Tor circuit fingerprinting defenses using adaptive padding

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Abstract

Online anonymity and privacy has been based on confusing the adversary by creating indistinguishable network elements. Tor is the largest and most widely deployed anonymity system, designed against realistic modern adversaries. Recently, researchers have managed to fingerprint Tor’s circuits – and hence the type of underlying traffic – simply by capturing and analyzing traffic traces. In this work, we study the circuit fingerprinting problem, isolating it from website fingerprinting, and revisit previous findings in this model, showing that accurate attacks are possible even when the application-layer traffic is identical. We then proceed to incrementally create defenses against circuit fingerprinting, using a generic adaptive padding framework for Tor based on WTF-PAD. We present a simple defense which delays a fraction of the traffic, as well as a more advanced one which can effectively hide onion service circuits with zero delays. We thoroughly evaluate both defenses, both analytically and experimentally, discovering new subtle fingerprints, but also showing the effectiveness of our defenses.

1 Introduction

Tor uses circuits for anonymous communication. Tor circuits are multi-hop paths through the Tor network carrying application data. There are various types of circuits, some of them for navigating the regular Internet, others for fetching Tor directory information, connecting to onion services or simply for measurements and testing. Although all traffic is encrypted, it is still possible for certain type of adversaries to distinguish Tor circuit types from each other using a wide array of metadata and distinguishers; such attacks are known as circuit fingerprinting.

Circuit fingerprinting attacks are dangerous because by determining the Tor circuit type, an adversary immediately gets to shrink the “world size” or “base rate” of traffic that it needs to consider for website fingerprinting or end-to-end correlation attacks to succeed [15]. A website fingerprinting adversary who learns that the client is visiting an onion service immediately enjoys a significantly smaller universe size of web pages that it needs to identify, effectively reducing the problem to a closed-world setting [20].

Contributions

In this paper, we study the circuit fingerprinting problem, isolating and formalizing it on its own, separately from other fingerprinting problems. We start by presenting our threat model (§2) and experimental methodology (§3). We then revisit and verify previous results by Kwon et al. [17] (§4) to show that distinguishing onion service circuits is possible with high accuracy, even when the application-layer traffic is identical, by exploiting fingerprints of the onion service protocol itself.

We design and implement a versatile adaptive padding framework (§5) which has since been merged in the mainline Tor client and deployed to the live network. Then, in §6, we proceed by analyzing onion handshakes and demonstrating how we can imitate accurately both their shape and timing characteristics using our adaptive padding framework. Employing our dummy onion handshakes as a primitive, we then design and evaluate two distinct padding defense strategies.

First, we present an intuitive delay-based defense (§7) which delays clearnet traffic to inject a dummy handshake. We show that the latency overhead can be reduced at no privacy cost by delaying only a fraction of the traffic and exploiting the base rate to our advantage. During the evaluation of this defense we also find previously unknown subtle behaviors that can act as circuits fingerprints.

We then present a more advanced zero-delay padding defense that employs preemptive circuits, an optimization mechanism that already exists in Tor. We provide both an analytic evaluation, giving precise expressions relating the parameters of the defense to the classification accuracy, as well as an experimental evaluation, confirming the analytic results, and showing that an effective defense is possible with no delays and limited bandwidth overhead.
**Tor network** The Tor network is among the most popular tools for digital privacy and anonymity. As of September 2020, the Tor network consists of almost 6,500 volunteer-run relays.

In its basic mode, Tor allows its clients to achieve anonymity when connecting to TCP/IP services. This is achieved by forming a virtual circuit through the relays of Tor network in an interactive and incremental fashion. This is typically done by extending the circuit to three hops: the *entry guard*; the *middle*; and the *exit*.

Once a circuit is established, the client, Alice, creates *streams* through the circuit by instructing the exit to connect to the desired external Internet destinations. Each pair of relays communicate over a single onion routing connection that is built using TCP. Application layer protocols rely on this underlying TCP connection to guarantee reliability and in-order delivery of application data, using fixed-size data packets (512 bytes) called *cells*, between each relay. Streams are multiplexed over circuits, which themselves are multiplexed over connections.

In the case of a website, Alice asks the *exit relay* to connect to the destination website and the communication between Alice and the website happens through the resulting circuit. We call the circuit that connects to the normal web an exit circuit and the whole connection a *clearnet connection*.

