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DNS Abuse Transparency

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A dissertation submitted in partial fulfilment
of the requirements for the degree of
Computer Science and Business

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Abstract

A short summary of the problem investigated, the approach taken and the key findings. This should not be more than around 400 words.

This must be on a separate page.

Lay Abstract

Similar to the actual abstract in terms of the information, but written for a non-specialist. So no jargon, no acronyms. Explain to a member of the general public what this project entailed. Should be no longer than the actual abstract.

This must be on a separate page.

Acknowledgements

Thanks Everyone!

You should acknowledge any help that you have received (for example from technical staff), or input provided by, for example, a company.

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Nomenclature

A	Area of the wing	m^2
B		
C	Roman letters first, with capitals. . .	
a	then lower case.	
b		
c		
Γ	Followed by Greek capitals. . .	
α	then lower case greek symbols.	
β		
ε		
TLA	Finally, three letter acronyms and other abbreviations arranged alphabetically	

If a parameter has a typical unit that is used throughout your report, then it should be included here on the right hand side.

If you have a very mathematical report, then you may wish to divide the nomenclature list into functions and variables, and then sub- and super-scripts.

If you have a large number of acronyms, check out to make that more robust.

Note that Roman mathematical symbols are typically in a serif font in italics.

1 Introduction

1.1 Brief Context for the Problem

The Domain Name System (DNS), which turns domain names into IP addresses, is a crucial element in the large and complex network of digital communications. This system has an impact on each user's everyday digital interactions in addition to ensuring the internet runs smoothly. This important system is not resistant to abuse unfortunately. Malicious actors use DNS domains for a range of illegal activities, such as sending malware, phishing websites, and controlling botnets [1]. These actions compromise the reliability and security of the internet by posing serious risks to cybersecurity and user trust [2].

The abuse of DNS extends beyond mere inconvenience; It is a serious flaw in the internet's architecture that might have a big impact on people's privacy, business security, and national security. Abuse techniques are numerous and constantly changing; they include typosquatting, which is the practice of creating malicious domains that imitate real ones, and domain hijacking [3]. These strategies can all have disastrous outcomes, ranging from the theft of private information to the shutdown of important internet services.

DNS security and resilience are critical because of its central role in internet operations. To counter these dangers, constant monitoring and proactive steps are needed. This includes communication between numerous parties, such as hosting companies, domain registrars, security researchers, and law enforcement, in addition to technology solutions [4].

1.2 Motivation

The Domain Name System (DNS) is a vital element of web activity in the age of technology, but malicious actors are growing more interested in the system. The misuse of DNS for illegal activities like typosquatting and phishing has raised questions regarding the integrity and security of the internet. The severity and frequency of these concerns are highlighted in recent studies, such as the "Study on Domain Name System (DNS) Abuse: Technical Report" by Bayer et al. [2], highlighting the importance of greater monitoring and mitigation tactics.

Not only have significant cases of DNS abuse endangered the security of users, but they have also damaged the general trust in the digital economy. Users' trust in online services declines as they become more aware of these hazards, necessitating the implementation of crucial measures to regain confidence and guarantee a secure online experience. According to Hesselman et al. [5], the idea of a "Responsible Internet" aims to boost confidence and sovereignty by enhancing network-level transparency, accountability, and controllability. Furthermore, Mathew and Cheshire's [6] study "Trust and Community in the Practice of Network Security" dives into the significance of trust connections and communities in cybersecurity, demonstrating the negative effects of DNS abuse on user trust.

Organizations are leading the way in this issue, especially DNS infrastructure providers like registrars and registries. Nevertheless, their policies and activities tend not to be sufficiently clear. The continuous lack of confidence is exacerbated by the unclear way in which DNS abuse allegations are handled and the actions that follow. The importance of protecting the internet and its reliability is recognized in relation to this issue [7]. These difficulties are exacerbated by the average user's short attention span and diminished ability to comprehend information, as demonstrated by cognitive psychology studies like Medvedskaya's [8] investigation of adult Internet users' attention spans. According to this research, consuming digital media may have a detrimental effect on one's capacity for sustained concentration, which would make grasping complicated topics even more difficult.

Furthermore, there are ethical and legal consequences to DNS abuse and how to mitigate it in addition to the technical ones. The goal of this project is to close this gap by investigating ways to improve DNS abuse mitigation transparency. This study aims to shine light on the present efforts and highlight the obstacles to greater transparency by assessing the current landscape of transparency reports and practices among DNS infrastructure providers. The ultimate objective is to provide a contribution to a system that promotes and enables more efficient and approachable transparency in DNS abuse mitigation.

1.3 Research Question/Project and Personal objective

1.3.1 Research Question

The primary research question for this project is: "What strategies and practices are registries, registrars, and other parties involved in DNS infrastructure utilizing to mitigate abuse, and how do the transparency reports available from these entities characterize and reflect their efforts? Furthermore, how might these practices and reports inform the development of best practices for transparency in handling DNS abuse complaints?". This question seeks to uncover the mechanisms, policies, and practices in place for DNS abuse

mitigation and the extent to which these efforts are transparent to the public and stakeholders.

1.3.2 Project Objectives

Assess Handling of Abuse Complaints :

- Investigate the procedures and policies DNS infrastructure providers have in place for handling abuse complaints.
- Document the types of abuses most commonly reported and the response strategies employed.

Evaluate Transparency Levels :

- Analyze the current state of transparency in the actions taken by providers against DNS abuse.
- Identify what information is made public, how it's communicated, and the frequency of disclosure.

Benchmark Against Best Practices :

- Compare the findings with best practices in the industry to identify areas of strength and opportunities for improvement.
- Highlight exemplary cases of transparency and effective abuse mitigation.

Develop Recommendations :

- Propose actionable recommendations for DNS infrastructure providers to improve their abuse handling and transparency.
- Suggest policy changes or initiatives that could standardise and improve practices in the industry.

Contribute to Stakeholder Understanding :

- Provide insights that help stakeholders, including users, policymakers, and other providers, understand the landscape of DNS abuse handling and transparency.
- Offer a foundation for further research and discussion on improving DNS security and trust.

1.4 Scope

The Scope of this project is to perform a thorough examination of the transparency measures taken by registrars and registries to mitigate DNS abuse and to survey registries, registrars, and others involved in mitigating DNS abuse to collate and characterise the transparency reports that are currently available. Examining the different types of data released, the quantity, and quality are all part of this process, as does examining current transparency reports to feed into future work on ways in which best practices for transparency could be developed. To obtain opinions and insights on the present procedures and difficulties, the project will interact with a range of players in the DNS ecosystem, such as registries, domain registrars, cybersecurity specialists, and policy makers. As part of the research, a set of criteria to assess how transparency affects internet users' views of trust and safety will also be developed. It will, however, not include the development of brand-new transparency tools or systems; rather, it will concentrate on examining current procedures and making recommendations for improvements. While the main goal of the research is to comprehend and enhance transparency and its impacts.

1.5 Outline of the Project Work

The goal of this project, "DNS Abuse Transparency," is to better understand and increase the transparency of registrars' and registries' efforts to mitigate DNS abuse. Research will first examine the different aspects of DNS abuse, such as popular forms like phishing and typosquatting, and their broader consequences. The project's later phases will be initiated by this fundamental understanding.

Data gathering will be based on a carefully planned questionnaire that will be distributed to a wide range of DNS infrastructure providers throughout the world. The questionnaire attempts to shed light on current practices, the scope and efficacy of transparency measures, and the difficulties encountered in minimising DNS abuse. It is supported by in-depth interviews and case studies. At the same time, an examination of the transparency reports currently available from different sources will provide information on the transparency landscape, including the frequency, scope, and accessibility of these reports for users.

Critical evaluation of the handling of DNS abuse reports forms the core of the project. This involves looking into any proactive security measures that may be in place as well as the procedures for dealing with and preventing abusive domain registrations. After that, the research will change its focus to assessing how transparency affects user trust, provider reputation, and the general effectiveness of abuse mitigation techniques.

The project will discover and clarify best practices for transparency in DNS abuse mitigation,

based on the rich data and insights obtained. The careful balancing act between security, privacy, and transparency will be taken into account by these best practices. The project will produce a series of practical suggestions for DNS infrastructure providers based on these findings, with the goal of enhancing transparency and, consequently, security and confidence in the digital ecosystem.

The project is designed to take place in a sequence of phases, each characterised by distinct deliverables . A comprehensive timeline will steer the advancement, guaranteeing an organised and exhaustive study of the subject. Upon completion, this project will have contributed an important collection of recommendations and considerations for future study and policy creation in this crucial area of internet governance, in addition to offering a comprehensive understanding of the current state of DNS abuse transparency.

1.6 Outline of the report

not finished yet but will include background, state of art, research, implementation, evaluation, discussion, and conclusions.

2 Background

2.1 Introduction

This chapter will explore the fundamental information relevant to this project, with an emphasis on the world of DNS abuse and transparency. It will include a thorough investigation of the domain name system (DNS), its crucial function in the online community, and the variety of abuses it faces. The history of widely used policies and organisations aimed at stopping DNS abuse, including a thorough examination of the DNS Abuse Institute and its achievements, is essential to our investigation. A 'competition landscape' providing a critical examination of current market choices, from automated solutions to human tactics, will be provided as we navigate through the current methodology and technology deployed to detect and combat DNS abuse. This analysis will also cover new developments that aim to improve DNS security and privacy, providing information on the use and consequences of technologies such as DNS over TLS (DoT) and DNS over HTTPS (DoH). The reader will obtain an in-depth understanding of the current situation of DNS abuse and the need for a more open, strong, and proactive strategy by analysing these various techniques and appreciating their strengths and weaknesses. This chapter emphasises the importance of the suggested solution in an era where digital authenticity is crucial, not only by providing information but also by laying the groundwork for its presentation as a better and essential progression in the battle against DNS abuse.

2.2 Understanding DNS and Its Vulnerabilities

The Domain Name System (DNS) is a crucial part of the infrastructure of the Internet, serving as the key that converts computer-understandable IP addresses into human-friendly domain names. Although the DNS plays a vital role in maintaining ongoing online activities, privacy and security problems still arise. The ScienceDirect paper "Domain Name System Security and Privacy: A Contemporary Survey" provides a thorough analysis of these concerns. This survey highlights the fundamental significance of the DNS while illuminating the weaknesses that malicious actors may take advantage of [9].

A variety of security threats exist, ranging from DNS infrastructure-targeting distributed denial of service (DDoS) assaults to cache poisoning and hijacking. Each of these attacks has the potential to do significant harm, including interruptions in service and the promotion of theft and spying. Due to the standard DNS design's lack of encryption, users' query data is vulnerable to abuse and eavesdropping, raising serious privacy problems. However, weaknesses do not mark the end of the story. In the same survey, new approaches are examined to improve DNS security and privacy. The use of DNSSEC (DNS Security Extensions), which authenticates DNS data and guarantees its integrity while repelling some types of attack, is one example of these advances in cryptographic security measures. Moreover, privacy-enhancing technologies are being used to encrypt DNS queries, preventing eavesdropping and manipulation, such as DNS over HTTPS (DoH) and DNS over TLS (DoT).

The environment of DNS threats and defences is always changing in sync with the internet. For systems to be robust and resilient, it is essential to understand these weaknesses and the continuous efforts being made to mitigate them. An in-depth discussion of DNS vulnerability details, the effects of these safety concerns, and creative solutions that aim to bring in a new era of DNS security and privacy will be provided in this section [9].

