of this obscurity, they are less likely to be blocked or monitored than conventional Tor relays. Users in countries where the internet is strictly censored could use these bridges to connect to the Tor network without drawing attention to themselves.

Furthermore, the Tor Project launched pluggable transports, a technique meant to change the look of Tor traffic, making it difficult for DPI systems to recognize. Obfsproxy (obfuscated proxy), for example, disguises Tor traffic as conventional, innocuous-looking internet traffic. This makes DPI detection much more difficult. (Loshin 2013)

Meek, another pluggable transport, employs a method known as domain fronting to make Tor traffic appear to be connecting with a prominent website such as Google or Amazon. This strategy takes use of the fact that restricting traffic to these important sites would cause enormous collateral harm, rendering censorship an unfeasible choice. (Fifield et al. 2015)

2.7.3. The Ongoing Cat-and-Mouse Game

The progression of DPI and the accompanying advancements in Tor technology symbolize an ongoing struggle between surveillance parties and proponents of internet privacy. As the technologies for DPI become more sophisticated, the techniques for circumventing them also become increasingly more complex. The implementation of Tor bridges and pluggable transports serving as a valid example of this continuing conflict.

Nevertheless, the usability of these approaches may differ depending on the geographical area and the particular DPI technology being employed. Tor bridges and other obfuscation techniques remain effective for evading detection in certain regions. In some cases, particularly in countries with sufficient government funding for advanced Deep Packet Inspection technologies, even these advanced methods encounter difficulties. (Winter & Lindskog 2012)

2.8. Modern DPI techniques

Recent studies have taken an in-depth examination of the latest techniques employed by the Great Firewall of China to identify and prevent fully encrypted internet traffic. The main techniques are as so (Wu et al. 2023):

- **Heuristic Rules for Exemption**: Based on the assumption that some types of traffic are unlikely to be fully encrypted, the GFW uses a set of heuristic rules to exempt them from blocking. This includes the fraction, position, and maximum contiguous count of ASCII characters; a rough entropy test based on the fraction of bits set; and rules based on common protocol fingerprints.

- **Entropy-Based Blocking**: The GFW denies access to connections based on the entropy of the client's initial TCP payload. As a sign of encrypted data, connections with a specific range of bits set per byte are blocked.

- **Exemption for ASCII Characters**: If the first six bytes are printable, more than half of the bytes are printable, or more than 20 consecutive printable bytes are present, the GFW will not block connections related to ASCII characters in the payload.

- **Protocol Exemptions**: Certain protocols—most notably TLS and HTTP—are specifically spared from blocking because their initial bytes match patterns that these protocols are known to use.

- **Blocking Mechanism**: The client's packets are dropped and never reach the server when the GFW detects encrypted traffic. This prevents further traffic from occurring.

- **Limited Scope and Probabilistic Blocking**: The GFW uses probabilistic blocking, which means that not all connections that satisfy the blocking requirements are obstructed. Blocking is purposefully restricted to particular IP ranges of well-known data centers.

- **UDP Traffic**: Sending UDP datagrams with a random payload does not result in blocking under the new censorship system, which is restricted to TCP.

- **Active Probing System**: Using a payload length-based rule in addition to similar rules, the GFW's active probing system operates in tandem with the traffic analysis system.

These methods highlight the GFW's sophisticated approach to censoring encrypted traffic while allowing standard internet communications. This aids in understanding the censorship mechanism and informs strategies to circumvent these blocks.

2.9. Use of modern DPI techniques

Since modern Deep Packet Inspection techniques have improved over time, effectively combating older methods used to evade such monitoring in the ever-changing world of internet restriction and spying, the capacity of authorities, such as those in charge of the Great Firewall of China, to identify and stop the many strategies that have historically been used to avoid censorship and surveillance has been greatly improved by recent developments in DPI technology.

- **Advanced Signature Detection**: Older ways of getting around security measures often relied on hiding traffic signatures to look like allowed protocols or hide what kind of data was being sent. These days, DPI systems use more complicated algorithms that can better find trends and oddities in data packets. This includes being able to find small changes in how a protocol works, strange headers, and even patterns that could mean steganography or the use of hidden channels.

- **Behavioral Analysis and Anomaly Detection**: Newer DPI methods use behavioral analysis instead of just looking at the static features of traffic. This lets the systems figure out what normal network behavior looks like and spot changes that might be signs of attempts to get around the system. Anomaly detection algorithms can spot strange traffic patterns, like packet sizes that aren't normal, data amounts that don't match up, or unexpected use of protocols.

- **Machine Learning and AI Integration**: Adding Machine Learning (ML) and Artificial Intelligence (AI) to DPI systems is a big step forward in terms of what they can do. These technologies let the systems learn from the information they handle, which makes them better at finding things over time. In real time, AI algorithms can look at huge amounts of data and find complicated patterns and correlations that humans would never be able to see. (Trivedi & Patel 2016)

- **Encrypted Traffic Analysis**: Many old DPI methods stopped working as much as encryption became more popular as a way to protect user privacy. Modern DPI methods, on the other hand, can look at encrypted data without having to decrypt it first. This is done by looking at statistics, time, and other side-channel data, which lets the authorities guess what kind of data is being encrypted.

- **Active Probing and Response Analysis**: These days' DPI systems don't just watch data; they also probe it and respond to it. These systems can figure out what kind of traffic or application is going on by sending specific packets or requests and looking at the replies. This works especially well against protocols that are made to look like other types of data.(Chakraborty et al. 2022)

All of these DPI advacements have resulted in the slow yet noticable decline of non-modern DPI evasion methods. The most prevalent methods of evading DPI have been proxies and VPNs. The use of known VPN servers or IP addresses, as well as specific traffic patterns and handshake features, can be detected and blocked by modern DPI techniques.

Even anonymity networks like Tor, which aim to let users browse the internet anonymously and securely, are becoming more and more susceptible to DPI attacks. The unique features of Tor traffic, like packet timing and data transfer sizes, can now be detected by DPI systems, even when Tor employs obfuscation methods like pluggable transports.

Traditional methods of evading DPI also include obfuscation and Secure Shell (SSH) tunneling. Even when communication is disguised or contained within other protocols, contemporary DPI systems can still detect SSH based on its unique handshake and session features. (Dusi et al. 2008)

Methods that masquerade as valid protocols (like HTTPS) in order to conceal harmful or restricted traffic are less successful when faced with current DPI. In order to distinguish between real protocol traffic and imposters, sophisticated algorithms examine time, packet size, and other subtle features. (Pandey et al. 2023)

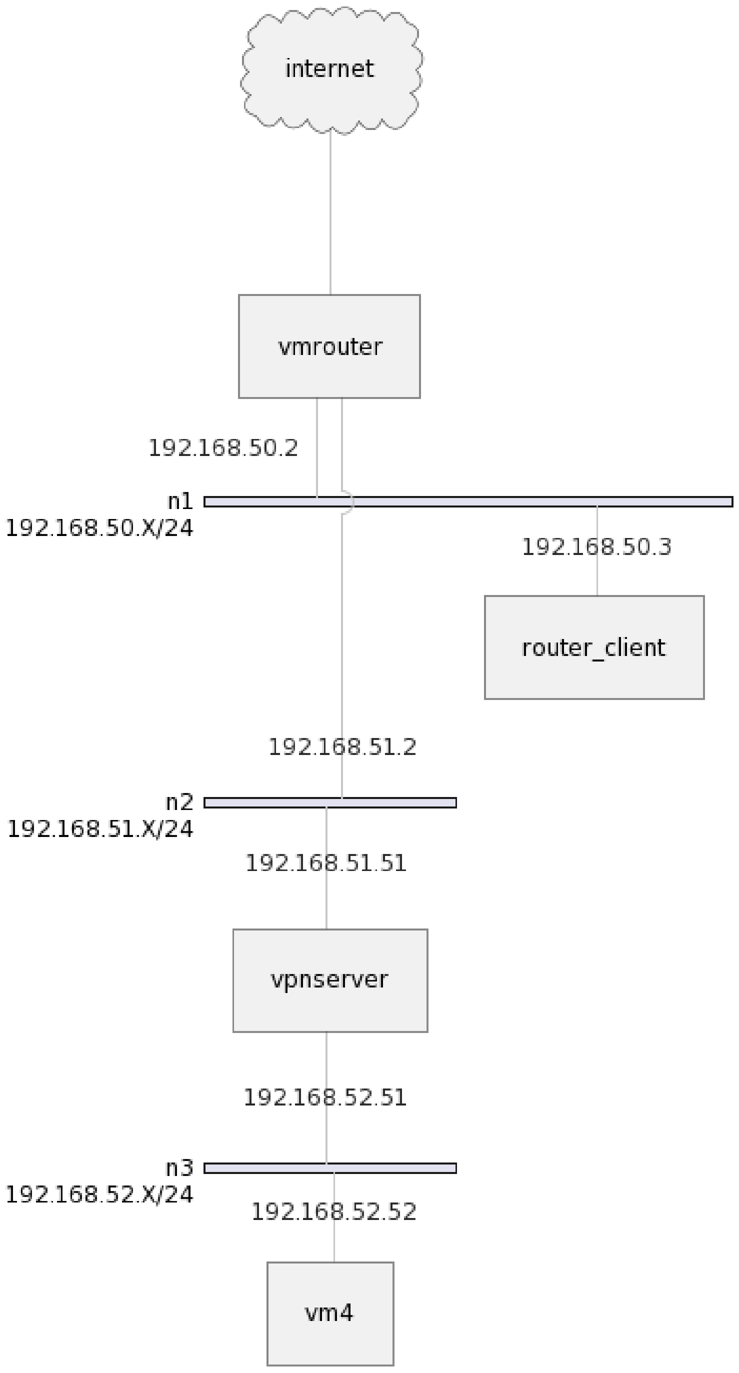
Data packets' genuine nature might be concealed by using traffic fragmentation and padding, which were common techniques in legacy evasion strategies. In order to determine the true type or content of the traffic, modern DPI can reconstruct broken packets by analyzing the padding.

3. EXPERIMENTAL TESTBED

When it comes to VPN encryption methods, building a virtual testbed is important for validating experimention results. This section is about the established testbed, including how it is set up, why certain tools were chosen, and how the network is structured overall. Vagrant and Libvirt were used to set up the testbed. These tools are essential for building and managing virtual machines (VMs) that mimic a real-world network environment so that VPN obfuscation methods can be tested.

