Honey Onions: a Framework for Characterizing and Identifying Misbehaving Tor HSDirs

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***Abstract*—In the last decade, Tor proved to be a very successful and widely popular system to protect users' anonymity. However, Tor remains a practical system with a variety of limitations, some of which were indeed exploited in the recent past. In particular, Tor's security relies on the fact that a substantial number of its nodes do not misbehave. In this work we introduce, the concept of honey onions, a framework to detect misbehaving Tor relays with HSDir capability. This allows to obtain lower bounds on misbehavior among relays. We propose algorithms to both estimate the number of snooping HSDirs and identify the most likely snoopers. Our experimental results indicate that during the period of the study (72 days) at least 110 such nodes were snooping information about hidden services they host. We reveal that more than half of them were hosted on cloud infrastructure and delayed the use of the learned information to prevent easy traceback.**

I. Introduction

Over the last decade, Tor emerged as a popular tool and infrastructure that protects users' anonymity and defends against tracking and censorship. It is used today by millions of ordinary users to protect their privacy against corporations and governmental agencies, but also by activists, journalists, businesses, law enforcements and military [1].

The success and popularity of Tor makes it a prime target for adversaries as indicated by recent revelations [2]. Despite its careful design, that significantly improved users privacy against typical adversaries, Tor remains a practical system with a variety of limitations and design vulnerabilities, some of which were indeed exploited in the past [3], [4]. Due to the perceived security that Tor provides, its popularity, and potential implication on its users, it is important that the research community continues analyzing and strengthening its security.

This is specially important since users typically have a poor understanding of the privacy protection that Tor really provides as evidenced by past events. For instance, in a highly publicized case, security researchers collected thousands of sensitive e-mails and passwords from the embassies of countries including India and Russia [5]. These embassies used Tor believing it provides end-to-end encryption, sending sensitive un-encrypted data through malicious exit nodes. Other research revealed that many users run BitTorrent over Tor, which is insecure and resulted in deanonymization [6]. Finally, recent incidents revealed that the Tor network is continuously being attacked by a variety of organizations from universities to governmental agencies, with difficult to predict ramifications [3], [7]. Even more recently, the still unexplained sudden surge in the number of hidden services (`.onion`), more than tripling their number before returning to relatively smaller numbers (See Figure 1), indicates that the Tor network is not well understood, in part due to its peer-to-peer nature, the privacy services it provides that limit measurements, and the attacks that it attracts [8].

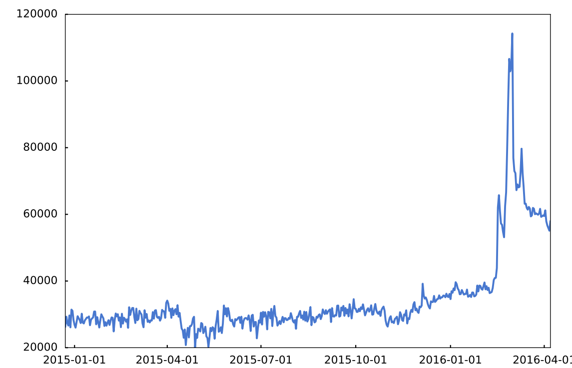


Fig. 1: Recent unexplained surge in the number of Hidden Services. The number of hidden services (`.onion`) suddenly tripled, before settling at twice the number before the surge.

Tor's security, by design, relies on the fact that a substantial number of its relays should not be malicious. It is however difficult to assess to what extent this condition holds true. The fact that many attacks are passive, makes it even harder to assess the significance of this threat. In this work, we developed a framework, techniques, and a system to provide some elements of the answer to this challenging problem.

We introduce the concept of *honey onions* (`honions`), to expose when a Tor relay with Hidden Service Directory (HSDir) capability has been modified to snoop into the hidden services that it currently hosts. We believe that such a behavior is a clear indicator of sophisticated malicious activity, for it not only is explicitly undesired by the Tor Project [9] but also requires a modification to the Tor software, indicating some level of sophistication of the perpetrator. Honions are hidden services that are created for the sole purpose of detecting snooping, and are not shared or publicized in any other form. Therefore, any visits on the server side of the honion is a clear indication that one of the HSDir that hosted it is snooping. Since hidden services are hosted on multiple HSDirs and change location on a daily basis, it is not easy to infer which

HSDir is the malicious[1] one. The visits information leads to a bipartite graph connecting honions and HSDirs. Finding the smallest subset of HSDirs that can explain honion visits provides a lower-bound on the number of malicious HSDirs. This has the benefit of giving a sense of the scale of malicious behavior among Tor relays. We show that this problem can be formulated as a Set Cover, an NP-Complete problem. We develop an approximation algorithm to this specific problem as well as an Integer Linear Program (ILP) formulation. We build a system to deploy the honions along with a schedule for the lifetime of each one of them to maximize the collected information without generating an excessive number of hidden services. The generated honions have a lifetime of one day, one week, or one month. Throughout the experiment, which lasted 72 days so far, the maximum number of generated honions did not exceed 4500 hidden services (which is significantly lower than the anomaly that hidden services are experiencing). Based on the experimental data, we are able to infer that there are at least 110 snooping HSDirs. A careful analysis of the experimental data and results from the ILP solution, allows us to infer most of the misbehaving HSDirs and their most likely geographical origin. Based on these results we are able to classify misbehaving HSDirs in two main categories, *immediate snoopers*, and *delayed snoopers*. Immediately and deterministically visiting a honion results in a higher detection and identification. However, delaying and randomization reduces the traceability (as other HSDir who hosted the honion could also be blamed) at the expenses of potentially missing key information that the hidden service creator might put for only a short period of time. Therefore, a smart HSDir snooper has to trade-off delay (and risk of missing information) with risk of detection. In this paper, we discuss the behavior and characteristics of the malicious HSDirs. We found out that more than half the malicious HSDirs are of the delayed type, and are hosted on cloud infrastructure. Our contributions can be summarized as follows:

- The honey onion framework for detecting snooping HSDirs.
- An approximation algorithm and Integer Linear Program for estimating and identifying the most likely snooping HSDirs.
- An experimental study leading to the discovery of at least 110 snooping HSDirs and a peek into their behavior.