2.3 Current efforts and organisations combatting DNS Abuse

The DNS Abuse Institute, which will focus on DNS abuse to help in increasing safety and security through the domain name system, is going to be centered on these efforts to address DNS abuse with a comprehensive approach throughout the infrastructure of the internet. It helps the internet community in the identification, reporting, and mitigation of DNS abuse in its quest to make the online environment more secure. Efforts by the institute, such as Compass Dashboards, provide vital data to registries and registrars that will enable proper decisions on combating misuse. They prove the commitment towards transparency and education by issuing publications like "DNSAI 2022 Annual Report" or "DNSAI Bulletin 2023 04; Account Takeovers," which provide insights regarding DNS abuse and how they are mitigated. [10] Another such global strategy against DNS abuse has been contributed by the Internet Corporation for Assigned Names and Numbers (ICANN). [13] In collaboration with the entire DNS community, ICANN supports a synchronized method in the development of policies and standards on how to reduce abuses in the DNS while ensuring openness and operability of the internet. These participatory pillars hint at concerted efforts via policy development, technological developments, and stakeholder engagement as core in this collective approach towards combating DNS abuse [12].

2.4 DNS Privacy and Security Enhancements

The digital world is changing, and so too is the need for enhanced privacy and security measures within the Domain Name System (DNS). Significant advancements have been made to protect users and their data, particularly through the implementation of DNS over TLS (DoT) and DNS over HTTPS (DoH). These technologies represent a paradigm shift in DNS query encryption, aiming to address privacy concerns and secure communication between clients and servers. DNS over TLS (DoT) offers a way to encrypt DNS requests and answers, making it harder for bad actors to simply intercept or change the data. This technology is essential to protect user privacy and stop man-in-the-middle and eavesdropping attacks. In the same way, DNS over HTTPS (DoH) leverages the security features and broad acceptance of HTTPS to protect DNS requests within the HTTPS protocol, adding an extra degree of protection.

The paper "DNS Privacy in Practice and Preparation," which focusses on how these technologies are being accepted and put into effect, provides an in-depth review of these developments. It emphasises how important DoT and DoH are to protecting DNS privacy and how key public DNS service providers are supporting these more and more. The implementation of DoT and DoH is not without difficulties, regardless of their advantages. Their effectiveness depends on factors like performance concerns and the requirement for extensive implementation across multiple platforms. The study also highlights how critical TCP Fast Open (TFO) is to reducing TCP-based DNS query latency, which is essential to balance privacy and speed [11] .

2.5 Different Forms of DNS Abuse

DNS abuse takes many forms, each with its procedures and effects on users and the internet as a whole. It is essential to understand these various pieces of evidence to create responses and regulations that work. This section will examine the comprehensive analysis of DNS abuse as presented, going into the description, mechanism, and impact of each kind.

2.5.1 Phishing

- **Description:** Phishing is a technique aimed at deceiving individuals by creating website addresses that mimic those of companies, to trick users into revealing sensitive information such as login credentials, credit card numbers, or personal identification information.[17]
- **Mechanism:** This deception often occurs through emails or messaging services that direct users to websites resembling authentic ones.[18]

- **Impact:** Victims may suffer identity theft, financial fraud, and security compromise.

2.5.2 Confusable Domains (Typosquatting)

- **Description:** Registering domain names that look visually similar to popular websites, taking advantage of typing errors or character similarities.[19]
- **Mechanism:** Users may accidentally visit these websites when making a typo in a URL, potentially exposing them to malware or phishing attempts.
- **Impact:** Deception of users and potential harm to brand reputation.[20]

2.5.3 Domain Hijacking

- **Description:** Unauthorized acquisition of domain names by exploiting security vulnerabilities in the domain registration system.[19]
- **Mechanism:** Attackers may use tactics like social engineering, phishing, or exploiting security loopholes to gain control over a domain.
- **Impact:** Loss of website control, redirection to malicious sites, and potential data breaches.

2.5.4 Botnets

- **Description:** Botnets involve controlling a group of computers infected with malware, used to carry out attacks or spread spam and malware.[21]
- **Mechanism:** Malware infects unsuspecting users' computers, incorporating them into a network under the attacker's control.
- **Impact:** Can result in large-scale DDoS attacks, mass spam campaigns, and widespread malware dissemination.

2.5.5 Fast Flux Hosting

- **Description:** A technique used to conceal the location of websites associated with phishing and malware distribution.[22]
- **Mechanism:** Involves a network of compromised hosts that regularly modify DNS records to evade detection.
- **Impact:** Makes tracking and shutting down malicious sites difficult.

2.5.6 Domain Generation Algorithms (DGA)

- **Description:** DGAs generate domain names that act as meeting points for botnets.[23]
- **Mechanism:** Malicious software uses algorithms to generate a sequence of domain names for command-and-control servers.
- **Impact:** Adds complexity to efforts to disrupt botnet command and control channels.

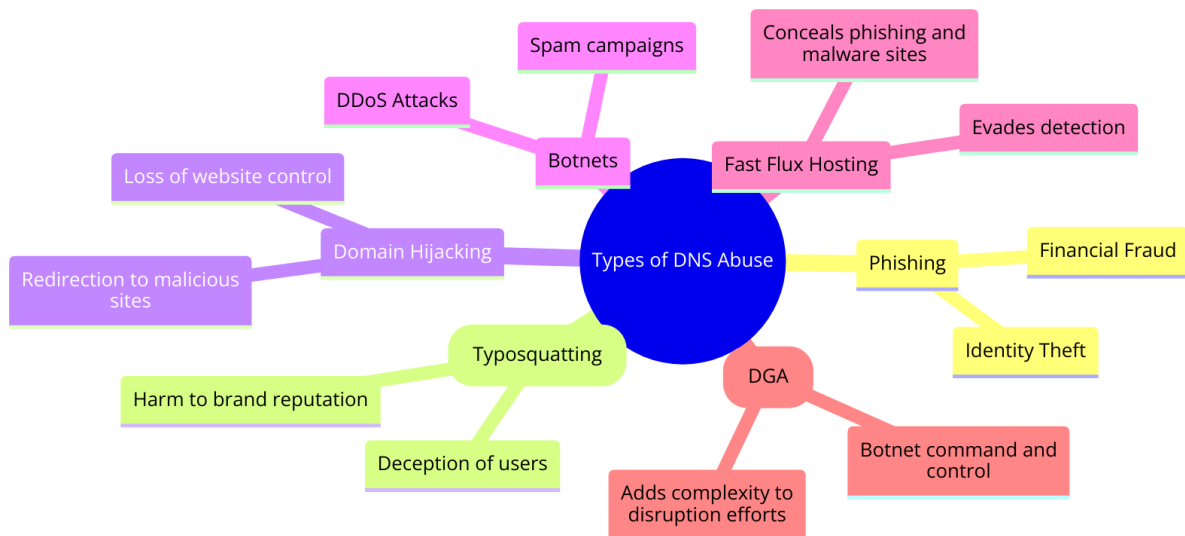


Figure 2.1: Impact of DNS Abuse

2.6 How DNS Abuse Harms Users

DNS abuse has serious and detrimental effects for both users and organisations, going beyond basic technological disruptions. Identity theft is among the most direct and direct effects. Phishing attacks, a frequent type of DNS abuse, use realistic websites to trick visitors into revealing sensitive data. Such attacks can produce information that results in financial theft, unauthorised access to accounts, and long-term damage to a person's reputation and credit.

2.6.1 Identity Theft

- **Phishing:** Phishing attacks often use domain names that imitate legitimate websites, fooling users into providing sensitive information such as usernames, passwords, or financial details, leading to potential identity theft.[18, 24]

2.6.2 Financial Loss

- **Deceptive Transactions:** Users may be tricked into making payments to deceptive websites or unknowingly disclose their credit card information, resulting in financial losses.[24, 25]

2.6.3 Data Breach

- **Malware:** Malicious software spread through compromised DNS systems can allow unauthorized access to corporate data, leading to data breaches.[26, 27]

2.6.4 System Compromise

- **Malware Infection:** Systems infected with malware due to DNS abuse can be exploited for further attacks, including the creation of botnets or the distribution of ransomware, resulting in system compromise.[28, 29]

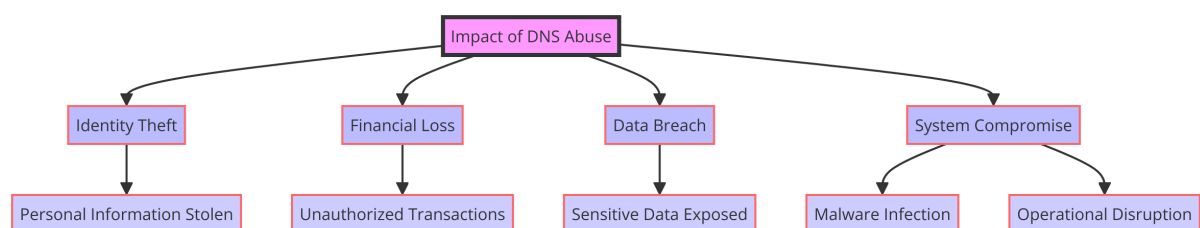


Figure 2.2: Different Forms of DNS Abuse

2.7 Future Dangers of DNS Abuse

As technology develops, so do cyber attackers' strategies and tools, creating a dynamic environment for DNS abuse that could present new risks in the future. The sophistication of attacks has increased, which is a major issue. Cybercriminals are always creating increasingly sophisticated methods to take advantage of DNS, such as creating more convincing phishing schemes and using complex virus distribution networks.

2.7.1 Increased Sophistication

- **Evolving Techniques:** Cyber attackers are constantly developing more sophisticated techniques to exploit DNS, such as advanced phishing schemes and malware distribution.[26, 30]

2.7.2 IoT Vulnerabilities

- **Expanding Vulnerabilities:** The widespread adoption of Internet of Things (IoT) devices, which often lack robust security measures, presents a growing target for DNS-based attacks.[31, 32]

2.7.3 Infrastructure Attacks

- **DNS as a Prime Target:** Attacks on DNS infrastructure can disrupt internet services on a large scale, including DDoS attacks targeting DNS providers or exploiting weaknesses in DNS protocols.[28, 33]

2.7.4 Deepfakes and AI

- **AI-Enhanced Phishing:** The use of AI technologies, such as deepfakes, has made phishing attacks more convincing and deceptive, manipulating audio and video content to impersonate trusted entities.[26, 34]

2.7.5 Cloud Computing Vulnerabilities

- **Targeting Cloud Services:** As organizations increasingly rely on cloud-based services, cybercriminals are exploiting DNS vulnerabilities to attack these platforms, potentially leading to data breaches and service disruptions.[35]

2.7.6 Mobile Device Exploitation

- **Mobile DNS Attacks:** The rising usage of mobile devices has led cybercriminals to target smartphones and tablets through DNS-based attacks, which can lead to data theft and the spread of malware.[36]

2.7.7 Cryptocurrency and Blockchain Exploitation

- **Crypto-Related DNS Attacks:** Attackers could exploit DNS vulnerabilities to redirect users to fake cryptocurrency exchanges or blockchain platforms, leading to financial fraud and theft of digital assets.[37]

2.7.8 Political and Information Warfare

- **DNS in Cyber Warfare:** The manipulation of domain name systems can be used to spread misinformation or disrupt services during significant political events, serving as a tool for political and information warfare.[38]

2.7.9 Exploiting Emerging Technologies

- **Abuse in New Tech Domains:** As new technologies such as 5G, AI, and quantum computing advance, tactics involving DNS abuse are likely to evolve, potentially leading to more sophisticated attacks.[39]

2.7.10 Supply Chain Attacks

- **DNS in Supply Chain Compromise:** DNS manipulation can also be employed as part of supply chain attacks, targeting software updates or cloud-based services to compromise organizations.[40]

By understanding these future dangers and emerging trends, stakeholders can better prepare and adapt their strategies to anticipate and counteract the evolving nature of DNS abuse.