An open-source software application, Vagrant allows to create and manage portable virtual environments for software development. It comes with a straightforward command-line client for controlling these settings, and a standard for configuration files to specify the virtual machines needed for a certain project. Because of its versatility, ease of use, and extensive support for several virtualization providers, including Libvirt, Vagrant was chosen for this testbed.

Libvirt, on the other hand, gives one a set of tools that can be used to talk to the virtualization features of later Linux distributions. This is a C toolkit that works with Linux's virtualization features to act as a management tool for platform virtualization. Because it has so many features and is known for being stable, it can be seen as a reliable choice for testing virtual networking.



3.1. Figure. **Testbed network topology**

The testbed consists of many virtual machines that are configured to imitate the major components of a VPN system as can be seen on Figure 3.1, such as routers, VPN servers, and clients. The Vagrant configuration file defines four different VMs: vmrouter, routerslave, vpnserver, and vm4. Each VM is given unique network interfaces and IP addresses to ensure that it mimics the common networking elements seen in a VPN situation.

The network topology was created to resemble a standard VPN environment with multiple network segments. The vmrouter acts as the primary router, connecting two different subnets. This VM is of course important as it simulates the gateway through which traffic is routed. The second VM, routerslave, is configured to act as a client to the router within the network, providing more realism to the client-server architecture commonly seen in VPN networks.

The VPN server is set up to be the vpnserver VM. This VM is very important to the testbed because it acts like the server side of a VPN. This is where the VPN service itself can be configured and started, and where server-side changes can be applied for implementing a VPN obfuscation method, if that is required. The last VM, vm4, is a normal client in the network that is only accessible from the VPN server and used to check whether the VPN is working correctly by having another VPN client (routerslave) connect to it.

In some VMs, the network's dual-interface design lets for a complicated routing situation that works like a real VPN, where data traffic often goes through multiple network segments. This set-up creates a more realistic environment for testing VPN obfuscation methods.

3.1. Router Configuration

The vmrouter virtual machine is an important part of the virtual network topology because it is meant to be a router in the Vagrant-based environment. This VM, which was set up using Vagrant with the ”generic/ubuntu1804” box and provisioned for the libvirt provider, serves as a crucial node for network traffic management and routing in the VPN obfuscation method testing setup.

3.1.1. Networking Interface Configuration

Table 1

Network interfaces configuration on vmrouter

	Interface	IP Address	Subnet Mask	State	MAC Address
0	lo	127.0.0.1	255.0.0.0	UP	00:00:00:00:00:00
1	eth0	192.168.121.216	255.255.255.0	UP	52:54:00:02:6d:7a
2	eth1	192.168.50.2	255.255.255.0	UP	52:54:00:a6:69:a2
3	eth2	192.168.51.2	255.255.255.0	UP	52:54:00:db:30:5d

The IP address table 1 shows that the vmrouter virtual machine has three network interfaces set up. Interfaces like as these are:

- **eth0**: The subnet mask is 255.255.255.0 and the IP address is 192.168.121.216. This port serves as the main interface for communicating with the outside world, connecting the virtual machine to the network ouside the virutal topology.
- **eth1**: Set up with 192.168.50.2 as the IP address and 255.255.255.0 as the subnet mask. This interface is used for internal routing, and it's devoted to a private network.
- **eth2**: This interface, which shares the same subnet mask as eth1 and an IP address of 192.168.51.2, is to link to a separate part of the virtual network and performs internal routing in a similar fashion.

In order to manage and guide traffic within the virtual network, these interfaces are paramount. The setup points to a planned-out topology in which vmrouter is the central hub connecting various parts of the virtual environment.

3.1.2. Routing Table Configuration

Table 2

Routing table on vmrouter

	Interface	Destination	Gateway	Flags	Metric	Mask
0	eth0	0.0.0.0	192.168.121.1	3	100	0.0.0.0
1	eth1	192.168.50.0	0.0.0.0	1	0	255.255.255.0
2	eth2	192.168.51.0	0.0.0.0	1	0	255.255.255.0
3	eth0	192.168.121.0	0.0.0.0	1	0	255.255.255.0
4	eth0	192.168.121.1	0.0.0.0	5	100	255.255.255.255

The routing table for vmrouter is seen depicted in table 2.

- Through the eth0 interface, 192.168.121.1 is established as the default gateway IP address for outgoing traffic. This indicates that this interface is the primary means by which data is sent to destinations outside the virtual network, to the internet.
- The fact that 192.168.50.0/24 and 192.168.51.0/24 are reserved for private networks shows that vmrouter uses the correct interfaces (eth1 and eth2) to route traffic intended for those networks.

By creating a barrier between internal and external network traffic, this configuration guarantees valid destination-based routing.

3.1.3. Iptables Configuration

Table 3

Iptables rules on vmrouter

	Chain	Target	Source	Destination	Additional Options
0	POSTROUTING	MASQUERADE	0.0.0.0/0	0.0.0.0/0	-o eth0 -j
1	POSTROUTING	MASQUERADE	0.0.0.0/0	192.168.51.0/24	-o eth2 -j
2	POSTROUTING	MASQUERADE	0.0.0.0/0	192.168.50.0/24	-o eth1 -j
3	FORWARD	ACCEPT	0.0.0.0/0	0.0.0.0/0	-i eth0 -o eth1 -j
4	FORWARD	ACCEPT	0.0.0.0/0	0.0.0.0/0	-i eth1 -o eth0 -j

Based on how iptables is configured, vmrouter is also in charge of firewall rules and network address translation (NAT). The main points are as follows:

- **MASQUERADE Rules:** These rules are set for all three interfaces (eth0, eth1, and eth2). The MASQUERADE target is used in to configure NAT. It allows outgoing traffic from the private network to appear as if it’s coming from the vmrouter itself.
- **FORWARD Chain Rules:** The ACCEPT rules in the FORWARD chain for traffic going from eth0 to eth1 and back again show that vmrouter lets traffic go both ways between these interfaces. This is very important for a router that connects different network segments.

3.2. Router Client Configuration

The router_client virtual machine is also an essential element in the network topology configuration. This virtual machine, labeled as ”router_client” , is setup to emulate a client within a network that interacts with a router and then later a VPN server. The router_client VM’s configuration demonstrates a setup that encompasses network interface settings, routing configurations, and script provisions to enhance setup and functionality.

3.2.1. Networking Interface Configuration

Table 4

Network interfaces configuration on router_client

	Interface	IP Address	Subnet Mask	State	MAC Address
0	lo	127.0.0.1	255.0.0.0	UP	00:00:00:00:00:00
1	eth0	192.168.121.199	255.255.255.0	UP	52:54:00:71:5c:29
2	eth1	192.168.50.3	255.255.255.0	UP	52:54:00:7b:49:f2

As can be seen on table 4 both eth0 and eth1 are set up as network interfaces in the router_client virtual machine. Separate subnets are used to assign IP addresses to each interface. Both the eth0 and eth1 interfaces have the same subnet mask and IP addresses: 192.168.121.199 and 255.255.255.0, respectively. With its two interfaces, the virtual machine can link to two different networks, each of which represents a different part of the virtual network architecture.

The fact that eth1 has the private network address 192.168.50.3 suggests that it is part of a private network. The 192.168.50.0/24 subnet is for VM-to-VM communication, such as between the router_client VM and vmrouter and other similar virtual machines. On the other hand, eth0's 192.168.121.199 IP address points to a separate portion of the network, which may be utilized for external communications or for connecting to a separate group of virtual devices or services however this eth1 interface has been rendered useless by the routing table configuration, in order to ensure all communication with other network devices happens through the vmrouter.

3.2.2. Routing Table Configuration

Table 5

Routing table on router_client

	Interface	Destination	Gateway	Flags	Metric	Mask
0	eth1	0.0.0.0	192.168.50.2	3	0	0.0.0.0
1	eth0	0.0.0.0	192.168.121.1	3	100	0.0.0.0
2	eth1	192.168.50.0	0.0.0.0	1	0	255.255.255.0
3	eth0	192.168.121.0	0.0.0.0	1	0	255.255.255.0
4	eth0	192.168.121.1	0.0.0.0	5	100	255.255.255.255

Important information on the management and routing of traffic can be found in the router-_client VM's routing table as shown on table 5. On the eth1 interface, the default gateway for the virtual machine is set to 192.168.50.2, which is the internal IP address of the vmrouter. With this configuration, all outgoing traffic from the router_client VM will be sent to the vmrouter for additional routing decisions if no specified route has been configured.

The two network interfaces are also represented in the routing table. The 192.168.50.0/24 network is shown as a direct route for eth1, meaning that any traffic going to this subnet will be handled internally and won't require an external gateway. Similarly, eth0 handles traffic within this specific subnet as there is a direct link to the 192.168.121.0/24 network.

Moreover, a higher metric entry for the gateway 192.168.121.1 exists on eth0. Metric field indicates the cost of a route. The high metric is meant to make eth1 gateway the preferred route since it has the lower metric value.

3.3. VPN Server Configuration

Creating a flexible and functioning network architecture for testing VPN obfuscation methods is the primary focus of the configuration of the vpnserver virtual machine in the virtual environment. This virtual machine, as stated before, is meant to act as a VPN server, which is a crucial component of a VPN network. The vpnserver VM's configuration includes network interface settings, routing configurations, and script provisions to enhance setup and functionality.

3.3.1. Networking Interface Configuration

Table 6

Network interfaces configuration on vpnserver

	Interface	IP Address	Subnet Mask	State	MAC Address
0	lo	127.0.0.1	255.0.0.0	UP	00:00:00:00:00:00
1	eth0	192.168.121.248	255.255.255.0	UP	52:54:00:09:e7:27
2	eth1	192.168.51.51	255.255.255.0	UP	52:54:00:12:b1:b6
3	eth2	192.168.52.51	255.255.255.0	UP	52:54:00:8a:d6:81

There are three network interfaces set up on the vpnserver VM as seen in table 6: eth0, eth1, and eth2. Each of these ports is used for a different thing in the network setup:

- **eth0:** The main interface that the VPN server uses to link to the outside world, created by default for the VM. Its subnet mask is 255.255.255.0 and its IP address is 192.168.121.248.

This link is necessary to connect the VM to the outside world, which makes it easier to connect to the Internet and talk to people outside of the VM.