The rest of the paper is structured as follows. In Section II we overview the architecture of Tor hidden services and HSDirs. Section III outlines our approach, and system architecture. Section IV provides the formalization of the detection and identification problem, shows the reduction to the set cover problem, and the approximation algorithm as well as the Integer Linear Programming formulation. In Section V, we discuss our implementation of the system, report on the experimental results when processed by the identification algorithms. In Section VI we discuss the experimental results and the characteristics and behavior of malicious HSDirs. In Section VII we summarize the prior and related work. We conclude the paper in Section VIII.

[1] In this paper, we use the terms malicious and snooping interchangeably.

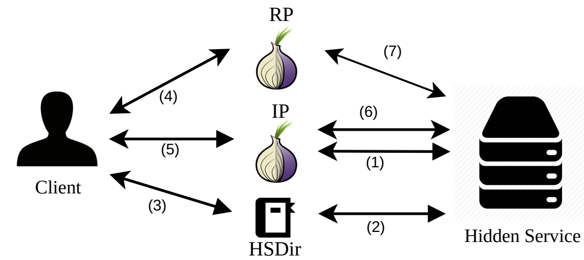


Fig. 2: Tor hidden service architecture and connection setup.

II. Hidden Services & Hidden Service Directories

Tor [10] is an anonymity network that allows users to circumvent censorship and protect their privacy, activities and location from government agencies and corporations. Tor also provides anonymity for the service provided with hidden services, which enables them to protect their location (IP address), yet allowing users to connect to them. Hidden services have been used to protect both legitimate and legal services for privacy conscious users (e.g., Facebook), and for illicit purposes such as drug and contraband market [11], [12], and extortion. This attracts attacks from a variety of actors. In order to understand the specific HSDirs snooping misbehavior we are interested and the honion system setup and algorithms, we first summarize some key mechanisms of Tor. In particular, we focus on the architecture of hidden services, both from the client and the service provider perspective.

The Tor hidden services architecture is composed of the following components:

- *Server*, that runs a service (e.g., a web server).
- *Client*, that wishes to access the server.
- *Introduction Points (IP)*, a set of Tor relays, chosen by the hidden service, that forward the initial messages between the server and the client's Rendezvous Point.
- *Rendezvous Point (RP)*, a Tor relay randomly chosen by the client that forwards the data between the client and the hidden service.
- *Hidden Service Directories (HSDir)*, a set of Tor relays chosen by the server to store its descriptors.

Server. To enable access to a server, the service provider, generates an RSA key pair. Then he calculates the SHA-1 digest of the generated public key, known as the `Identifier` of the hidden service. The `.onion` hostname is the base-32 encoding of the identifier. To connect to a hidden service, the aforementioned identifier needs to be communicated to the clients through an external out-of-band channel. As depicted in Figure 2, the hidden service, chooses a set of relays, called Introduction Points (IP), and establishes Tor circuits with them (step 1). After setting up the circuits, the hidden service calculates two service descriptors to determine which relays are the responsible HSDirs, using the below formula and uploads the descriptors to them (step 2).

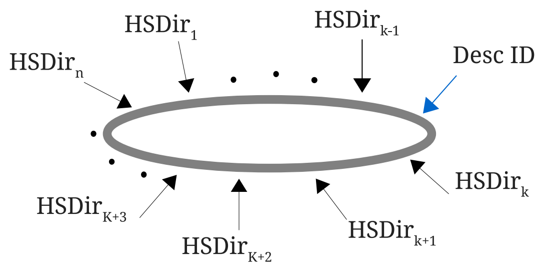


Fig. 3: Fingerprints circle or Hidden Service Directories (HSDir) and placement of a hidden service descriptor.

$$\begin{aligned}
\texttt{descriptor-id} &= \texttt{H(Identifier}||\texttt{secret-id-part)} \\
\texttt{secret-id-part} &= \texttt{H(time-period}||\texttt{descriptor-cookie} \\
&\quad \texttt{||replica)} \\
\texttt{time-period} &= (\texttt{current-time} + \\
&\quad \texttt{permanent-id-byte} * 86400/256) \\
&\quad /86400
\end{aligned}$$

In the above equations, `H` is the SHA-1 hash digest. `Identifier` is the 80 bit truncated SHA-1 digest of the public key of the hidden service. `Descriptor-cookie` is an optional 128 bit field which could be used for authorization. The hidden services periodically change their HSDir. The `time-period` determines when each descriptor expires and the hidden services need to calculate the new descriptors and upload them to the new corresponding HSDirs. To prevent the descriptors from changing all at the same time, the `permanent-id-byte` is also included in the calculations. The `Replica` index, takes values of 0 or 1, and results in two descriptors. Each descriptor is uploaded to 3 consecutive HSDirs, a total of 6. Consider that the circle of HSDirs is sorted based on their fingerprint (SHA-1 hash of their public key) as shown in Figure 3. If the descriptor of a hidden service falls between the fingerprint of HSDir$_{k-1}$ and HSDir$_k$, then it will be stored on HSDir$_k$, HSDir$_{k+1}$ and HSDir$_{k+2}$.

Client. When a client wishes to contact a hidden service, he first needs to compute the `descriptor-id` using the above formula, and contact the corresponding HSDirs (step 3). To communicate with a connection with the hidden services, the client first needs to choose a set of random relays as his Rendezvous Point (RP), and establish a circuit with them (step 4). Then he contacts the hidden service's IPs to indicate his desire to contact the hidden service, and announcing his RPs (step 5). Then, the IP will forward this information to the hidden services (step 6). At last, the hidden service establishes a circuit to the RPs, and the two can start communicating.

III. Approach

In the following we overview the approach and the architecture of our detection platform. The steps of flow of actions is depicted in Figure 4. It consists of the following main components.

A. HOnions Generation

In order to automate the process of generating and deploying honions in a way that they cover a significant fraction of HSDirs, we developed several scripts. The scripts create configuration files for Tor relays, called `torrc`. In particular, the torrc files specifies the SOCKS port, the hidden service directory to store and read the private key, the advertised port of hidden service, and the port where a server is running on the localhost as described in the next subsection.