**Tor Onion services** In addition to client anonymity, Tor allows operators to set up anonymous servers, typically called *onion services* [2]. This is achieved by routing communication between the client and the onion service through a rendezvous point which connects anonymous circuits from the client and the server.

When a client, Alice, connects to an onion service Bob, she first creates a directory circuit (in this work we call it HSDir circuit) and fetches the *descriptor* document of the onion service. The descriptor contains the *introduction points* of the onion service which are also relays on the Tor network.

Alice opens a *rendezvous circuit* to a randomly sampled relay on the Tor network, and asks it to become the *rendezvous point* for this session. Alice then connects to one of the introduction points of Bob using an introduction circuit and instructs Bob to meet at the determined rendezvous point. When Bob connects to the given rendezvous point, the latter bridges Alice’s and Bob’s circuits and the rest of the communication happens over the spliced rendezvous circuit.

During this work, we call the set of an HSDir circuit, introduction circuit and rendezvous circuit the onion service circuit triplet. All the communication over Tor circuits described above occurs using Tor cells and each circuit type has its own unique cell pattern. Recognizing those cell patterns and distinguishing the circuit purposes from each other is the art of circuit fingerprinting that we explore in this paper.

**Related work** While circuit fingerprinting has been assumed to be possible in the past, Kwon et al. [17] were the first to formally present the problem, their methodology and demonstrate successful classifiers against onion service circuits. They extracted specific features from the circuit cell flow and trained classifiers in a way that offered very high accuracy. Kwon et al. focused on entry guard and network-level adversaries launching circuit fingerprinting attacks, while subsequent research by Jansen et al. [12] explored circuit fingerprinting by middle nodes for the purpose of measuring the popularity of specific onion services.

The circuit fingerprinting methodology is inspired by the related field of website fingerprinting. Website fingerprinting was first studied in the context of SSL encrypted traffic [5], and in recent years there is increasing focus in fingerprinting websites over Tor [11, 21, 22]. Website fingerprinting experiments have been using machine learning for classification [29] and feature selection has been deeply studied [26, 33].

In terms of defenses, padding is a well-established technique in the field of low-latency anonymity networks [8, 28]. The WTF-PAD adaptive padding system proposed by Juarez et al. [16] was designed against website fingerprinting and has been shown to be effective and also versatile enough to be used for multiple purposes.

Finally, several attacks have been proposed to deanonymize onion services and their clients using Sybil and other protocol attacks [4, 14, 19].

## 2 Threat model

Tor aims to minimize the amount of metadata leaked to various external adversaries. This work concerns circuit fingerprinting which allows attackers to distinguish onion service connections from other types of connections. In this section, we isolate this problem and investigate the types of adversaries that can launch such attacks. We assume that the attacker is either a network adversary or a relay adversary. This is because the attacker needs to be able to extract fine-grained features out of the client’s traffic and in particular distinguish cells from each other.

A relay adversary can be part of the Tor network by setting up relays as part of a *Sybil attack*. This allows the attacker to spectate or even influence the user’s traffic. During this work, the main adversary class we are concerned about is adversarial guard nodes since they are in position to know the location of the user and hence have more power if they manage to carry out a circuit fingerprinting attack. A guard adversary can perform traffic analysis attacks on the user’s traffic since they have full visibility on the Tor circuit and the cells transferred within. While they cannot see the types or contents of Tor cells, they can still see the exact number of incoming and outgoing cells.

A network adversary can be the network administrator of the user, their ISP, or any other intruder between the user and their guard node. A network-level adversary can collect TCP traces from the user and then use heuristic algorithms
to turn those traces into fine-grained cell sequences. For the purposes of this research we assume this is possible with high accuracy [32]. The website fingerprinting literature has been working with the assumption that this is possible with a high-probability of success [17, 31]; in §9 we discuss how that assumption ties into the circuit fingerprinting problem.

Separating the problems In this work, we tackle the circuit fingerprinting problem, which we believe is a distinct problem, related to, but separate from website fingerprinting.

- In circuit fingerprinting, a relay or network adversary distinguishes circuit types and purposes in a Tor session. It concerns the Tor protocol traffic.
- In website fingerprinting, a relay or network adversary distinguishes websites from each other within a Tor session. It concerns the application-layer traffic.