- **eth1:** This interface has an IP address of 192.168.51.51 and a subnet mask of 255.255.255.0. It is only used for interactions within the subnet connecting vpnserver and vmrouter.
- **eth2:** This interface is also used for internal network transmission, but on a different subnet to vm4, making it so only vpnserver has direct access to vm4. Which will be necessary for the testing of the VPN server.

3.3.2. Routing Table Configuration

Table 7

Routing table on vpnserver

	Interface	Destination	Gateway	Flags	Metric	Mask
0	eth0	0.0.0.0	192.168.121.1	3	100	0.0.0.0
1	eth1	192.168.50.0	192.168.51.2	3	0	255.255.255.0
2	eth1	192.168.51.0	0.0.0.0	1	0	255.255.255.0
3	eth2	192.168.52.0	0.0.0.0	1	0	255.255.255.0
4	eth0	192.168.121.0	0.0.0.0	1	0	255.255.255.0
5	eth0	192.168.121.1	0.0.0.0	5	100	255.255.255.255

The IP routing table 7 of the vpnserver VM provides critical insights into how network traffic is managed and routed through the VM. The table consists of several entries, each defining a specific route:

- The default route is the one that uses eth0 and has the following parameters: destination 0.0.0.0, gateway 192.168.121.1. It sends data packets to the public internet if they don't fit any of the other routing criteria.
- Both 192.168.51.0/24 and 192.168.52.0/24 routes, with eth1's gateway set to 0.0.0.0 and eth2's set to 0.0.0.0, manage traffic within their respective subnets for internal network traffic.
- Another entry in the routing table is the one for the 192.168.50.0/24 network, which goes via 192.168.51.2 on eth1. This route is reserved for sending data packets to a different subnet so that virtual machines can communicate with one another.

3.3.3. Iptables Configuration

Table 8

Iptables rules on vpnserver

	Chain	Target	Protocol	Source	Destination	Additional Options
0	POSTROUTING	MASQUERADE	N/A	192.168.0.0/24	0.0.0.0/0	-o eth0 -j
1	POSTROUTING	MASQUERADE	N/A	0.0.0.0/0	192.168.52.0/24	-o eth2 -j
2	FORWARD	TCPMSS	tcp	192.168.0.0/24	0.0.0.0/0	-p tcp -m tcp

In the case of the vpnserver, an important part of controlling and protecting network traffic is the iptables setup on the vpnserver virtual machine as depicted on table 8. Network Address Translation rules, packet forwarding rules, and TCP maximum segment size settings are all part of it:

- MASQUERADE (POSTROUTING): The VM can transform the IP addresses of packets coming from the internal networks (192.168.0.0/24 and 192.168.52.0/24) since the MASQUERADE rules are configured for NAT. In order to manage traffic from several sources and make it appear as though it is originating from a single IP, this is necessary for the VPN server.

- TCPMSS (FORWARD Chain): For packets coming from 192.168.0.0/24, the TCP maximum segment size is adjusted by the rule in the FORWARD chain. For VPN setups in particular, this improvement is essential to preventing fragmentation and enhancing speed. The default MSS for an Ethernet network with an MTU of 1500 bytes is 1460 bytes (*A Standard for the Transmission of IP Datagrams over Ethernet Networks* 1984); if this rule is not followed, TCP connections may use this value. However, the effective MTU is decreased when a VPN is utilized since the VPN protocol introduces extra headers. Inefficiencies and possible connectivity problems could result from packet fragmentation or dropping if the MSS is not adjusted appropriately.

3.4. Remote Client Configuration

The last essential part is the virtual machine ”vm4”, also known as the remote client. In order to test different VPN scenarios, this machine is built to mimic a distant client in a network. Most notably this VM is used to test whether a VPN still works correctly after an obfuscation method was implemented and also remote client is the recipient of requests from the router client VM during testing for measuring latency and throughput.

3.4.1. Networking Interface Configuration

Table 9

Network interfaces configuration on vm4

	Interface	IP Address	Subnet Mask	State	MAC Address
0	lo	127.0.0.1	255.0.0.0	UP	00:00:00:00:00:00
1	eth0	192.168.121.97	255.255.255.0	UP	52:54:00:19:0e:09
2	eth1	192.168.52.52	255.255.255.0	UP	52:54:00:bf:1f:e6

As seen on the above table 9, the vm4 virtual machine has two network interfaces set up. The following are the interfaces:

- **Interface eth0**: Vagrant provides this as the default interface. IP address is 192.168.121.234 with the subnet mask 255.255.255.0, as seen in the IP address column. The ip route table indicates that the gateway for this interface, which is used to connect to the outside world, is set at 192.168.121.1.
- **Interface eth1**: This interface is allocated the IP address 192.168.52.52 with a subnet mask of 255.255.255.0. It is configured in Vagrant as a private network (via vm4.vm.network ”private_network”, ip: ”192.168.52.52”). Within the virtual network structure, this interface is meant for internal network connections.

3.4.2. Routing Table Configuration

Table 10

Routing table on vm4

	Interface	Destination	Gateway	Flags	Metric	Mask
0	eth0	0.0.0.0	192.168.121.1	3	100	0.0.0.0
1	eth1	192.168.52.0	0.0.0.0	1	0	255.255.255.0
2	eth0	192.168.121.0	0.0.0.0	1	0	255.255.255.0
3	eth0	192.168.121.1	0.0.0.0	5	100	255.255.255.255

- **Default Gateway (eth0)**: 192.168.121.1 is the gateway for the 0.0.0.0 default route. This suggests that this gateway is used to route any traffic that isn’t intended for the local network.

- **Local Network (eth1)**: Since 192.168.52.0/24's route is directly connected, vm4 can speak with other computers on the network without the use of a gateway.
- **Additional Routes**: The machine's configuration for managing traffic on the eth0 interface is indicated by the routes connected to 192.168.121.0/24 and the particular IP 192.168.121.1.

4. EXPERIMENTATION RESULTS

Experimentation with VPN obfuscation approaches is explained in depth, along with the findings, in this section. To determine how well each approach performed in different contexts, it was subjected to extensive testing in a controlled environment.

Resistance to detection, latency, throughput, and client-server accessibility are all part of the comprehensive set of evaluation criteria. With practical uses like evading censorship, protecting personal information, or communicating securely in dangerous settings in mind, the goal is to weigh the pros and cons of each approach.

The section concludes with a comparative analysis. A detailed table summarizing the results of each VPN obfuscation method in comparison to the specified criteria is included in this analysis. In addition, this part presents a new approach to using the collected data to choose the best VPN obfuscation method for individual users and their unique situations.

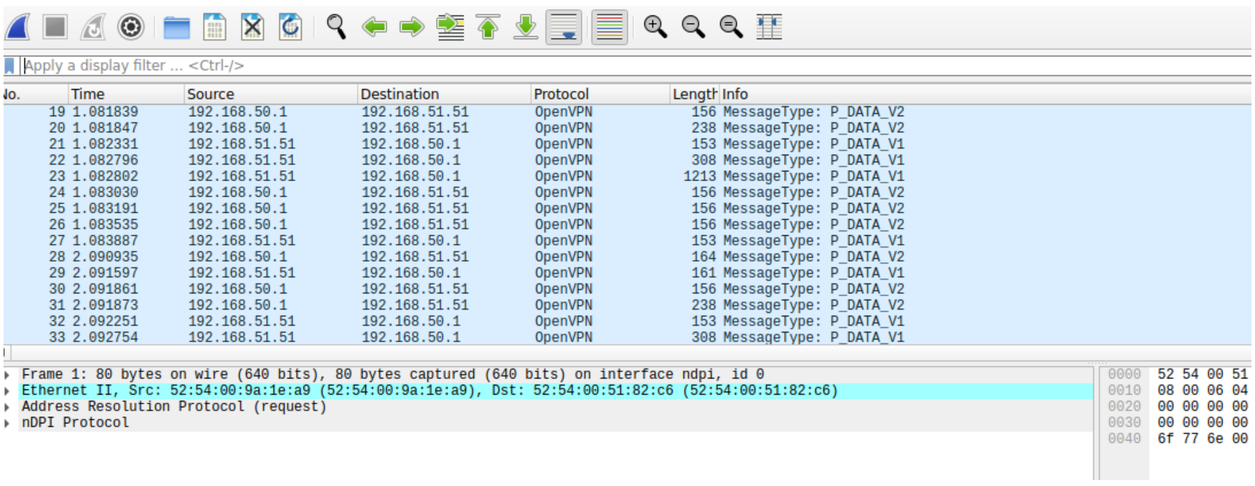
4.1. Method Evaluation Criteria

4.1.1. Detection Resistance

The most important measure for VPN obfuscation is detection resistance. A simple yet effective way to evaluate the practicality of an approach, this criterion assigns a pass or fail grade to its efficacy. Obfuscating VPN traffic is primarily done to avoid detection by Deep Packet Inspection technologies. Therefore, obfuscation effectiveness is proportional to how well it masks VPN traffic from DPI devices.

Determining how resistant a VPN obfuscation approach is to detection is a complex task. The well-known network protocol analyzer Wireshark is one of the main tools used in this evaluation. For delving into the complexities of network traffic, it is an indispensable tool. We get a full picture of how DPI interacts with VPN data by combining Wireshark with nDPI, a powerful open-source DPI tool. To better comprehend the detection resistance of different obfuscation strategies, nDPI enhances Wireshark's capabilities and permits a more thorough examination of packet data.

