

Anonymity with Tor: A Survey on Tor Attacks

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Abstract—Anonymity networks are becoming increasingly popular in today's online world as more users attempt to safeguard their online privacy. Tor is currently the most popular anonymity network in use and provides anonymity to both users and services (hidden services). However, the anonymity provided by Tor is also being misused in various ways. Hosting illegal sites for selling drugs, hosting command and control servers for botnets, and distributing censored content are but a few such examples. As a result, various parties, including governments and law enforcement agencies, are interested in attacks that assist in de-anonymising the Tor network, disrupting its operations, and bypassing its censorship circumvention mechanisms. In this paper, we survey known Tor attacks and identify currently available techniques that lead to improved de-anonymisation of users and hidden services.

I. INTRODUCTION

Over the past few decades, many online services have impacted the daily lives of Internet users. With that, a natural concern has emerged as to how to browse the Internet while maintaining privacy. Privacy-preserving mechanisms over the Internet are all the more important for whistle-blowers and citizens of totalitarian governments, who are usually in dire need to protect their online identity. Other use cases of anonymous networks include sensitive communications of military and business organisations over the public Internet [1]. This has led to research and development of anonymous communication systems [2]. The early anonymity systems such as Mix-Net [3], Babel [4] and Mixminion [5] were not widely adopted as they suffered from high latency issues, and are now superseded by low-latency systems, as we now discuss.

The Onion Router project, which is more commonly known as Tor [6], is the most popular low latency anonymity network to date. However, as the anonymity provided by Tor was available to everyone, it quickly became an accessory to cybercrime and other criminal activities [7], forcing Law Enforcement Agencies (LEA) and governments to find ways to break its anonymity. On the other hand, pro-anonymity researchers attempted to strengthen users' expected anonymity. In this paper, we survey Tor attacks and provide a taxonomy for categorising such attacks. Some taxonomies proposed previously in the literature [8], [9], [10], lack a common basis¹ for

their classification. To overcome this issue, we use a common determiner for every layer of our taxonomy and clearly define the scope of each category. Several other survey works [12], [13], [11], [14], lack details of website fingerprinting attacks or attacks on hidden services which are very important types of Tor attacks.

Being an anonymity network, the most common objective of a Tor attack is to de-anonymise its users and services. Since Tor's initial deployment, researchers have worked to further strengthen its anonymity objectives. Here, we try to present an extensive list of de-anonymisation attacks and discuss their feasibility in the live Tor network. Our work also provides useful insights into how these attacks have evolved over the years, and new trends and directions they have taken more recently. We present the following components in our survey. 1. A generalised categorisation of all Tor attacks. We divide Tor attacks into four high-level categories based on the objective of the attack. 2. A corpus of other survey work that is related to Tor attacks. 3. A comprehensive list of *de-anonymisation attacks* which are a subset of Tor attacks. We discuss these attacks under a well-defined taxonomy based on the component/s of the Tor network required by the adversary to execute the attack. We summarise almost fifty de-anonymisation attacks on Tor, found in the literature. 4. Information on several major milestones in Tor development over the years that are relevant to de-anonymisation attacks. We try to provide insights into how Tor's research has impacted its development over the years and how some of the attacks in the literature actually affect the live network.

The rest of the paper is organised as follows. Section II provides the necessary background information required to understand the content of this paper while Section III compares the scope of our survey with other related work. Section IV introduces and explains our novel taxonomy. Details of individual de-anonymisation attacks are presented in Section V, mainly focusing on their method of execution. In Section VI, we discuss the applicability of de-anonymisation attacks in the literature on the live Tor network and Tor's security against such attacks. We conclude in Section VII with a discussion on potential directions for future work.

II. BACKGROUND

In this section, we provide some background information to explain our taxonomy and the attacks discussed in this paper. The Tor network [6], which is one of the most widely used

¹For example, if we use traffic analysis attacks and hidden service attacks as two categories in a taxonomy, there can be an overlap as certain hidden service attacks may use traffic analysis for their execution. On the other hand, a taxonomy having categories such as attacks on Tor's users, attacks on the Tor network, or attacks on hidden services [11] has a common basis which is the target of the attack.

anonymity networks today (along with other popular networks such as I2P [15] and Freenet [16]), has been using the concept of onion routing [17]. This is an overlay network based on Transmission Control Protocol (TCP) that builds circuits from a user to their destination server via a circuit, which generally consists of three voluntary relays.² Each hop uses a separate TCP connection. Figure 1 (standard Tor circuit) and Figure 2 (hidden services) show the components of a Tor network. The descriptions of some of the key components and their features are as follows.

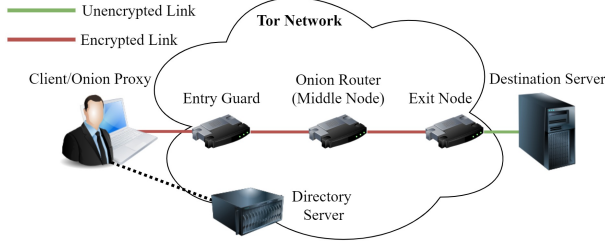


Fig. 1. Components of the Tor Network (standard Tor circuit)

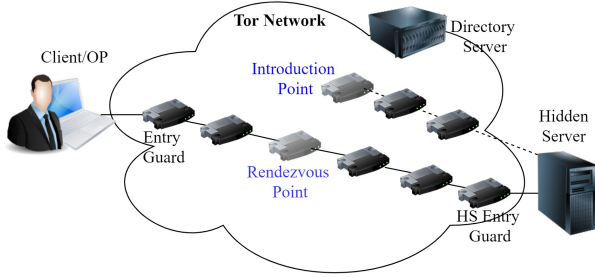


Fig. 2. Components of a Hidden Service

- **Onion Proxy (OP):** This is a small piece of local software that needs to be installed on the user's device. It enables communication with the directory servers (DSs), establishes connections in the Tor network, and handles connections from the user's applications. In this paper, we also refer to this as the Tor client.
- **Directory Servers (DS):** These are a small set of trusted and known servers in the network that actively keep details about the complete network status. DSs produce a consensus document with the status of the network relays, bandwidth availability, exit policies, etc. The OPs can download this document from a DS and select three suitable relays to establish the communication circuit to a destination.
- **Entry Node/Guard:** This is the relay in the Tor network that the client directly connects to and hence, it knows the identity of the client. Therefore, several early Tor attacks either compromised existing entry nodes or installed new nodes to participate as entry nodes in order to de-anonymise the user. We discuss these de-anonymisation

attacks in Section V. Another important feature of entry nodes came with the introduction of guard nodes. As Tor creates new circuits quite frequently, there was always a chance that at some point it would select an adversary-controlled relay as the entry node. To reduce the probability of this situation, *Guard nodes* were introduced. Now, OPs select a small set of trusted nodes as guard nodes and use only one of these nodes as the entry node for all circuits until another set of nodes are selected as guards. A node is assigned a *Guard Flag* by the DSs after considering its bandwidth, uptime and time in the Tor network. Any node is eligible to become a guard node on the eighth day after joining the Tor network [18].

- **Exit Node:** This is the final hop of the Tor circuit. Therefore, it knows the IP address of the destination server accessed via the Tor network. Moreover, as the last layer of encryption provided by the Tor network ends here (unless the client's application is also using end-to-end encryption such as TLS), a malicious exit node can easily observe the Tor traffic flowing through it.
- **Hidden Services (HS):** This is a web server that can be hosted in a node inside the Tor network or outside of the Tor network. These have a top-level domain name called *.onion*. The OP in the server is configured to publish a *service descriptor* of the HS on the DS. This service descriptor contains the HS's public key, expiration time, and the selected introduction points. In addition, the HS owner can advertise the onion address over the public Internet. A potential client has to find out about this service from the web or other similar means. When the user searches this particular onion address in their browser, the OP retrieves the service descriptor from the DS and starts the connection establishment process. The anonymity provided by HS attracts those engaged in criminal and unethical conduct, including those who sell drugs [7] and child pornography [19], forcing LEAs to identify and shut down these services.
- **Introduction Points:** These are random nodes selected by the HS at the start of the connection establishment process. Once the HS has selected an introduction point, it provides the HS's public key to the introduction point. To avoid any impact from possible Denial of Service (DOS) attacks against a single introduction point, the HS usually selects several of them. The HS then advertises these selected introduction points in the Hidden Service Directories (HSDirs)³ and signs the advertisement with the HS's public key. The introduction points do not know the IP address of the HS as they are connected to the HS via a Tor circuit, which also consists of relays.
- **Rendezvous Points (RPs):** This is a random Tor node selected by the client OP before the client initialises a connection with any of the introduction points advertised by the DS. The client establishes a circuit to the RP and informs the HS to meet at the RP. The HS then creates

³HSDirs are a type of DSs with some specific properties that are used to publish the service descriptors of HSs. We use DS and HSDir interchangeably when referring to HS circuit creation throughout the paper.

²We use nodes, routers and relays interchangeably throughout this paper.

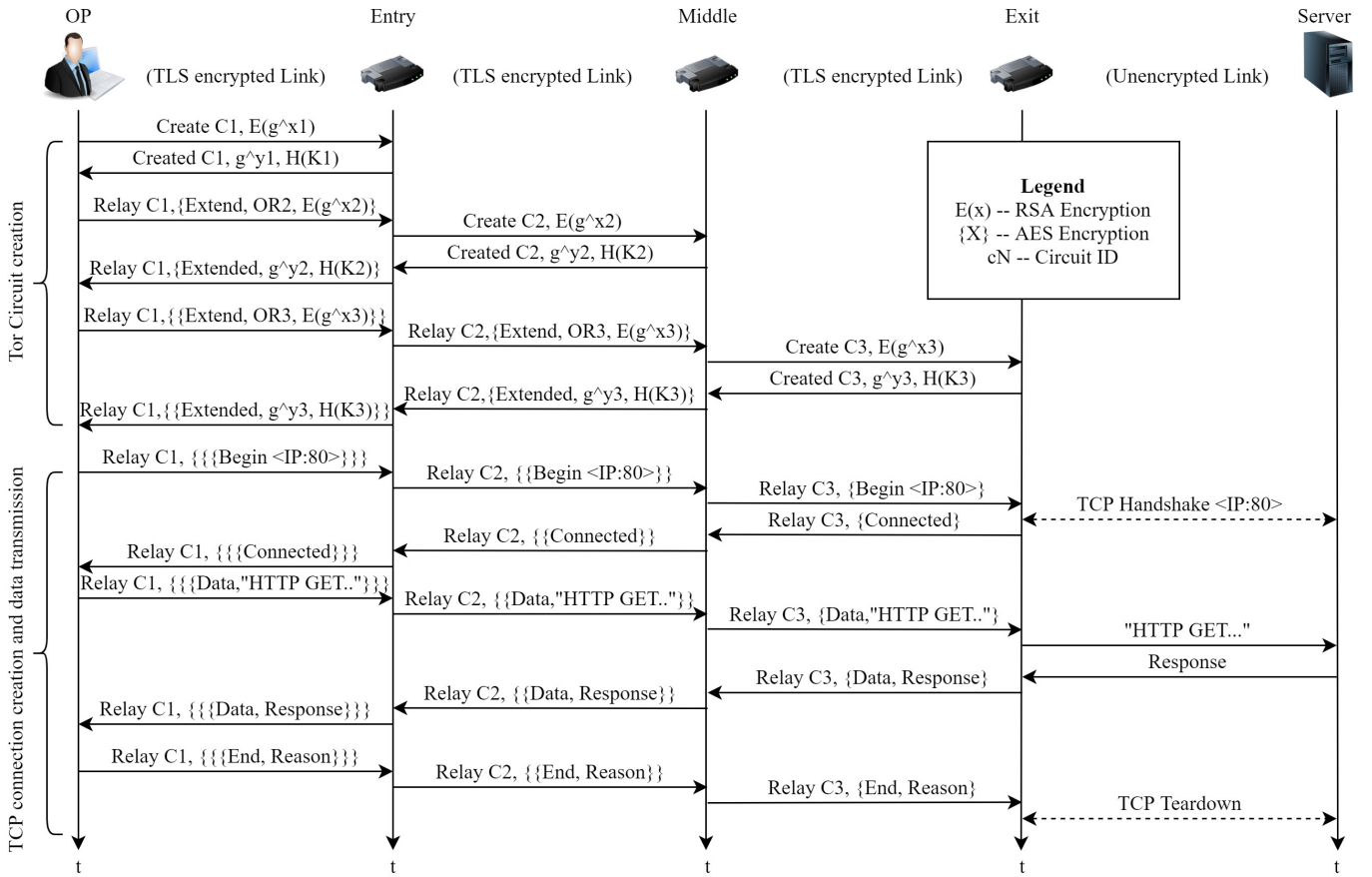


Fig. 3. Tor circuit creation and data transmission

a connection to the RP. Following this, the client and the HS can communicate using a six hop circuit via the RP, as shown in Figure 2. RPs do not know the identity of the user or the HS.

- **Bridges:** As DSs keep a list of relays in the Tor network to advertise to all clients, this information could easily be used to censor and block the Tor network. To mitigate this issue, bridges were introduced. Bridges are normal Tor relays that are not listed publicly in the main Tor directory. They replace guard nodes in the circuit, however, only a few bridges are provided to each client. Therefore, no authority is able to obtain a complete list of bridge nodes. It is not necessary to have bridges as middle or exit relays as they can be connected via relays outside the censored area. In addition, having bridges as middle and exit relays would require more bridges to be published for a single client, rendering them useless. There are a few ways in which a user can obtain these bridge addresses. They can visit the Tor project website, email the Tor project team or request bridges through the Tor browser.