Separating these problems from each other allows us to isolate them, gain a greater understanding on how they interact with each other and design better defenses.

Website fingerprinting attacks are difficult to defend against because the universe size of web pages is vast and there is no centralized way to make them all look alike. On the other hand, the Tor protocol has a smaller fingerprinting surface and circuit fingerprinting defenses can be designed and deployed with agility through Tor’s protocol upgrades.

Leaving any of those two problems unsolved, allows the adversary to leverage it to solve the other problem. For instance, an adversary who can solve the website fingerprinting problem can use its distinguisher to make circuit fingerprinting easier by classifying all websites found as a specific type of circuit. Similarly, an adversary who can solve the circuit fingerprinting problem can use its distinguisher to make website fingerprinting easier, by classifying non-website circuits as irrelevant for the purposes of website fingerprinting.

With the goal of not conflating these problems, we devise a methodology for studying circuit-fingerprinting in isolation.

3 Experiment methodology

This section describes the methodology employed in all experiments performed in this paper in order to evaluate the various defenses against a circuit fingerprinting adversary.

Data collection, processing and classification Our data consists of 100 real onion addresses, selected based on their popularity and availability. We locally fetched every home page and lightly processed them by stripping off any external resources. Finally, we hosted each cached website on our own server twice: once on a clearnet server, and an identical version on an onion service. Serving the same content over both types of connections follows the core foundation of our methodology of keeping the application-layer traffic identical. The circuit fingerprinting problem is solely concerned with the Tor protocol layer and hence the application-layer traffic should not play a role in the classification process.

To collect the actual traffic traces we used Tor Browser and automated it using Selenium [1]. We patched the Tor client to log fine-grained details about its operation, in particular log every incoming and outgoing cell. During data collection we instructed Selenium to fetch pages off our dataset multiple times. The amount of times and the set of pages to fetch depends on the experiment. Between each page fetch we forced Tor to avoid reusing guards and to create a new set of circuits instead of using already used circuits.

During the website caching procedure, we make sure that every page element is downloaded on our machine and no external resources need to be loaded when we browse our cached web pages. This way we eliminate any obstacles that may arise during a web request, such as broken links or resources that might return corrupted content (CDN resources, URL redirects, etc.).

After the data collection step, we need to prepare the data for classification. For this purpose we created a processing script that reads the Tor log file and keeps track of all the circuits and their cells. The script outputs a dataset for the classifier, depending on the current classification scenario. The latter provides the logic for our processing script to classify circuits as onion-related or not. Each experiment uses a different classification scenario, described in the respective sections of this work. The generated dataset contains an entry for each circuit, including its label (whether it is an onion circuit or not), and a vector of features.

Finally, we pass the processed data to our classifiers. Depending on the experiment, the classifier splits the set of circuits into a training set and a testing set, and then trains itself using the training set. After evaluating different types of machine learning and deep learning classifiers, we used SVM and decision tree classifiers because they are robust and their resulting fingerprints are easy to analyze and comprehend.

The label field of the intermediate file is solely used as ground truth for training purposes, and to measure the final accuracy of the classifier.

Timing analysis methodology While the primary focus of this work are defenses that can imitate the shape of onion circuits, that is their precise cell sequence, we also perform preliminary analysis on the timing fingerprints of onion handshakes in §6. For this purpose, we enhanced our data collection logic to keep the times of incoming and outgoing cells and wrote code that analyzes them to derive statistical data.

We found that working with timing features on the Tor network was complicated because the network’s performance exhibits wild short-term fluctuations due to its unpredictable user model, overuse, and the lack of congestion control [24]. To reduce the timing noise observed in our measurements...
we carried out measurements over multiple days and pruned extreme performance outliers.

Classification Scenarios  Similar to the website fingerprinting world, our experiments also carry the concept of open and closed world. We call an experiment open world when the hosts in the training URL dataset are different from the hosts in the test URL dataset. On the other hand, we call an experiment to be closed world when the training URL dataset and the test URL dataset contain sessions to the same destinations. It is important to note here, that in closed world scenarios we never share the exact same session between training and test sets; instead we share different connection sessions to the same destination.