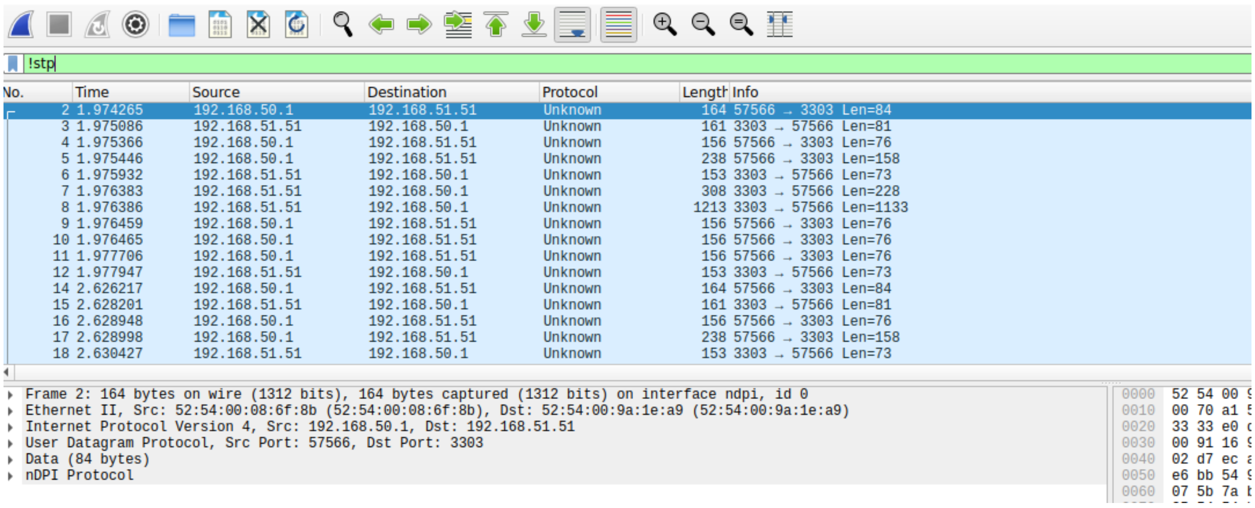
It should be kept in mind that no obfuscation technique is foolproof. Methods that work now in the provided testbed may become obsolete in the near future due to the dynamic nature of internet surveillance.



```
No.   Time        Source          Destination     Protocol   Length Info
   19 1.081839    192.168.50.1    192.168.51.51   OpenVPN       156 MessageType: P_DATA_V2
   20 1.081847    192.168.50.1    192.168.51.51   OpenVPN       238 MessageType: P_DATA_V2
   21 1.082331    192.168.51.51   192.168.50.1    OpenVPN       153 MessageType: P_DATA_V1
   22 1.082796    192.168.51.51   192.168.50.1    OpenVPN       308 MessageType: P_DATA_V1
   23 1.082802    192.168.51.51   192.168.50.1    OpenVPN      1213 MessageType: P_DATA_V1
   24 1.083030    192.168.50.1    192.168.51.51   OpenVPN       156 MessageType: P_DATA_V2
   25 1.083191    192.168.50.1    192.168.51.51   OpenVPN       156 MessageType: P_DATA_V2
   26 1.083535    192.168.50.1    192.168.51.51   OpenVPN       156 MessageType: P_DATA_V2
   27 1.083887    192.168.51.51   192.168.50.1    OpenVPN       153 MessageType: P_DATA_V1
   28 2.090935    192.168.50.1    192.168.51.51   OpenVPN       164 MessageType: P_DATA_V2
   29 2.091597    192.168.51.51   192.168.50.1    OpenVPN       161 MessageType: P_DATA_V1
   30 2.091861    192.168.50.1    192.168.51.51   OpenVPN       156 MessageType: P_DATA_V2
   31 2.091873    192.168.50.1    192.168.51.51   OpenVPN       238 MessageType: P_DATA_V2
   32 2.092251    192.168.51.51   192.168.50.1    OpenVPN       153 MessageType: P_DATA_V1
   33 2.092754    192.168.51.51   192.168.50.1    OpenVPN       308 MessageType: P_DATA_V1
```

```
▸ Frame 1: 80 bytes on wire (640 bits), 80 bytes captured (640 bits) on interface ndpi, id 0     0000  52 54 00 51
▸ Ethernet II, Src: 52:54:00:9a:1e:a9 (52:54:00:9a:1e:a9), Dst: 52:54:00:51:82:c6 (52:54:00:51:82:c6)   0010  08 00 06 04
▸ Address Resolution Protocol (request)                                                        0020  00 00 00 00
▸ nDPI Protocol                                                                                0030  00 00 00 00
                                                                                               0040  6f 77 6e 00
```

4.1. Figure. **WireShark capture of VPN traffic before obfuscation**



```
No.   Time        Source          Destination     Protocol   Length Info
    2 1.974265    192.168.50.1    192.168.51.51   Unknown       164 57566 → 3303 Len=84
    3 1.975086    192.168.51.51   192.168.50.1    Unknown       161 3303 → 57566 Len=81
    4 1.975366    192.168.50.1    192.168.51.51   Unknown       156 57566 → 3303 Len=76
    5 1.975446    192.168.50.1    192.168.51.51   Unknown       238 57566 → 3303 Len=158
    6 1.975932    192.168.51.51   192.168.50.1    Unknown       153 3303 → 57566 Len=73
    7 1.976383    192.168.51.51   192.168.50.1    Unknown       308 3303 → 57566 Len=228
    8 1.976386    192.168.51.51   192.168.50.1    Unknown      1213 3303 → 57566 Len=1133
    9 1.976459    192.168.50.1    192.168.51.51   Unknown       156 57566 → 3303 Len=76
   10 1.976465    192.168.50.1    192.168.51.51   Unknown       156 57566 → 3303 Len=76
   11 1.977706    192.168.50.1    192.168.51.51   Unknown       156 57566 → 3303 Len=76
   12 1.977947    192.168.51.51   192.168.50.1    Unknown       153 3303 → 57566 Len=73
   14 2.626217    192.168.50.1    192.168.51.51   Unknown       164 57566 → 3303 Len=84
   15 2.628201    192.168.51.51   192.168.50.1    Unknown       161 3303 → 57566 Len=81
   16 2.628948    192.168.50.1    192.168.51.51   Unknown       156 57566 → 3303 Len=76
   17 2.628998    192.168.50.1    192.168.51.51   Unknown       238 57566 → 3303 Len=158
   18 2.630427    192.168.51.51   192.168.50.1    Unknown       153 3303 → 57566 Len=73
```

```
▸ Frame 2: 164 bytes on wire (1312 bits), 164 bytes captured (1312 bits) on interface ndpi, id 0   0000  52 54 00
▸ Ethernet II, Src: 52:54:00:08:6f:8b (52:54:00:08:6f:8b), Dst: 52:54:00:9a:1e:a9 (52:54:00:9a:1e:a9)   0010  00 70 a1
▸ Internet Protocol Version 4, Src: 192.168.50.1, Dst: 192.168.51.51                           0020  33 33 e0
▸ User Datagram Protocol, Src Port: 57566, Dst Port: 3303                                      0030  00 91 16
▸ Data (84 bytes)                                                                              0040  02 d7 ec
▸ nDPI Protocol                                                                                0050  e6 bb 54
                                                                                               0060  07 5b 7a
```

4.2. Figure. **WireShark capture of VPN traffic after obfuscation**

The above Figure 4.1 and Figure 4.2 serve as an example of how the traffic looks like before and after successful obfuscation. The first image shows the traffic before obfuscation, and the second shows it after obfuscation. The traffic is identified to be OpenVPN in the first image, but it is completely unknown in the second. This is a good example of how a VPN obfuscation method should work.

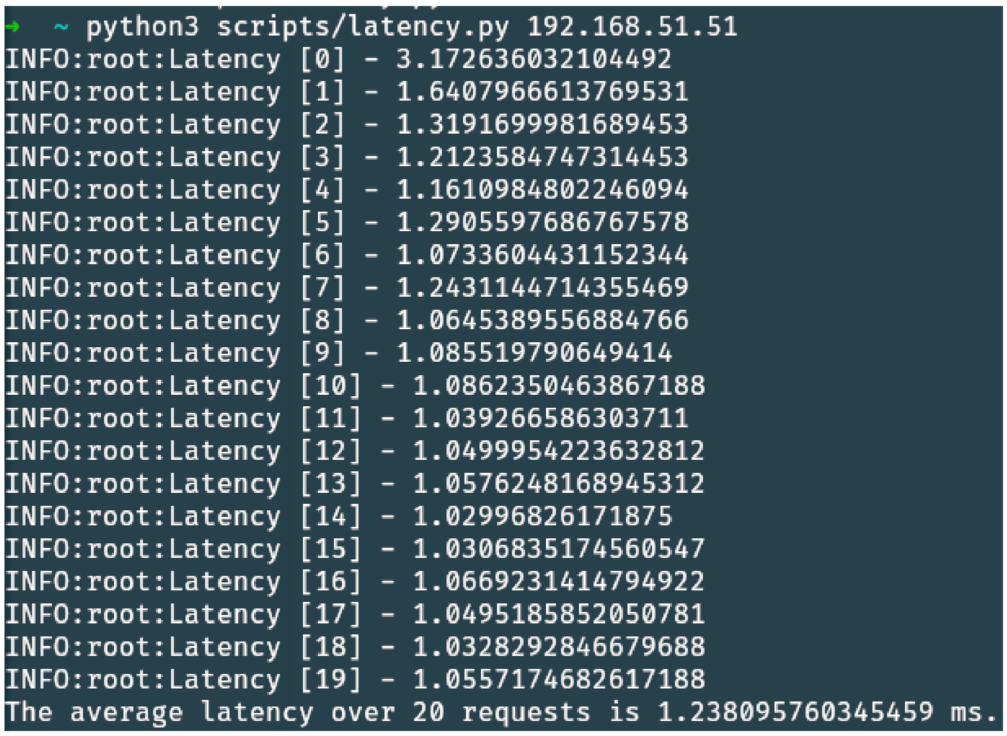
4.1.2. Latency

The term ”latency” tells one how long it takes for a data packet to travel from its origin to its final destination. Usually, milliseconds (ms) are used to assess latency. Common methods for gauging network latency include the ”ping” and ”traceroute” commands, which track how long it takes for a packet to go from sender to receiver. However, since it is possible that ICMP requests are prioritized by an operating system, which would lead to the ICMP requests getting better latency results than what might be expected in real-life scenarios. As such, latency is tested by making a number of simple HTTP requests.

A data packet's latency—the time it takes to travel from its source to its destination—is one of the most critical variables in network communications. From simple web browsing to complex real-time data processing, latency—which is typically measured in milliseconds (ms)—has considerable implications for the efficiency of network communications, the satisfaction of users, and the general performance of systems.

People often use tools like 'ping' and 'traceroute' to measure latency. By using the 'ping' command, one can determine how long it takes for a message to go from its origin to its final destination. The findings may be misleading, though, because 'ping' isn't flawless and different OSes assign different priorities to ICMP requests.