Having explained different components of the Tor network, we will now discuss how a typical Tor circuit is created. Before communicating over the Tor network, the Tor client must establish a circuit through the Tor network. The user is required to have the Onion Proxy (OP) installed on their device, which contacts a DS and requests a list of active

relays in the network. The OP then selects three relays from the list and incrementally creates a circuit by exchanging encryption keys with each node, one hop at a time [6]. The key exchange is done via the Diffie-Hellman handshake [20], as shown in Figure 3. Once this connection consisting of three hops (generally) has been established, the user uses it to communicate with the intended destination server.

Tor uses fixed-length cells of 512 bytes for communication to make traffic analysis harder [6]. There are two types of cells; control cells and relay cells. Figure 5 shows the structure of these two cell types. Control cells are always interpreted at the receiving nodes, and issue commands such as *create*, *created*, *destroy* or *padding*. Relay cells carry end-to-end data and consist of an additional relay header. This relay header includes a stream ID (as multiple streams are multiplexed over a single circuit), an end-to-end checksum for integrity checking, a payload length and a relay command. The relay command can be *relay data*, *relay begin*, *relay end*, *relay teardown*, *relay connected*, *relay extend*, *relay extended*, *relay truncate*, *relay truncated*, or *relay sendme*. The relay header and the payload are encrypted together with the 128-bit counter mode Advanced Encryption Standard (AES-CTR), and uses symmetric keys negotiated via the Diffie Hellman Key Exchange (DHKE) [20].

Although the above mechanism provides anonymity to the user, it does not hide the identity of the website being accessed.

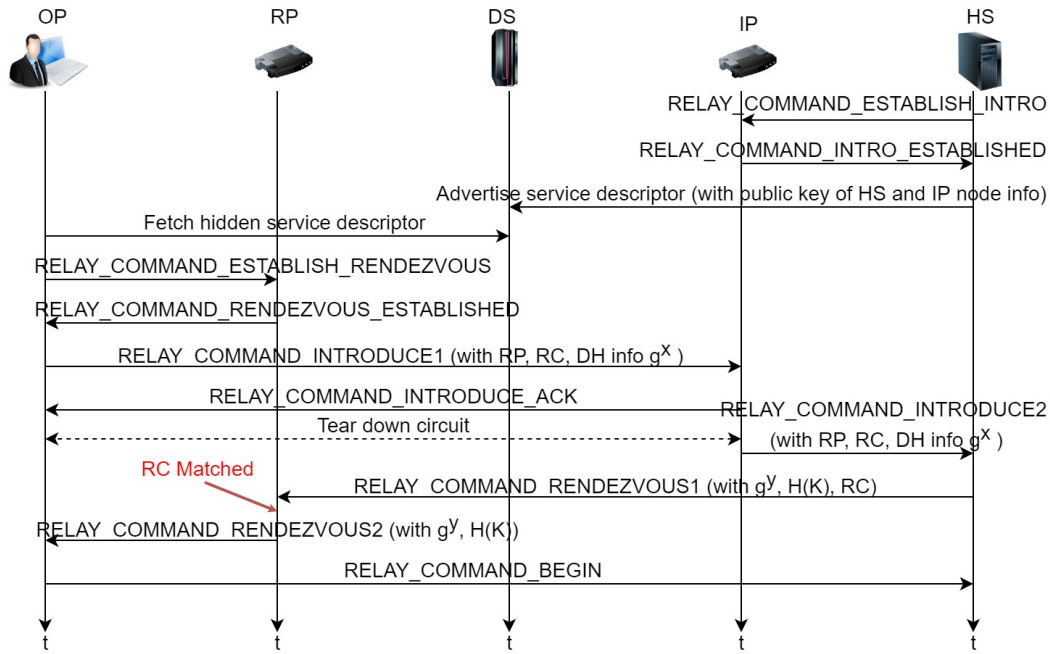


Fig. 4. Hidden server connection establishment

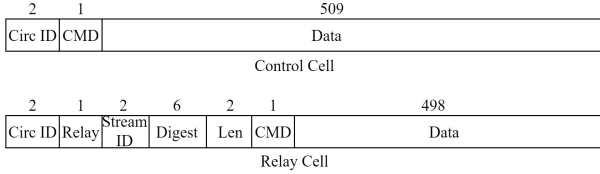


Fig. 5. Tor cells

An entity with access to traffic at the exit node of the Tor circuit or at the link between the exit node and the website can retrieve the website's IP address. To address this issue, the Tor network supports Hidden Services (HS) also known as Onion Services. This is a TCP service which hides its IP address from the user. The establishment of a connection between a user and a HS is shown in Figure 4. It should also be noted that there are multiple relays involved between the components shown in Figure 4 (see Figure 2) although we have only displayed the sending and receiving ends of the relevant communications. Firstly, the HS selects introduction points from the available nodes in the Tor network and builds connections to those nodes. Following this, it connects to the DS and advertises a *service descriptor* with the HS's public key and the details of the introduction points. The HS owner can then advertise their service's onion address using platforms they expect to reach their targeted users (e.g. websites, blogs, other hidden services). If someone wants to access a HS, they need to find out its onion address on these platforms. When the user searches an address in their browser, the OP fetches the service descriptor of that particular HS from the DS. This way the OP finds out about the HS's introduction points and its public key. The OP then selects an RP and sends a message with the RP's address and a one time secret called the Rendezvous Cookie (RC) to one of the introduction

points. The introduction point forwards this message, which is encrypted with the HS's public key, to the HS. Once the HS receives the message, and if it wants to establish a connection with this client, it creates an anonymous connection to the RP. Following this, the user can communicate with the HS in the same way they communicate with a traditional web service [21].

III. RELATED WORK

In this section, we present other survey papers and related work that cover Tor attacks. In 2009, Edman *et al.* [2] published a survey on existing anonymous communication systems. Their survey mainly describes the research on designing, developing, and deploying such communication systems. Furthermore, the authors present a few adversary classifications based on properties like capability, visibility, mobility, and participation. Their survey has a section on traffic analysis attacks categorised under website fingerprinting [22], timing analysis [23], [24], predecessor attacks [25], and disclosure attacks [26]. This is a comprehensive survey in terms of research on anonymous communication designs and approaches but not in terms of attacks.

In 2010, Salo [8] presented an initial attempt to survey and categorise Tor attacks. Salo classified around 14 attacks into five categories: 1. probabilistic models that provide information about the network, based on mathematical modelling, 2. entry and exit onion router selection attacks that attempt to compromise the victim's entry and exit nodes, 3. Autonomous System (AS) and global level attacks by a passive global adversary, 4. traffic and time analysis attacks, and 5. protocol vulnerabilities that address weaknesses in the Tor protocol. However, Salo's work does not take into account attacks on HS [27] [28] as well as website fingerprinting attacks against Tor which began to emerge at that time [29].

A survey on de-anonymisation attacks against HS was conducted by Nepal *et al.* [12] in 2015, however, it is limited to the three attack schemes presented by Ling *et al.* [21], Jansen *et al.* [30], and Biryukov *et al.* [31]. Nepal *et al.* explain the basic functionality of these attacks and provide a comparison between the attack schemes in terms of the simulation environment, the time required for de-anonymisation, the true positive rate, and the number of compromised nodes required to successfully launch the attack.

In 2015, Erdin *et al.* published a survey paper on de-anonymisation attacks [13]. However, in their paper, the authors have focused only on de-anonymisation of users. They discuss such type of attacks on both Tor and I2P [15] networks. In [13], the authors explain de-anonymisation attacks under two categories: 1. Application-based attacks, and 2. Network-based attacks. Most of the time, Application-based attacks are a result of insecure applications or user's carelessness. Erdin *et al.* discuss the attack vectors of Application-based attacks such as plugins, DNS lookups, java applets, active documents, and BitTorrent. In contrast, Network-based attacks exploit limitations or trade-offs of the anonymity network. The authors in [13] discuss examples of this type of attack under five approaches. 1. Intersection attacks, 2. Flow multiplication attacks, 3. Timing attacks, 4. Fingerprinting attacks, and 5. Congestion attacks. They explain how these attack types affect Tor and I2P networks and present potential remedies against these attacks.

Alsabah *et al.* [9] present a comprehensive survey focused on the performance and security aspects of Tor in 2016. They evaluated Tor research in several areas including security, which is relevant in our context. 1. Traffic management - Tor's congestion control, quality of service, etc. are discussed in this category under application layer and transport layer approaches. 2. Router selection - The chances of a Tor node being selected by the OP depend primarily on the node's bandwidth. However, there are other factors affecting this, including the node being a guard node. The research on Tor's router selection problem is explored in this category. 3. Scalability - Tor's scalability approaches are investigated here under a peer to peer approach and a scalable centralised approach that uses private information retrieval (PIR-TOR). 4. Circuit construction - Improving the computational overhead of Tor's circuit construction is discussed in this category. 5. Security - This section investigates Tor attacks. These are broadly categorised into active and passive attacks. Passive attacks are further categorised into AS level adversaries [32] and website fingerprinting (this will be discussed in section V), while active attacks are sub-categorised into end-to-end confirmation attacks, path selection attacks, and side-channel information attacks. Alsabah *et al.* discuss 22 attacks on the Tor network within the above categorisation.

A survey on a very broad area of overall Tor research (performance, architectural improvements, attacks, and experimentation) was published in 2018 [10]. In their paper, Saleh *et al.* [10] divide all Tor research into three main categories: de-anonymisation, path selection and performance analysis, and architectural improvements. The de-anonymisation category is discussed under six subcategories: 1. HS identification, 2. Tor

traffic identification, 3. attacking the Tor network with a focus on blocking access to it, 4. Tor traffic analysis attacks, 5. Tor improvements, and 6. providing anonymity without Tor. We find this categorisation somewhat vague and unable to provide an adequate overview of the Tor attacks. The main reasons for this claim are the lack of a clear and common basis for the categorisation and the vagueness of the naming convention. Although Saleh *et al.* describe around 30 attacks using their categorisation, they have missed several important attacks including recent attacks such as Raptor [33] and many website fingerprinting attacks [34] [29] [35]. However, their paper compares Tor with other anonymity services and surveys the literature on all Tor research, focusing on experimentation, simulations, and analysis. Therefore, Saleh *et al.*'s paper [10] enables readers to gain a broader knowledge of Tor research that has been conducted over the years.

Evers *et al.* [37]⁴ report on Tor attacks known before 2016. Their report contains a corpus of references of around 84 attacks under their taxonomy. These attacks have been sorted into seven categories: correlation attacks, congestion attacks, timing attacks, fingerprinting attacks, DOS attacks, supportive attacks, and revealing HS attacks. This categorisation is inspired by the classification of de-anonymising techniques presented by Yang *et al.* [36] in 2015. Yang *et al.* divide de-anonymising attacks into four categories based on the following two dimensions: 1. *passive* and *active* attacks based on their ability to manipulate traffic, and 2. *single-end* and *end-to-end* attacks based on the capability of the attacker to monitor and/or control the traffic and/or devices at one end of the connection (either the sending or receiving end), or both. Evers *et al.* try to associate this classification with their taxonomy e.g. by classifying correlation attacks as end-to-end passive attacks, congestion and timing attacks as end-to-end active attacks, and fingerprinting attacks as single-end passive attacks. Their report also contains some details on countermeasures against these attacks.

Cambiaso *et al.* [11] provide a recent review of Tor attacks under a taxonomy based on the target of the attack. In this situation, the client, the server, and the network were considered to be the targets. Although Cambiaso *et al.*'s work was published in 2019, they only referenced the survey by Nepal *et al.* [12] as existing survey literature. In Cambiaso *et al.*'s paper, although attacks on the Tor clients include de-anonymising the Tor user, the authors only reference less than ten such attacks, while, in our paper, we present more than thirty such attacks. In [11], attacks on the server focus on de-anonymisation or weakening the HS, while attacks to the network consider DOS attacks and bridge discovery attacks. Moreover, Cambiaso *et al.* mention some attacks under a general category in which multiple targets are considered. However, this work does not discuss much details on website fingerprinting attacks - a widely researched attack in recent times.

In a publication released this year, 2020, Basyoni *et al.* [14] present details on several Tor attacks from the perspective of

⁴The work is only found on Github as it appears to be an internal university report. We could not find any published work based on this report. Also, note that this report has not been cited in any other publication previously.

TABLE I
SUMMARY OF RELATED WORK

Publication	Year	Main Focus	No of * Tor Attacks	Include WF attacks	Include HS attacks
Edman <i>et al.</i> [2]	2009	Survey existing anonymous communication systems	19	✗	✗
Salo [8]	2010	Survey Tor attacks	14	✗	✗
Nepal <i>et al.</i> [12]	2015	Survey de-anonymisation attacks on hidden services	3	✗	✓
Erdin <i>et al.</i> [13]	2015	Survey de-anonymisation attacks on users	19	✓	✗
Yang <i>et al.</i> [36]	2015	Classification of de-anonymisation techniques	6	✗	✗
AlSabah <i>et al.</i> [9]	2016	Survey the research on performance and security of Tor	22	✓	✓
Evers <i>et al.</i> [37]	2016	Survey Tor attacks	84	✓	✓
Saleh <i>et al.</i> [10]	2018	Survey all aspects of Tor research	30	✓	✓
Aminuddin <i>et al.</i> [38]	2018	Survey existing approaches for classifying Tor traffic	N/A	✗	✗
Kohls <i>et al.</i> [39]	2018	An evaluation framework for confirmation attacks	22	✗	✗
Cambiaso <i>et al.</i> [11]	2019	Survey Tor attacks	16	✗	✓
Basyoni <i>et al.</i> [14]	2020	Survey traffic analysis attacks on Tor	10	✗	✓
Our paper	2020	Survey Tor attacks while prioritising de-anonymisation attacks	50	✓	✓

* This has been counted by using a table, a chart, a mind map, or a similar component in the paper itself or by counting the attack references included in the section where the attacks are described. Therefore, the actual number of intended attacks by the authors might differ than the value mentioned in this table.

the attack’s adopted threat model. The authors categorise their attack corpus into three threat models; a global adversary, capturing entry flows and compromising Tor nodes. They compare Tor’s original threat model with the above threat models. Additionally, the practicality of these threat models is discussed in their paper. Basyoni *et al.*’s paper is the only paper about Tor attacks that has referenced a substantial amount of work since 2015. However, they do not reference any of the other survey work related to Tor attacks and only describe 10 attacks in detail. Also, very little information is provided in their paper on website fingerprinting attacks and attacks on hidden services, when compared with our paper.