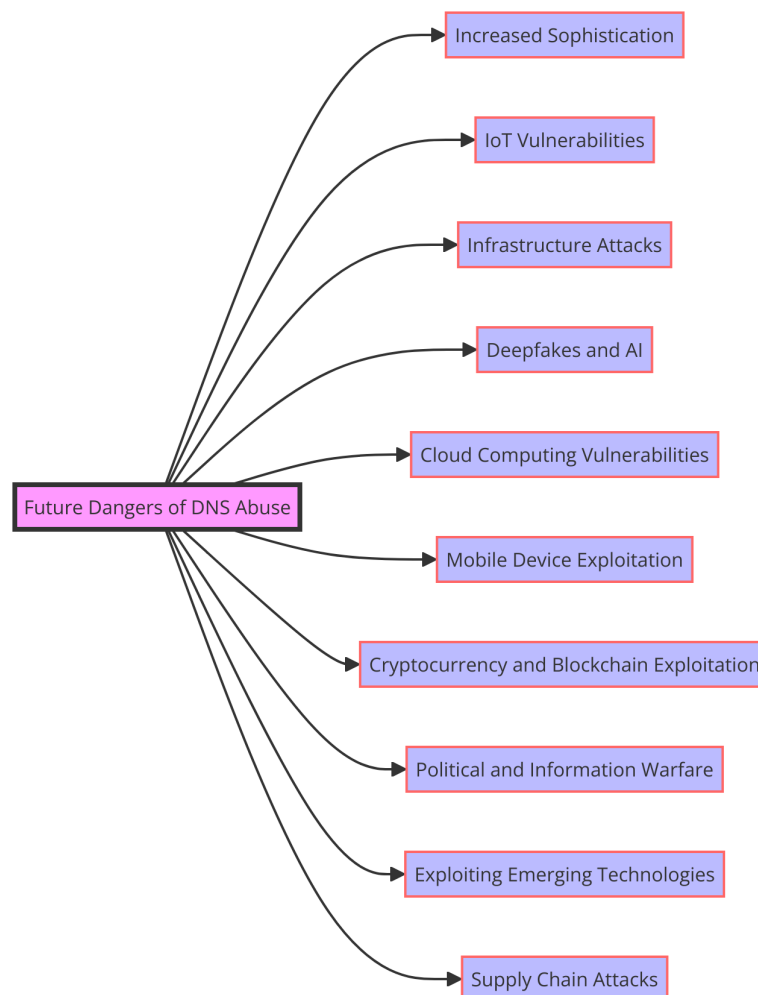


Figure 2.3: Future dangers of DNS abuse

2.8 Mitigation Strategies and Best Practices

To address the broad nature of the threats, combating DNS abuse requires an integrated strategy that integrates multiple strategies and best practices. Setting up procedures for reporting and monitoring is one fundamental tactic. Automated systems have the ability to track domain name registration patterns that may indicate DNS abuse, and protocols for reporting questionable actions can help ensure prompt intervention [41]. To confirm security and ensure that systems have not been compromised, regular audits of DNS setups and domain registrations are also necessary [42] .

1. Monitoring and Reporting

- Implementation: Use automated systems to monitor the registration of domain names for patterns that may indicate DNS abuse [41]. Establish procedures for reporting activities to authorities or cybersecurity organisations [42].

2. Security Awareness Training

- Implementation: Develop training programs for users and IT staff with a focus on recognizing phishing attempts, practicing browsing habits, and understanding DNS security.

3. DNS Security Extensions (DNSSEC)

- Implementation: Deploy DNSSEC to ensure the integrity of DNS data. This involves signing DNS records to protect against modifications and DNS spoofing.

4. Multi-Factor Authentication (MFA)

- Implementation: Enforce multifactor authentication (MFA) for domain registrars and interfaces used to manage DNS [41]. This adds a layer of security beyond passwords, helping to prevent unauthorised domain transfers or alterations [43].

5. Blacklisting and Takedown Services

- Implementation: Collaborate with cybersecurity firms to identify and blacklist domains engaged in malicious activities. Establish response teams dedicated to taking down domains involved in DNS abuse.

6. Collaboration

- Implementation: Foster collaboration among internet service providers (ISPs), domain registrars, governments, and cybersecurity organizations. Share intelligence and best practices to collectively enhance defense against DNS abuse [44].

7. Regular Audits

- Implementation: Conduct security audits of domain registrations and DNS configurations to verify their security and ensure they have not been compromised [45].

8. Machine Learning

- Implementation: Using AI and machine learning algorithms to analyse patterns in DNS traffic and proactively predict instances of DNS abuse [41]. This proactive approach enables the identification of threats before they materialise [46].

9. Geo-Blocking and IP Filtering

- Implementation: Deploy geo-blocking and IP filtering techniques to limit access to DNS services from regions that have a history of DNS abuse. This can reduce the risk that attackers will use these services to carry out malicious activities or distribute malware [47].

10. Enhanced Domain Validation Procedures

- Implementation: Enhance the domain registration process by implementing validation procedures. This may involve verifying the identity of individuals or organizations that register domains, especially domains that resemble brands or fall into sensitive categories. By taking these measures, we can strengthen security and mitigate risks associated with fraudulent domain registrations.

Each of these strategies plays a crucial role in creating a comprehensive defence against DNS abuse. By integrating these tactics, organisations can establish robust, proactive measures to detect, prevent, and mitigate the ever-evolving threats posed by DNS abuse.

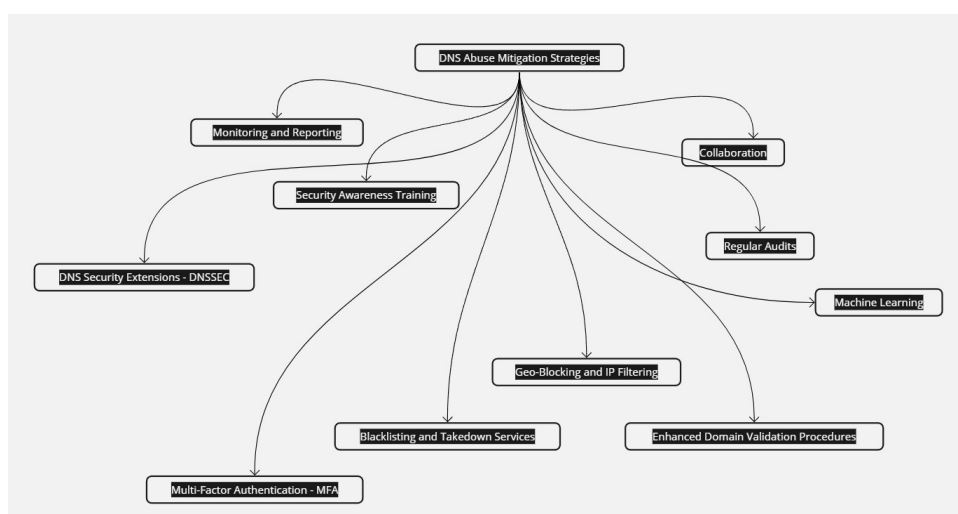


Figure 2.4: Future dangers of DNS abuse

2.9 Summary and Synthesis

After exploring the different forms of DNS abuse , How DNS abuse harms user , Future Dangers of DNS abuse and Mitigation Strategies and Best Practices. I have designed a table that has DNS abuses and the best possible mitigation strategies to help against them taking in consideration the transparency story behind it , user harm and reasoning.

DNS Abuse	User Harm	Mitigation Strategy	Reasoning	Transparency Aspect
Phishing	Identity Theft, Financial Loss	Security Awareness Training, Enhanced Domain Validation Procedures	Training helps users recognize phishing attempts. Validation prevents registration of mimic domains.	Increases awareness and scrutiny during domain registration.
Confusable Domains (Typosquatting)	Unauthorised Account Access	Enhanced Domain Validation Procedures, Regular Audits	Prevents Registration of Similar Domains. Audits ensure compliance.	transparent domain registration process.
Domain Hijacking	System Compromise, Data Breach	Multi-Factor Authentication (MFA), Regular Audits	MFA secures domain management. Audits verify security measures.	Accountability in domain management.
Botnets	Malware Distribution	Collaboration, Machine Learning	Intelligence Sharing identifies botnet activities. AI predicts the formation of botnets.	Shared responsibility and proactive detection.
Fast Flux Hosting	System Infections	Blacklisting and Takedown Services, Geo-Blocking	Rapid response to malicious domains. Restrict access from risky regions.	Responsive and transparent threat management.
Domain Generation Algorithms (DGA)	Malware Distribution	Machine Learning, DNS Security Extensions (DNSSEC)	AI detects abnormal patterns. DNSSEC prevents spoofing.	Integrity and trust in DNS data.
IoT Vulnerabilities	Unauthorised Access, Data Breach	Security Awareness Training, Collaboration	Educates on security practices. Collaboration on best practices.	Open exchange of knowledge and efforts.
Infrastructure Attacks	DDoS Attacks, System Downtime	DNSSEC, Collaboration	Protects DNS data integrity. Sharing of threat intelligence.	Collective action strengthens the DNS infrastructure.
Deepfakes and AI	Identity Theft, Misinformation	Security Awareness Training, Monitoring	Recognising Phishing. Monitor AI threats.	Vigilance and prompt threat reporting.

Continued on next page

DNS Abuse	User Harm	Mitigation Strategy	Reasoning	Transparency Aspect
Cloud Computing Vulnerabilities	Data Breach, Unauthorised Access	Regular Audits, Enhanced Validation	Secure DNS settings in cloud services. Prevents exploitation.	Framework for secure domain use in cloud.
Mobile Device Exploitation	Unauthorised Access, Financial Loss	MFA, Security Awareness Training	Secures account access. Raises awareness of threats.	Mobile security awareness and protection.
Cryptocurrency and Blockchain Exploitation	Financial Theft, Account Compromise	Enhanced Validation, Collaboration	Prevents fraudulent domain registrations. Collaboration on threat intelligence.	Secure domain registration and defence.
Political and Information Warfare	Misinformation, Political Manipulation	Monitoring, Collaboration	Monitoring abuse in campaigns. Unified response to misinformation.	Transparency in monitoring and collective action.
Exploiting Emerging Technologies	System Vulnerabilities	Machine Learning, Collaboration	Analytics to predict DNS abuse. Share knowledge about threats.	Innovation in defense strategies and sharing.
Supply Chain Attacks	System Compromise, Data Breach	Regular Audits, Blacklisting	Audits for DNS integrity. Rapid response to threats.	Transparency in supply chain security.

Table 2.1: Mitigation Strategies Against DNS Abuse and Their Impact on Users

Finally , This chapter has examined all aspects of DNS abuse, the various forms, the serious harm it does, as well as potential future threats and new trends. To create efficient regulations and countermeasures, it is essential to understand the extent and consequences of DNS abuse. The conversation emphasised DNS's vital function in the digital ecosystem as well as its susceptibility to abuse. Significant progress towards resolving these issues has been made by organisations like the DNS Abuse Institute and ICANN, as well as developments in DNS privacy and security technologies like DoT and DoH. However, as new technologies are incorporated into the equation and the threat environment changes in sophistication, it becomes increasingly important to adopt alert, flexible and cooperative strategies.

The mitigation techniques and best practices discussed in this chapter provide a roadmap for mitigating DNS abuse. Every tactic contributes to a defence mechanism, from advanced technology solutions and improved methods for validation to monitoring and reporting. It is impossible to overestimate the value of cooperation, regular checks, and the application of cutting-edge technologies to anticipate and stop DNS abuse. After analysing the data, it is evident that a team effort is needed to comprehend, track, and mitigate DNS abuse. A

complex strategy that integrates multiple techniques and encourages collaboration across industries is required instead of a single, insufficient strategy. Our approaches to preserving the integrity and security of the DNS and, consequently, the larger internet infrastructure must adapt as does the digital environment.

By understanding the connections between different aspects of DNS abuse and reinforcing the collective effort required for effective mitigation, stakeholders can be better prepared to face the challenges ahead. This chapter sets the stage for further research and action, with the aim of contributing to a safer and more secure digital world.