In my testing methodology, latency is assessed by making HTTP requests. This method is chosen to more accurately mimic the user's real-world interaction with the network. HTTP requests are a standard part of web browsing and online communications, thus providing a realistic measure of the latency that users are likely to experience.



```
→  ~ python3 scripts/latency.py 192.168.51.51
INFO:root:Latency [0] - 3.172636032104492
INFO:root:Latency [1] - 1.6407966613769531
INFO:root:Latency [2] - 1.3191699981689453
INFO:root:Latency [3] - 1.2123584747314453
INFO:root:Latency [4] - 1.1610984802246094
INFO:root:Latency [5] - 1.2905597686767578
INFO:root:Latency [6] - 1.0733604431152344
INFO:root:Latency [7] - 1.2431144714355469
INFO:root:Latency [8] - 1.0645389556884766
INFO:root:Latency [9] - 1.085519790649414
INFO:root:Latency [10] - 1.0862350463867188
INFO:root:Latency [11] - 1.039266586303711
INFO:root:Latency [12] - 1.0499954223632812
INFO:root:Latency [13] - 1.0576248168945312
INFO:root:Latency [14] - 1.02996826171875
INFO:root:Latency [15] - 1.0306835174560547
INFO:root:Latency [16] - 1.0669231414794922
INFO:root:Latency [17] - 1.0495185852050781
INFO:root:Latency [18] - 1.0328292846679688
INFO:root:Latency [19] - 1.0557174682617188
The average latency over 20 requests is 1.238095760345459 ms.
```

4.3. Figure. **Latency test results**

4.1.3. Throughput

An important metric in computer systems and networks, throughput represents the quantity of data successfully sent from one location to another during a specific time period. One common unit of measurement is bits per second, but others include kilobits per second, megabits per second, and gigabits per second. The throughput of a network is an important performance metric since it measures how quickly data actually travels over the network.

Though it may be noted that throughput and bandwidth are similar but different concepts. The real pace at which data may be moved over a network is known as throughput, whereas bandwidth is the theoretical maximum rate. Factors such as protocol overhead, packet loss, and network latency cause throughput to be lower than bandwidth. So in real-life, throughput is more helpful than bandwidth in determining network performance.

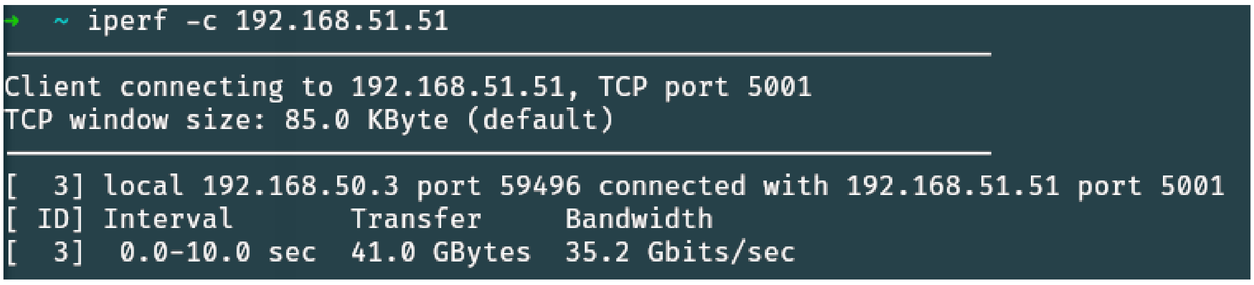
For measuting throughput the tool ”iperf”” was utilized. It’s an open-source program that works with most operating systems and has a command line interface. Iperf is a popular tool for testing and debugging network performance; it measures the maximum throughput a network can manage. Two computers, a server and a client, need to be connected for Iperf to function. The Iperf client establishes a connection to the server and transmits data to it, while the Iperf server listens on a certain port. A brief overview of Iperf’s usual usage is as follows:

- The first step in configuring Iperf is to choose a computer to function as the server and another to connect to the network. While clients initiate data transfers, servers listen for incoming connections.

- After establishing a connection, the Iperf client starts transmitting data to the server. A number of parameters can be set to control this data transfer, including the test duration, the size of the data blocks, and the protocol (TCP in the latter case).

- Measurement and Output: Iperf tracks the data transfer duration and amount. The system then computes the throughput and generates a performance report, showing the throughput’s average and peak values throughout the testing time.

With Iperf’s advanced features, users can test the network for jitter, packet loss, and duplex connection performance, among other things. The following figure gives a demonstration of the output Iperf generates:



```
→  ~ iperf -c 192.168.51.51
------------------------------------------------------------
Client connecting to 192.168.51.51, TCP port 5001
TCP window size: 85.0 KByte (default)
------------------------------------------------------------
[  3] local 192.168.50.3 port 59496 connected with 192.168.51.51 port 5001
[ ID] Interval       Transfer     Bandwidth
[  3]  0.0-10.0 sec  41.0 GBytes  35.2 Gbits/sec
```

4.4. Figure. **Throughput test results**

4.1.4. Client-Server Accessibility

Depending on the specifics, client-server accessibility may also be an important factor to consider. This criteria becomes significant if the user does not have access to the VPN server or is not permitted to make changes to it, since most of the investigated obfuscation methods require the user to make changes on the VPN server. The ability of a VPN obfuscation method to be used without any changes to the VPN server is important to its success. The more accessible a method is to the user, the more likely it is to be effective in a real-world situation. A method can either pass or fail based on this boolean criteria.

4.2. Port switching

4.2.1. Concept and Overview

One way to obfuscate a VPN is by adjusting the port that the server uses to communicate with the network. When discussing computer networks, the term ”port” refers to either a physical location or an abstract concept that serves as a communication endpoint. VPN services usually employ widely recognizable and well-known ports. It is possible to evade Deep Packet Inspection (DPI) technologies by masking VPN traffic as another sort of communication and switching these ports.

In order to monitor or prevent VPN traffic, many network managers and national firewalls utilize DPI technologies. These programs examine data packets and identify them according to properties such service type, source, and destination. Because DPI systems can detect standard VPN ports, they can restrict or throttle VPN traffic.

A user can make their VPN communication look like any other kind of valid traffic by altering the port number of the VPN server. One way to make VPN traffic seem like conventional secure online browsing is to set it to run on port 443, which is the standard port for HTTPS communication. The idea behind this approach is that most DPI systems won't censor or overly analyze traffic on popular ports like 443 because it would interfere with everyday internet operations.

While port switching can get around simple DPI methods, it might not work against more advanced DPI systems that look at things like data patterns, packet size, and time.

4.2.2. Method Implementation

Port switching can be implemented by the settings of the VPN server software. When using OpenVPN this can be accomplished by modifying the server configuration file's 'port' directive. Having administrator privileges on the VPN server is necessary for this procedure.

Changing the OpenVPN port is a fairly straightforward process and involves the following steps:

- To access the server configuration file, titled server.conf.
- Find the line that has the directive for the port. The current port number that the OpenVPN server listens on is specified.
- Put in a new value for the port number. Port 443 is often used for HTTPS communication, for example, therefore it's a good choice.
- To apply the changes, save the configuration file and restart OpenVPN.
- The client's configuration files should also be adjusted to reflect the new server port.

This procedure shows that access to the server is required to accomplish port swapping. The new port must also be enabled on any network devices (such as routers or firewalls) that control the server's traffic.

4.2.3. Evaluation

In regards to the specified criteria for assessing port switching:

- **Resistance to Detection**: When tested against state-of-the-art DPI technologies, this strategy tends to fall flat. Due to their comprehensive analysis, DPI systems such as nDPI are able to detect OpenVPN traffic irrespective of the port number. Thus, port switching may provide some obfuscation, but it isn't a great way to get past advanced DPI systems.
- **Client-Server Accessibility**: In order to implement port switching, it is necessary to have access to the VPN server. Due to the fact that proper communication requires congruence of server and client settings, it cannot be considered a client-side solution. Due to this requirement, the method cannot be used in situations where the user does not have the necessary permissions or access to the server.
- **Latency**: The latency effect is not directly proportional to the port number of the VPN server. The delay is unchanged because the method merely entails rerouting traffic through an other port; it does not impose any extra processing or routing overhead.
- **Throughput**: is also unaffected by changing ports. Since the approach does not incorporate any extra data encryption or rerouting that may decrease the traffic, the data transmission rate remains constant with the VPN service's baseline performance.

4.3. Steganography

The practice of steganography dates back many years and involves concealing data within apparently harmless carriers. The field of steganography has expanded in the field of digital communications to include a wide range of methods for concealing information within many digital formats, including but not limited to photos, audio, video files, network protocols, and more.

4.3.1. Protocol Field Stegonagraphy

Protocol Field Steganography is a method of obfuscation which involves embedding secret information within the redundant or unused fields of network protocol headers. Unlike traditional steganography, which primarily focuses on media files, this technique leverages the inherent structure of network protocols. Since many fields in protocol headers, like IP or TCP headers, are often unused or contain predictable values, they can be repurposed to covertly transmit data.

The essence of Protocol Field Steganography lies in its ability to blend in with regular network traffic. By utilizing the unused areas of protocol headers, data can be transmitted in a way that is nearly indistinguishable from normal traffic. This method is particularly effective against Deep Packet Inspection as the embedded data does not alter the expected patterns of the protocol. Moreover, since this method does not significantly alter the packet size or structure, it maintains a low profile, making detection considerably more challenging.

One of the primary advantages of Protocol Field Steganography is its low impact on network performance. Since it utilizes existing protocol structures, it does not significantly increase packet size, thus maintaining network efficiency and avoiding bandwidth overhead. However, its capacity for data transmission is limited by the size and number of available unused fields in the protocol headers. Additionally, implementing this technique requires a deep understanding of network protocols and the ability to manipulate packet headers, which may pose a challenge for average users.

4.3.2. Multimedia Embedding Stegonagraphy

Multimedia Embedding Steganography takes a different approach by embedding data directly into digital media files such as images, audio, or video. This technique is particularly popular with images due to their ubiquity and the high tolerance for slight alterations without perceptible changes. One common method employed in image steganography is the Least Significant Bit (LSB) technique, where information is hidden in the least significant bits of the pixel values, thus altering the image in a way that is imperceptible to the human eye.

The strength of Multimedia Embedding Steganography lies in its ability to hide large amounts of data effectively while maintaining the original appearance and properties of the carrier medium.

This method is especially resistant to casual inspection and basic automated analysis. However, it may be more susceptible to advanced steganalysis techniques, especially if the patterns of embedding are not carefully managed or if the alterations to the medium are too systematic.