There have been several other works associated with Tor attacks that focus on a different aspect of Tor research. For example, Aminuddin *et al.* [38] investigate the existing literature on Tor traffic classification. Their work focuses on how machine learning techniques have been applied to such classifications and compares those techniques. The authors present a traffic classification taxonomy based on input, method, and output. The input data is categorised into circuit, flow, and packet features, while the method is categorised into supervised, semi-supervised, and unsupervised categories. The output is divided into five categories, namely, traffic cluster, application type, application protocol, application software, and fine-grained. The last category is the one that contains the most detailed information on the classified traffic. Almost 14 previous works have been referenced in this survey. The authors in [38] claim that no classification algorithm can be presented as superior as the algorithm’s efficiency and capabilities depend on the classification objective, implementation strategy, and the training dataset. Aminuddin *et al.* suggest that the five factors; accuracy, training time, computational resources, number of features, and number of parameters must be considered when deciding the right algorithm for any situation.

Kohls *et al.* [39] present an analysis framework called *DigesTor* for the evaluation of traffic analysis attacks. The main attack scenario considered by *DigesTor* is a passive attack, executed by correlating traffic features at the entry and

exit of the Tor circuit. The authors address the difficulties associated with comparing different types of traffic analysis attacks as a result of the diversity of the methods used. *DigesTor* has two main features: 1. a traffic analysis framework that considers five comparison metrics (namely attack type, adversary model, evaluation setup, consideration of background noise, and consideration of different application types) and estimates the similarity between the network observations, and, 2. a virtual private Tor network that is used to generate traffic for representative scenarios. The authors claim that they have provided the first performance comparison of existing attacks based on their de-anonymisation capabilities.

Table I summarises the main features of the prior work discussed and highlights our contributions. Although some previous work has included details of Tor attacks, the main focus of these papers is not to survey the attack literature, but to study a different or broader aspect of Tor, e.g. anonymity networks [2], performance improvements for Tor [9], or broader Tor research [10]. On the other hand, several works have referenced only a small number Tor attacks, even when their main focus is to present a survey on Tor attacks [8], [12], [11], [14]. Moreover, we have observed that most of the surveys do not provide much information of website fingerprinting attacks. Erdin *et al.*’s [13] work does not address attacks on HS, while Nepal *et al.*’s [12] work only focuses on de-anonymisation of HS. None of the papers except for Saleh *et al.* [10] present information on other survey work and only Basyoni *et al.* [14] have referenced a significant number of attacks published since 2015. In this paper, we try to overcome all of these shortcomings and provide a comprehensive survey focused on de-anonymisation attacks.

IV. TAXONOMY OF TOR ATTACKS

In this section, we present a new taxonomy of Tor attacks and explain its components. First, we divide all Tor attacks into four main categories based on their primary objective; De-anonymisation attacks, Network Disruption attacks, Censorship attacks, and Supportive attacks.

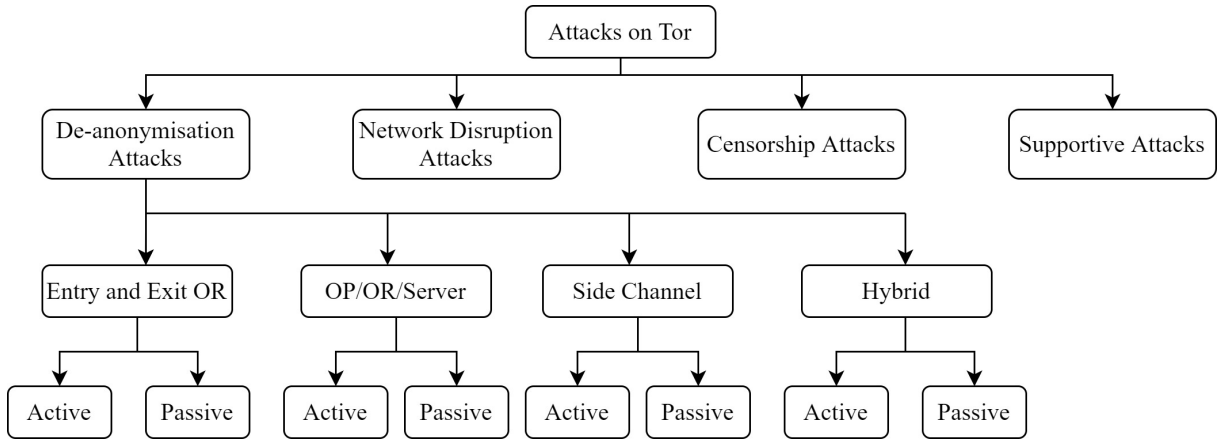


Fig. 6. Taxonomy for Tor Attacks

De-anonymisation attacks: Tor being an anonymity network, this is the most common type of attack that has been researched in the past. There are two main areas of Tor de-anonymisation. One links a Tor user with their online activity (associates a user’s IP address with a destination’s IP address). An entity such as a LEA might want to investigate an individual and find out what websites they have visited, or else, to monitor a specific web service to identify its users. Therefore, such an entity needs to link users with websites. The second area is when an attacker tries to find the actual IP address of a HS that is involved in providing illegitimate services. We provide more information on de-anonymisation attacks in Section V.

Network Disruption attacks : The main intention of these attacks is to disrupt the network and make it unavailable for users. The Sniper attack by Jansen *et al.* [30], the CellFlood attack by Barbera *et al.* [40], the packet spinning attack by Pappas *et al.* [41], and the most recent bandwidth based DOS attacks by Jansen *et al.* [42] are some examples for these kinds of attacks. In this paper, we do not cover these attacks in detail.

Censorship attacks: Tor is popularly used as a censorship circumventing tool. It allows users in oppressive and totalitarian governments to bypass their censorship measures and access restricted content. Tor introduces bridges that are unadvertised relays to facilitate this. Therefore, such governments are motivated to find the means to prevent access to the Tor network. Attempts by various parties to block access to the Tor network are therefore considered to be Censorship attacks. China’s attempts to block Tor [43] [44] and blocking systems such as Nymble [45] are some examples of such attempts. Deep packet inspection to block Tor traffic [46] and Tor bridge discovery attacks [47] can also be categorised under censorship attacks.

Supportive attacks: There are certain attacks and research that do not present a major threat to the network itself but can assist and improve the execution of attacks that come under other categories. Some de-anonymising attacks require the attacker to control the entry node of the circuit. Therefore, an attack that manipulates the client to select compromised guard nodes, as discussed by Li *et al.* [48] can be advantageous in circumstances. Sybil attacks [49] that control a disproportionate

amount of the network can be used to execute de-anonymisation attacks as well as network disruption attacks. Distinguishing Tor traffic from network traffic [50] can provide new opportunities for censoring systems to be implemented. We do not cover Censorship attacks and Supportive attacks in detail in this paper.

When surveying past research efforts different terminologies are used to classify Tor attacks. We will now explain some of these terminologies and how they fit into our taxonomy.

Traffic confirmation attacks: These are mostly de-anonymisation attacks, in which an adversary can monitor both ends of a network (either by compromising the entry and exit nodes or by monitoring the links to and from the Tor network), and can try to link the user and the destination. In these attacks, the adversary tries to confirm the actions of a targeted user rather than trying to uncover a random user’s online activity. The confirmation attack conducted by Rochet *et al.* [51] is one of many such examples.

Correlation attacks: These attacks also come under de-anonymisation attacks. Almost all confirmation attacks require a correlation mechanism to link traffic observed at different parts of the Tor network. Different correlation techniques, such as the Spearman’s rank correlation coefficient used in Raptor attacks [33], Mutual Information [52], and Cross-correlation [23], can be used to identify a user’s online activity from monitored traffic features.

Timing attacks: These can be categorised as a subcategory of correlation attacks where timing characteristics in network traffic are correlated to find the link between Tor users and their online activity. The most intuitive feature used in these attacks is the inter-packet arrival time [23]. Packet rate, used by Gilad *et al.* [53], and latency are some other features used in the timing attacks.

Watermarking attacks: These attacks are also a form of correlation attack where the attacker can actively manipulate the network traffic by injecting, modifying or deleting traffic. A recognisable pattern is therefore introduced into the traffic stream at one point, expecting it be observed at another [54].

Traffic analysis attacks: This is a very broad categorisation of attacks. Analysing traffic features is required for most attacks in the literature, and all attack types discussed above

can be considered as subcategories of this. Any attack that has been previously categorised as a traffic analysis attack, is inserted into our taxonomy based on the attacker's capabilities and the components required to launch that attack.

V. DE-ANONYMISATION ATTACKS

As previously mentioned, in this paper we mainly consider the attacks that try to de-anonymise the user, the HS, or both. De-anonymising the user is usually conducted with one of two objectives: finding out who is visiting a certain website, or finding out what websites are being visited by a targeted user. Research on de-anonymisation attacks contributes to a larger portion of work carried out under Tor research. Therefore, we aim to provide an explicit categorisation and an extensive analysis of such type of attacks.

In our taxonomy of de-anonymisation attacks, we consider four subcategories based on the attacker's capabilities to compromise network component/s and control them. The network components considered are the OP (Tor client), ORs (entry, middle, exit, introduction point, RP), HS and an external web server. Any other resources that exist outside these components are considered to be side channels. We further explain the classification below.

Entry and Exit routers: These attacks require the attacker to control both the entry and exit nodes of the circuit to carry out the attack.

OP/OR/Server: These attacks require the attacker to control either one Tor node, a Tor client, or a server. This category might seem a bit broader than the others but the fact that Tor's threat model itself makes it very hard to carry out a *de-anonymisation* attack with a single component has been taken into consideration here.

Side channel: This considers attacks carried out using other means, for example by monitoring and manipulating the links between circuit components, e.g. the link between the user and the entry node.

Hybrid: This category considers a combination of components used in the above categories.

We have further divided all the above categories into *active* and *passive* attacks. In passive attacks, the adversary does not modify, insert, or delete traffic on the network, but can only observe and collect network traffic passively to be used in the attacks. In active attacks, the adversary manipulates network traffic in various ways to identify traffic patterns. Figure 7 shows a summary of all the attacks we have categorised in this paper. Now we present details on these attacks and explain how they fit into our taxonomy.

A. Entry and Exit Onion Routers

This category of attacks requires an adversary to have access to both entry and exit ORs of a Tor circuit. This can be achieved by either compromising existing Tor nodes or introducing new attacker controlled nodes into the Tor network. When introducing new nodes, certain steps can be taken to increase the chances of a Tor node being selected as an entry or an exit node. Tor nodes can specify that they must only be used as exit nodes and configure exit policies to allow

selected protocols. This improves the possibility of a particular Tor node to be selected as an exit node. Furthermore, a node can falsely advertise high bandwidths and high uptime to be selected as an entry guard. Once the attacker gets access to the entry and exit router of a circuit, the traffic features required for the attack are usually sent to a centralised authority for processing and correlating. In the early stages of the Tor network, which featured a small number of active nodes, there was a high probability of success for this approach. Figure 8 shows the general attack scenario for this category.

1) **Passive Attacks:** Bauer *et al.* [55] in 2007 described one of the earliest attacks to de-anonymise Tor circuits. Their attack is carried out in two phases. In the 1st phase, the attacker assumes that they control a large number of Tor relays. This can be achieved by either introducing new malicious nodes into the network or by hijacking existing nodes in the network. In the earlier versions of the Tor network, the router could advertise an incorrect bandwidth and uptimes to the DS. These values were not verified by either the DS or the OP when selecting that particular router for a circuit. Therefore, resources required for this attack could be reduced by advertising false bandwidths for low bandwidth connections, thus increasing the chances of the adversary-controlled routers being selected as the entry or exit nodes of a circuit. Moreover, the malicious routers could have fewer restrictions on their exit policies to further increase their chances of being selected as exit nodes. If a circuit selects only one compromised relay, that relay can stop the traffic flow and force the circuit to rebuild with a different set of relays. This path disruption can be repeated until a target circuit selects two compromised routers as its entry and exit nodes. The next phase of the attack requires traffic correlation. In this phase, each malicious router in the network has to log information for each cell received, including its position in the circuit, local timestamp, previous connection's IP address and port, and next-hop's IP address and port. A centralised authority that receives the above details from all malicious routers in the network can execute a correlating algorithm to associate the sender with the receiver.