In the context of this distinction, we should point out that isolating the two problems led us to an interesting observation: while open world scenarios have been traditionally much harder to a website fingerprinting attacker, this asymmetry was not present in our results. The reason is that, in the isolated circuit fingerprinting problem, the fingerprints lie in the Tor protocol itself and not the application-layer content. In other words, an adversary learns to identify any onion circuit, not those to a particular website.

We also employ two types of scenarios based on the number of websites they involve: a single-site scenario contains a single destination hosted both in clearnet and as an onion. The classifier is called to classify whether a visit to the destination happened over clearnet or over onion. This is easier for the classifier and it is meant to model a future hypothetical world where website fingerprinting has been solved and all application-layer traffic is identical.

A multi-site scenario contains multiple destinations hosted both in clearnet and as an onion. The classifier is called to decide whether a visit to the destination happened over clearnet or over onion without knowing the actual destination. This is meant to model the current world where all websites look different and can produce uncertainty to the adversary.

We pick the classification scenarios that suit each experiment. Specifically, a single-site closed scenario is good for demonstrating defenses since classifying a single known website is the easiest scenario for the adversary. On the other hand, a multi-site open scenario is good for demonstrating attacks since classifying multiple unknown websites is the hardest scenario for the adversary.

4 Evaluating vanilla circuit fingerprinting

We start off our work by examining whether the claims of Kwon et al. [17] are still valid if we restrict classification to the circuit fingerprinting problem alone. In particular, we want to examine whether rendezvous and introduction circuits can be differentiated from all other circuits, when the application-layer traffic is identical for both clearnet and onion connections. This is important for ensuring that the information leak lies in the onion service protocol itself.

To perform this experiment, we employ two classifiers: first, a classifier which separates introduction circuits from all other types, and second, a classifier which separates rendezvous circuits from all other types. These classifiers are similar to those of previous research [17], where all circuit types apart from the target type are considered to be noise. Dataset sizes are available in Appendix A.

We used the complete cell sequence (an array of −1 and +1 elements) as a feature vector for classification. This is possible since cells are large and onion websites are generally small, fitting in a few hundred cells. Note that, since cells have fixed size, any shape-related feature (eg. number or percentage of incoming/outgoing cells) can be deduced from this feature vector; we tried including such features explicitly but it made no difference to the classifier. Finally, following [17], we included the lifetime of the circuit as a feature.

For this experiment we used 100 websites from our dataset. In contrast to [17], we used the same websites served over both clearnet and onion connections, in order to restrict classification to the circuit fingerprinting problem alone. In both the closed world and open world setting, our classifiers performed very well having an average accuracy of 98-99%. This shows that circuit fingerprinting is possible without relying on the traffic of the websites themselves; in other words, the traffic pattern produced by the protocol itself can be used as a fingerprint.

Even more importantly, since the traffic pattern of the website is not exploited in the attack, circuit fingerprinting is possible with high accuracy even in the open world model. An adversary with no prior knowledge of a website can infer whether the website is accessed as a clearnet or onion service. In that sense, circuit type fingerprinting is an inherently “closed world” problem, as there are only a handful of different circuit types.

5 An adaptive padding framework for Tor

After confirming that fingerprinting onion connections is indeed possible, we started experimenting with padding defenses by designing an extensible adaptive padding framework based on WTF-PAD [16]. We then implemented it and our padding framework has been merged into upstream Tor since the 0.4.0.1-alpha release. We have also written detailed developer documentation that can be used by researchers to design and experiment with padding defenses in Tor [6]. Since its creation, our framework has been used to protect against website fingerprinting [25] and we envision that it can also be used to build defenses against guard discovery and other correlation attacks [10].

Using the Tor padding framework we can schedule arbitrary circuit-level padding patterns to overlay on top of non-padding traffic; such padding can occur between clients and
relays at any hop of the client’s circuits. Both parties need to support the same padding mechanisms for the system to function. We added a padding negotiation cell to the Tor protocol that clients can use to negotiate with relays which padding patterns should be used.

Padding is performed by padding machines which have finite state. Every state specifies a different form of padding style, or stage of padding, in terms of inter-packet timings and total packet counts. Padding state machines are implemented by filling in a C structure, which specifies the transitions between padding states based on various events, probability distributions of inter-packet delays, and the conditions under which padding machines should be applied to circuits.