Implementing Multimedia Embedding Steganography requires a careful balance between the amount of data to be embedded and the preservation of the medium's integrity. The key challenge is to embed data in a way that avoids detection while ensuring that the carrier medium remains functional and unchanged to casual observation. This requires sophisticated algorithms that can subtly manipulate the medium while maintaining its original properties.

4.3.3. Method Implementation

For my thesis, I chose to focus on Multimedia Embedding Steganography, specifically using images as the carrier medium. I believed this method would be more effective in evading Deep Packet Inspection techniques, as it is less susceptible to automated analysis and inspection. Since DPI systems are unable to decrypt and directly analyse packet data they simply search for uncertain patterns withing the data. If most of the data within a packet is legitimate, finding the hidden data becomes a challenging task, making multimedia embedding a compelling solution. Unlike, protocol field steganography which may be more susceptible to detection due to its use of protocol fields that are not encrypted and can be directly inspected.

A Python script was developed that employs the Least Significant Bit (LSB) method combined with a key-dependent embedding mechanism. The LSB method involves altering the least significant bits of the pixel values in an image to encode the hidden data. This method is effective as it causes minimal perceptible changes to the image, thus maintaining its appearance while embedding the secret data.

To enhance the security and robustness of the embedding process, a simple key-dependent mechanism was integrated. This mechanism requires a secret key for both embedding and extracting the data, adding an extra layer of security to the process. The secret key impacts the order in which bits and pixels are embedded into. The use of a key ensures that even if the presence of steganography is suspected or detected, the hidden data remains inaccessible without the correct key. (Masud Karim et al. 2011)

The implementation involved configuring both the client and the server to route all network traffic through the steganography scripts. This was achieved using iptables NFQUEUE and the Python library Scapy. NFQUEUE is a feature of the Netfilter framework in the Linux kernel, designed to delegate the handling of packet filtering and manipulation to user-space programs. When network packets match certain iptables rules, they are enqueued to NFQUEUE, where a user-space application, in this case, the steganography script, can inspect, modify, or even drop them.

This interaction is facilitated by the libnetfilter_queue library, which provides an API for queuing and retrieving packets from the kernel to user space. In order to route all network traffic through the steganography script, iptables rules were configured to redirect all packets to NFQUEUE with the command: `iptables -A INPUT -j NFQUEUE -queue-num 1` for all inbound packets and `iptables -A OUTPUT -j NFQUEUE -queue-num 1` for all outbound packets. This ensures that all packets are enqueued to NFQUEUE, where they can be intercepted and manipulated by the steganography script.

Scapy, a powerful Python library for packet manipulation, was chosen to handle these packets in user space. It provides a more intuitive and high-level interface for packet analysis and manipulation compared to raw sockets, simplifying the process. The use of Scapy, in conjunction with NFQUEUE, allowed for efficient and effective interception and modification of network traffic. This approach also elegantly circumvents the complexities of IP fragmentation and TCP segmentation, which can be challenging when using raw sockets. By leveraging NFQUEUE and Scapy together, one can seamlessly integrate the steganography process into the network flow, significantly simplifying the implementation while ensuring the effectiveness and reliability of the steganography process.

The chosen image for the steganography process was approximately 13kb in size. Based on this size, the maximum amount of data that could be effectively hidden within the image was calculated to be about 1664 bytes. This calculation was derived using the formula:

$$(isz/bpp) * lsb/8 \tag{1}$$

where:

isz - image size in bytes

bpp - bytes per pixel

lsb - number of least significant bits to use for embedding (3 in this case, since each pixel has 3 color channels)

This formula takes into account the size of the image, the number of bytes per pixel, and the number of bits used for embedding the data.

4.3.4. Evaluation

In evaluating the effectiveness of the implemented steganography method, the following results were obtained:

- Detection Resistance: The method successfully passed the detection test, with nDPI failing to identify the traffic as originating from OpenVPN. This indicates a high level of effectiveness in evading Deep Packet Inspection techniques.
- Client-Server Accessibility: The implementation was evaluated as a failure in terms of client-server accessibility. This is because the method requires access to both the client and the server for setting up and receiving the steganographed image, making it less accessible for scenarios where server access is restricted or not possible.
- Latency Impact: The implementation resulted in a significant increase in latency, measured at a 560% increase. This substantial rise in latency is attributed to the additional processing required for embedding and extracting data from the images as well as the increased size of the message being sent.
- Throughput: The throughput observed a decrease of 88%, which is a considerable reduction. This decrease is primarily due to the added overhead of processing the steganography and the limitations imposed by the size of the carrier image.

It should be noted that these tests were conducted in a controlled virtual environment using a custom-made Python script. The script was not optimized for performance, and the results may vary in real-world scenarios when implementing this method with optimizations and in different operational contexts.

4.4. Geneva

The Geneva (Genetic Evasion) algorithm represents a significant advancement in the field of Internet censorship evasion. Developed with the aim to automate the discovery of censorship evasion strategies, Geneva adopts a unique approach to bypass deep packet inspection (DPI) techniques employed by state-level censors.

4.4.1. Concept and Overview

Geneva operates on the principle of evolving network traffic patterns to evade censorship. It employs a genetic algorithm to automatically generate and test different strategies for bypassing censorship, adapting to the censor's DPI techniques. This process involves modifying network traffic in a way that avoids detection and blocking by censors, yet maintains the integrity of client-server communication.

4.4.2. Censorship Evasion Strategies

At the core of Geneva's functionality are censorship evasion strategies. These strategies are not coded algorithms but rather descriptions of how network traffic should be modified to evade censorship. Geneva's strategy engine uses these descriptions to manipulate network traffic at the packet level, aiming to circumvent censorship mechanisms without disrupting the normal flow of data between the client and the server.

Geneva's basic building blocks for these strategies include actions like duplicate, drop, tamper, and fragment. These actions are applied to network packets to generate a variety of effects. For instance, duplicate creates two copies of a packet, while tamper modifies a packet in a specified manner.

An important aspect of these strategies is the use of action trees, a binary-tree structure where each tree has a trigger and a set of actions. The trigger determines which packets the tree should act upon, and the tree dictates the modifications to be applied to these packets. These triggers are packet-level triggers, ensuring that Geneva operates seamlessly at the network packet level.

Strategies in Geneva are composed of two forests: one for outbound traffic and another for inbound traffic. The strategy DNA is a formatted string syntax that expresses these strategies. Each strategy specifies how it handles outbound and inbound packets, differentiated by the ”\/” symbol in its DNA.

4.4.3. Strategy DNA

The Strategy DNA in Geneva is a critical component that defines the manipulation of network traffic to bypass censorship. It outlines the blueprint for how Geneva's engine interacts with and modifies network packets.

Structure and Syntax

- **Trigger**: Each strategy begins with a trigger, formatted as `[<protocol>:<field>:<value>]`. This trigger condition, when met, initiates the defined actions. For instance, `[TCP:flags:SYN]` would activate actions on TCP packets with the SYN flag.
- **Actions**: Following the trigger is a series of actions, represented by keywords like `duplicate`, `drop`, `tamper`, and `fragment`, dictating the operations on the packets.
- **Branching and Parameters**:
  - *Branching*: Actions like `duplicate` introduce branching, represented by syntax showing left and right children, e.g., `duplicate(tamper, fragment)`.

  - *Parameters*: Actions such as `tamper` include parameters within `{}`, specifying the exact modifications, like `tamper{TCP:flags:replace:ACK}`.

An example is `[TCP:flags:A]-duplicate(tamper{TCP:flags:replace:R}(tamper{TCP :chksum:corrupt},),)-| \/` , dissected as follows:

- **Trigger**: `[TCP:flags:A]` - Activates for TCP packets with the ACK flag.
- **Actions**:
  - `duplicate` - Duplicates the packet for multiple outcomes.
  - `tamper{TCP:flags:replace:R}` - Replaces the TCP flag from ACK to RST on one path.
  - `tamper{TCP:chksum:corrupt}` - Corrupts the TCP checksum on another path.
- **Branch Closure**: `-|` - Ends the action tree.
- **Outbound and Inbound Separation**: `\/` - Differentiates between strategies for outbound and inbound traffic.

Implications and Effectiveness Strategy DNA's format allows Geneva to define complex packet manipulations in a concise way. It provides flexibility to create diverse strategies against various DPI techniques. Being able to define changes for both outgoing and incoming traffic makes it possible to protect against bidirectional traffic inspection. This format simplifies strategy creation and allows for rapid deployment and testing in response to evolving censorship methodologies.

4.4.4. Method Implementation

In the practical implementation of the Geneva algorithm, I specifically executed the Geneva engine using the strategy `[TCP:flags:PA]-fragment{tcp:8:True}(,fragment{tcp:4:True})-|`. This strategy was selected for its potential to intricately manipulate TCP traffic and effectively evade DPI systems used for Internet censorship.

The chosen strategy operates on TCP packets with the PA (PUSH-ACK) flag set. The strategy is composed of two main actions: fragmenting these TCP packets first into 8-byte segments, and then further into 4-byte segments. This dual fragmentation approach was designed to disrupt the typical packet size and structure that DPI systems rely on for traffic analysis and filtering.

- The first action, fragment{tcp:8:True}, breaks down the TCP packets into segments of 8 bytes each. This fragmentation disrupts the standard packet size, making it more challenging for DPI tools to analyze and categorize the traffic based on size and structure.

- The second action, fragment{tcp:4:True}, further divides these segments into smaller 4-byte units. This additional fragmentation step adds an extra layer of complexity to the packet structure, further obscuring the traffic from DPI analysis.

Running the engine itself is a very simple matter. The Geneva engine is provided as a Python script that can be executed from the command line. The following command can be used to run the engine: `python3 engine.py --server-port 80 --strategy "..." --log debug`

4.4.5. Evaluation

In evaluating this implementation of Geneva, several key criteria were considered:

- Detection Resistance: The strategy successfully passed the detection resistance test, as nDPI (a widely used DPI tool) failed to identify the traffic as OpenVPN. This indicates a high level of effectiveness in evading DPI systems.
- Client-Server Accessibility: This strategy can be implemented entirely from the client side, which significantly enhances its usability and deployability in various scenarios where server-side modifications are not feasible.
- Latency Impact: The implementation resulted in a 14% increase in latency. While this indicates a notable impact, it remains within acceptable limits considering the benefit of evading DPI. Throughput: There was an 11% decrease in throughput, which is a trade-off for the increased complexity of the packet manipulation required to bypass DPI systems.