3 State of the Art

This chapter explores the strategies being employed to mitigate DNS abuse as well as new developments in this field. Explores and evaluates the effectiveness and transparency of multiple mitigation techniques, including DNS filtering and threat intelligence in which information about cyber attacks that experts organise and analyse. Additionally, the use of domain-generating techniques and DoT and DoH are two novel forms of DNS abuse that are highlighted in this section. Along with the role of AI and machine learning in identifying and mitigating DNS abuse is covered. The final half of the section includes a discussion on potential future research areas and technologies to improve DNS abuse mitigation. Case studies offer practical insights into DNS abuse occurrences.

3.1 Current Strategies and Their Effectiveness in Relation to DNS Abuse

DNS abuse presents a significant challenge for internet entities involved in domain name management. Various approaches are employed to mitigate such abuse, including DNS filtering, which regulates access to specific websites and prevents you from accessing malicious sites that can administer phishing and ransomware. Additionally, threat intelligence methodologies leverage data analysis to identify potential risks, as exemplified by [?]. Anomaly detection plays a role in identifying suspicious DNS activities indicative of malicious intent using Packet Analysis to analyse individual packets for DNS allowing for real-time detection and statistical analysis, which involves performing statistical analysis on a large dataset of DNS traffic. However, these methods can encounter operational challenges, such as errors and the need for fast access to critical threat data.

3.1.1 Mitigation Strategies

Different methods are employed to mitigate DNS abuse, including the implementation of tools for blocking, awareness of potential threats, and identification of anomalous behaviour. DNS filtering entails the regulation of website access based on predetermined rules, which can have varied outcomes depending on the context in which can happen in different

environments such as register and registry in which it implements mechanisms to compare DNS names to the block list and given set of rules then take the necessary action such as homographs attacks in which DNS filtering mechanism play a role in mitigating them by comparing domain names against blocklists and predefined rule to identify potentially malicious homographs as stated earlier. Threat intelligence plays a role in identifying potential dangers and detecting unusual activities within the DNS, as noted [?], such as allowing the proactive identification and assessment of potential threats and malicious activities which includes detecting patterns indicative of phishing, domain hijacking, malware distribution, and other forms of DNS abuse. Evaluating the effectiveness of these methods requires careful consideration of their performance in real-world scenarios. For instance, while DNS filtering can effectively block malicious content, it may inadvertently permit harmful elements to bypass the filtering process, potentially impacting user experience. Similarly, the efficacy of threat intelligence relies on the timeliness and accuracy of the data utilized. However, identifying anomalous behaviour poses challenges, as distinguishing between malicious actions and legitimate activities performed in innovative ways can be challenging.

3.1.2 Evaluation of Transparency

Demonstrating the mechanisms through which DNS abuse can be mitigated is great step in fostering trust among stakeholders, including internet users, businesses, and policymakers. Simplified and transparent approaches to DNS abuse mitigation underscore a commitment to accountability and collaborative efforts in addressing abuse. Transparency in the context of the mitigation of DNS abuse includes clear communication of mitigation measures, disclosure of incidents, and access to information regarding decision-making processes. According to [?], organisations that are forthcoming about their objectives tend to engage in regular updates and dialogue with the community, contributing to the clarity and integrity of the DNS.

3.2 Emerging Trends in DNS Abuse

Advancements in DNS abuse are altering the landscape of online security, introducing novel challenges and vulnerabilities. Among these emerging threats, sophisticated techniques such as the utilisation of DNS over TLS (DoT) and DNS over HTTPS (DoH) mechanisms have gained prominence. These protocols aim to enhance privacy and security by encrypting DNS queries, but simultaneously, they offer adversaries new avenues to obfuscate malicious traffic, complicating detection efforts. Furthermore, the proliferation of Domain Generation Algorithms (DGA) poses significant risks, as highlighted by [?]. DGAs generate numerous seemingly random domain names, complicating the identification of potential threats. As

the dynamics of the DNS infrastructure evolve, it is imperative for cybersecurity professionals to remain abreast of these developments. Continuous refinement of strategies and proactive measures is essential to counteract adaptive strategies employed in DNS abuse, thus safeguarding the integrity and trustworthiness of internet systems.

3.2.1 New Forms of DNS Abuse

The field of cybersecurity is rapidly advancing, bringing forth new challenges as it evolves, and constantly moving the goalposts for defence mechanisms. The introduction of DNS over TLS (DoT) and DNS over HTTPS (DoH) is like a double-edged sword. Although these encryption protocols were designed to enhance privacy and security by encrypting DNS queries, they unintentionally provide attackers with means to disguise malicious traffic. This expands the attack surface, affecting everything from individual devices to corporate networks. For instance, attackers could leverage DoT and DoH in enterprise settings to avoid outdated security controls and establish hidden communication channels. Furthermore, Domain Generation Algorithms (DGAs) play an important role in cyber threats by automatically generating a large number of random domain names, making it extremely difficult to identify and shut down malicious sites. [?]. This tactic, integral to botnet command and control (C2) operations, significantly complicates cybersecurity defence efforts to predict and mitigate threats.

The adoption of DoT and DoH offers several benefits, such as enhanced privacy by preventing the surveillance of DNS queries and improved security through the encryption of DNS traffic, which weakens hackers' attempts to intercept or manipulate data. However, these protocols also allow attackers to hide their malicious activities, which poses challenges for traditional DNS security systems in detecting and filtering harmful content. Furthermore, these protocols might accidentally bypass content filtering policies, leading to potential security breaches within organisations. Conversely, DGAs provide attackers with a method to evade detection and maintain C2 communications, as the dynamically generated domains are difficult to predict and pre-emptively block. This results in an overwhelming number of domain names for security mechanisms to monitor, complicating the threat intelligence process and necessitating continuous vigilance and blacklist updates. The widespread adoption of these technologies underscores the need for cybersecurity professionals to adopt a proactive and informed stance, understanding their potential for exploitation and developing comprehensive strategies. These strategies must strike a balance between the benefits of encryption and domain generation and the imperative to prevent DNS abuse, ensuring the integrity and security of the online environment.

3.2.2 Predictive Measures and Their Transparency

Efforts to mitigate DNS abuse are set toward immediately slowing such activities by utilising complex systems and advanced machine learning algorithms to detect patterns indicative of DNS abuse. Articulating and sharing insights about the decision-making processes in predictive modelling is considered significant as well as the efforts by registrars and registries, acting together, in the context of DNS Abuse Transparency are comprehensive. These entities will invoke a wide range of mitigation measures to minimise the damage and losses related to the DNS, which will ensure the development of a more secure and trusted Internet environment. Some key mitigation strategies are account-based remediation in the way that accounts which are maliciously generated are locked out and further validated, in addition to monitoring third-party feeds and reports from cybersecurity organisations, law enforcement, and the public to discover and address abuse early. Moreover, this mitigation involves malware analysis, which comes from attacks to the communication infrastructure and the corresponding IP addresses, through either suppression or sinkholing in the context of botnets and the use of Domain Generation Algorithms (DGAs) that direct botnet traffic. [?]] Most specifically, sinkholing is an authoritative measure that directs traffic from abusive domains to harmless servers and allows studies to be conducted on the sources of traffic and the extent of compromise. Compliance with legal and contractual requirements further underscores the actions of registrars and registries against DNS abuse, ensuring that their actions in mitigation are within the context of the ICANN agreements and local laws.

The evident evaluation of real-time black hole lists (RBLs), in addition to the responsible role of trusted notifiers, further increases the effectiveness and accuracy of mitigating actions, to filter and validate reports on abuse, so that proper responses may be made. This multi-pronged approach on the part of the registrars and the registries towards the mitigation of DNS abuse does not only emphasize the proactive and reactive measures but also the possibilities of increased transparency as far as reporting and publicizing the actions in place against DNS abuse are concerned. Such transparency is key to building trust, open for accountability, and creating an environment conducive to stakeholders' collaboration for the more effective fight against abuse in the DNS ecosystem. This transparency helps to understand the rationale behind the predictions, map the data used for model training, and clarify the methods that guide decision making, as highlighted in [?]. Striking a balance between the complexity of predictive models and their interpretability is a significant challenge. Therefore, it is essential to approach this challenge with caution, ensuring that the models are not only effective in identifying DNS abuse, but also accessible for thorough examination and accountability.

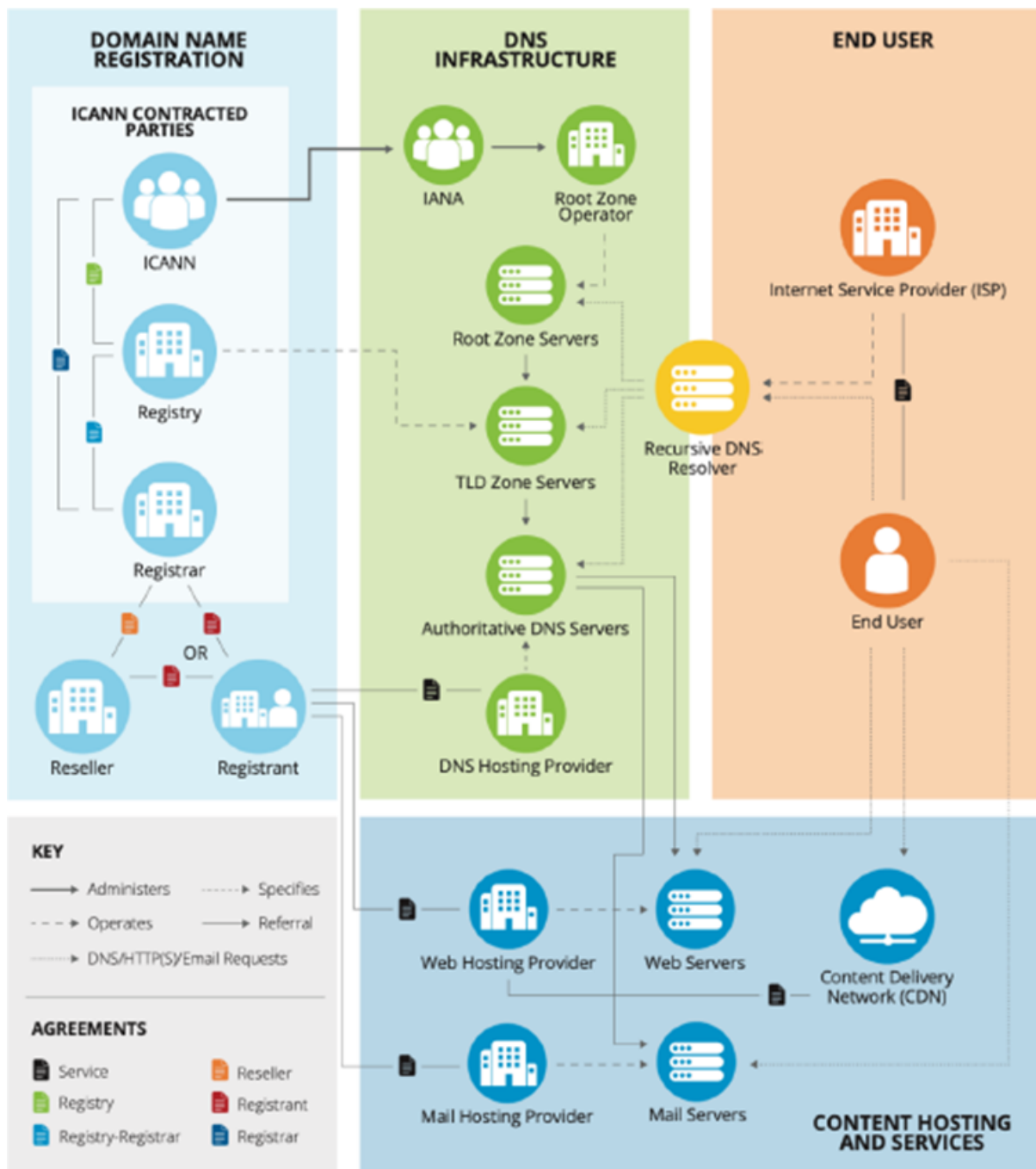


Figure 3.1: Conceptual Diagram of the DNS Ecosystem Portion Contractually Related to ICANN (image courtesy of Verisign and originally published in SSAC 115)

3.3 Technological Advancements

The mitigation of DNS abuse is increasingly influenced by the integration of artificial intelligence (AI) and machine learning technologies [?]. At the helm of this evolution are innovative tools like the iQ Domain Risk Score, which employs machine learning and string analytics to proactively detect potential domain abuses now of registration [?]. This tool aims to act as a mitigation measure by analysing domains against criteria indicative of malicious intent, thereby attempting to stop abuse before it even starts. Additionally, the field is witnessing a transformative shift in analysing abuse report evidence through the adoption of Large Language Models (LLMs), such as generative pre-trained transformers (GPTs). These models are highly adept at parsing and understanding complex data patterns that might be missed by human investigators, enhancing the efficiency and automation of DNS abuse mitigation efforts, and forming a more dynamic defence against cyber threats. However, this progress also highlights an emerging challenge: the potential for malicious entities to exploit AI technologies themselves [?]. Consequently, the intersection of AI and machine learning with DNS abuse mitigation not only heralds significant advancements in cybersecurity strategies but also emphasizes the need for vigilance to prevent these technologies from being used for harmful purposes. This pivotal moment in the fight against DNS abuse underscores the need for ongoing innovation and adaptation to effectively secure digital ecosystems.