A key constraint in this process was to minimize the number of deployed honions. This derives primarily from our desire to not impact the Tor statistics about hidden services (specially given the recent surge anomaly). Secondarily, given that behind each honion there should be a running process to serve the pages and to log the visits, we are practically limited by our infrastructure hardware/server capabilities. We now discuss the process that allowed us to determine how many honions should be generated to cover at least 95% of the HSDir for every batch.

If each honion was only placed on a single random HSDir, the probability for each HSDir to host an honion is $p_0 = \frac{1}{N_{hsdirs}}$, where N_{hsdirs} is the number of HSDirs. Since there are two descriptors, derived independently, this is equivalent to doubling the number of honions (m). Since each descriptor is placed on a set of three adjacent HSDirs, the probability of a descriptor being hosted on a HSDir is approximated by $p \approx 3p_0 = \frac{3}{N_{hsdirs}}$. After generating m honions, the probability that an HSDir is not covered by the $2m$ descriptors is approximated $(1-p)^{2m}$. To cover a fraction f of HSDir, we need:

$$f = 1 - (1 - \frac{3}{N_{hsdirs}})^{2m}$$

This implies that the necessary honions to be generated should be as follows:

$$m = \frac{\log(1-f)}{\log(1-(1-\frac{3}{N_{hsdirs}}))}$$

Using this formula and considering that the number of HSDirs N_{hsdirs} is approximately 3000, we could infer that we need to generate 1497 (rounded to 1500) honions to cover all HSDirs with 0.95 probability. We used 1500 honions per batch (daily, weekly, or monthly) and could verify that 95% of the HSDirs were systematically covered therefore validating our approximation.

An alternative approach would have been to generate a very large number of honions or interactively generating them until all HSDirs are covered. However, both approaches have drawbacks and limitations. For instance, to iteratively cover the HSDirs, one needs to have a perfect synchronization between the generation process and Tor consensus documents. As for generating a large number of honions, it can overload the Tor network, disturb its statistics primitives, and also requires us to run an excessive number of server processes.

B. HOnion back end servers

Each honion corresponds to a server process/program that is running locally. The server behind hidden services, should not be running on a public IP address. Otherwise it can be detected and deanonymized by exploiting its unique strings and other leakages. This has become relatively easy given the availability of databases of the whole Internet scans [13]. To avoid leaking information we return an empty page for all the services. It does not allow an adversary to draw any conclusion about the hosting server. We initially considered using fake pages mimicking real typical hidden services websites. However, similarities between pages might alert an adversary about the existence of a honeypot/honey onion.

C. HOnions generation and deployment schedule

To keep the total number of honions small, we decided on three schedules for the generation and placement of the honions, *daily*, *weekly*, and *monthly*. The three schedules allow us to detect the malicious HSDirs who visit the honions shortly (less than 24 hours) after hosting them. Since the HSDirs for hidden services change periodically, more sophisticated snoopers may wait for a longer duration of time, so they can evade detection and frame other HSDirs. The daily schedule would miss such snoopers, therefore we defer to the weekly and monthly honions to spot such adversaries. Imagine there is a visit on weekly or monthly honions, while there is no visits to the daily honions. Since all honions are running simultaneously, and all HSDirs are hosting honions in all three schedules, this indicates that some malicious HSDirs are delaying their snooping. For the adversary, this a trade-off between accuracy and stealthiness, since some hidden services may have a short life span and will be missed by the snooping HSDir if he waits too long.

D. Logging HOnions visits

We log all the requests that are made to the server programs and the time of each visit. The time of a visit allows us to determine the HSDirs that have hosted any specific honion. Recording the content of the requests allows us to investigate the behavior of the snoopers. Since we advertise our servers on port 80, we can investigate the request types and content that are made by snoopers. Furthermore, we can detect automated headless crawls as opposed to the requests made by browsers (e.g., Tor browser), since they make request for extra elements such as the small icon that is shown in the browser near the URL address bar (i.e., favicon.ico).

E. Identifying snooping HSDirs

Based on the visited hidden server, the time of the visit, and the HSDir that have been hosting the specific onion address prior to the visit, we can mark the potential malicious and misbehaving HSDirs. Then we add the candidates to a bipartite graph, which consists of edges between HSDirs and the visited honions, as further described in section IV. The analysis of this graph allows us to infer a lower bound on the number of malicious HSDirs as well as the most likely snoopers.

IV. Estimation & Identification of Snooping HSDirs

In order to formally reason about the problem of identifying malicious HSDirs, we first introduce a formal model and notation for the Honey Onions system. First, HO denotes the set of honey onions generated by the system that were visited, and HSD the set of Tor relays with the `HSDir` flag (so far referred to as HSDir relays). The visits of honions allow us to build a graph $G = (V, E)$ whose vertices are the union of HO and HSD and edges connect a honion ho_j and HSDir d_i iff ho_j was placed on d_i and subsequently experienced a visit. G is by construction a bipartite graph.

$$
\begin{aligned}
HSD &= \{d_i : \text{Tor relays with } \texttt{HSDir} \text{ flag}\} \\
HO &= \{ho_j : \text{Honey Onion that was visited}\} \\
V &= HSD \cup HO \\
E &= \{(ho_j, d_i) \in HO \times HSD | ho_j \text{ was placed on } d_i \\
&\quad \text{and subsequently visited}\}
\end{aligned}
$$

We also note that each honion periodically changes descriptors and therefore HSDirs (approximately once a day). However, a HSDir currently a honion ho cannot explain visits during past days. Therefore, each time a honion changes HSDirs we clone its vertex ho to ho' and only add edges between ho' and the HSDirs who know about its existence when the visit happened.

A. Estimating the number of snooping HSDirs

Since each honion is simultaneously placed on multiple HSDirs, the problem of identifying which ones are malicious is not trivial. We first formulate the problem of deriving a lower-bound on their number by finding the smallest subset S of HSD that can explain all the visits (meaning that for each visited honion, there is a member of S who knew about its existence and could therefore explain the visit). The S is therefore a solution to the following problem:

$$\underset{S \subseteq HSD}{\operatorname{argmin}} |S : \forall (ho_j, d_i) \in E \exists d_i' \in S \wedge (ho_j, d_i') \in E| \qquad (1)$$

The size s of the minimal set tells us that there cannot be less than s malicious HSDirs who would explain the visits. Furthermore, when s is relatively small compared to N_{hsdirs}, any HSDir identified as an explanation of multiple visits is highly likely to be malicious. This derives from the fact that the probability of co-hosting a honion with a malicious HSDir once being small, it decreases exponentially as a function of number of visits.