In 2009, Bauer *et al.* [56] presented their investigations on the impact of application-level protocols for the path compromising phase in [55], which we discussed previously. In this follow-up paper [56], it is assumed that the adversary can configure their routers with an exit policy to attract a specific application type. As an external web service can only view the IP address of the exit router, it is usually the exit router operator who is contacted when illegal activities are carried out using a Tor connection. To mitigate this abusive use of exit nodes, node operators can define *exit policies*, allowing only selected services to be used, and imposing several other restrictions. Due to the ability to restrict certain ports using these policies, the exit bandwidth is not uniformly distributed among different application types. This makes some application types more vulnerable to path compromise. The results of [56] show that an adversary with control of 6 routers out of 1444 total active routers can compromise 7.0% of all circuits that transport HTTP traffic, while the number is between 18.5-21.8% for circuits which are transporting SMTP

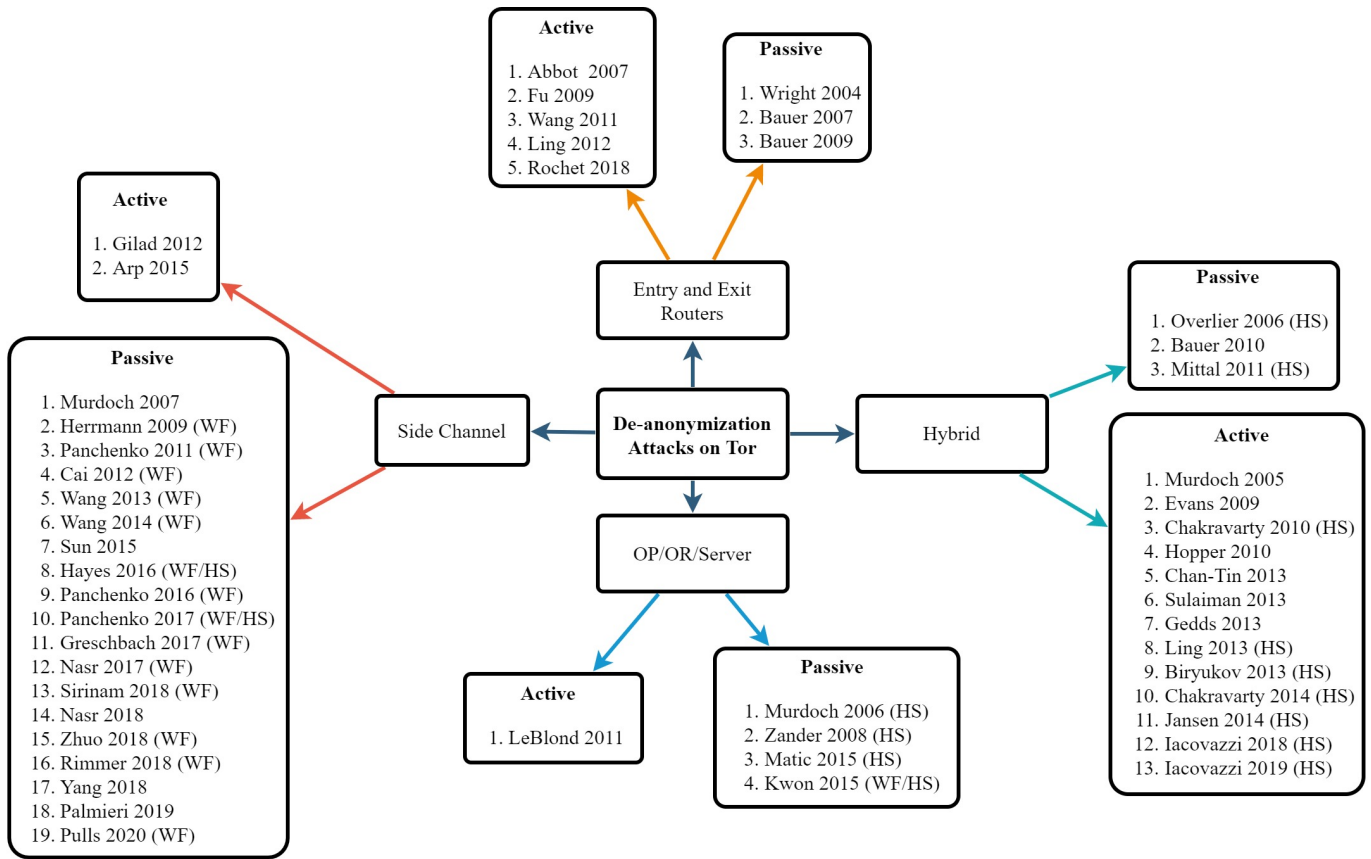


Fig. 7. Classification of de-anonymisation attacks

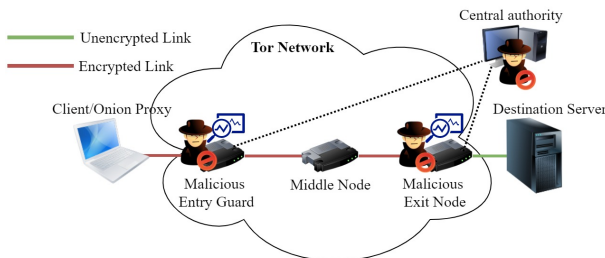


Fig. 8. Attack Scenario with compromised Entry and Exit nodes

and peer-to-peer file-sharing traffic.

Wright *et al.* [25] first introduced the *Predecessor Attack*, a de-anonymisation attack that is applicable to many anonymity networks. In the generic predecessor attack, the attacker controls multiple nodes in the anonymity network, and attempts to determine circuits consisting only of these nodes. Various techniques, such as timing analysis, are used to achieve this objective. If the complete circuit consists only of attacker-controlled nodes, the attacker can then identify the user (the sender's IP address). However, it is important to note this attack is based on multiple assumptions. 1. Nodes in a path are chosen uniformly at random. 2. Repeated connections are established between the user and destination until the connection is de-anonymised. 3. Only one user maintains a session with a given destination. 4. The last node can associate

a session with the target destination. When applying the predecessor attack specifically to the Tor network, the attacker only needs to control two nodes - the entry and exit nodes.

2) **Active Attacks:** In 2007, Abbot *et al.* [57] published a paper describing a timing analysis attack. In their attack, a malicious exit router modified the HTTP traffic to the client by inserting an invisible *iframe* that contained a JavaScript code. The Tor user's browser executed this JavaScript code, which sent regular distinctive signals to a malicious web server. As the Tor client selects a new circuit at regular intervals to increase their anonymity, if one of the malicious entry guards is selected at a certain time, the attacker will be able to use timing analysis to de-anonymise the user. For this attack, it is not necessary for the attacker to control both the circuit's entry and exit nodes at the same time. This is because once the victim's browser starts sending the signal, the attacker only needs an entry node to identify the user. The authors show that even when JavaScript is disabled, this attack can be carried out using the HTML meta refresh tag, although this is more noticeable to the user. In addition, this attack can easily be executed if the user uses the *Tor Button*⁵ to toggle the Tor proxy, while keeping the browser tab open. This attack is more simplified when there is less traffic in a Tor connection. The authors suggest two features that can

⁵Before the introduction of the Tor Browser Bundle, Tor users had to use Firefox to access the Tor network. TorButton is an add-on for Firefox to switch the browsers' Tor usage.

be exploited to achieve this: 1. using unpopular ports and 2. maintaining the TCP stream on the circuit for more than ten minutes. This attack fails if a malicious node is not selected as an entry guard. In such situations, the attacker can use this technique to identify entry guards and execute DOS attacks, forcing the client to select a different set of entry guards. This provides the opportunity for the malicious nodes to be selected as entry guards, increasing the effectiveness of this attack.

Wang *et al.* [58] present another active attack that utilises entry and exit nodes. For this attack, the adversary needs to control an exit router and monitor the traffic pattern at the entry guard. When the malicious exit node detects a web request of interest, it inserts a forged web page (forged web page injection attack) or alters a web page received from the server (target web page modification attack). This malicious web page causes the victim's browser to send detectable traffic patterns which can be identified by the adversarial entry guard to confirm the identity of the user. However, this attack can be executed with only a malicious exit node if the adversary is able to monitor the link between OP and the Tor network. The authors claim that the attack is highly efficient and can identify clients using a single web request while supporting normal web browsing. This provides an additional advantage to the attacker to remain undetected. Furthermore, this attack can be executed even when active content systems (e.g. Javascript) are disabled.

A new class of active attacks, *protocol level attacks*, are introduced by Fu *et al.* [59]. These can be executed by manipulating a single cell in the circuit. These attacks need the attacker to control both the entry guard and the exit router of the circuit, and need to have the ability to modify, duplicate, insert, or delete cells at the entry node. It logs the source IP address and port, circuit ID, and the time the cell was manipulated. The cell can be manipulated by duplicating and forwarding it at a suitable time, modifying a few bits of the cell, inserting a new cell into the flow, or deleting the cell. As Tor uses AES-CTR for encryption, when the cells are decrypted at the exit OR, the above changes in cells disrupt the counters and cause cell recognition errors that can be observed by the attacker if they are monitoring the exit node. The attacker records the time of these errors along with the destination IP, port, and the circuit ID. Therefore, if the attacker controls both the entry and exit nodes of a circuit, they can use this information to correlate and link the source and the destination.

In 2012, Ling *et al.* [60] proposed a type of attack requiring the attacker to control a few of the Tor network's entry guards and exit nodes. This type of attack is motivated by the observation that even though Tor uses equal-sized cells at the application layer, the size of the network's IP packets generally vary. The attacker selects an appropriate time and embeds a signal into the incoming traffic from the server. This task is undertaken at the exit node, which is recognised by an entry guard. This signal is a sequence of binary bits (three cells for binary "1" and one cell for binary "0"), however, it is possible that due to network delays and congestion this signal may be distorted at the middle node or the links connected to it. The adversary entry node records information relevant to received

cells along with the client's IP address, port, and circuit ID. Following this, the attacker decodes the embedded signal and if they find a match they are able to link the user with the destination.

The Tor protocol has a packet dropping behaviour that is common in network protocols. Rochet *et al.* [51] exploit this behaviour to launch a de-anonymisation attack, referred to as a *dropmark attack* against Tor clients. In most cases, when a Tor edge node receives an unwanted cell such as a *relay drop* cell or an unknown subtype of relay data cell, those cells are dropped at the edge of the circuit without tearing the circuit down. In a de-anonymisation attack, the attacker requires control of both a guard node and an exit node. Also, the circuit must have an idle time-interval. In Tor, the authors of [51] have identified such a gap in the cell's transmission from the exit node to the client, between the *connected* cell after a Domain Name System (DNS) query, and the response of the client's GET request. The attacker sends three relay drop cells from the exit nodes during this period that are identified by the malicious guard node.

B. Onion Proxy/Onion Router/Server

In this category, the adversary uses the OP, the server, or an OR (single router). If the OP (the Tor client) is used to execute the attack, its default functionality will usually be altered to match the requirements of the attack, e.g. sending periodic traffic patterns. If the attack requires a compromised server, this can be accomplished by hosting a server or taking control of a targeted server. An OR can be compromised in the same way as was explained in the previous section. Table II summarises the attacks that fit into the first two categories and which use an entry or exit node. It also shows how the Tor network has scaled with time, making it difficult to execute attacks by controlling Tor nodes.

1) *Passive Attacks*: In 2006, an attack to de-anonymise HSs was published by Murdoch [28]. The attack described in Murdoch's paper does not require any node in the circuit to be controlled, and the attacker cannot observe, modify, insert, or delete any network traffic. However, the attacker needs to control the client in order to execute this attack. This type of attack is based upon the fact that there is a significantly different clock skew (the ratio between actual and nominal clock frequencies) in different machines, even in identical models. The attack is executed by accessing the HS with varying traffic which affects the clock skew of the machine hosting the service. By requesting timestamps, these changes to the clock skew can be captured. The attacker then probes all suspecting machines for their timestamps. Finally, the attacker is able to reveal a correlation between the clock skew and the traffic pattern, thus de-anonymising the HS. In 2008, Zander *et al.* [64] improved upon Murdoch's [28] attack. [64] focuses on the weakness of the previous attack [28], in which the quantisation noise limited its execution. Clock skew has two main sources of noise, namely network jitter and timestamp quantisation error. Zander *et al.* show that this quantisation error can be significantly minimised by synchronised sampling, reducing the impact on clock frequency.

TABLE II
SUMMARY OF ATTACKS DEPENDENT ON A MALICIOUS ENTRY OR AN EXIT (IN THE FIRST TWO CATEGORIES)

Publication	Year	Component/s used	Active/Passive	Target	No of nodes in Tor *
Wright <i>et al.</i> [25]	2004	Entry and Exit	Passive	Standard Tor user	32
Bauer <i>et al.</i> [55]	2007	Entry and Exit	Passive	Standard Tor user	1344
Abbot <i>et al.</i> [57]	2007	Entry and Exit	Active	Standard Tor user	1344
Bauer <i>et al.</i> [56]	2009	Entry and Exit	Passive	Standard Tor user	1880 (350 bridges)
Fu <i>et al.</i> [59]	2009	Entry and Exit	Active	Standard Tor user	1880 (350 bridges)
Wang <i>et al.</i> [58]	2011	Entry and Exit	Active	Standard Tor user	3216 (781 bridges)
Le Blond <i>et al.</i> [61]	2011	Exit node	Active	BitTorrent user over Tor	3216 (781 bridges)
Ling <i>et al.</i> [60]	2012	Entry and Exit	Active	Standard Tor user	4083 (1107 bridges)
Kwon <i>et al.</i> [62]	2015	HS Entry node	Passive	Hidden service	9590 (2647 bridges)
Rochet <i>et al.</i> [51]	2018	Entry and Exit	Active	Standard Tor user	6862 (804 bridges)

* This column shows the number of Tor nodes in the network (including bridges) by 31st of December for each corresponding year. The values were taken from the Tor project metrics [63]. However, for the value corresponding to 2004, we have used the number given as of mid May 2004 in the Tor deployment paper [6]. From these numbers, we intend to highlight that due to the growth in the number of nodes in the network, these attacks require many compromised nodes to increase their probability of success in the live Tor network.

CARONTE is a tool that can de-anonymise HS by using location leaks in their content and configuration. This tool was developed by Matic *et al.* [65]. Their approach consists of 3 steps. 1. *Exploration*, which takes a set of onion URLs as input and extends each of them to include a root page, all resources, and one random resource that is added to trigger a “not found” error page. Following this, all onion URLs in the extended set are visited through Tor, using HTTP and HTTPS to collect the content and the certificate chain of the HS. 2. *Candidate selection*, in which a list of candidate pairs is generated using the collected information. A candidate pair consists of an onion address and an internet endpoint which can either be an IP address or a DNS domain. These are generated by examining endpoints, unique strings, and HTTP certificates of collected onion pages. 3. *Validation*, in which *CARONTE* verifies whether a candidate endpoint hosts the HS. This is done by visiting the endpoint separately to collect their content and certificates and finally comparing them with those of the onion address. This approach does not rely on a weakness in the Tor network but exploits sensitive information embedded in a HS’s content and configuration. This attack only uses OP for its execution.