This compact C structure representation is designed to function as a microlanguage which can be compiled down into a bitstring. This allows the padding machine’s parameters to be tuned using optimization methods such as gradient descent, or generative adversarial networks. When performing such an optimization search, each padding machine can have a fitness function, which allows researchers to compare padding machines for relative effectiveness [25].

The event driven, self-contained nature of this framework is also designed to make evaluation both expedient and rigorously reproducible.

Minimizing delays in defenses One of the goals of our padding-based defenses, is that we should avoid delaying traffic if possible. Given the low-latency model of Tor, we aim to avoid additional latency by delaying useful traffic as part of our defenses. This means that we want to achieve our security goals only by inserting padding traffic.

We envision that extra padding traffic can scale well in the future since bandwidth costs decrease over time and throughput increases and hence the bandwidth is not our most scarce resource. On the other hand, communication speed between computer links will improve much more slowly.

Padding machines for circuit fingerprinting After deploying our framework to the live Tor network, we tested our framework by designing padding machines that hide introduction circuits, based on the fingerprints identified in [17] and §4. Our deployed machines aimed to make introduction circuits look like directory circuits fetching directory information. The machines obfuscate the handshake sequence of introduction circuits by carefully adding cells to the right place. The padding was initiated by the client and went up to the middle relay, at which point the middle relay replied with padding of its own.

We built and deployed these machines on the live Tor network; in doing so we verified that adaptive padding works and solved various engineering hurdles and issues that arose. We also hardened our framework and improved its correctness which is fundamental for future research on this topic.

On the other hand, we also build a similar machine aimed at hiding rendezvous circuits, which however failed its goal. Repeating the experiments of §4 with this machine enabled, we found that the classification accuracy was only slightly reduced. Moreover, we also discovered that HSDir circuits are fingerprintable and can be used to distinguish between onion and clearnet connections.

The main takeaway from this experiment is that hiding just one circuit of the entire onion service setup is not sufficient to hide the entire onion connection. In the following section, we will explore this more deeply.

6 Onion Handshakes

Our previous experiments have shown that we must convincingly imitate the onion service setup protocol in its entirety. Onion connections are fundamentally different from clearnet connections in that they involve three extra handshakes: the HSDir fetch, the introduction and the rendezvous. If the adversary can fingerprint one of those onion handshakes, they immediately fingerprint the entire connection.

These three handshakes occur on separate circuits and follow the timeline displayed in Fig. 1. First the onion descriptor is fetched from an HSDir, followed by the first half of the rendezvous handshake, followed by the introduction and finally the second half of the rendezvous. After all handshakes are complete, the rendezvous circuit is used for transferring application data, while the other two circuits are destroyed.

To avoid distinguishing onion from clearnet connections, we need to generate dummy HSDir, introduction and rendezvous handshakes. We refer to these three handshakes combined as a dummy onion handshake or dummy triplet. In this section we describe how to generate dummy handshakes.
using adaptive padding, while maintaining both the cell sequence and the timing characteristics of the corresponding real ones. In the following sections, we use onion handshakes as a building block to design two different defense strategies.

**Cell sequence** All onion handshakes have deterministic cell sequences (Fig. 3) which allows us to accurately recreate them using padding machines. For instance, consider a real introduction handshake displayed in Fig. 2. First, the circuit is extended to Middle 2 before the user connection arrives (such preemptive circuits improve performance; they are displayed as dotted lines and further discussed in §8). Then, the introduction involves two round-trips to the Intro Point, one to extend the circuit and another one to establish the intro point.

To generate a dummy introduction handshake, we use a padding machine running on Middle 1. First, the circuit is preemptively extended to Middle 2 as in the paragraph above. Then, for each of the two round-trips to the Intro Point, we instruct the client padding machine to send a padding cell to Middle 1, to which the padding machine of Middle 1 responds with its own padding cell. Using this method, we effectively fake the communication between the client and the Intro Point.

The same technique can be used for HSDir and rendezvous handshakes; the exact sequences are shown in Appendix B. Padding machines using our framework that implement a dummy introduction handshake can be seen in Appendix C.