B. Reduction from set cover

Finding the smallest set S as defined by Equation 1, is not trivial as one can easily see that it is equivalent to the hitting set problem, which itself is equivalent to the set cover problem. The set cover problem is well known to be NP-Complete. An intuitive sketch of proof for the equivalence to set cover is as follows. For each HSDir d_j define the set of honions $O_j = \{ho_i | (ho_i, d_j) \in E\}$. Solving Equation 1

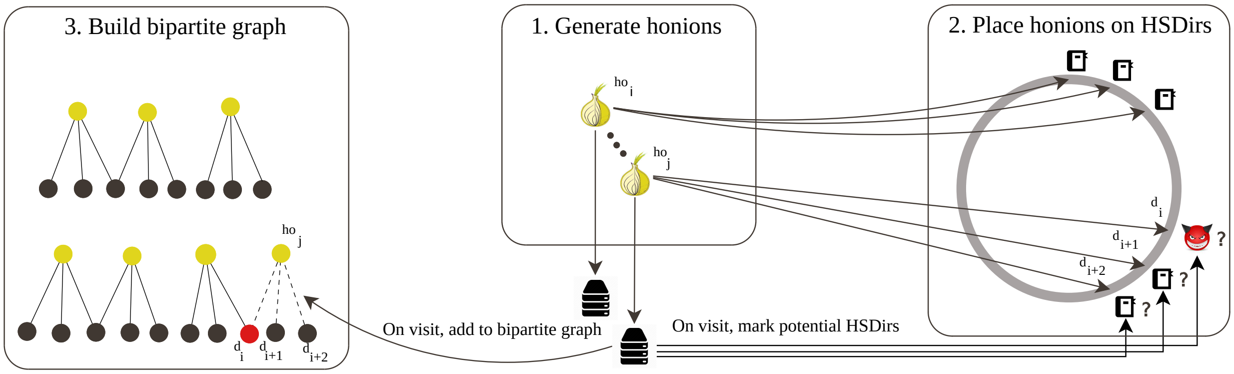


Fig. 4: Flow diagram of the honion system. We generate a set of honions to cover all the HSDirs and run a server behind each one, Here, we only show one descriptor per honion. When a visit happens to one of the honions, we can infer which HSDirs hosted it (and knew about its existence) using the consensus document and the list of relays. After identifying the potential suspicious HSDirs, we add the candidates to the bipartite graph.

amounts to finding the smallest set of O_j that covers all the visited honions. The set cover problem has an $\ln(n)+1$ approximation algorithm where n is the size of the set to be covered [14]. Based on this, we derive the following heuristic, with $\ln(|HO|)+1$ approximation ratio. The advantages of this heuristic is its low computation complexity $O(|E|)$.

Input: $G(V,E)$: Bipartite graph of honions to HSDirs
Output: S: Set explaining visits
$S \leftarrow \emptyset$
while $V \cap HO \neq \emptyset$ **do**
  Pick $d \in V \cap HSD$: with highest degree
  $V \leftarrow V \setminus \{d$ and its honion neighbors$\}$
end

Algorithm 1: Minimal HSDir Heuristic

C. Formulation as an Integer Linear Program

Solving the problem defined by Equation 1, can also be formulated as an Integer Linear Program. Let $x_{1\leq j\leq|HSD|}$ be binary variables taking values 0 or 1. Solving Equation 1, consists of finding Integer assignments to the x_j such that:

$$\begin{array}{ll} \min_{(x_1,\ldots,x_{HSD})} & \sum_{j=1}^{|HSD|} x_j \\ \text{subject to } \forall ho_i \in HO & \sum_{\forall j:(ho_i,d_j)\in E} x_j \geq 1 \end{array}$$

While this ILP will give the optimal solution, it has exponential computation complexity in the worst case. In a subsequent section, our experimental results show that although it performs fairly well for our setup, it is significantly slower than the heuristic.

V. Detection Infrastructure & Results

In this section we discuss the implementation and deployment of the detection infrastructure as highlighted in Section III and depicted in Figure 4.

Cloud	Exit	Cloud & Exit	Not Cloud & Not Exit
81	27	23	25

TABLE I: Type of the snooping HSDirs. More than 70% are hosted on Cloud.

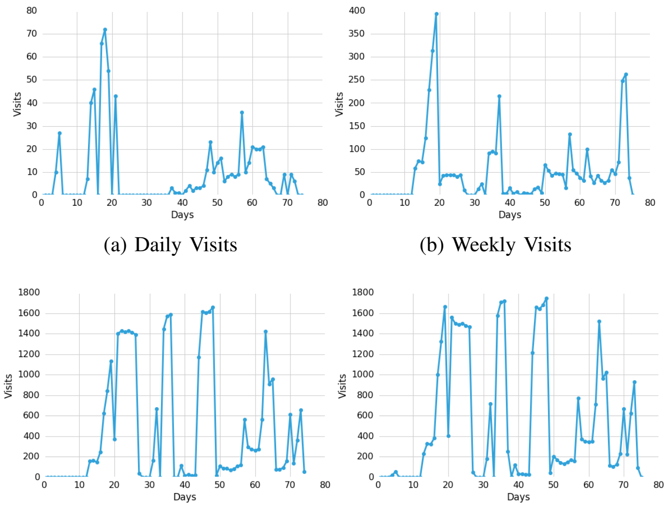
Alibaba	Digital Ocean	Online S.A.S.	OVH SAS	Hetzner Online GmbH
15	7	7	6	6

TABLE II: Top 5 Cloud Providers.