Many fingerprinting attacks in the literature (discussed in more detail under side-channel attacks) have focused on de-anonymising a standard Tor connection (i.e. trying to figure out what webpages/websites are visited by a targeted user). Kwon *et al.* [62] propose a *circuit fingerprinting* attack to identify HSs. For this attack, the attacker needs to be able to extract circuit-level information, such as the number of incoming and outgoing cells, sequence of packets, lifetime, and timing information. Although under certain conditions a network administrator or an ISP is able to obtain this information, the most realistic and effective way to execute the attack described in [62] is to control an entry guard. Firstly, the authors discuss how certain distinctive circuit features such as incoming and outgoing cells, duration of activity, and circuit construction sequences can be used to classify a given circuit into five different categories: 1. HS - Introduction point, 2. Client - RP, 3. Client - Introduction point, 4. HS - RP, and 5. General Tor circuits. Subsequently, Kwon *et al.* discuss how website fingerprinting can be used in conjunction with the

circuit classification to de-anonymise a HS. According to their paper, to obtain training data from the HS-side, the attacker first downloads the content from different HSs and then starts up a HS with this downloaded data in a sub-directory. The objective of the attacker is to link a given network trace with a HS by using website fingerprinting techniques. Then, by using the circuit classification technique described in [62], the attacker can determine whether the trace belongs to the client-side or server-side. If it belongs to the server-side the IP address of the HS can be identified.

2) *Active Attacks*: Le Blond *et al.* [61] describe two attacks for de-anonymising Tor users by exploiting insecure applications. One attack requires the adversary to control an exit node and a publicly connectable BitTorrent peer. In this attack, the BitTorrent tracker’s response is hijacked by the malicious exit node, and the IP address and port of the malicious peer are inserted into it. If the user connects to the peer directly, without using Tor, the attacker can trace them easily. The authors claim that a majority of BitTorrent users use Tor, only to connect to the centralised tracker. By comparing the publicly available IP addresses of the exit nodes with the IP addresses connected to the malicious peer, it is possible to verify their claim. In the second attack, Distributed Hash Table (DHT) tracking is exploited, as it is carried over the User Datagram Protocol (UDP). As Tor only supports TCP, the BitTorrent client cannot connect to DHT using Tor, however, DHT keeps track of the IP addresses and ports of peers downloading specific content. This type of attack is carried out when the exit node identifies a target user connecting to the BitTorrent tracker via Tor. The content identifier and the port number for a specific download are included in the BitTorrent subscription to the tracker and the handshake messages. Following this, the attacker tries to match a user with a similar port number from the list of candidate IP/ports for that specific content ID in the DHT. If they find a match then the Tor user can be de-anonymised. In addition to the above attacks, Le Blond *et al.* present an attack, known as the *Bad apple attack*, which can be used to identify the IP address of other streams once a BitTorrent stream is de-anonymised. The fact that all streams that are multiplexed into the same circuit originate from the same user can be used to de-anonymise the other streams in that circuit. When it

comes to different circuits, the attack exploits two BitTorrent signaling patterns; 1. the peer identifier that can only be used if the peer-to-peer communication is not encrypted, and 2. the IP address and the port that are returned in the tracker response. Therefore, two circuits can be linked if a peer in one circuit communicates with an IP/port included in the tracker response of another circuit. The authors were also able to use this technique to trace HTTP streams.

C. Side Channels

Side-channel attacks use means other than compromising the main Tor components to execute the attack. The most common type of side-channel used against Tor is the traffic intercepted between the Tor client and the entry node. Network administrators or Internet Service Providers (ISPs) can monitor this traffic.

1) **Passive Attacks:** In 2007, Murdoch *et al.* [66] addressed the ability of adversaries controlling Internet Exchange Points (IXPs) to do passive correlation attacks. This type of attack assumes that, 1. traffic going in and coming out of the Tor network for a targeted flow passes through an attacker-controlled IXP, 2. the packet sampling is distributed over the flow independently and identically, and 3. the attacker can distinguish Tor traffic from normal network traffic. The attacker then tries to match the target flow going into the network with the traffic flow coming out of the network, or vice versa. A Bayesian approach is used to infer the best possible match. To evaluate the attack, simulations have been carried out by varying the number of flows, sampling rate, mean network latency, and the attack method. In 2013, Johnson *et al.* [67] discussed the realistic nature of this type of adversary in their paper.

A novel set of attacks, known as *RAPTOR* attacks, which can be launched by ASes, were presented by Sun *et al.* [33] in 2015. These attacks can either be executed individually or combined for improved performance. 1. Asymmetric traffic analysis - This attack considers the realistic asymmetry of the internet paths and shows that anonymity network users can be de-anonymised by observing only a single traffic direction at both communication endpoints. 2. Exploiting natural churn - This attack is based on the fact that internet paths fluctuate over time due to changes in physical topology. 3. BGP hijacking attack - This attack is also known as prefix hijacking attack. In this attack, a malicious AS advertises false BGP control messages in order to capture a part of the traffic to the victim. This captured traffic is then used to learn the IP address of the guard relay. 4. BGP interception attack - This is also called prefix interception attack. In this attack the malicious AS becomes an intermediate AS on the Internet path. Here, the connection is kept alive, unlike in the hijacking attack, which enables asymmetrical traffic analysis. The authors also point out that the adversary can execute an interception attack at both the guard relay and exit relay simultaneously. Sun *et al.* execute a real-world BGP interception attack against a live Tor relay by collaborating with AS operators. These attacks exploit the dynamics of internet routing such as routing symmetry, and routing churn.

More recently, researchers have focused on deep learning techniques to execute de-anonymisation attacks on the Tor network. Nasr *et al.* [68] demonstrate a traffic correlation attack by using deep learning. In their attack, a correlation function, tailored to the Tor network is learned and used by the *DeepCorr* system to cross-correlate live Tor flows. This system can correlate two ends of the connection - even if the destination has not been used in the training process - as its correlation function can link arbitrary circuit flows as well as flows to arbitrary destinations. DeepCorr's neural network learns generic features of noise in Tor, allowing it to correlate circuit flows that are different to those used during the learning process. Furthermore, DeepCorr's performance improves with higher observation times and larger training datasets.

Palmieri [69] presents a flow correlation attack based on wavelet multi-resolution analysis. This is a passive attack in which the adversary must eavesdrop on ingress and egress traffic. Wavelets are functions that satisfy certain mathematical properties and are used to represent data or other functions [70]. Wavelet analysis can be used to obtain a clearer and more complete view of a signal, its generation and other less evident dynamics by decomposing the signal on multiple scales. Properties that are not evident by direct observation are thus identified and used to correlate the captured flows.

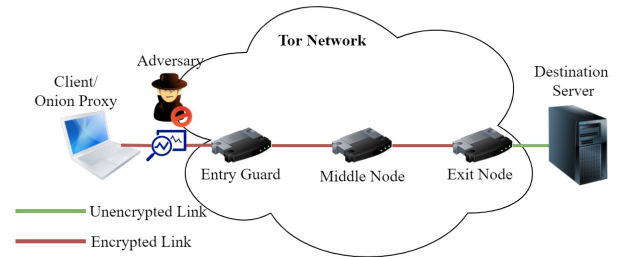


Fig. 9. Attack Scenario for Website Fingerprinting

Concepts related to Website Fingerprinting (WF) were first explored in the late 90's. The term, *Website fingerprinting*, was coined by Hintz in 2002 [22]. However, it was in 2009 that Herrmann *et al.* [29] presented a WF attack on the Tor network in which the adversary was able to monitor the traffic between the privacy-enhancing system and the user. This is a passive attack, based on the Multinomial Naive Bayes classifier. This type of attack consists of two phases: namely, the training phase and the testing phase. In the training phase, traffic fingerprints are created for either a large number of generic sites or a small number of *targeted sites*. These are then stored in a database with the corresponding URLs. In the testing phase, fingerprints are created from the traffic recorded from users and are then compared with the database records to find any matching fingerprints. Figure 9 shows the attack scenario for generic WF attacks.

In 2011, Panchenko *et al.* [71] presented another WF attack based on Support Vector Machines (SVM). The authors define features based on volume and time while previous WF attacks only considered packet sizes and their direction (incoming or outgoing). The experiments were carried out in a closed world

scenario, and were later extended to an open-world scenario. In a closed world scenario, the attacker is aware of all the web pages ordinarily visited by the victim, while in the open world this is not the case. Panchenko *et al.* also present preliminary results on how camouflage affects these attacks. In their work, a randomly chosen web page is simultaneously loaded with the requested web page to achieve the camouflage effect.

Cai *et al.* [72] describe a *web page* fingerprinting attack as well as a *website* fingerprinting attack. Both these attacks assume that an adversary can monitor a user's internet connection. For the web page fingerprinting attack, network traces are converted into strings and the *Damerau-Levenshtein Distance*⁶ (DLD) is calculated. Following this, a SVM classifier with a distance-based kernel is used for classification. This is then extended to a website classifier by using the Hidden Markov Models. These models help the attacker to conclude whether a sequence of web pages are from the same website or not. Cai *et al.* have evaluated their datasets against the work of Panchenko *et al.* [71] and Herrmann *et al.* [29] and claim that the proposed attack mechanism in [72] is far more effective. Furthermore, Cai *et al.* claim that their work is the first to evaluate the security provided by application level defences such as HTTPoS [73] and random pipelining [74], while the previous attacks only considered packet padding and other network-level defences.

In subsequent years, several works have been published on WF attacks. In 2013, Wang *et al.* [75] published the results of a WF attack that used a SVM classifier and two new distance based metrics to compare packet traces. Their paper demonstrates that one metric - introduced as the *combined OSAD* (Optimal String Alignment Distance) - reduces the error rate while the other metric - presented as the *fast Levenshtein-like algorithm* - significantly reduces the training time. Wang *et al.* follow up on the work of Cai *et al.* [72], comparing their work. When reviewing Cai *et al.*'s code and results, Wang *et al.* note that the metric used by Cai *et al.* in their work was actually the OSAD (which is a more restricted version of DLD) and not the DLD. Wang *et al.*'s attacks are evaluated in a closed world scenario as well as an open-world scenario.

Again in 2014 Wang *et al.* [76] published a WF attack with a local passive adversary, applying the k-Nearest Neighbour (k-NN) classifier to a large feature set with weight adjustments. This feature set included general features such as total transmission size, the numbers of incoming and outgoing packets, as well as unique features such as packet lengths, packet ordering, concentration of outgoing packets, and bursts. Wang *et al.*'s [76] paper also discusses WF defences and claims that all previous defences only work against specific attacks. Hence the authors propose a *provably effective defence* which has the capability to defeat any attack and requires fewer resources.

Hayes *et al.* introduced K-fingerprinting, a novel WF technique based upon random decision forests [34]. In their paper, the authors evaluate this type of attack against standard web pages as well as HSs. This type of attack assumes the presence of a passive attacker who can observe the client's encrypted

traffic. It consists of two stages. In the first stage, the attacker captures network traffic generated from a set of web pages that they wish to monitor and a large number of other unmonitored web pages and uses these traces to train a random forest for classification. Following this, the attacker captures traces from the client's browsing session. In k-fingerprinting, random forests are used to extract a fixed-length fingerprint rather than directly using the classification. Therefore, after capturing all traces, the attacker computes the fingerprint's Hamming distance from the client's traffic with the set of fingerprints collected for classification in stage one.

In 2016, Panchenko *et al.* [35] published another WF attack using a passive eavesdropper that served to monitor the traffic between the client and the entry node. This fingerprinting approach was named CUMUL, and requires the use of an SVM classifier. Panchenko *et al.*'s paper mentions three limitations of previous datasets; 1. the previous datasets contain only index pages, 2. they don't allow an evaluation of fingerprinting for complete websites, and 3. small datasets do not allow for generalisation as the world wide web consists of billions of web pages. Therefore, the authors in [35] use novel datasets to overcome these issues.

Following Kwon *et al.*'s work [62] in 2015, in 2017, Panchenko *et al.* [77] published their work on de-anonymising HSs using fingerprinting techniques. However, for the approach taken by Panchenko *et al.*, the attacker does not need to control an entry guard but instead needs to have the ability to observe the link between the client and the guard. Their technique consists of two phases. In the first phase, they try to detect whether there is communication with the HSs. They further break down this phase into detecting unknown HS communications and detecting known HS communications. For both of these scenarios, the authors apply a binary classifier. In the second phase, they try to detect the HS visited by the client. Assuming that HS communication has already been detected in phase 1, phase 2 is explored by the authors in the following two ways: 1. the adversary wants to detect a targeted set of HSs, and 2. the adversary knows all the HSs and wants to find out which one is being visited by the client. However, the authors claim that in general, neither this attack nor other existing attacks scale in realistic settings. The claim that WF attacks are not properly scaled to be effective in the live network had previously been discussed by Juarez *et al.* [78] in 2014.

One of the main disadvantages of any traffic-analysis based attack is the huge storage and computational overheads required due to massive traffic volumes. Nasr *et al.* [79] address this issue by introducing *compressive traffic analysis*, a technique in which traffic analysis is conducted on compressed features and not raw features. This approach is inspired by *compressed sensing* [80], which is an active area in signal processing. Nasr *et al.* present two main reasons for the feasibility of compressive traffic analysis. 1. Traffic features such as packet timings and sizes are *sparse* signals, in which the compressed sensing algorithms work best. 2. The *restricted isometry property* of compressed sensing algorithms [80] allows traffic features to keep their *Euclidean distances* after compression, which allows traffic analysis to be conducted

⁶Damerau-Levenshtein distance is a metric that evaluates the distance between two strings to compute their dissimilarity to each other.

on compressed features. Based on this concept, *compressive flow correlation* and *compressive website fingerprinting* are introduced and compared with state of the art techniques. The authors used k-NN and SVM classifiers for the website fingerprinting attack, thus demonstrating that compressive website fingerprinting requires lower storage and computational time compared to its traditional counterparts.