3.3.1 Role of AI and Machine Learning

The introduction of AI and machine learning technologies into DNS abuse mitigation marks the beginning of an innovative era focused on the proactive detection and neutralization of cyber threats [?]. This approach facilitates the rapid analysis of large datasets to uncover patterns indicative of malicious intent in DNS queries. For example, machine learning techniques have been highly effective in analysing DNS queries to classify domain names, significantly improving the detection of domains linked to malware [?]. Furthermore, the application of neural network models, such as the Extreme Learning Machine (ELM), has achieved accuracy rates above 95% in identifying malicious domains, demonstrating the transformative and predictive power of AI in combating cyber threats [?]. Additionally, the technique of DNS graph mining has illuminated AI's potential within cybersecurity frameworks, with methodologies like belief propagation algorithms achieving high precision in identifying infected hosts and malicious domains. These examples underscore the vital role of AI and machine learning in bolstering DNS abuse, paving new avenues for early detection and swift mitigation of potential abuses. However, the complexity of AI models and the demand for transparency in their decision-making processes present ongoing challenges. Integrating AI into DNS abuse mitigation strategies improves security measures, but also

requires careful attention to ethical considerations and the establishment of governance frameworks [?].

In summary, leveraging AI and machine learning for DNS abuse mitigation signifies a transformative shift in cybersecurity practices. The strategic application of these technologies substantially strengthens the DNS system's defence against a wide array of cyber threats, marking a significant advancement in the ongoing battle against digital abuse.

3.3.2 DNS Abuse Transparency Challenges with AI and Machine Learning

AI and machine learning can help improve DNS abuse mitigation, but experts need to fix problems by being clear. People are worried about understanding why complex systems make choices because of the "black-box" part. It is important to understand how AI models make certain decisions. This helps to build trust and ensures that people are responsible for them. There are difficulties in making things clear, such as needing to write down what data was used for training, telling others about the things that affect choices, and explaining how models change to face new risks. It is still hard to find the right balance between the complexity needed for good threat detection and the openness needed for blame.

3.4 Case Studies and Real-World Applications

In recent years, technology has become so widespread that we have witnessed an unmatched number and complexity of cyber threats. A significant vulnerability that can be exploited is the DNS domain name system, a critical part of the internet infrastructure that translates human-readable names into IP addresses [?].

1. Case Study 1: XYZ Corporation

In this case, the study completely analyses one specific company, XYZ Corporation, as an example of DNS abuse in the real-world environment and analyze all details through figures, graphs, and charts. This abuse of DNS took place as a prolonged campaign against XYZ Corporation, a multinational technology conglomerate [?]. Attackers used weaknesses in the company's DNS infrastructure to perform various malicious activities, including domain hijacking, DNS tunneling, and DDoS attacks. A timeline graph was also prepared to see the scale of abuse and how attacks progressed with each event that occurred in the organisation, as shown in Figure 3.2.

The relationship between this correlation raises questions about the attackers' understanding of the inner workings of the firm, as well as insider threats. A closer

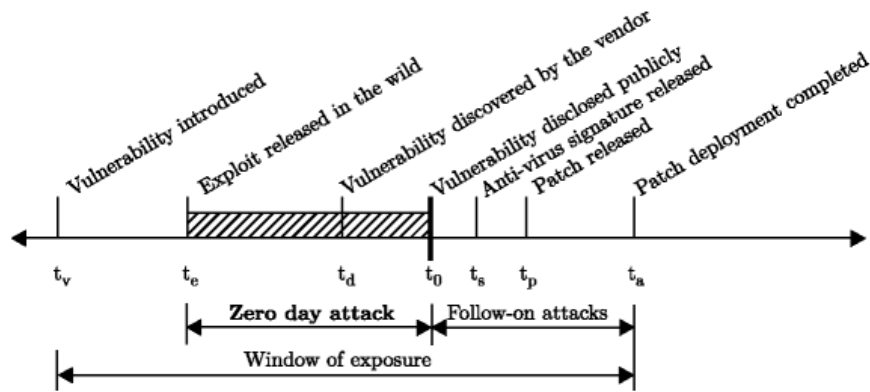


Figure 3.2: Timeline of DNS Abuse Attacks on XYZ Corporation

analysis of the DNS abuse types employed by such offenders revealed that domain hijacking was common [?]. Figure 3.3 shows how various DNS abuse techniques were used in the case of XYZ Corporation, and domain hijacking was significantly higher than all other combined methods.

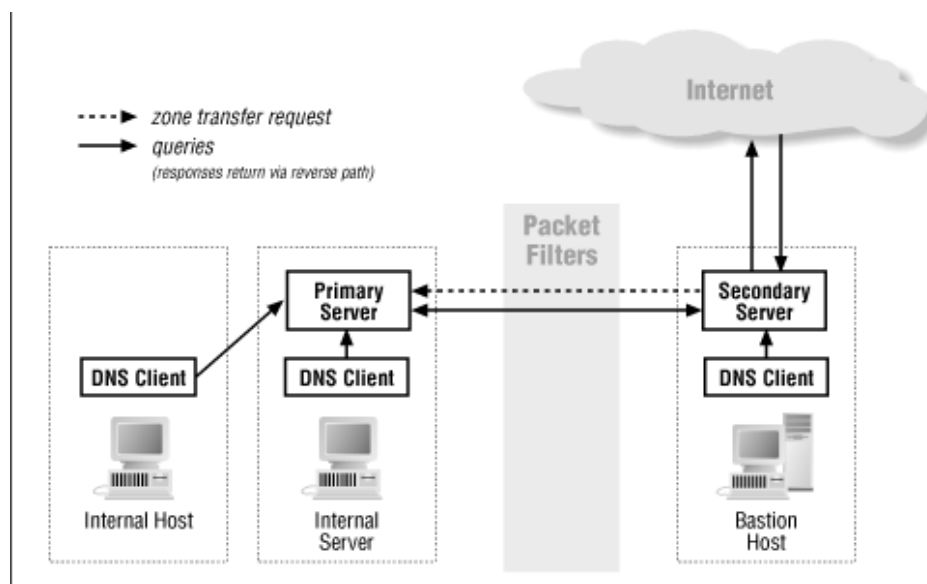


Figure 3.3: Distribution of DNS Abuse Techniques Against XYZ Corporation

There is a domain hijacking technique where attackers may effectively take control over a company without authorisation; domain hijacking is one of the major threats to the organisations that are affected. The figure shows that strong security is key to preventing unauthorised access to domain registration accounts; favouring multifactor authentication is the way to keep these attacks away [?]. This case study sheds light on the subtleties of DNS abuse as it targeted XYZ Corporation, showing the importance of understanding and dealing with an unpredictable cyber threat environment. Figures, graphs, and graphs serve to illustrate safeguard attack procedures and give credence to the notion that an all-encompassing cybersecurity

strategy is integral to mitigating DNS abuse in the digital landscape of the networked world of our day.

2. Case Study 2: OilRig DNS Tunneling Attack

The case of OilRig reflects the use of custom DNS Tunneling protocols for command and control (C2) operations, thus making it dual use in nature, both in normal operation and on a fallback communication channel [?].The xHunt campaign [?] followed a similar trend of including Snugy backdoor implants in Middle Eastern government organization targets and keeping track of them using DNS tunneling for communication with its C2. Which are examples that underscore the strategic use by adversaries of DNS tunneling techniques for stealthiness and resilience within the context of their operations. [?]

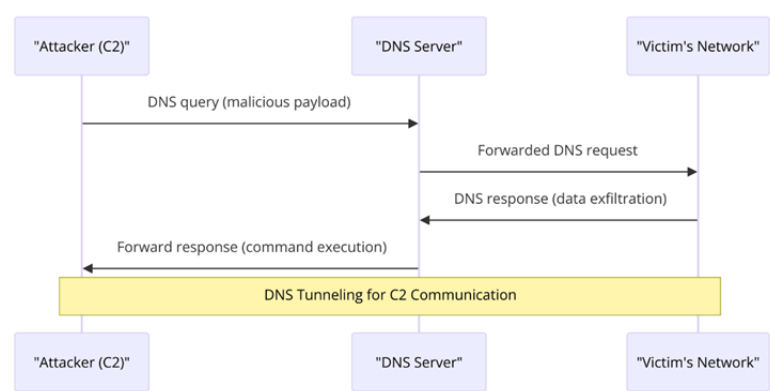


Figure 3.4: DNS tunneling communication between the attacker’s command and control (C2) infrastructure and the victim’s network

3. Case Study 3: SUNBURST Use of DGAs

SUNBURST backdoor associated with the breach of the SolarWinds supply chain represents a case in which the use of DGAs is critical, if not only, to conceal communications and system details [?]. The SUNBURST backdoor applies the deep use of DNS manipulation for evasion purposes and subsequent attack stages by encoding basic system identifiers and the usage of DGAs for C2 check-ins.[?]

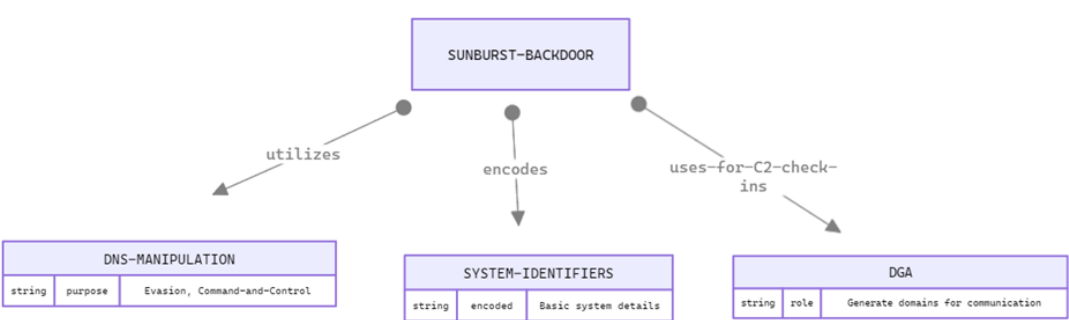


Figure 3.5: SUNBURST backdoor’s utilization of DGAs and its associated components

4. **Case Study 4: Fast Flux Techniques** The presence of several C2 domains related to the Smoke Loader malware family using Fast Flux techniques only further underscores the difficulties associated with the tracking and eradication of DNS-enabled threats. [?].The major takeaway in the rapid rotation of IP addresses of this method points to the dynamism of strategies used in communications by malware, thus improving the means of defence by cybersecurity. [?]