A. Implementation and Deployment of the Detection Platform

We developed simple HTTP servers to listen on specific ports for incoming requests. Upon receiving a request, each server would log the time and full request into separate files. At first we developed the HTTP servers using Python and Flask web framework. However, because of the size that is occupied by the framework and the interpreter we faced difficulties in scaling our detection platform. The programs when instantiated in memory would take up to 40 MB, including the shared libraries. Running 1500 instances would take up to 12GB. Meaning each instance on average could take about 8-9 MB. As a result, we decided to port the code to C, without using any external third party library or framework. We relied solely on the BSD Sockets API. This allowed us to reduce the size of the code including the shared libraries to 6 MB. Running 1500 instances with the ported code only occupied around 2GB, meaning each instance on average occupied less than 1.5 MB, therefore, reducing the resource allocations by 6 times.

We distributed the 1500 honions over 30 Tor relays equally, to avoid overloading a single relay and reducing performance and responsiveness of the hidden services. We created scripts that would automatically generate and place new honions based on the three schedules discussed earlier (daily, weekly, monthly). Each schedule was running on a separate Virtual Machine to isolate the infrastructures.



(a) Daily Visits

(b) Weekly Visits

(c) Monthly Visits

(d) All Visits

Fig. 5: Plot of the visits to the honions. The daily onions show snooping HSDirs, before the "mystery" spike in hidden addresses. The number and intensity of the visits is increased after the spikes.

B. Analyses of the Results and Observations

We started the daily honions on Feb 12, 2016; the weekly and monthly experiments on February 21, 2016, which lasted until April 24, 2016. During this period there were three spikes in the number of hidden services, with one spike more than tripling the average number of hidden services (Figure 1). First spike was on February 17, second on March 1 (the largest), and the last on March 10. These spikes attracted a lot of attention from the media [15]. However, there is still no concrete explanation for this sharp influx of hidden services. There are some theories suggesting that this was because of botnets, ransomware, or the success of the anonymous chat service, called Ricochet. However, none of these explanations can definitely justify the current number of hidden services.

Our daily honions spotted snooping behavior before the spike in the hidden services, this gives us a level of confidence that the snoopings are not only a result of the anomaly (Figure 5a). Rather, there are entities that actively investigate hidden services. Note that, we started the weekly and monthly honions after the first spike, even more sophisticated entities may have been active before, which we are not able to detect. As we can see in Figure 5 the visits from snooping HSDirs increases after the "mystery" spikes. Note that, the delay between the appearance and activity of the snooping HSDirs and the surge of hidden services, is because of the time it takes for a relay to acquire the HSDir flag (96 hours and the Stable flag) [16], [17]. Also, whenever a relay gets restarted it loses its HSDir flags, and they would not see the new honions, therefore, it introduce further gaps in the daily visits (Figure 5a), while the weekly (Figure 5b) and monthly (Figure 5c) visits would still spot activity even if the HSDir loses its flag.

Snooping HSDirs Nature. In total we detected at least 110 malicious HSDir using the ILP algorithm (the ILP took about 2 hours), and about 40000 visits. More than 70% of these HSDirs are hosted on Cloud infrastructure. Around 25% are exit nodes as compared to the average, 15% of all relays in 2016, that have both the HSDir and the Exit flags. Furthermore, 20% of the misbehaving HSDirs are, both exit nodes and are hosted on Cloud systems. The top 5 cloud providers are Alibaba-California (15 detected HSDirs), Digital Ocean (7), Online S.A.S. (7), OVH SAS (6), and Hetzner Online GmbH (6). Table II summarizes the cloud providers and the number of malicious HSDirs each one is hosting. Alibaba cloud belongs to Alibaba Group, the Chinese e-commerce company, with servers in the US, Europe and Asia. All instances that we spotted were hosted on the US West Coast data centers. Digital Ocean is an American cloud provider that targets software developers, located in New York. Online S.A.S and Hetzner Online GmbH are two German cloud provider, and OVH SAS is another European cloud provider, located in France. Exit nodes play a significant and sensitive role in the Tor platform, and can cause legal problems for their operators [18]. At the same time it is known that some Exit nodes are not benign and actively interfere with users' traffic. There is a `Bad Exit` flag, to warn users not to use these relays as exit nodes. None of the exit nodes that we identified have been identified as Bad Exit nodes. This can be because they do not perform active MITM attacks, and evade detection. Table I summarizes the type of the HSDir relays.

Figure 6 illustrates a typical bipartite graph of a daily visit. The black nodes indicated the malicious HSDir marked by ILP. The gray nodes are the honions that have been visited, and the colored nodes are all other HSDirs that have hosted the honions. Note that many of the honions belong to a separate component in the graph, and in one connected component more than one HSDir is suspicious.

Snooping HSDirs Geolocation. Figure 7 depicts the most likely geolocation and type of the misbehaving HSDirs. In the interest of space we have omitted the only HSDir in Australia. The black icons represent the HSDirs hosted on a cloud platform that are exit nodes as well. The Red icons represents the nodes hosted on clouds that are not exit nodes, the blue icons represent the exit nodes that are not hosted on the cloud, and the green icons are the relays that are neither exit nodes, nor hosted on the cloud. Our results indicate that there are no snooping HSDirs in China, Middle East, or Africa. It is not surprising since in these regions and countries Tor is heavily blocked [19]. Furthermore, more than 70% of the snooping HSDirs are hosted on Cloud systems, and many of the cloud providers' data centers are located in Europe and Northern America. Table III summarizes the top 5 countries where the malicious HSDirs are located. Note that 15 of the 37 HSDir in the USA, belong to Alibaba cloud data centers, followed by Digital Ocean and Linode.