An inherent issue of WF attacks in the literature is that they often neglect realistic scenarios. For example, researchers often assume that there are only discrete visits to webpages, thus ignoring hyperlink transmissions. Zhou *et al.* [81] propose a WF attack based on the Profile Hidden Markov Model (PHMM), a technique that is used for DNA sequencing analysis in bioinformatics. Their main argument is that even though there may be noise impacting the results in scenarios such as subsequent visits by a user to a webpage using hyperlinks, key elements can still be used to identify a website. The authors equate this to the fact that while there are different genes in an organism under different environmental factors, its essential functionality genes do not change. Based on this argument, Zhou *et al.* claim that their WF attack is more applicable in practice. Furthermore, their paper provides a useful taxonomy and a comparison of WF attacks up to 2016.

Different WF attacks use different classifiers or feature sets. Most of the time, these features are manually extracted and are specific to a certain attack. A paper published by Rimmer *et al.* [83] in 2018 claims to present the first WF approach that carries out automatic feature extraction. The authors argue that since the classifier and the features are fixed for most of the attacks, it is easy to develop defences against them. However, this is not the case against their attack. Deep learning models such as the feedforward Stacked Denoising Autoencoder (SDAE), Convolutional Neural Networks (CNN), and recurrent Long Short-Term Memory (LSTM) were applied to their approach.

Sirinam *et al.* [84] describe a more recent WF attack against the Tor network, titled *Deep Fingerprinting*, which uses CNNs. They claim that this attack has an accuracy of 98% without defences, more than 90% against WTF-PADs [86], and 49.7% against Walkie-Talkies [87]; two main defences against WF attacks that were seriously being considered for deployment by the Tor project [88]. As a result, the authors have expressed their concerns and disclosed their findings to the Tor project. This attack was conducted in both closed and open-world settings.

Greschbach *et al.* [82] present a new set of correlation attacks called *DefecTor attacks* that use DNS traffic for precision improvement. As DNS uses the User Datagram Protocol (UDP), which is not supported by Tor, Tor provides a workaround. The OP transfers the hostname and port to the exit node, and the exit node resolves the address. If the DNS resolution is successful, the exit node opens a new TCP connection to the target server. In Greschbach *et al.*'s paper, a conventional WF attack is combined with the egress DNS traffic observed by a passive attacker. The attack can be carried out by observing the links or running a compromised entry node and a DNS resolver or server. Two DefecTor classifiers are proposed by extending Wang *et al.*'s k-NN classifier [76].

In a very recent publication, Pulls *et al.* [85] introduce the security notion of a *Website Oracle*, which can be combined with a WF attack to increase its effectiveness. A WO provides information on whether a particular monitored website was visited via Tor at a given time. In general, WO further improves the WF classification's performance. DNS resolvers used by Greschbach *et al.* [82] are an example of a WO source. However, Pulls *et al.* also mention other WO sources. Web server access logs, content delivery networks, exit relays, Tor DSs, Real-Time Bidding (RTB) [89], and dragnet surveillance programs, are some such examples. For their experiments, the authors used Sirinam *et al.*'s Deep Fingerprinting attack [84] in conjunction with WOs. Table III provides a summary of all the WF attacks we have discussed in this paper.

Yang *et al.* [90] worked on a completely different de-anonymisation scenario to previous attacks we have described in this section. In their attack, they tried to identify the websites visited by a smartphone user via Tor. A malicious USB charging device, such as the ones in public USB charging stations, was the assumed attacker. The authors used the official Tor apps on Android - Orbot and Orfox. 1. Orbot implements a local proxy to provide Tor access to mobile phones, and 2. Orfox is a Firefox based browser for smartphones. For their attack, the authors considered some realistic factors such as the network type (LTE or Wifi) and the battery level. Following this, the authors extracted time and frequency features from these traces and used them in a random forest classifier. However, as they only used 100 websites (50 regular and 50 onion services) in their experiments, they have claimed their work as a proof of concept.

2) **Active Attacks:** Most side-channel attacks available in the surveyed literature are passive. However, Gilad *et al.* [53] describe an active attack where the attacker influences the rate of communication between the exit node and the server and is therefore able to observe the traffic between the client and the entry guard. Firstly, the attacker sends spoofed packets (with the server's address and port as a source) from the probe circuit to the exit node. Then the exit node sends a duplicate acknowledgement (ACK) to the server. Three such duplicate ACKs are interpreted by TCP as a congestion event, and the servers' congestion window shrinks, resulting in a reduction of the transmission rate. This is observed by the attacker at the client end, thus de-anonymising the communications. However, it should be noted that Gilad *et al.*'s paper [53] was published with only preliminary results for this type of de-anonymisation attack.

Arp *et al.* [91] introduce another side-channel de-anonymisation attack on Tor called *Torben*. This attack exploits an interplay of the following scenarios. 1. The ability to manipulate a web page to load content from an untrusted origin, and 2. the visibility of the size of requests-response pairs of web traffic, regardless of them being encrypted. The basic idea of this attack is to implant a web page marker into the response from the server which induces a recognisable traffic pattern that can be observed by a passive attacker at the user's end. Arp *et al.* discuss two variants of the attack, depending on the type of marker. A *remote marker* can be used for web pages that allow content from other origins such

TABLE III
SUMMARY OF WEBSITE FINGERPRINTING ATTACKS AGAINST TOR

Publication	Year	Classifier	Setting	Unique/Novel claims
Herrmann <i>et al.</i> [29]	2009	Multinomial Nave-Bayes	Closed	Apply WF to anonymous networks
Panchenko <i>et al.</i> [71]	2011	Support Vector Machine	Both	First successful attack for open-world scenario
Cai <i>et al.</i> [72]	2012	Support Vector Machine	Closed	Propose both <i>web page</i> and <i>website</i> fingerprinting attacks
		Hidden Markov Model	Open	First evaluation of application level defences
Wang <i>et al.</i> [75]	2013	Support Vector Machine	Both	Propose 2 new distance based metrics to compare packet traces
Wang <i>et al.</i> [76]	2014	k-Nearest Neighbour	Open	Design a provably effective defence against WF attacks
Kwon <i>et al.</i> [62]	2015	k-Nearest Neighbour	Both	Apply WF for hidden services
Hayes <i>et al.</i> [34]	2016	Random decision forests	Both	Possible to launch WF attacks even with lots of noise
Panchenko <i>et al.</i> [35]	2016	Support Vector Machine	Both	Web page fingerprinting in not practical at internet scale
Panchenko <i>et al.</i> [77]	2017	Binary classifier & SVM	Both	Performance and limits of fingerprinting attacks on HSs
Greschbach <i>et al.</i> [82]	2017	Modified k-NN	Both	Associate DNS traffic for WF attacks
Nasr <i>et al.</i> [79]	2017	k-NN & SVM	Open	Introduce compressive website fingerprinting
Zhou <i>et al.</i> [81]	2018	Profile Hidden Markov Model	Both	Consider hyperlink transitions made by users
Rimmer <i>et al.</i> [83]	2018	SDAE, CNN & LSTM	Both	Apply DL algorithms for WF and automatic feature extraction
Sirinam <i>et al.</i> [84]	2018	Convolutional Neural Network	Both	Undermine WF defences considered for deployment in Tor
Pulls <i>et al.</i> [85]	2020	Convolutional Neural Network	Open	Introduce the notion of a <i>Website Oracle</i>

SDAE - Stacked Denoising Autoencoder, CNN - Convolutional Neural Network, LSTM - Long Short-Term Memory, DL - Deep Learning

as advertisements, and a *local marker* is an item on a web page into which the attacker directly injects content. Arp *et al.*'s attack assumes a real-world adversary who has access to the traffic between the Tor client and the entry node.

D. Hybrid

If a mix of Tor network components from the previous categories is used for an attack, it is categorised under the *Hybrid* category. For example, if an attack requires any combination of a Tor node, a server, a client, and a side-channel, they are considered here.

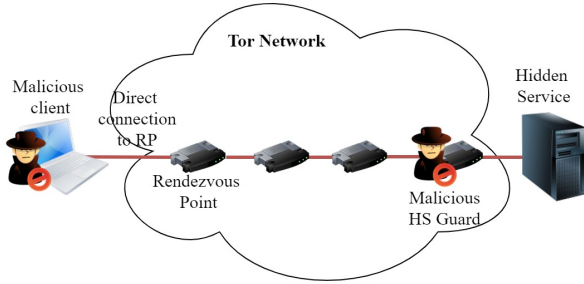


Fig. 10. Client Scenario in Øverlier *et al.*'s HS attack

1) **Passive Attacks:** In 2006, Øverlier *et al.* [27] presented the first known attack on Tor's HSs. In their attack scenario, an attacker-controlled client directly connected to the RP in order to reduce the latency between the client and the HS. In addition, Øverlier *et al.* controlled a *middleman* Tor node which advertised false up-time and bandwidth, expecting to be selected as a part of the circuit between the HS and the RP. Figure 10 shows this attack scenario. Following this, a traffic pattern was generated from the client and was expected to be observed by the malicious node to determine whether the node was selected as a part of the circuit with the HS. This type of match confirmation is based on basic packet counting with regard to timing information and the direction of traffic. The next issue faced by the authors was to identify the position of

the node in the circuit. As the client was aware of the RP's IP address, it was able to determine when the malicious node was closest to the RP. When this happens, the circuit is torn down and a new connection is forced in the next attempt. If both IP addresses connected to the attacker node are unknown, follow-up attacks are suggested to determine its position. 1. Service Location Attack - HS can be hosted either on a node in the Tor network (server scenario) or an external client using the Tor network (client scenario). This approach is based on DSs having a public list of all server nodes in the network. If an IP address connected to the attacker node is not available in the public list of nodes then it must be the IP address of a HS, hosted in an external client (client scenario). 2. Predecessor attack - The basic concepts of this type of attack [25] were initially discussed under *Entry and Exit router passive attacks*. By collecting the IP address statistics, the IP address of the HS can be deduced via traffic pattern matches that have been found while communicating with the HS. 3. The distance attack - This approach calculates the round trip time of a node's traffic to determine whether it's closer to the HS or not. Moreover, the authors point out that if the attacker owns the RP in addition to the other malicious Tor node, the speed and accuracy of the attack can be increased. This is because if the attacker-controlled Tor node is selected as the middle node of the circuit, it can be easily identified as the RP knows the IP address of the node next to it.

Bauer *et al.* [92] investigate the benefits and drawbacks of two-hop and three-hop paths in Tor, based on security and performance perspectives. Their paper describes an attack based on *Adaptive Surveillance* in which the objective is to find the identity of the entry guard, assuming that the LEAs or other powerful adversaries can *adaptively* demand network logs from the entry guard's network. They experiment with three-hop scenarios where the attacker controls exit and middle routers to identify the entry guard.

Mittal *et al.* [93] present two types of attacks, one to identify the Tor circuit's guard relays and another one to link two streams multiplexed over the same circuit using *Throughput fingerprinting*. For the first attack, the attacker should have the

ability to observe the throughput of the target flow. This can be achieved by using a compromised exit relay, a web server or an ISP. In this type of attack, one-hop circuits are developed through suspected Tor relays and probed. The attacker does not need to alter the traffic. In addition, the probing can be conducted from a suitable vantage point. If the throughput of the target flow and the probe flow correlate highly it can be assumed that the experimenting node is a part of the target flow. Mittal *et al.* demonstrate that by doing this for several of a client's circuits and observing the frequency of Tor nodes that are discovered as part of the flow, it can be assumed that these nodes are the circuit's guard nodes as guard nodes have a very high probability of being in a client's circuits. This concept is further used to identify HSs hosted on Tor relays as that relay will have the highest frequency of being part of the circuit.

2) **Active Attacks:** One of the earliest de-anonymisation attacks against the Tor network was published by Murdoch *et al.* [24] in 2005. This traffic analysis attack takes into account the fact that a Tor node's load affects the latency of all connections through that node. The attack uses a corrupt server to send unique traffic patterns, consisting of sequences of short data bursts. The attacker also controls a Tor node, which creates a connection through a targeted node. Following this, the attacker sends probe traffic through the established connection to identify the latency and to detect traffic signals passing through the node. This way, the attacker can identify a target circuit's nodes. However, the attacker must access the victim's entry guard to identify the actual originator of the connection. The authors mention that a simple strategy to use cover traffic does not prevent this type of attack, as the attack depends on indirect measurements of stream traffic. Additionally, the authors propose a *linkability attack*, which tries to determine whether two streams coming out of a node belong to the same initiator or not. Furthermore, the authors suggest a few variants of their attack as follows. 1. If the corrupt server cannot significantly modulate the traffic, the modulated probe traffic can be sent to the victim's Tor node in a loop and can detect the effect upon requests sent by the targeted sender. 2. If the attacker cannot modify the traffic but can observe the link, a known traffic pattern on the server can be used for this attack. 3. If the attacker cannot modulate or observe link traffic then they may resort to observing response times on the server. 4. A DOS attack can be executed on the destination server and can observe the decreased load upon the Tor nodes.

Hopper *et al.* [94] present two attacks based on network latency: a de-anonymisation attack and a linkability attack. The de-anonymisation attack is carried out using a malicious client, server, and a Tor node. The first step of the attack is similar to the attack presented by Murdoch *et al.* [24] wherein the malicious Tor node and the server collude to reveal the nodes in the target circuit. Following this, the attacker estimates Round Trip Times (RTT) for several candidate victims. Afterwards, the malicious client connects to the server using the same set of nodes and checks its RTT to compare it with those of candidate victims. The authors also propose a linkability attack using two colluding servers and calculating

the RTT.