It should be noted that the specific strategy used in this test may not work against DPI systems in other real-world scenarios, in which case a different strategy may be required. The Geneva algorithm's ability to automatically generate and test strategies is its most significant advantage in this regard. Though due to the stochastic nature of the algorithm, the results may vary case by case.

4.5. Encryption tunneling

Encryption tunneling is a sophisticated method used in Virtual Private Networks (VPNs) to enhance the security and privacy of data transmission. This technique involves creating an additional secure tunnel, which encapsulates the primary VPN traffic. This added layer of encryption can be particularly effective in preventing Deep Packet Inspection (DPI) from identifying and possibly blocking VPN traffic.

4.5.1. Concept and Overview

Encryption tunneling, specifically through tools like stunnel, is a crucial method in circumventing DPI technologies. Stunnel is a software application used to provide an extra encryption layer, making VPN traffic appear as regular HTTPS traffic. This process involves wrapping OpenVPN traffic in SSL/TLS encryption, which is the same type of encryption used in secure web transactions. By mimicking HTTPS traffic, stunnel makes it challenging for DPI systems to distinguish this traffic from regular, secure web browsing activities.

The effectiveness of stunnel lies in its encryption methods. It uses Secure Sockets Layer (SSL) and Transport Layer Security (TLS) protocols, the foundations of secure internet communication. These protocols provide confidentiality and integrity of the data in transit. They achieve this through a combination of symmetric-key cryptography for data privacy (where the same key is used for both encrypting and decrypting the data), public-key cryptography for key exchange (allowing secure transmission of the symmetric key), and digital certificates for server authentication.

4.5.2. Method Implementation

The implementation of stunnel for encrypting OpenVPN traffic on Linux involves configuring both the VPN server and the client. **Server-Side Configuration:**

- Generate SSL Certificates: First step was to create an SSL certificate and key for stunnel. This was done using OpenSSL with commands to generate a private key and a certificate. The generated certificate and key are then combined into a single file used by stunnel.
- Configure stunnel: Then the stunnel configuration file, located at /etc/stunnel/stunnel.conf, was edited. In this file, the port stunnel should listen on (443) and the port to forward the traffic to (OpenVPN server port) were specified. Also, the path to the combined certificate and key file were included.
- Enable and Start stunnel: After configuration, the stunnel service was enabled and started using the system's service management commands (systemd commands in my case).

Client-Side Configuration:

- Configure stunnel: On the client side, the stunnel configuration involves specifying the server's address and the port to connect to (matching the listening port specified in the server's stunnel configuration).

- Integrate with OpenVPN: The OpenVPN client configuration was modified to route traffic through stunnel. This involved adjusting the OpenVPN client configuration file to connect to stunnel's local listening port.
- Start stunnel and OpenVPN Client: lastly, the stunnel service on the client was started, followed by initiating the OpenVPN connection. Ensure that stunnel is running before connecting with OpenVPN.

4.5.3. Evaluation

Detection Resistance In terms of detection resistance, stunnel encapsulating OpenVPN traffic has shown considerable success. In tests using nDPI, a common DPI tool, the encrypted traffic was not identified as OpenVPN. This result indicates that stunnel effectively disguises VPN traffic as regular HTTPS traffic, making it difficult for DPI technologies to detect and block it.

Client-Server Accessibility However, the implementation of stunnel scores lower in client-server accessibility. Since the solution requires access and configurations on both the client and the VPN server, it is not a client-only solution. This requirement can be a significant hurdle in scenarios where users do not have the necessary permissions or technical knowledge to configure the server-side settings.

Latency Impact The latency impact of implementing stunnel with OpenVPN was observed to be a 6% increase. This increase is a trade-off for the enhanced security and undetectability provided by the additional encryption layer. The slight latency increase is often considered acceptable given the benefits of bypassing DPI and maintaining secure communication.

Throughput Throughput, on the other hand, experienced a decrease of about 10%. This reduction is attributed to the additional processing required for encrypting and decrypting data packets in the stunnel layer. While this decrease in throughput is noticeable, it is a common consequence of enhanced security measures in VPN technologies.

CONCLUSION

This thesis represents a significant foray into the domain of VPN obfuscation, a critical facet of modern cybersecurity. In an era where digital communication is paramount, the tug of war between maintaining privacy through VPNs and efforts to detect and block such encrypted connections is more relevant than ever. This research pivots around an in-depth analysis of various VPN obfuscation methods, their effectiveness against deep packet inspection (DPI) systems, particularly nDPI, within a simulated network environment.

The core questions at the heart of this thesis were:

- Which VPN obfuscation methods can successfully evade detection by the nDPI system?
- How do these methods perform based on selected criteria?
- Which method is most suitable in practical scenarios?

The findings reveal a diverse landscape of obfuscation techniques, each with its strengths and trade-offs. The assessment, detailed in the following table, provides a clear comparison across key metrics:

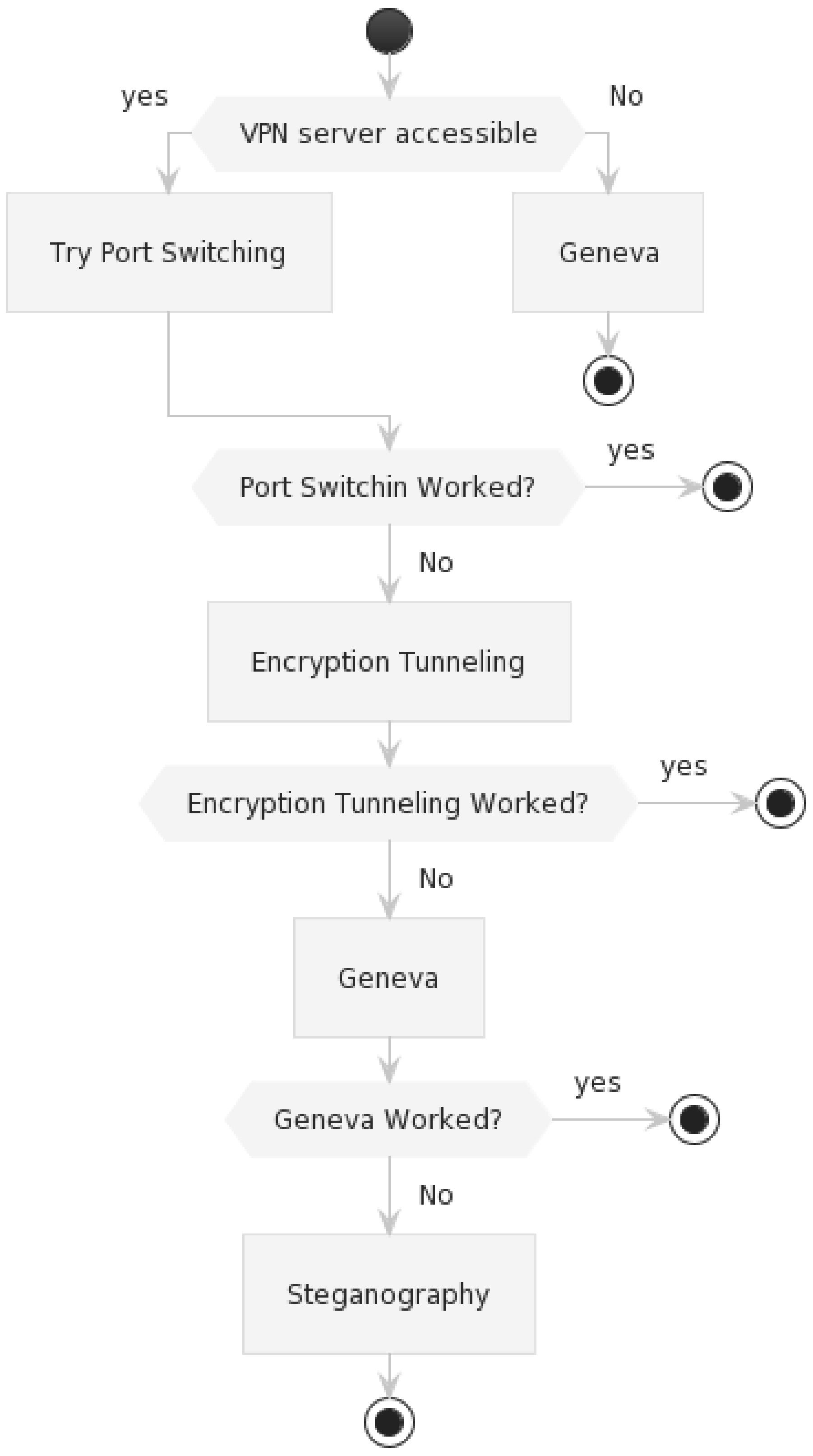
Table 11

Comparison of VPN Obfuscation Methods

Method	**Detection Resistance**	**Client-Server Access**	**Latency Impact**	**Throughput**
Encryption Tunneling	Pass	Server required	+6%	-10%
Geneva	Pass	Client only	+14%	-11%
Steganography	Pass	Server required	+560%	-88%
Port Switching	Fail	Server required	No Impact	No Impact

The different levels of efficiency and efficacy of each strategy are illustrated in this table. Both Geneva and Encryption Tunneling are quite resistant to detection, and their effects on throughput and latency are minor. The substantial latency and throughput penalties imposed by steganography render it unsuitable for applications that are performance-sensitive, notwithstanding its great effectiveness. In contrast, Port Switching isn’t a dependable defense against DPI.

The decision-making process for selecting an appropriate VPN obfuscation method is crucial in practical scenarios. The Figure 4.5 provided in this thesis offers a systematic approach to this selection process:



4.5. Figure. **Methodology for Selecting a VPN Obfuscation Method**

The first step in the diagram is to determine whether or not the virtual private network server is available. Geneva is the only realistic choice in the event that there is no access to the VPN server. In any other case, port switching should be utilized. Since port switching does not have any impact on performance indicators, it is suggested to attempt it first if it is possible to take advantage of it.

If Port Switching is able to circumvent DPI without negatively impacting performance, then the process is said to have been completed. On the other hand, because it has a low resistance to detection, the next step is to attempt encryption tunneling in the event that it is unsuccessful.