Classifying the Behavior and Intensity of the Visits. Most of the visits were just querying the root path of the server and were automated. However, we identified less than 20 possible manual probing, because of a query for favicon.ico, the little icon that is shown in the browser, which the Tor browser requests. Some snoopers kept probing for more information even when we returned an empty page. For example, we had queries for `description.json`, which is a proposal to all HTTP servers inside Tor network to allow hidden

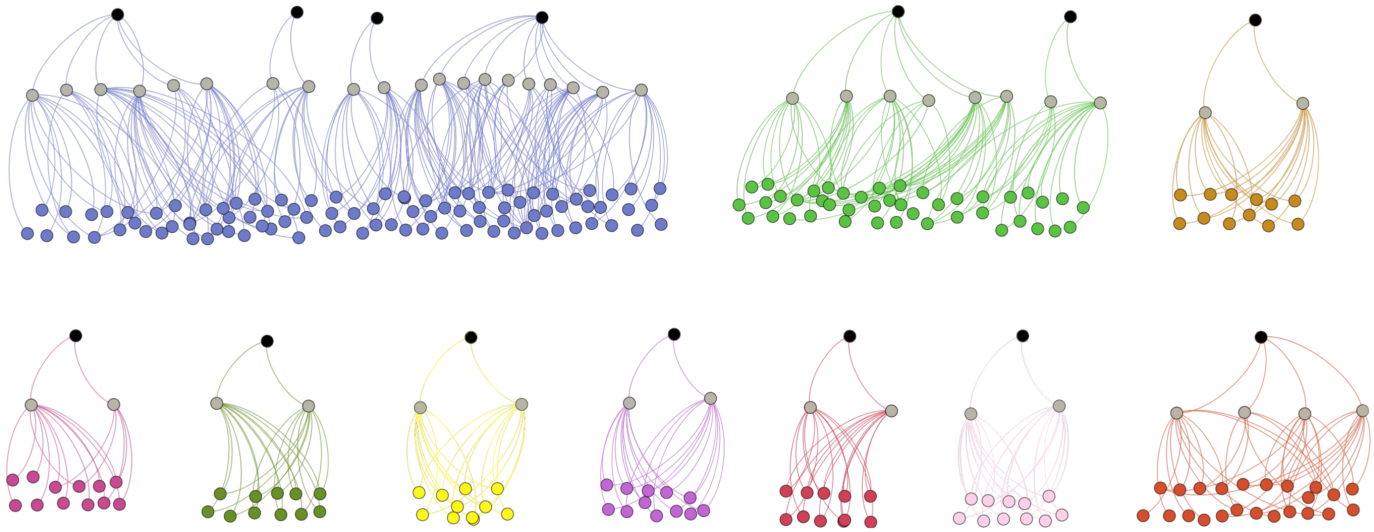


Fig. 6: A typical graph representation of the visited honions, and the hosting HSDirs. The black nodes are the candidate malicious HSDirs calculated by the ILP algorithm. The gray nodes are the visited honions, and the colored nodes are all the HSDirs that hosted the honions, prior to a visit.

USA	Germany	France	UK	Netherlands
37	19	14	8	4

TABLE III: List of top 5 countries with the most likely misbehaving HSDirs.

services search engines such as Ahmia, to index websites. We identified a small number of well behaving civilized crawler, asking for robots.txt and sitemap. One of the snooping HSDirs (5.*.*.*:9011) was actively querying the server every 1 hour asking for a server-status page of Apache. It is part of the functionality provided by mod_status in Apache, which provides information on server activity and performance. This can be an indication of the adversaries' effort for reconnaissance and finding vulnerabilities and generally more information about the platform. Tools such as onionscan [20] look for such characteristic to ensure attackers cannot easily exploit and deanonymize hidden services, because of an oversight in the configuration of the services. Additionally, we detected different attack vectors, such as SQL injection, targeting `the information_schema.tables`, username enumeration in Drupal (admin/views/ajax/autocomplete/user/), cross-site scripting (XSS), path traversal (looking for `boot.ini` and `/etc/passwd`), targeting Ruby on Rails framework (rails/info/properties), and PHP Easter Eggs (?=PHP*-*-*-*-*).

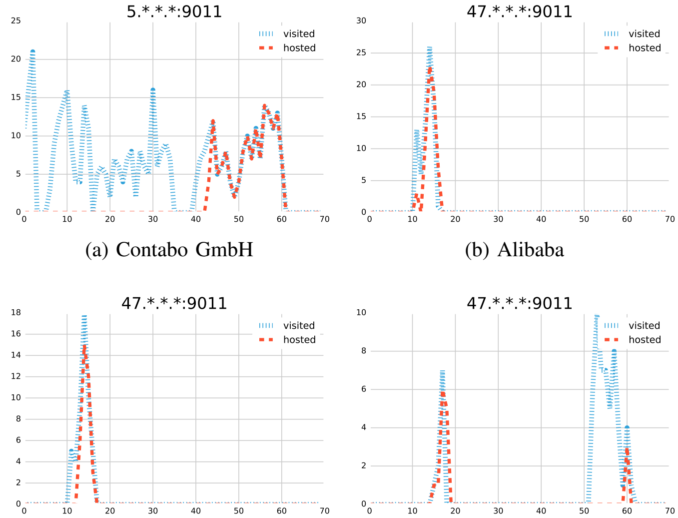
In general the snoopers showed a wide range of behavior. Some only appeared after the first spike in the number of hidden services and disappeared afterwards and gone offline (Figures 8b & 8c) (gone offline), while some of them came back after a month (Figure 8d). On the other hand, one snoopers changed its behavior and turned into a snooping HSDirs after a while (Figure 8a).

Fig. 7: The global map of detected misbehaving HSDirs and their most likely geographic origin (in the interest of space we have omitted the only HSDir in Australia). The black icons represent the HSDirs hosted on a cloud platform that are exit nodes as well. The Red icons represents the nodes hosted on cloud that are not exit nodes, the blue icons represent the exit nodes that are not hosted on the cloud, and the green icons are the relays that are neither exit nodes, nor hosted on the cloud.

VI. Discussion & Future Work

Based on our observations not all snooping HSDirs operate with the same level of sophistication. While some do not visit the hosted honions immediately and therefore evade detection though daily honions, our weekly and monthly honions can detect them. We believe that behavior of the snoopers can be modeled and categorized into four groups. Persistent-Immediate snoopers, where they immediately (within a day) and systematically probe all .onion addresses they service. Persistent-Delayed, where they systematically probe all .onion addresses they service but with a fixed delay d. Randomized with Deterministic Delay, where they probe a learned .onion address with probability p after d days. Probabilistic Snoopers, where once they learn about .onion addresses, they probe, after d days, according to distribution function $p(d)$. Further work is needed to define more models and develop techniques to detect and identify the more sophisticated snoopers.