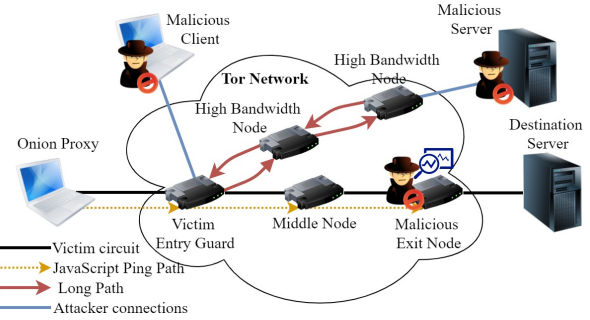


Fig. 11. Attack Scenario of Evans *et al.*

In 2009, Evans *et al.* [95] published a paper arguing that the attack presented by Murdoch *et al.* in 2005 [24] was not practical due to the growth of the Tor network. Evans *et al.* present a new solution by combining the original attack with a novel bandwidth amplification attack. In this scenario, the adversary has to control an exit node, a client and a server to execute their attack. Firstly, the attacker injects a JavaScript code into an HTML response. This JavaScript code sends periodical HTTP requests, including the time stamp, to which the exit node returns an empty response. Then the malicious client and malicious server create a long path (where the circuit is being looped) for each candidate node (and two helper nodes with high bandwidth). They then start transmitting data to initiate a congestion attack on the candidate node. If the candidate node is part of the target circuit, the exit router observes a significant delay pattern matching the power of the attack. Figure 11 shows the attack scenario for this attack. It should also be noted that in 2013, Chan-Tin *et al.* [96] revisited the Murdoch *et al.* attack [24] and demonstrated that it was still possible to execute regardless of Evans *et al.*'s claims. The attack by Chan-Tin *et al.* is very similar to that of Murdoch *et al.*, with a few modifications.

Chakravarty *et al.* [97] present an attack by estimating the bandwidth of Tor nodes by using *available bandwidth* estimation tools. They used *LinkWidth*, a tool that can estimate the available and capacity bandwidth on a path [98]. This type of attack requires a malicious server to inject bandwidth fluctuations to the circuit. Following this, all Tor nodes are probed repeatedly to detect these bandwidth fluctuations using *LinkWidth*. However, this process only allows the attacker to identify the Tor nodes in the target circuit. In order to find out the identity of the Tor client, the attacker has to monitor the fluctuations on the link between the client and the entry node, an action that would only be practical to an AS-level adversary or an ISP. This process can also be used to identify HSs with the use of a malicious client instead of a server to induce the bandwidth fluctuations.

Ling *et al.* [21] discuss a type of attack that can be used to de-anonymise HSs. For this, the attacker has to have control over a Tor client, an RP, some entry routers, and a central server. The attack is carried out in three steps. 1. Identifying the HS, presumably by trying to connect it to one of the compromised entry nodes. A special combination of cells of

different types is used for this. 2. Confirming the HS by sending a modified cell from the RP, which destroys the circuit. 3. Recording the details about timing and IP addresses from the RP and entry routers in the attacker-controlled central server, which is finally correlated to conclude the IP address of the HS. The authors claim that their true positive rate is 100% but mention two complications of this attack. 1. The typical expiry date of entry guards is 30-60 days, and if no compromised routers are selected as HS entry guards, this approach fails. 2. If the operator selects their trusted routers or bridges as entry guards, the attacker has to resort to an additional step to find out what these routers are and compromise them before executing the original attack.

Gedds *et al.* [102] introduce a set of attacks, known as *Induced Throttling Attacks*. These attacks assume a scenario in which the attacker controls an exit node and some middle nodes to identify candidate entry guards. One attack exploits a feature of Tor's congestion control algorithm. These algorithms send "backward control cells" to request data from edge nodes. When the nodes do not receive these cells, they stop sending data until the next cell is received. A malicious exit node can use this mechanism to artificially create congestion and create specific patterns in a circuit. This affects all circuits going through the relevant node. The attacker then uses malicious middle nodes to create one-hop probe circuits through suspicious entry guards, in order to identify these patterns by measuring the throughput and congestion on these circuits at regular intervals. The second attack also utilises the fact that the throttle rate of a circuit depends on the number of *client-to-guard* connections. To execute this attack the adversary only needs a malicious client and an exit node. They can create multiple connections to a guard node and toggle its throttling rate while the exit node tries to identify the pattern. However, as this attack can only be used to identify the entry guard, additional steps are required to de-anonymise the sender.

Sulaiman *et al.* [103] describe an attack using unpopular ports in Tor. For reasons like bandwidth greediness, associated spamming and de-anonymisation risks, many volunteers restrict certain ports from use in their Tor nodes. Some of these ports include SMTP (25), NNTP (119), NNTPS (563), and many P2P ports. The attack explained in [103] happens in several steps. Firstly, the attacker compromises a web server, then they inject malicious entry and exit routers to the network, each advertising a high bandwidth. These exit routers allow targeted unpopular ports. When a client connects to the compromised web server through a *popular* port, it sends back a hidden script with the requested web page. When the client executes the hidden script, the script forces the client to create a connection through Tor using the targeted *unpopular* port. If a circuit is established via two malicious nodes then the attacker is able to use traffic analysis to de-anonymise the user.

Chakravarty *et al.* [99] present an attack using NetFlow records. The authors mention two attack scenarios; one that de-anonymises the client and one that de-anonymises a HS. For the first attack, the adversary must have a malicious server and entry nodes under their control. The attacker then injects traffic patterns that are identified by the entry guards. In the second

attack, a malicious Tor client injects a traffic pattern that can be identified by an adversary-controlled HS entry node. The flow records in these scenarios are used to calculate a correlation coefficient to link the two endpoints.

Biryukov *et al.* [31] suggest an attack to de-anonymise HSs. In this type of attack, the attacker requires a malicious client, an RP, and some guard nodes. When a client tries to connect to the HS, they send a Rendezvous Cookie (RC) and the RP's address to an introduction point of the HS (refer Figure 4). Following this, the introduction point communicates these details to the HS. The HS sends a RELAY_COMMAND_RENDEZVOUS1 cell containing the RC to the RP to build the circuit between RP and the HS. Upon receiving this, the malicious RP sends 50 padding cells back to the HSs (which are discarded by the HS) followed by a DESTROY cell. If there is an attacker-controlled guard node in this circuit, it is identified as follows. 1. Whenever the attacker node receives a DESTROY cell it checks whether the DESTROY cell was received just after the RELAY_COMMAND_RENDEZVOUS1 cell. 2. Following this, it checks whether the number of cells forwarded from the HS is 3 (2 RELAY_COMMAND_EXTEND cells + 1 RENDEZVOUS1 cell) and transmitted to the HS is 53 (50 Padding Cells + 2 RELAY_COMMAND_EXTENDED cells + 1 DESTROY cell). If both of these conditions are met then the attacker node is selected as a guard node. As the guard node knows the IP address of the HS, it can be de-anonymised. The same concept can be used to identify when the attacker node is selected as the middle node of the HS-RP circuit when the numbers of forwarded cells are 2 and 52 (without 1 RELAY_COMMAND_EXTEND cell and RELAY_COMMAND_EXTENDED cell respectively). In this scenario, the attacker can identify the guard nodes and try to compromise or block them.

Jansen *et al.* [30] propose a DOS attack known as the *Sniper Attack* that can disable arbitrary Tor relays by exploiting Tor's flow control mechanisms. They discuss few variants of the attack targeting entry and exit relays of a circuit. The attack scenarios are as follows. 1. In the first attack, the attacker controls the client and an exit relay, intending to disable the entry guard. Here, the exit relay generates packages - ignoring the package window limits - and sends these through the circuit. The client does not read any packages coming from the entry node. The entry node buffer overflows and the Tor process is terminated. 2. In the second attack, the adversary controls the client and file server and targets the exit node. Similarly to the previous attack, the client generates packages while the server stops reading from the TCP connection, and the Tor process in the exit relay is killed by the relay's OS when memory resources are depleted. 3. In the third attack, the adversary only needs to control the client and download a large file from an external server. The client then stops reading from its TCP connection while sending SENDME cells to the exit node. Similar to attack one, the Tor process of the entry node is killed when the buffer overflows. However, we are interested in this attack because it can be used to de-anonymise HSs. In order to do that, the attacker needs to control a guard node and an RP in addition to the client. Firstly, the attacker must

TABLE IV
SUMMARY OF HIDDEN SERVICE ATTACKS

Publication	Year	Components used	Active/Passive	Comments
Øverlier <i>et al.</i> [27]	2006	HS Entry and OP	Passive	First attack on HSs
Murodch [28]	2006	Onion proxy	Passive	Use changes in clock skew
Zander <i>et al.</i> [64]	2008	Onion proxy	Passive	Reduce quantisation error in Murdoch 2006 attack
Chakravarty <i>et al.</i> [97]	2010	OP and LinkWidth	Active	Use <i>available bandwidth</i> estimation tools
Mittal <i>et al.</i> [93]	2011	Onion proxy	Passive	Can only be used for HSs hosted in Tor nodes
Ling <i>et al.</i> [21]	2013	HS Entry, OP and RP	Active	Protocol-level discovery approach
Biryukov <i>et al.</i> [31]	2013	HS Entry, OP and RP	Active	Use a special padding cell technique in Tor
Chakravarty <i>et al.</i> [99]	2014	HS Entry and OP	Active	Use NetFlow traffic records
Jansen <i>et al.</i> [30]	2014	HS Entry, OP and RP	Active	Complementary DOS attack for Biryukov 2013 attack
Matic <i>et al.</i> [65]	2015	Onion proxy	Passive	Use location leaks in HS's content and configuration
Kwon <i>et al.</i> [62]	2015	HS Entry node	Passive	Circuit fingerprinting attack for HS
Hayes <i>et al.</i> [34]	2016	ISP/Network admin	Passive	Propose k-fingerprinting against both normal services and HSs
Panchenko <i>et al.</i> [77]	2017	ISP/Network admin	Passive	Evaluate the scalability of fingerprinting attacks on HSs
Iacovazzi <i>et al.</i> [100]	2018	HS Entry and OP	Active	First method to embed watermarks at destination and detect at source
Iacovazzi <i>et al.</i> [101]	2019	HS Entry and OP	Active	Exploits a weakness in Tor's congestion control mechanism

identify the guard nodes of the circuit. The methods proposed by Biryukov *et al.* [31] discussed previously can be used for that. Next, the sniper attack is used to disable these guards, forcing the HSs to select a new set of guards. These steps can be repeated until the adversarial guard node is selected as the entry node for the HS. The authors argue that even though it is possible to use the sniper attack to de-anonymise Tor clients, it is much easier to attack HSs because they create circuits on demand.

Iacovazzi *et al.* [100] introduce an inverse flow watermarking attack called *INFLOW* to de-anonymise HSs. The authors argue that in previous watermarking attacks, the attack was only effective in tracking watermarks from source to destination, as a watermark only travels in the direction of the traffic flow. They claim that *INFLOW* is the first technique that can insert a watermark at the destination which is detectable at the source. It exploits Tor's congestion management, which stops sending messages until an ACK for the previous message is received. When the user is downloading large amounts of content from a server, there are increased traffic flows from the server to the client, whereas only a few packets and ACKs are transmitted from the client to the server. Therefore, sometimes this amount of traffic from the client to user may not be enough to ensure that watermarks are embedded. However, using this concept, a modified client can drop bursts of ACKs and prompt traffic patterns from the server which can be identified by an attacker-controlled HS guard node.

Iacovazzi *et al.* [101] present a more recent active traffic analysis attack called the *Duster Attack*. In this attack, the objective is to de-anonymise HSs. A malicious client and a set of guard relays are used for the attack. Firstly, the attacker selects a HS and starts downloading content from it after establishing a connection. During the data transfer, a watermark is injected into the traffic by the Tor client. If a malicious guard detects this watermark, it will record the IP address of the circuit endpoint and cancel the watermark. Tor uses a technique based on SENDME cells for congestion control, which can be exploited to embed the signal into the Tor traffic in this type of attack. Iacovazzi *et al.* experiment on the live Tor network, and claim that this attack possesses the following properties, lacking in previous active attacks in

the literature: 1. it works on both standard and rendezvous circuits, 2. it is hidden from the target endpoint, 3. it has a small overhead and does not affect network performance, 4. it exploits vulnerabilities in Tor's congestion control mechanism, and 5. it works on Tor versions up to 2019. Table IV provides a summary of all the attacks on HSs that we have discussed in this paper while Figure 12 depicts the evolution from 2004 to 2020 of all the attacks we have discussed.

VI. SECURITY AGAINST DE-ANONYMISATION: A DEVELOPER'S PERSPECTIVE

In this section, we try to provide insights into some of the main security improvements and changes to Tor that are designed to protect it against de-anonymisation attacks. We try to present these changes from the perspective of a developer. For this, we select several articles from the *Tor Blog* (<https://blog.torproject.org/>) and we summarise the important information in them. A three-part article series [104], [105], [106] written in 2012, presents major changes in Tor since its initial design paper in 2004 [6]. We will first discuss the security-related changes in these articles, and then move on to some of the later updates.