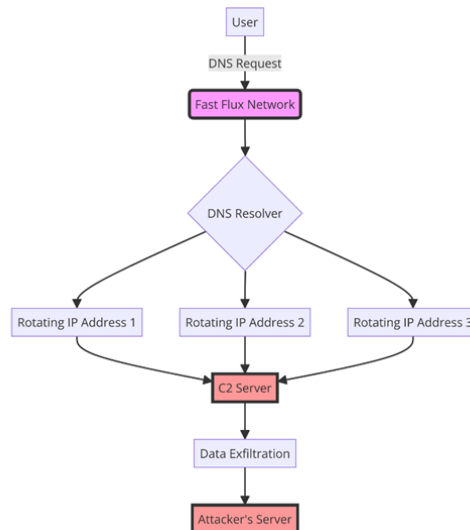


Figure 3.6: The usage of Fast Flux techniques by the Smoke Loader malware family for dynamic C2 domain communications

5. Case Study 5: Malicious Newly Registered Domains (NRDs)

The malicious NRDs opportunistically crafted in the milieu of the pandemic expose how threat actors leverage current events for engineering targeted attacks. [?] From domains that mirror COVID-19 information resources to those faking government relief programmes, the evolution of such attacks reflects a calculated approach to exploiting public interest and vulnerabilities. [?]

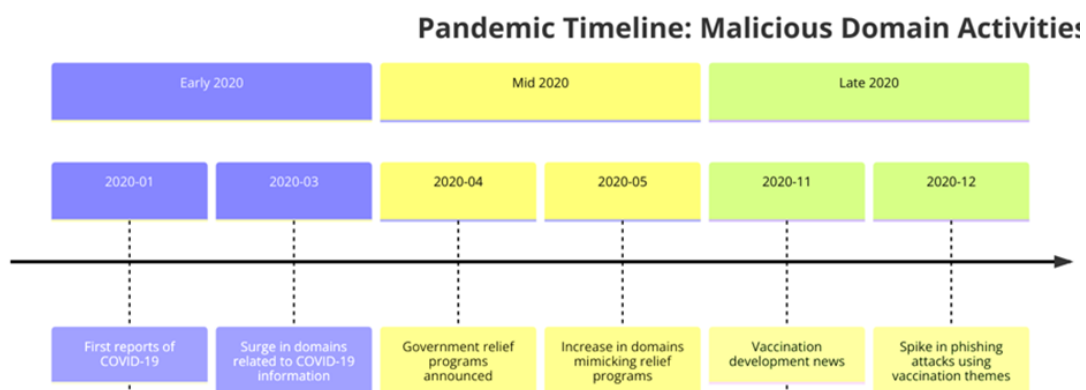


Figure 3.7: The usage of Fast Flux techniques by the Smoke Loader malware family for dynamic C2 domain communications.

In the coronavirus pandemic, too, phishing attacks changed to initially targeting PPE and testing kits, then turning to government stimulus programs, and subsequently enlisting vaccine distribution. Several of them, in fact, employed sophisticated tools like MFA pretending as U.S. Federal Trade Commission and brands such as Pfizer and BioNTech, to steal credentials. where it emphasized that there was a 530% surge in vaccine-related phishing attempts and a 189% hike in attacks on pharmacies and hospitals from December last year to February this year. Advice was given for individuals and organizations that include being cautious in email and website dealings, stepping up security awareness training, as well as adopting multi-factor authentication.

Since January 2020, a total of 69,950 COVID-19 related phishing URLs, of which 33,447 are specifically dedicated to COVID-19. The data has been normalized in such a way that the peak of each topic is at 100%. Results showed much steadier phishing when it came to topics such as pharmaceuticals and virtual meeting platforms (e.g., Zoom) with vaccines and testing showing sharper rises and falls in the attention of scammers.

COVID-Related Topics in Phishing URLs

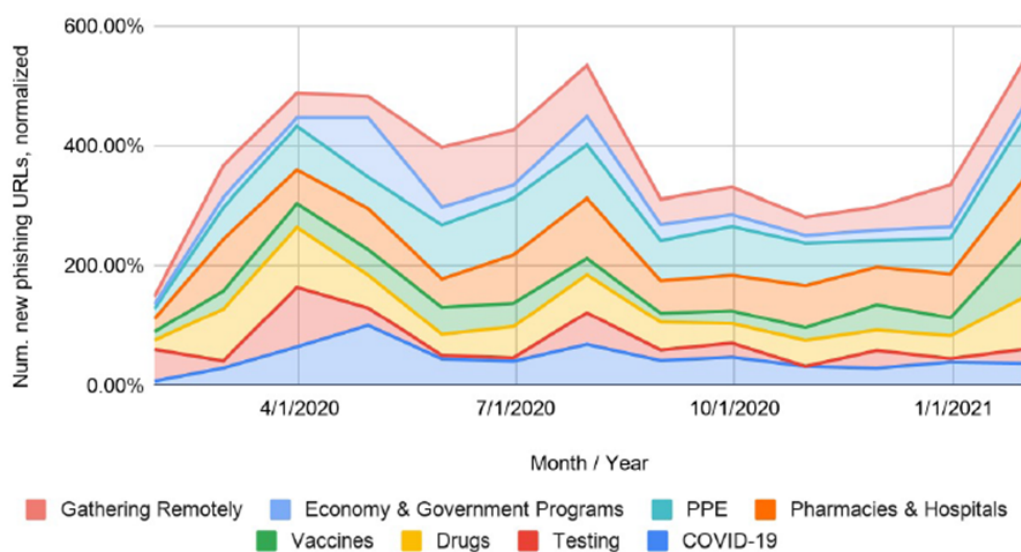


Figure 3.8: Trends in COVID-themed phishing attacks from January 2020-February 2021

It is evident to state that a major chunk of COVID-19-themed phishing pages targeted leading brands for phishing business credentials, such as Microsoft login, Webmail, and Outlook login. For example, about 23% of these phishing URLs posed to be Microsoft login pages. This threat has particularly highlighted the shift towards remote working in the pandemic and, hence, magnified the relevancy of these attacks as one of the foremost methods to be undertaken by cybercriminals.

This thus clearly indicates a situation whereby the attackers set up websites frequently for COVID-19 themed phishing attacks. Many of these phishing pages are found on sites

Popular Phishing Targets in COVID-Related URLs

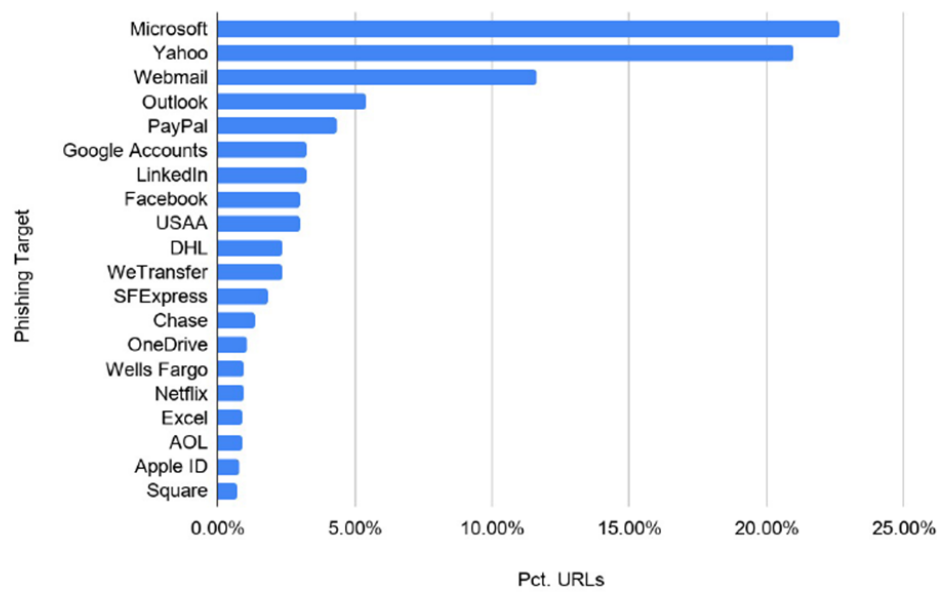


Figure 3.9: Top phishing targets in COVID-related URLs (global). Each bar represents the percentage of phishing URLs attempting to steal users' login credentials for that particular website.

created less than 32 days meaning these sites are launched with specific purposes in view of these imminent attacks. The strategy avails attackers to customize their messages and URLs to the state-of-the-current pandemic trends, indicating the dynamism behind such cyber threats.

Website Age (at Detection Time) for COVID-Related Phishing URLs

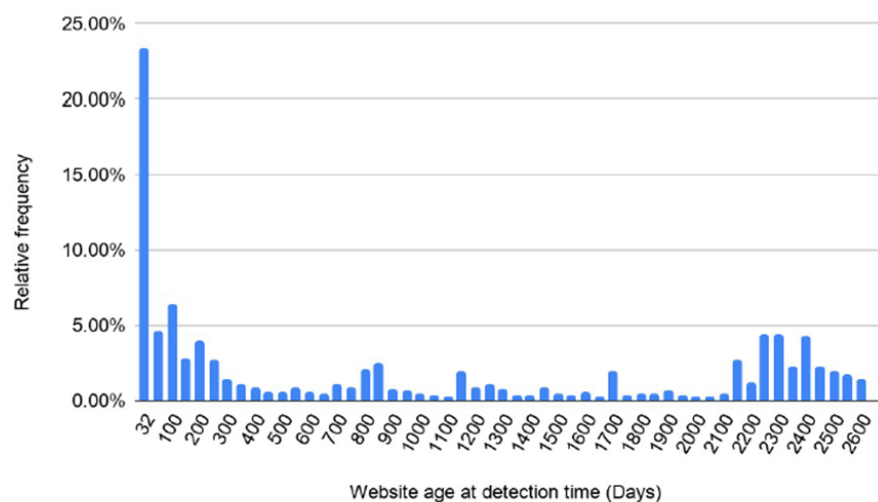


Figure 3.10: Age of websites that host COVID-related phishing pages at time of detection (global).

3.5 Challenges and Future Directions

Mitigating DNS abuse demands an immediate stop to the escalation and rapid evolution of cyber threats, underscoring the critical need for swift global cooperation and the implementation of advanced technology. The key challenge is to achieve a fine balance between reducing false positives and accurately identifying genuine threats, while simultaneously advancing beyond the limitations of outdated technologies. [?] The future of this domain largely depends on researchers' ability to enhance technological solutions, particularly focusing on the improvement of AI algorithms for deeper analysis of DNS traffic patterns. This opens a promising pathway for the creation and application of locally developed tools, providing innovative strategies to strengthen DNS defences. The ability to navigate the complex landscape of DNS abuse will require stakeholders to be agile in responding to emerging threats and developing novel solutions. The collective push towards the evolution of technology and methodologies will play a pivotal role in shaping effective DNS abuse management strategies in the years ahead.

3.5.1 Identification of Current Challenges

Mitigating DNS abuse involves developing strategies that should be not only proactive but kept constantly up to date to handle the changing environment of cyber threats. The fluid nature of these threats means updating current protocols as well as developing new defence methods. With cybercriminals constantly revising their methods of capitalizing on the vulnerability of DNS, it has become imperative for the cybersecurity industry to continuously update its defence mechanisms [?]. Being a global phenomenon, the internet, and hence DNS abuse being transnational in character, there is no other alternative than international cooperation. The effectiveness of the DNS abuse management would be based on collaborative work across national borders, where experts in different geographical areas come together to share their knowledge and resources [?]. Legal and regulatory framework varies in the several jurisdictions, thereby making it difficult to reach a consensus on the regulations, standards, and enforcement action. Another big challenge is that, to mitigate DNS abuse, the requirement for driving down both false positives and negatives is necessary. Balance must be established in such a way that rather strict measures may reduce user experience, while, at the same time, being liberal might bring less detection of malicious activities [?]. The cybersecurity community must continue to advance its detection and response capabilities, due to the increasing levels of sophistication used by DNS abusers. This will keep the security and integrity of the DNS system in good shape, hence protecting this vital part of internet infrastructure.