If successful, encryption tunneling provides a balanced solution that has a moderate impact on both throughput and latency. In the event that it is unable to avoid notice, the procedure will proceed by way of Geneva. Geneva is a good competitor due to the fact that it is effective in evasion and has flexibility on the client's side. The process is finished here if it works. Else, the final option is to use steganography.

Due of the enormous impact that this option has on the performance of the network, it is recommended as the final choice. The employment of this technique is most suitable for situations in which performance implications are less of a concern, despite the fact that it is quite effective in evading. a

REFERENCES

1. AbuHmed, T., Mohaisen, A. & Nyang, D. (2008), ‘A survey on deep packet inspection for intrusion detection systems’.

2. Aceto, G. & Pescapé, A. (2015), ‘Internet censorship detection: A survey’, *Computer Networks* **83**, 381–421.
URL: *https://www.sciencedirect.com/science/article/pii/S1389128615000948*

3. Alshalan, A., Pisharody, S. & Huang, D. (2016), ‘A survey of mobile vpn technologies’, *IEEE Communications Surveys & Tutorials* **18**(2), 1177–1196.

4. *A Standard for the Transmission of IP Datagrams over Ethernet Networks* (1984), RFC 894.
URL: *https://www.rfc-editor.org/info/rfc894*

5. Bock, K., Fax, Y., Reese, K., Singh, J. & Levin, D. (2020), Detecting and evading Censorship-in-Depth: A case study of Iran ’s protocol whitelister, *in* ‘10th USENIX Workshop on Free and Open Communications on the Internet (FOCI 20)’, USENIX Association.
URL: *https://www.usenix.org/conference/foci20/presentation/bock*

6. Bock, K., Hughey, G., Qiang, X. & Levin, D. (2019), Geneva: Evolving censorship evasion strategies, pp. 2199–2214.

7. Chakraborty, R., Jain, H. & Seo, G.-S. (2022), ‘A review of active probing-based system identification techniques with applications in power systems’, *International Journal of Electrical Power & Energy Systems* **140**, 108008.
URL: *https://www.sciencedirect.com/science/article/pii/S0142061522000539*

8. Chen, H.-Y. & Lin, T.-N. (2021), ‘The challenge of only one flow problem for traffic classification in identity obfuscation environments’, *IEEE Access* **PP**, 1–1.

9. Clowwindy, Madeye & Max, L. (n.d.), ‘Shadowsocks’.
URL: *http://www.shadowsocks.org/*

10. Crawford, D. (2019), ‘How to hide openvpn traffic – a beginner’s guide’.
URL: *https://proprivacy.com/vpn/guides/how-to-hide-openvpn-traffic-an-introduction*

11. Dingledine, R. & Mathewson, N. (2006), ‘Design of a blocking-resistant anonymity system draft’.

12. Dusi, M., Gringoli, F. & Salgarelli, L. (2008), A preliminary look at the privacy of ssh tunnels., pp. 626–632.

13. El-Maghraby, R. T., Abd Elazim, N. M. & Bahaa-Eldin, A. M. (2017), A survey on deep packet inspection, *in* '2017 12th International Conference on Computer Engineering and Systems (ICCES)', pp. 188–197.

14. Ermoshina, K. & Musiani, F. (2021), 'The telegram ban: How censorship "made in russia" faces a global internet', *First Monday* .

15. Ferguson, P. & Huston, G. (1998), What is a vpn ? — part i.
URL: *https://api.semanticscholar.org/CorpusID:140112970*

16. Fifield, D., Lan, C., Hynes, R., Wegmann, P. & Paxson, V. (2015), 'Blocking-resistant communication through domain fronting', *Proceedings on Privacy Enhancing Technologies* **2015**.

17. Ghatikar, T. & Sai, V. (2022), 'Vpn detection and blocking', p. 2022.

18. Handel, T. G. & Sandford, M. T. (1996), Hiding data in the osi network model, *in* R. Anderson, ed., 'Information Hiding', Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 23–38.

19. He, Y. & Chen, M. (2016), 'Protocol mimicry technique and its development', **40**, 1–8.

20. Iacovazzi, A. & Baiocchi, A. (2014), 'Internet traffic privacy enhancement with masking: Optimization and tradeoffs', *Parallel and Distributed Systems, IEEE Transactions on* **25**, 353–362.

21. Kailanya, E., Omamo, A. & Mwadulo, M. (2022), 'Deep packet analysis firewall model', *African Journal of Science, Technology and Social Sciences* **1**(1).
URL: *https://journals.must.ac.ke/index.php/AJSTSS/article/view/62*

22. Khattak, S., Javed, M., Anderson, P. D. & Paxson, V. (2013), Towards illuminating a censorship monitor's model to facilitate evasion, *in* '3rd USENIX Workshop on Free and Open Communications on the Internet (FOCI 13)', USENIX Association, Washington, D.C.
URL: *https://www.usenix.org/conference/foci13/workshop-program/presentation/khattak*

23. Kim, Y.-J., Kolesnikov, V., Kim, H. & Thottan, M. (2011), Sstp: a scalable and secure transport protocol for smart grid data collection, pp. 161 – 166.

24. Knapp, E. D. & Langill, J. T. (2015), Chapter 3 - industrial cyber security history and trends, *in* E. D. Knapp & J. T. Langill, eds, ‘Industrial Network Security (Second Edition)’, second edition edn, Syngress, Boston, pp. 41–57.
URL: *https://www.sciencedirect.com/science/article/pii/B9780124201149000034*

25. Kundur, D. & Ahsan, K. (2003), ‘Practical internet steganography: Data hiding in ip’.

26. Lipp, B., Blanchet, B. & Bhargavan, K. (2019), A mechanised cryptographic proof of the wireguard virtual private network protocol, pp. 231–246.

27. Liu, J., Gao, N., Tu, C., Zhang, Y. & Sun, Y. (2023), A pure hardware design and implementation on fpga of wireguard-based vpn gateway, *in* ‘2023 26th International Conference on Computer Supported Cooperative Work in Design (CSCWD)’, pp. 1220–1225.

28. Loshin, P. (2013), Chapter 4 - tor relays, bridges, and obfsproxy, *in* P. Loshin, ed., ‘Practical Anonymity’, Syngress, Boston, pp. 69–80.
URL: *https://www.sciencedirect.com/science/article/pii/B9780124104044000043*

29. Masud Karim, S. M., Rahman, M. S. & Hossain, M. I. (2011), A new approach for lsb based image steganography using secret key, *in* ‘14th International Conference on Computer and Information Technology (ICCIT 2011)’, pp. 286–291.

30. Matalgah, M., Sheikh, K., Thaker, M., Chaudhry, G., Medhi, D. & Qaddour, J. (2002), Performance analysis of ipsec protocol: Encryption and authentication, Vol. 2, pp. 1164 – 1168 vol.2.

31. Munshi, A. (2023), ‘Hybrid detection technique for ip packet header modifications associated with store-and-forward operations’, *Applied Sciences* **13**(18).
URL: *https://www.mdpi.com/2076-3417/13/18/10229*

32. Naidu, D. & Jha, M. (2023), ‘Detection technique to trace ip behind vpn/proxy using machine learning’, *International Journal of Next-Generation Computing* .

33. Network Solutions LLC (2021).
URL: *https://openvpn.net/community-resources/how-to/*

34. Pandey, J., Rai, S. & R, S. (2023), ‘Assessment of deep packet inspection system of network traffic and anomaly detection’, *International Journal of Scientific Research in Science, Engineering and Technology* pp. 680–688.

35. Pang, Y., Jin, S., Li, S., Li, J. & Ren, H. (2013), Openvpn traffic identification using traffic fingerprints and statistical characteristics, *in* Y. Yuan, X. Wu & Y. Lu, eds, 'Trustworthy Computing and Services', Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 443–449.

36. Papadogiannaki, E. & Ioannidis, S. (2021), 'Acceleration of intrusion detection in encrypted network traffic using heterogeneous hardware', *Sensors* **21**(4).
URL: *https://www.mdpi.com/1424-8220/21/4/1140*

37. Rathore, M. S., Razzaq, A., Hidell, M. & Sjödin, P. (2009), Site-to-site vpn technologies : A survey.
URL: *https://api.semanticscholar.org/CorpusID:35973654*

38. Sun, S. H. (2011), The advantages and the implementation of ssl vpn, *in* '2011 IEEE 2nd International Conference on Software Engineering and Service Science', pp. 548–551.

39. Trivedi, U. & Patel, M. (2016), A fully automated deep packet inspection verification system with machine learning, *in* '2016 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS)', pp. 1–6.

40. Wang, Y., Ji, P., Ye, B., Wang, P., Luo, R. & Yang, H. (2014), Gohop: Personal vpn to defend from censorship, pp. 27–33.

41. Wang, Z., Cao, Y., Qian, Z., Song, C. & Krishnamurthy, S. V. (2017), Your state is not mine: A closer look at evading stateful internet censorship, *in* 'Proceedings of the 2017 Internet Measurement Conference', IMC '17, Association for Computing Machinery, New York, NY, USA, p. 114–127.
URL: *https://doi.org/10.1145/3131365.3131374*

42. Wang, Z., Zhu, S., Cao, Y., Qian, Z., Song, C., Krishnamurthy, S. V., Chan, K. S. & Braun, T. D. (2020), Symtcp: Eluding stateful deep packet inspection with automated discrepancy discovery, *in* 'NDSS'.

43. Winter, P. & Lindskog, S. (2012), 'How the great firewall of china is blocking tor'.

44. Wu, M., Sippe, J., Sivakumar, D., Burg, J., Anderson, P., Wang, X., Bock, K., Houmansadr, A., Levin, D. & Wustrow, E. (2023), How the great firewall of china detects and blocks fully encrypted traffic, *in* '32nd USENIX Security Symposium (USENIX Security 23)', USENIX Association, Anaheim, CA, pp. 2653–2670.
URL: *https://www.usenix.org/conference/usenixsecurity23/presentation/wu-mingshi*

45. Yoo, H. & Ahmed, I. (2019), Control logic injection attacks on industrial control systems.

46. Zhao, Y., Ma, X., Li, J., Yu, S. & Li, W. (2018), Revisiting website fingerprinting attacks in real-world scenarios: A case study of shadowsocks, *in* M. H. Au, S. M. Yiu, J. Li, X. Luo, C. Wang, A. Castiglione & K. Kluczniak, eds, 'Network and System Security', Springer International Publishing, Cham, pp. 319–336.