A. Security Improvements in the Directory System

In the initial Tor versions, every router in the network generated a *router descriptor* which was signed and uploaded onto one of the DSs [104]. Every DS created a signed list of its descriptors and sent them to the clients at their request. Among the many issues of the above mechanism, were a few security concerns as well. 1. There was no distributed trust and each DS was trusted individually. Hence, a compromised DS could be used to execute an attack on all its clients. 2. The directory content was not encrypted and easy to eavesdrop on. 3. Disagreeing DSs could divide client knowledge, which could allow an attacker to categorise clients based on their recent connections to DSs. There were a few changes in DSs along the way, including assigning flags (such as *fast*, *stable*, *good guard nodes*) to nodes before the introduction of a directory voting system. Under the directory voting system, the DSs would share periodic vote documents and produce a

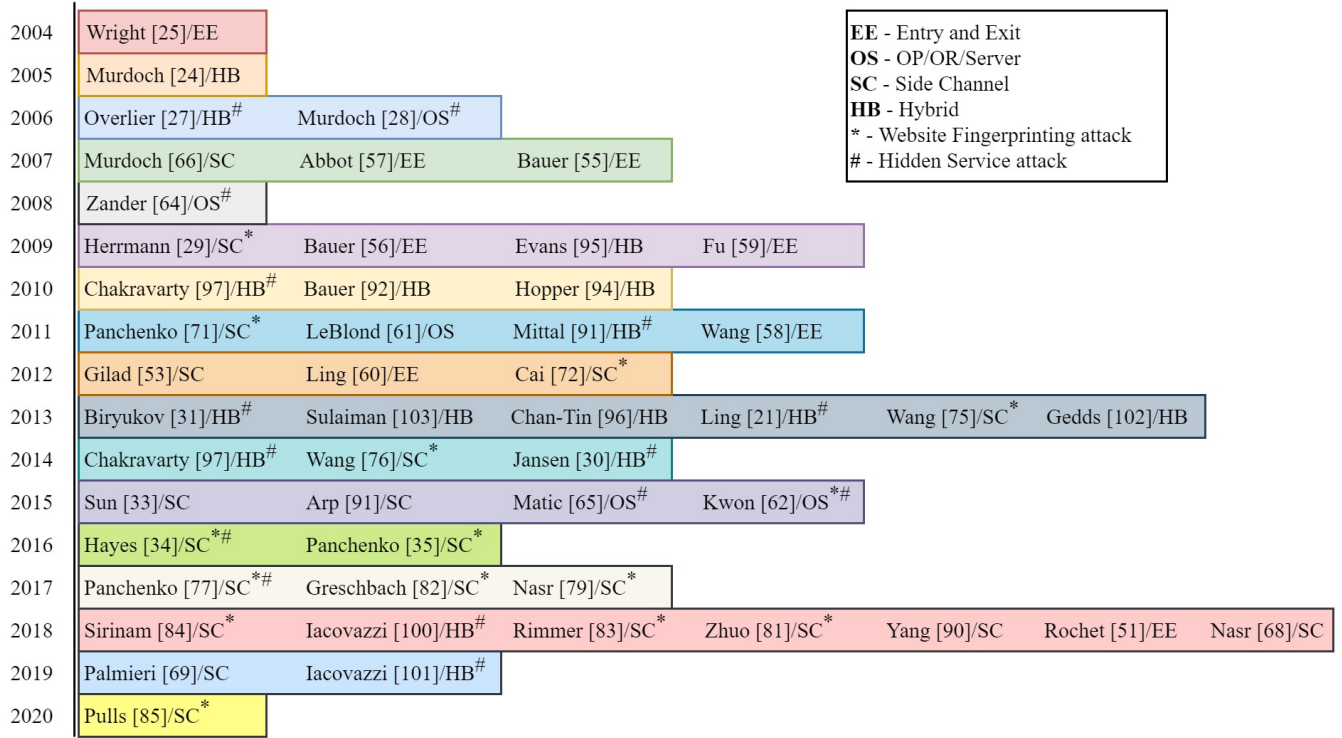


Fig. 12. Evolution of De-anonymisation Attacks

consensus document, and every DS would sign it. As a result, the clients only needed to download one document and make sure it was signed by a majority of known DSs. These changes helped to address some security issues that were in the original design.

B. Introducing Guard Nodes

In Section II, we briefly introduced guard nodes and their purpose. Several of the early de-anonymisation attacks were based on having an adversary-controlled entry node. Based on the recommendations of Overlier *et al.* [27], Tor implemented the *Guard Node* feature to reduce the probability of circuits being compromised [105]. Ordinary Tor nodes are now assigned guard flags based on several features such as bandwidth and uptime. Once a Tor client selects a set of guard nodes it will keep them for 30-60 days. This greatly reduces the chances of an adversary compromising circuits by introducing new Tor nodes and expecting them to be selected as entry nodes. On the other hand, if an adversary-controlled node is selected as a guard node, the adversary has a significant chance of achieving their objective, as that node will repeatedly be used for many circuits for a considerable duration.

C. Introducing Bandwidth Authorities

The nodes of a circuit were uniformly picked at random in the earliest versions of Tor. However, this created many bandwidth bottlenecks, hugely impacting Tor's performance. As a result, the Tor protocol was changed to select nodes proportionally to node's bandwidth and based on its capabilities (e.g. entry guard, exit node). This feature increased the chances

of attackers compromising more circuits by claiming high bandwidths for the nodes under their control. Initially, a maximum bandwidth limit was imposed to minimise the impact of this, but later a set of *Bandwidth Authorities* were assigned to measure and vote on the observed node bandwidth. These measured values were published in the *consensus document*, preventing the previous loophole. Also, honest node operators were allowed to declare their nodes under the same *family*, to stop the client from selecting two nodes from the same family in the client's circuit. This prevented node operators from unintentionally having their nodes selected as both entry and exit nodes of a circuit.

D. Mitigating Linkability Attacks

We mentioned a couple of attacks related to linking Tor streams in Section V (e.g. the bad apple attack [61], [93]). Due to the computational and bandwidth overhead to the network when creating new circuits, Tor clients try to reuse circuits, sending multiple TCP streams through them. The issue with this scenario is that if one stream leaks information to de-anonymise the user, a compromised exit node may be able to de-anonymise other streams in that circuit as well [61]. To mitigate this risk, Tor limits the circuit usage time to ten minutes before switching to a new circuit. The Tor user also has the ability to create new circuits for new streams and configure Tor to isolate streams based on the destination IP/port. By default, Tor separates streams from different clients, different SOCKS ports on a Tor client or SOCKS connections with distinct authentication credentials.

E. A Defence Against Website Fingerprinting

We discussed several WF attacks on Tor over the years. However, it was only following Panchenko *et al.*'s attack [71] in 2011 that Tor developers became concerned with securing the Tor network from such attacks. Panchenko *et al.* used new features based on volume, timing and the direction of traffic, which led to the successful outcome of their attack. In an article in 2011 [74], its author mentions an experimental defence they deployed against WF attacks. The proposed defence - introduced as *Random pipelining* - was aimed at reducing the information leakage that enabled the extraction of features used by Panchenko *et al.*. Additionally, the author of the article questions the practicality of WF attacks in the live Tor network, a notion which was critically analysed and supported later by the work of Juarez *et al.* [78].

F. Security Against the Relay Early Confirmation Attack

In July 2014, the Tor development team identified a set of malicious relays in the live network which they believed were trying to de-anonymise Tor users [107]. These relays were in the network for almost five months and were able to obtain *Guard* and *HSDir* flags. The compromised relays were used to execute an attack known as the *relay early confirmation attack*, which was an active attack that exploited a vulnerability in Tor's protocol headers. A new type of cells known as *relay early cells* were introduced in 2008 to prevent the creation of long paths in Tor circuits [95]. These cells were used in the above attack, hence giving the attack its name. In this attack, when the onion proxy tries to either publish or retrieve a service descriptor from an attacker-controlled HSDir node, it will insert a signal into the traffic using the above-mentioned vulnerability in relay early cells. The attacker-controlled guard nodes are then able to identify this signal at the other end. After finding out about this issue, all the malicious relays were removed from the network. Moreover, a fix for the issue was given with the next version update of the Tor protocol. Additionally, the above incident brought into attention the importance of monitoring bad relays in the Tor network. Therefore, any interested party can now report any suspicious relays (malicious, damaged or misconfigured) to the Tor project [108]. The development team would then investigate the issue and take necessary actions.

G. Deploying a Padding Scheme

Following up on the traffic analysis attack suggested by Chakravarty *et al.* [99] that makes use of flow records, the Tor development team published a couple of articles explaining that although this type of attack is theoretically possible, it would be hard to execute it practically against the live Tor network [109], [110]. They interpreted the 6% false-positive rate⁷ as meaning that 6000 out of 100000 flows will look similar, rendering it ineffective when scaled. Furthermore, the authors of the articles asserted that Tor protects its users by encryption of data within the Tor network, authentication of

relays and use of signatures to make sure all clients have the same relay information. In another article from 2015 [111] written about the circuit fingerprinting attack against HSs by Kwon *et al.* [62], the author of the article brings up a similar argument about Kwon *et al.*'s attack not being scaled in reality. However, in response to the approach introduced by Kwon *et al.* to identify traffic between different circuit components, Tor has deployed a padding scheme to disguise the client-side traffic in HS circuit creation [112].

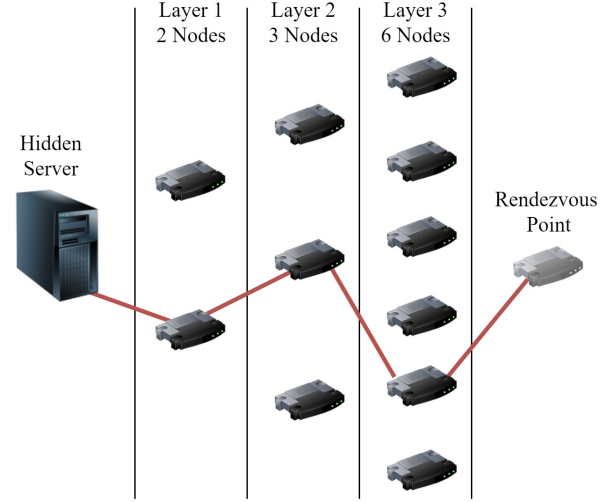


Fig. 13. Vanguard system: 2-3-6 Topology

H. Introducing the Vanguard System

There have been real-world attacks against Tor hidden services. In November 2014, 16 European countries along with the United States Intelligence agencies brought down several marketplaces hosted as HSs through a coordinated international action called *Operation Onymous* [113]. Under this operation, the LEAs took down 410 HSs and arrested 17 people who were suspected to be running the operations. The notorious dark market known as the Silk Road 2.0 [7] was also shut down and its operator was arrested. In response to this massive scale attack, the Tor development team acknowledged that they were unsure as to why this attack was carried out and how it was carried out [114]. In an article published shortly after the above attack [114], they discuss possible scenarios that might have enabled this attack. HS operators' failure to use adequate operational security measures, the exploitation of web bugs such as SQL injections or remote file inclusions are some such scenarios. The authors of [114] advised the HS operators to be better informed about HSs' security limitations and to make sure their services do not lack adequate memory, processing, and network resources. The authors also suggested to manually select known and trusted relays as the guard nodes of the HS.

In 2018, the Tor project released the first stable version of Tor and the Tor browser for the V3 onion service protocol [115]. According to the article [115], this protocol version provides more secure onion addresses and improved authentication to HSs. It further provides service enumeration

⁷In the original paper this value is 5.5% although in the article [109], this is used as 6%

resistance and upgraded cryptography. However, the authors of the article claim that the new upgrade does not address any de-anonymisation attacks against HSs. Also, they state that the highest threat faced by HSs at present are the *Guard Discovery* attacks. As the second and third nodes of the HS-RP circuit are selected from all existing Tor relays in the network, an adversary can force circuits until it is selected as the middle node and can then identify the guard node [31], [30]. The guard nodes can then be compromised, attacked or surveilled until the IP address of the HS is obtained. To address this issue, Tor introduces a 3-component add-on to be used with HSs [115]. As shown in Figure 13, the *Vanguard* component introduces second and third layer guards. In addition, to further increase the anonymity provided by this system, the circuit lengths (e.g. Client - RP, HS - RP) will also be altered. The *Bandguard* checks for bandwidth side-channel attacks and closes circuits more than 24 hours old, and circuits that are transmitting the maximum threshold of megabytes. The third component of the add-on known as the *RendGuard*, analyses RPs to check whether they have been overused. The aim of this component is to minimise the use of malicious RPs in potential attacks.

I. Mitigating the Risks of Website Oracles

In a follow up article [116] to the WF attack with WO by Pulls *et al.* [85], the Tor development team mentions that they are concerned about the use of low cost, high coverage WOs such as DNS and RTB [89] to assist attackers. In [116], the authors suggest some precautions that can be taken by various user groups to mitigate the risks of this situation. Users can engage in multiple activities at once with the Tor client, exit relay operators can avoid high-risk public DNS resolvers and stay up to date with Tor releases, and HS operators can use V3 onion services. Additionally, in an article on *Browser Fingerprinting* [117], a technique that is becoming popular to de-anonymise users, it is explained that Tor has always been concerned with such techniques, and the Tor browser is currently one of the most resilient browsers against browser fingerprinting attacks.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we classified Tor attacks into four main categories based on the objective of the attack and explained those categories with examples. Following this, we elaborated on de-anonymisation attacks with a taxonomy based on the components used for attack execution. Under the classification of de-anonymisation attacks, we provided a corpus of attacks published in the literature, giving brief descriptions on how the attacks are executed and how de-anonymisation is achieved. We also provided insights into the evolution of these attacks over the years. Finally, we discussed several security related issues in Tor using information on articles written by the Tor development team.

We noticed a few important features while completing this work. 1. Most of the earlier de-anonymisation attacks focus on compromising network components of the Tor circuit. The main reason for this is the low number of relays in the

Tor network at the time they were published. However, with Tor's increasingly popularity, the number of voluntary relays has increased and the practicality of the attacks that can be executed by compromising a small set of Tor relays has decreased. Therefore, recent attacks assume passive adversaries that can observe the traffic at the source and destination links. 2. Techniques and concepts from other research domains have inspired Tor researchers to introduce novel attack schemes for Tor [79] [81]. 3. Recent works are also experimenting with techniques such as deep learning [68] [84] to attack the Tor network.

Our work provides an up-to-date review of the most important Tor attacks. It also provides new insights into how a critical class of these attacks, the de-anonymisation attacks, have evolved over the years. Important issues on the deployment of these latter attacks on the live Tor network are also provided. We hope our review and the insights it provides will form a useful resource to the wider Tor research community.

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