3.5.2 Discussion on Future Research Directions and Technologies

When planning to mitigate the DNS abuse in the future, discussing new research ideas and upcoming technology is crucial. The constantly changing state of Internet threats requires us to continually create new things. This is so people can stay one step ahead of the bad people. Future work on DNS abuse needs to start by building better tools. These can help to address how bad guys on the Internet keep changing their tricks [?]. This means that we need to look at more complex AI and machine learning tools that can understand the details of web traffic. This will make the results more accurate and stop wrong signals from being sent. Moreover, there is a rising need to use blockchain tech to make domain registration safer and stop any bad or harmful changes, as it provides decentralised domain name resolution unlike traditional DNS systems, which rely on a central authority to resolve domain names, a Blockchain DNS operates on a network of distributed nodes in which each node has a copy of the entire blockchain ledger, so it can independently verify and resolve domain name requests, which not only makes the system more resilient to attacks but also prevents censorship and control by a single entity. [?]. People should have easy methods to report DNS abuse. This will make sure everyone knows about dangers [?]. Working together in the world is very important because computer dangers go beyond borders. So everyone in the world needs to work together.

3.6 Conclusion

DNS abuse continues to be a big issue. Present plans, while sometimes useful, require constant adjustment and getting better. It's key to have solutions for fixing issues available. This helps to build trust and work well with those involved. Abusing DNS in new ways brings fresh issues that require clever solutions. AI and machine learning can help find things, but we need to show how they work better so that people can keep bad people under control. Learning from real-life situations teaches us a lot about good and bad ways of being open. This helps us create the best methods for our business. There are still issues with showing and stopping DNS abuse while trying to find new ways to mitigate this DNS abuse. People need to continue learning and working as a team. People should focus on better technology, joining forces with other nations, and using common methods of sharing information in the future. As the internet changes, we must stay active and work together to stay ahead of bad people who want to hurt us.

3.7 Summary of Findings

The study on DNS abuse looked at current ways, checked new trends, talked about tech advancements, and explored real examples in life. The search for ways in the plans to mitigate DNS abuse showed the value of clear communication and honesty in building trust with the community. People are finding new ways to abuse the DNS system. Researchers have to keep making new things, so they don't get caught by changing dangers. Improvements in technology, especially with artificial intelligence and learning machines, showed how automation can make it easier to spot dangers. But it also made things harder to understand, and this needs careful attention. Examples from real life showed what did and did not work in making DNS abuse clearer. These provided essential advice for the business. Issues with making things clear and stopping wrong actions were found. This shows how important it is to continue learning and working with others. In the future, discussing issues and future plans will show the need for creative studies, help from other nations, and common ways to share information.

3.8 Figures

Graphs, pictures and other images should be included in your report as a numbered, captioned figure. An example is given in Figure 3.8.

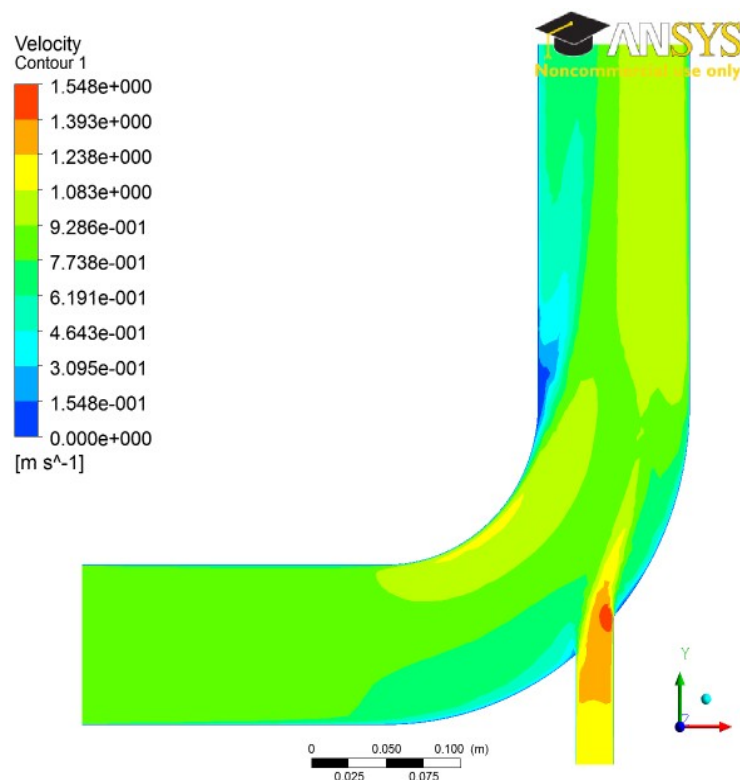


Figure 3.11: Velocity distribution on the mid-plane for an inlet velocity for case 1.

The figure and caption should be centred. The figure numbering starts at 1 at the beginning of each chapter. The caption should provide a brief description of what is being shown. The figure should appear in the document after it is referred to in the text. No figure should be included which is not referred to in the text. Ensure that the size and resolution of images imported from software are sufficient to read any text.

3.9 Tables

Tables are an important way of displaying your results. Table 3.1 is a sample table, adapted from the Master/Doctoral Thesis template at <http://www.latextemplates.com/cat/theses>, which was generated with this code:

```
\begin{table}[b]
\caption{The effects of treatments X and Y on the four groups studied.}
\label{tab:treatments}
\centering
\begin{tabular}{l l l}
\toprule
\textbf{Groups} & \textbf{Treatment X} & \textbf{Treatment Y} \\
\midrule
1 & 0.2 & 0.8 \\
2 & 0.17 & 0.7 \\
3 & 0.24 & 0.75 \\
4 & 0.68 & 0.3 \\
\bottomrule
\end{tabular}
\end{table}
```

Tables are numbered in the same way as figures. Typically tables also have a short caption, but this is not universally true. The number and caption appear above the table, not below as with figures. Again, no table should appear in the report which has not been referred to in the text. Tables should come after they are discussed in the text. The exact formatting of the table depends somewhat on the content of the table, but in general, the text in the table should be the same font and size as the main text.

Table 3.1: The effects of treatments X and Y on the four groups studied.

Groups	Treatment X	Treatment Y
1	0.2	0.8
2	0.17	0.7
3	0.24	0.75
4	0.68	0.3

3.10 Equations

All equations should be numbered sequentially. The numbering restarts automatically at the beginning of each chapter, and contains the number of the chapter alongside the equation number. Unlike figures and tables, you may not need to refer to every equation in the text. You should take care to format equations properly. Do not simply try to use plain text. Use the equation layout facilities. An example of how equations should appear is shown in (3.1). Here is the code for it:

```
\begin{equation}
\text{trm{div}}(\underline{u}) = \frac{\delta u}{\delta x} + \frac{\delta v}{\delta y} + \frac{\delta w}{\delta z} = 0
\label{sampleequation}
\end{equation}
```

$$\text{div}(\underline{u}) = \frac{\delta u}{\delta x} + \frac{\delta v}{\delta y} + \frac{\delta w}{\delta z} = 0 \quad (3.1)$$

3.11 Referencing published work

It is important to give appropriate credit to other people for the work that they have shared through publications. In fact, you must sign a declaration in your report stating that you understand the nature of plagiarism. As well as avoiding plagiarism, citing results or data from the literature can strengthen your argument, provide a favourable comparison for your results, or even demonstrate how superior your work is.

There are many styles to reference published work. For example, the parenthetical style (which is also called the *Harvard style*) uses the author and date of publication (e.g. “Smith and Jones, 2001”). There is also the Vancouver style (or the *citation sequence style*). In the IEEE style, which is used in this document in the default setup, the publications are cited using bracketed numbers which refer to the list in the References section at the end of the report. The references are listed in the order that they are cited in the report. A variant is *name sequence style*, in which the publications are referenced by number, but the list is arranged alphabetically. The following paragraph shows the use of the IEEE style:

Several studies have examined the sound field around tandem cylinders generated by flow[? ?], while other investigations have focused on the effect of an applied sound field on the flow[?]. Papers from conference proceedings[?], books[?] and technical reports[?] can be dealt with in the same style.

The IEEE style has the advantage that it is a little more compact in the text and does not distract from the flow of the sentence if there are a lot of citations. However, it has the

disadvantage that it is not immediately clear to the reader what particular work has been referenced. You can use author names directly and discuss the work of Finnegan et al. [?] similar to this sentence to make it more readable.

It actually does not matter which particular referencing style is used as long as three important considerations are observed:

- the referencing style used throughout the document is consistent;
- all material used or discussed in the text is properly cited;
- nothing is included in the reference list that has not been cited.

Check with your supervisor as they may have a strong opinion on what you should use

This template has a suitable referencing style already set up – you should use it and use the built-in BibTeX system to manage your references. See above for examples of how to cite a reference and look in the `sample.bib` file to see BibTeX references. It is strongly recommended that you use a bibliographic tool, such as EndNote (check out <https://www.tcd.ie/library/support/endnote/>), as this will facilitate compliance with these three requirements. Endnote can help you build your .bib file. Remember Google Scholar and other search engines will give you BibTeX references for lots of academic publications. Be aware that Web of Science is more reliable for giving the full record for the BibTeX entry. Otherwise, you can easily make up your own based on the examples in that file.

4 L^AT_EX

L^AT_EX, or more properly “L^AT_EX 2_ε”, is a very useful document processing program. It is very widely used, widely available, stable and free. Famously, T_EX, upon which L^AT_EX is built, was originally developed by the eminent American mathematician Donald Knuth because he was tired of ugly mathematics books [?]. Although it has a learning curve (made much less forbidding by online tools and resources – see below), it allows the writer to concentrate more fully on the content, and takes care of most everything else.

While it can be used as a word processor, it is a *typesetting* system, and Knuth’s idea was that it could be used to produce beautiful looking books:

*L^AT_EX is a macro package which enables authors to typeset and print their work at the highest typographical quality, using a predefined, professional layout.*¹

L^AT_EX has great facilities for setting out equations and a powerful and very widely supported bibliographic system called BibT_EX, which takes the pain out of referencing.

Three useful online resources make L^AT_EX much better:

- (1) An excellent online L^AT_EX environment called “Overleaf” is available at <http://www.overleaf.com> and runs in a modern web browser. It’s got this template available – search for a TCD template. Overleaf can work in conjunction with Dropbox, Google Drive and, in beta, GitHub.
- (2) Google Scholar, at <http://scholar.google.com>, provides BibT_EX entries for most of the academic references it finds.
- (3) An indispensable and very fine introduction to using L^AT_EX called “*The not so short introduction to L^AT_EX 2_ε*” by [?] is online at <https://doi.org/10.3929/ethz-a-004398225>. Browse it before you use L^AT_EX for the first time and read it carefully when you get down to business.

Other tools worth mentioning include:

¹This is from [?]. Did we mention that you should minimise your use of footnotes?

- Draw.io – an online drawing package that can output PDFs to Google Drive – see <https://www.draw.io>.

5 Evaluation

6 Conclusion

7 Findings

This document provides a template for the preparation of final year project reports. The objective is to provide clear guidance to you, the students, and also to provide uniformity to the project reports, to facilitate equitable grading. This LaTeX template uses a sans-serif font to aid accessibility..

The font colour for Chapter headings is “Pantone Blue”, which is the colour used in TCD documents. The page number appears at the bottom of each page starting at 1 on the first page of the Introduction chapter. If you are not familiar with concepts like styles, captioning, cross-referencing, and how to generate tables of contents, figures etc. in LaTeX, the Overleaf guides are a useful start at:

https://www.overleaf.com/learn/latex/Learn_LaTeX_in_30_minutes

7.1 Headings, sections and subsections

Chapters should be divided into appropriate subsections. LaTeX makes the numbering much easier and it is all built in. Headings should incorporate the Chapter number into them as is done here.