Since some HSDirs, probe deep in the hidden services,



(a) Contabo GmbH (b) Alibaba (c) Alibaba (d) Alibaba

Fig. 8: The behavior of the HSDirs. Some of them turned malicious after a while, and some disappeared shortly after the spikes in the number of hidden services.

by using vulnerability discovery and automated attack tools, it would be interesting to create pages with login forms or more enticing content to engage the snoopers. However, one should carefully consider the legal and ethical aspects of such investigations and studies.

The rise and popularity of cloud services allows entities to provision infrastructures without much overhead, which makes it difficult to detect malicious Tor nodes. In this competitive market many cloud providers try to distinguish themselves by providing more privacy and anonymity for their clients. For example, `flokinet.is`, advertises its services as a platform suitable for freedom of speech, investigative journalism, and perfect for whistleblowers, with servers in Romania, Finland, and Iceland. Although, one can not deny the benefit of such privacy infrastructures, they can also be subverted and misused for malicious and harmful activities. Furthermore, cloud providers such as Vultr, even accepts payments in the form of bitcoins, which prevents the traceback and identification of misbehaving entities.

It is noteworthy that we continued the deployment of the honions, and after making our work public [21], we observed a new trend of snooping behavior. The snoopers delay their visits to avoid identification, which indicates that the misbehaving HSDirs have already adapted their techniques. Figure 9 depicts the new trend of visits, where snoopers are becoming more sophisticated and delay their visits. Note that, we count multiple visits to the same honion within one day, only once for this graph. We also discussed our work with some of the Tor Project people [22] and learned that they have been aware of the problem and developed techniques (although different from ours) to identify and block misbehaving HSDir relays. Furthermore, they are also working on a new design to mitigate various attacks against hidden services [23]. Another direction is to explore the capabilities of Intel SGX [24], [25], and make modifications to Tor to run inside enclaves [26].

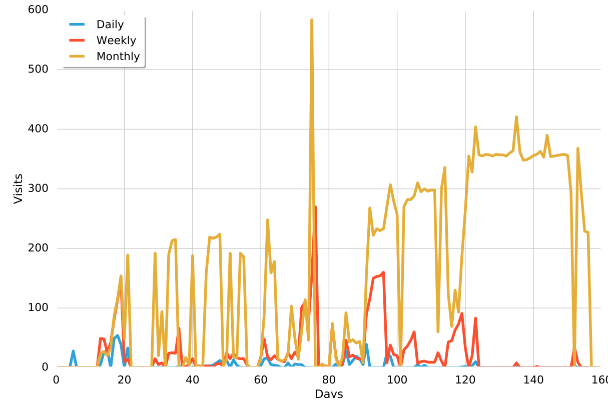


Fig. 9: The new trend of visits. The snoopers are delaying their visits to avoid identification.

VII. Related Work

Previous research studied malicious traffic and misbehaving relays in the Tor network, however it was mostly limited to the traffic carrying relays and exit nodes [27], [28], [29], [30]. Our work focuses on detection and classification of misbehaving hidden services directories (HSDirs), an essential component of the hidden services architecture and the privacy of users. Winter et al. [31] expose malicious exit nodes by developing two exit relay scanners, one for credential sniffing and one for active man-in-the-middle (MITM) attacks. The authors discovered 65 malicious or mis-configured exit relays participating in different attacks. They proposed an extension to the Tor browser to thwart MITM attacks by such malicious exit nodes. In another work [32], the authors propose *sybilhunter*, a technique to detect Sybil relays based on their characteristics such as configuration, fingerprint, and uptime sequence using the consensus document. Ling et al. [33] present TorWard, a systems for the discovery and the systematic study of malicious traffic over Tor. The system allows investigations to be carried out in sensitive environment such as a university campus, and allows to avoid legal and administrative complaints. The authors investigate the performance and effectiveness of TorWard by performing experiments and showing that approximately 10% of Tor traffic can trigger IDS alert.

Other work explored attacks against Tor to deanonymize users and hidden services. For example, Biryukov et al. [34], document their findings on probing the network topology and connectivity of Tor relays. The authors demonstrate how the leakage of the Tor network topology can be used in attacks to traceback from an exit node to a small set of possible entry nodes. Therefore, defeating the anonymity of the users in Tor. In another work [4], the authors discover and exploit a flaw in the design and implementation of hidden services in Tor, which allows an adversary to measure the popularity of any hidden service, block access to hidden services, and ultimately deanonymize hidden services.

Other research looked at the content and popularity of hidden services and the leakage of .onion address. Biryukovhs et al. [35] collected 39824 hidden services descriptors and scanned them for open ports. The author findings reveal that the majority of hidden services belong to botnets, followed by adult content and drug markets. Another study [36], measures the leakage of onion addresses at the root DNS servers (A and J), and provides the popularity of different hidden services categories based on the leaked requests.

VIII. Conclusion

Tor is a widely popular system for protecting users anonymity. However, at its core it relies on the non-malicious behavior of its peer-to-peer nodes. In this work, we introduced honey onions, a framework for methodically estimating and identifying the most likely Tor HSDir nodes that are snooping on hidden services they are hosting. We propose algorithms to both estimate the number of snooping HSDirs and identify them. Our experimental results indicate that during the period of the study (72 days) at least 110 such nodes were snooping information about hidden services they host. We reveal that more than half of them were hosted on cloud infrastructure and delayed the use of the learned information to prevent easy traceback. Another interesting finding is that although a large number of snooping HSDirs were hosted on US IP addresses (37), several (15) were actually hosted on Alibaba's data center in California.

IX. Acknowledgements

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References

[1] "Tor metrics," https://metrics.torproject.org/userstats-relay-country.html.

[2] "Tor stinks presentation," https://edwardsnowden.com/wp-content/uploads/2013/10/tor-stinks-presentation.pdf, 2013.

[3] "Confirmed: Carnegie mellon university attacked tor, was subpoenaed by feds," http://motherboard.vice.com/read/carnegie-mellon-university-attacked-tor-was-subpoenaed-by-feds, February 2016.

[4] A. Biryukov, I. Pustogarov, and R. Weinmann, "Trawling for tor hidden services: Detection, measurement, deanonymization," in *Security and Privacy (SP), 2013 IEEE Symposium on*, 2013.