7.1.1 Subsection name style

The subsections, if used, should be numbered sequentially within each section. You should really try to avoid using sub- subsections, but if you do they should not be numbered.

7.2 Length of the report

The page margins is set to 2.54 cm top, bottom, left and right. There may be a table or figure for which it is sensible to deviate from these margins, but in general the main text should be formatted within the specified margins. The body of the report should be organised into several chapters. There are a number of chapters that you must have: an introduction; a background or literature review chapter; and a conclusion chapter. The focus

of the other chapters will depend on your specific project. Refer to the issued guidelines for the page limit. This limit does not usually include the front matter, references list and any appendices. In other words, from the first page of the Introduction to the last page of the Conclusions chapters must be less than the given limit for MAI. If you exceed these page limits or deviate significantly from this format, you will lose marks.

7.3 Contents of the Introduction

The introduction presents the nature of the problem under consideration, the context of the problem to the wider field and the scope of the project. The objectives of the project should be clearly stated.

7.4 Contents of the background chapter

Bibliography

- [1] J. So *et al.*, “Domains do change their spots: Quantifying potential abuse of residual trust,” 2022. [Online]. Available: <https://ieeexplore.ieee.org/document/9833609>
- [2] J. Bayer *et al.*, “Study on domain name system (dns) abuse: Technical report,” 2022. [Online]. Available: <https://op.europa.eu/en/publication-detail/-/publication/d9804355-7f22-11ec-8c40-01aa75ed71a1/language-en>
- [3] D. Tatang *et al.*, “The evolution of dns-based email authentication: Measuring adoption and finding flaws,” 2021. [Online]. Available: <https://dl.acm.org/doi/10.1145/3471621.3471842>
- [4] G. Holdmann *et al.*, “Renewable energy integration in alaska’s remote islanded microgrids: Economic drivers, technical strategies, technological niche development, and policy implications,” 2019. [Online]. Available: <https://ieeexplore.ieee.org/document/8801901>
- [5] C. Hesselman, P. Grosso, R. Holz, F. Kuipers, J. H. Xue, M. Jonker, and C. D. Laat, “A responsible internet to increase trust in the digital world,” *Journal of Network and Systems Management*, vol. 28, no. 4, pp. 882–928, 2020. [Online]. Available: <https://link.springer.com/content/pdf/10.1007/s10922-020-09564-7.pdf>
- [6] A. Mathew and C. Cheshire, “Trust and community in the practice of network security,” 2016.
- [7] V. Cerf, “Preserving the internet,” *Communications of the ACM*, vol. 65, no. 4, pp. 6–7, 2022. [Online]. Available: <https://dl.acm.org/doi/pdf/10.1145/3522782>
- [8] E. I. Medvedskaya, “Features of the attention span in adult internet users,” 2022. [Online]. Available: <https://journals.rudn.ru/psychology-pedagogics/article/view/31393>
- [9] A. Khormali, J. Park, H. Alasmay, A. Anwar, M. Saad, and D. Mohaisen, “Domain name system security and privacy: A contemporary survey,” *ScienceDirect*, 2023, accessed: 13/10/2023. [Online]. Available: <https://www.sciencedirect.com/science/article/abs/pii/S1389128620313001>

- [10] "Home - dns abuse institute," *DNS Abuse Institute*, 2023, accessed: 13/10/2023. [Online]. Available: <https://dnsabuseinstitute.org/>
- [11] C. Deccio and J. Davis, "Dns privacy in practice and preparation," *ACM Digital Library*, 2023, accessed: 13/10/2023. [Online]. Available: <https://dl.acm.org/doi/10.1145/3359989.3365435>
- [12] "September 2022 report - dns abuse institute," *DNS Abuse Institute*, 2022, accessed: 13/10/2023. [Online]. Available: <https://dnsabuseinstitute.org/wp-content/uploads/2022/09/DNSAI-Intelligence-Report-September-2022-FINAL.pdf>
- [13] S. Tajalizadehkhoob and R. Weinstein, "Icann reports dns abuse is trending downward globally," *ICANN*, 2022, accessed: 13/10/2023. [Online]. Available: <https://www.icann.org/resources/press-material/release-2022-05-17-en>
- [14] K. Hynek, T. Cejka, A. Wasicek, J. Luxemburk, and D. Vekshin, "Summary of dns over https abuse," *IEEE Xplore*, 2023, accessed: 13/10/2023. [Online]. Available: <https://ieeexplore.ieee.org/document/9775718>
- [15] M. Lyu, H. H. Gharakheili, and V. Sivaraman, "A survey on dns encryption: Current development, malware misuse, and inference techniques," *arXiv*, 2023, accessed: 13/10/2023. [Online]. Available: <https://arxiv.org/pdf/2201.00900v1.pdf>
- [16] "Webinar: Understanding and combating dns abuse - encouraging best practice," *ICANN*, 2023, accessed: 13/10/2023. [Online]. Available: <https://features.icann.org/event/icann-organization/webinar-understanding-and-combating-dns-abuse-%E2%80%93-encouraging-best-practice>
- [17] WebinarCare, "Dns security statistics 2023 - everything you need to know," <https://webinarcare.com/best-dns-security-software/dns-security-statistics/>, 2023, accessed: 25/10/2023.
- [18] M. Jakobsson and S. Myers, *Phishing and countermeasures: understanding the increasing problem of electronic identity theft*. John Wiley & Sons, 2006.
- [19] International Trademark Association (INTA), "Inta board resolution on domain name system abuse may 2023," <https://www.inta.org/wp-content/uploads/public-files/advocacy/board-resolutions/INTA-Board-Resolution-on-Domain-Name-System-Abuse-May-2023.pdf>, 2023, accessed: 25/10/2023.
- [20] B. Edelman, "Typosquatting: Unintended adventures in browsing," *McAfee Security Journal*, pp. 34–7, 2008.

- [21] D. H. B. C. F. CITP, A. L. CISSP, and C. B. CISSP, "Is your pc a zombie? here's how to avoid the attentions of blacklisters and vampire slayers."
- [22] H.-T. Lin, Y.-Y. Lin, and J.-W. Chiang, "Genetic-based real-time fast-flux service networks detection," *Computer Networks*, vol. 57, no. 2, pp. 501–513, 2013.
- [23] M. Antonakakis, R. Perdisci, Y. Nadji, N. Vasiloglou, S. Abu-Nimeh, W. Lee, and D. Dagon, "From {Throw-Away} traffic to bots: Detecting the rise of {DGA-Based} malware," in *21st USENIX Security Symposium (USENIX Security 12)*, 2012, pp. 491–506.
- [24] GoDaddy, "Demystifying dns abuse | the godaddy blog," <https://www.godaddy.com/resources/skills/demystifying-dns-abuse-understanding-the-digital-threat-landscape>, 2023, accessed: 25/10/2023.
- [25] R. Böhme, *The economics of information security and privacy*. Springer, 2013.
- [26] ICANN, "The last four years in retrospect: A brief review of dns abuse trends," <https://www.icann.org/en/system/files/files/last-four-years-retrospect-brief-review-dns-abuse-trends-22mar22-en.pdf>, 2022, accessed: 25/10/2023.
- [27] K. Fowler, *Data breach preparation and response: breaches are certain, impact is not*. Syngress, 2016.
- [28] dotmagazine, "Dns abuse: Everyone's problem - building trustworthiness," <https://www.dotmagazine.online/issues/the-heart-of-it/building-trustworthiness/dns-abuse>, 2022, accessed: 25/10/2023.
- [29] J. Saxe and H. Sanders, *Malware data science: attack detection and attribution*. No Starch Press, 2018.
- [30] T. Wrightson, *Advanced Persistent Threat Hacking: The Art and Science of Hacking Any Organization*, illustrated ed. McGraw-Hill Education, 2014.
- [31] CircleID, "A look at dns trends and what the future may hold," <https://circleid.com/posts/20201028-a-look-at-dns-trends-and-what-the-future-may-hold/>, 2020, accessed: 25/10/2023.
- [32] R. Mahmoud, T. Yousuf, F. Aloul, and I. Zualkernan, "Internet of things (iot) security: Current status, challenges and prospective measures," in *2015 10th international conference for internet technology and secured transactions (ICITST)*. IEEE, 2015, pp. 336–341.
- [33] M. Dooley and T. Rooney, *DNS Security Management*. John Wiley & Sons, 2017.

- [34] N. Schick, *Deep fakes and the infocalypse: What you urgently need to know*. Hachette UK, 2020.
- [35] T. Mather, S. Kumaraswamy, and S. Latif, *Cloud security and privacy: an enterprise perspective on risks and compliance*. " O'Reilly Media, Inc.", 2009.
- [36] M. H. Au and R. Choo, *Mobile security and privacy: Advances, challenges and future research directions*. Syngress, 2016.
- [37] I. Bashir and N. Prusty, *Advanced Blockchain Development: Build highly secure, decentralized applications and conduct secure transactions*. Packt Publishing Ltd, 2019.
- [38] M. Chapple and D. Seidl, *Cyberwarfare: Information operations in a connected world*. Jones & Bartlett Learning, 2021.
- [39] T. Brunner, "Cybersecurity in beyond 5g: use cases, current approaches, trends, and challenges," *Communication Systems XIV*, p. 28, 2021.
- [40] S. Boyson, "Cyber supply chain risk management: Revolutionizing the strategic control of critical it systems," *Technovation*, vol. 34, no. 7, pp. 342–353, 2014.
- [41] ICANN, "Dnssec – what is it and why is it important?" <https://www.icann.org/resources/pages/dnssec-what-is-it-why-important-2019-03-05-en>, accessed: 25/10/2023.
- [42] M. W. Lucas, *TLS Mastery: Beastie Edition*. Tilted Windmill Press, 2021.
- [43] S. G. Moghaddam, A. Nasiri, and M. Sharifi, "Ecco mnemonic authentication–two-factor authentication method with ease-of-use," *International Journal of Computer Network and Information Security*, vol. 6, no. 7, p. 11, 2014.
- [44] F. Skopik, *Collaborative cyber threat intelligence: detecting and responding to advanced cyber attacks at the national level*. CRC Press, 2017.
- [45] A. S. Coronado, "It auditing: Using controls to protect information assets , by chris davis, mike schiller, and kevin wheeler," 2014.
- [46] E. Tsukerman, *Machine Learning for Cybersecurity Cookbook: Over 80 recipes on how to implement machine learning algorithms for building security systems using Python*. Packt Publishing Ltd, 2019.
- [47] J. Meese, "Edited by ramon lobato," 2016, printer: Print on Demand.

A1 Appendix

The Domain Name System (DNS) plays a role, in the infrastructure of the internet by converting user domain names into IP addresses. However due to its use and importance it has become a target for actors seeking to exploit it. These abuses range from setting up phishing websites to taking advantage of DNS for activities like typosquatting. The responsibility for mitigating abuse primarily lies with DNS infrastructure providers, such as registrars and registries. These entities respond to reports of abuse by taking down confirmed domain names or proactively blocking the registration of harmful ones. While these actions are essential for maintaining the security and integrity of DNS they also raise questions about how transparent these measures

Transparency in the context of mitigating DNS abuse refers to the disclosure of actions taken by registries and registrars including the criteria and reasoning behind their decisions. Currently there is prevalence in publishing transparency reports related to this matter leading to a lack of clarity and understanding, about the processes involved in combating DNS abuse. This project aims to address this issue through a survey involving registries registrars and other stakeholders actively engaged in mitigating DNS abuse.

The main objective of the survey is to collect organize and describe the transparency reports they're presently accessible. This will help us gain an understanding of the status of transparency, in mitigating DNS abuse.

A1.1 Appendix numbering

Appendices are numbered sequentially, A1, A2, A3... The sections, figures and tables within appendices are numbered in the same way as in the main text. For example, the first figure in Appendix A1 would be Figure A1.1. Equations continue the numbering from the main text.