[5] "Security researcher intercepts embassy passwords from tor," http://www.infoworld.com/article/2649832/security/security-researcher-intercepts-embassy-passwords-from-tor.html, September 2007.

[6] S. Le Blond, P. Manils, A. Chaabane, M. A. Kaafar, C. Castelluccia, A. Legout, and W. Dabbous, "One bad apple spoils the bunch: Exploiting p2p applications to trace and profile tor users," in *Proceedings of the 4th USENIX Conference on Large-scale Exploits and Emergent Threats*, ser. LEET'11.

[7] "Deanonymizing tor hidden service traffic through hsdir is a cake walk, say researchers: Hitb presenters showcase new threats," http://www.idigitaltimes.com/deanonymizing-tor-hidden-service-traffic-through-hsdir-cake-walk-say\researchers-hitb-445328, May 2015.

[8] A. Sanatinia and G. Noubir, "Onionbots: Subverting privacy infrastructure for cyber attacks," in *The Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN)*, 2015.

[9] "Tor onion services: more useful than you think," https://media.ccc.de/v/32c3-7322-tor_onion_services_more_useful_than_you_think, 2015.

[10] R. Dingledine, N. Mathewson, and P. Syverson, "Tor: The second-generation onion router," in *Proceedings of the 13th Conference on USENIX Security Symposium*, 2004.

[11] N. Christin, "Traveling the silk road: A measurement analysis of a large anonymous online marketplace," in *Proceedings of the 22Nd International Conference on World Wide Web*, ser. WWW, 2013.

[12] "'silk road 2.0' launches, promising a resurrected black market for the dark web," http://www.forbes.com/sites/andygreenberg/2013/11/06/silk-road-2-0-launches-promising-a-resurrected-black-market-for-\the-dark-web, November 2013.

[13] Z. Durumeric, D. Adrian, A. Mirian, M. Bailey, and J. A. Halderman, "A search engine backed by internet-wide scanning," in *Proceedings of the 22nd ACM SIGSAC Conference on Computer and Communications Security*, 2015.

[14] T. H. Cormen, C. Stein, R. L. Rivest, and C. E. Leiserson, *Introduction to Algorithms*, 2nd ed. McGraw-Hill Higher Education, 2001.

[15] C. Baraniuk, "Tor: 'mystery' spike in hidden addresses," http://www.bbc.com/news/technology-35614335.

[16] arma, "Getting the hsdir flag should require the stable flag," https://trac.torproject.org/projects/tor/ticket/8243.

[17] asn, "Update spec with regards to 25-26 hours hsdir flag uptime that turned to 96 hours." https://trac.torproject.org/projects/tor/ticket/14149.

[18] Tor, "Five years as an exit node operator," https://blog.torproject.org/blog/five-years-exit-node-operator.

[19] M. C. Tschantz, S. Afroz, Anonymous, and V. Paxson, "Sok: Towards grounding censorship circumvention in empiricism," in *Security and Privacy (SP), Symposium on*, 2016.

[20] "Scan onion services for security issues," https://github.com/s-rah/onionscan/, April 2016.

[21] G. Noubir and A. Sanatinia, "Honey onions: Exposing snooping tor hsdir relays," in *DEFCON 24*, 2016.

[22] Donncha O'Cearbhaill, Personal Communication, 2016.

[23] "Next-generation hidden services in tor," https://gitweb.torproject.org/torspec.git/tree/proposals/224-rend-spec-ng.txt.

[24] P. Jain, S. J. Desai, M.-W. Shih, T. Kim, S. M. Kim, J.-H. Lee, C. Choi, Y. Shin, B. B. Kang, and D. Han, "Opensgx: An open platform for sgx research," in *NDSS*, 2016.

[25] G. Noubir and A. Sanatinia, "Trusted code execution on untrusted platform using intel sgx," in *Virus Bulletin*, 2016.

[26] V. Costan and S. Devadas, "Intel sgx explained," Cryptology ePrint Archive, Report 2016/086, 2016, http://eprint.iacr.org/2016/086.

[27] A. Kwon, M. AlSabah, D. Lazar, M. Dacier, and S. Devadas, "Circuit fingerprinting attacks: Passive deanonymization of tor hidden services," in *24th USENIX Security Symposium (USENIX Security 15)*, 2015.

[28] R. Jansen, F. Tschorsch, A. Johnson, and B. Scheuermann, "The sniper attack: Anonymously deanonymizing and disabling the tor network," DTIC Document, Tech. Rep., 2014.

[29] Y. Sun, A. Edmundson, L. Vanbever, O. Li, J. Rexford, M. Chiang, and P. Mittal, "Raptor: Routing attacks on privacy in tor," in *24th USENIX Security Symposium (USENIX Security 15)*, 2015.

[30] K. Bauer, D. McCoy, D. Grunwald, T. Kohno, and D. Sicker, "Low-resource routing attacks against tor," in *Proceedings of the 2007 ACM workshop on Privacy in electronic society*, 2007.

[31] P. Winter, R. Köwer, M. Mulazzani, M. Huber, S. Schrittwieser, S. Lindskog, and E. Weippl, "Spoiled onions: Exposing malicious tor exit relays," in *Privacy Enhancing Technologies*, 2014.

[32] P. Winter, R. Ensafi, K. Loesing, and N. Feamster, "Identifying and characterizing sybils in the tor network," *arXiv preprint arXiv:1602.07787*, 2016.

[33] Z. Ling, J. Luo, K. Wu, W. Yu, and X. Fu, "Torward: Discovery, blocking, and traceback of malicious traffic over tor," in *IEEE Transactions on Information Forensics and Security*, 2015.

[34] A. Biryukov, I. Pustogarov, and R.-P. Weinmann, "Torscan: Tracing long-lived connections and differential scanning attacks," in *Computer Security–ESORICS 2012*, 2012.

[35] A. Biryukov, I. Pustogarov, F. Thill, and R. P. Weinmann, "Content and popularity analysis of tor hidden services," in *ICDCSW*, 2014.

[36] M. Thomas and A. Mohaisen, "Measuring the leakage of onion at the root: A measurement of tor's. onion pseudo-tld in the global domain name system," in *Proceedings of the Workshop on Privacy in the Electronic Society*, 2014.