**Timing analysis** To successfully generate dummy handshakes, our padding machines need to properly imitate the delays of real ones, both between cells of the same circuit and between different circuits. Revisiting the introduction handshake of Fig. 2, the only difference between a real and a dummy handshake is the communication between Middle 1 and the Intro Point, which is faked by the padding machine. (dashed lines in Fig. 2). Hence the machine in Middle 1 needs to emulate the delay between the moment EXTEND is sent and EXTENDED is received from the Intro Point (and similarly for INTRODUCE1/INTRODUCE_ACK). Since the time to process the handshake is negligible compared to network times, we essentially need to imitate the round-trip delay between Middle 1 and the Intro Point.

Delays of the same nature are exhibited on HSDir and rendezvous circuits. For the latter, we need to imitate both the round-trip between Middle 1 and Rend, but also the delay between REND_ESTABLISHED and REND_2 (Fig. 11).

Finally, note that the communication in each circuit starts when the previous one finishes (Fig. 1). Hence, if inter-cell delays are properly imitated, the inter-circuit delays will also match with no extra effort.

**Faking inter-cell delays** Using our methodology from §3, we collected a dataset of the relevant round-trip delays for each pair of cells in onion handshakes. We fitted the resulting distributions in a variety of well-known ones, and found that they can be most accurately approximated by a Log-Logistic model [9]. An example can be seen in Fig. 4 for the round-trip delay between INTRODUCE1 and INTRODUCE_ACK and a dataset of 10,000 circuits.

To experimentally verify our findings we created a dataset of dummy onion handshakes whose inter-cell delays were sampled from the corresponding fitted Log-Logistic distributions. We then ran an experiment against cell traces of real data, in which the +1/-1 feature vector is replaced by the exact inter-cell delays. The resulting accuracy was at most 0.52 in all types of circuits, showing that our ML adversary could not distinguish dummy onion handshakes from real ones, despite the availability of detailed inter-cell timing information.

The next question is when exactly to perform these dummy handshakes, and on which circuits. We answer this question in two different ways, giving rise to two padding strategies...
discussed in the next sections. First, we inject dummy handshakes only in the clearnet traffic while delaying the actual data. Second, we avoid delays by injecting dummy handshakes preemptively, to both clearnet and onion traffic.

7 The fractional-delay strategy

We first present a simple and intuitive strategy which pads clearnet connections to make them look like onion connections: when Tor receives a clearnet request from the user, we pause that request and inject a dummy onion handshake, as described in §6. When the dummy handshake is complete, the clearnet request is resumed by sending the application data over the rendezvous-handshake circuit.

More precisely, when the user tries to access a destination on an exit circuit, the Tor client delays the request and promptly creates two new two-hop circuits, extended to random middle nodes. We then use the techniques from §6 to inject a dummy HSDir handshake to the first circuit and a dummy introduction handshake to the second circuit. Finally, the actual exit circuit for the clearnet connection is created, but we first instruct our padding machine to inject a dummy rendezvous handshake to the circuit before the actual traffic. After the dummy rendezvous handshake is complete, the application data is sent as usual. This procedure, overall, creates three circuits whose traffic looks indistinguishable from a real HSDir, introduction and rendezvous triplet.

This technique makes clearnet connections indistinguishable from onion ones with respect to both the shape (size and cell sequence) and the timing of their traffic. The reason is that the dummy handshake itself is indistinguishable from a real one wrt both its shape and timing (§6), and moreover, it is injected at the exact moment where the real handshake appears in an onion connection.

In the remaining of this section, we first experimentally evaluate the effectiveness of this strategy. Then, we introduce fractional-delay, a simple improvement of this strategy, which reduces latency without sacrificing privacy by padding only a fraction of clearnet connections.

7.1 Experimental evaluation

In this section we perform a thorough evaluation of this strategy, which reveals previously unknown aspects of the network that can act as fingerprints.

As previously discussed, the need to delay traffic makes this defense unimplementable in the currently deployed framework of §5. As a consequence, we evaluate the defense by simulating its padding as part of our experiment pipeline, as follows.

We call fake a circuit with only dummy handshakes sent on it, and padded a circuit with both dummy and real data. First, for each exit circuit in our dataset, we create two new circuits, a fake HSDir and a fake introduction one, simulating those used in the defense. We inject a dummy HSDir handshake to the first circuit and a dummy introduction handshake to the second one, and add them to the dataset. Then, we pad the exit circuit itself, injecting a dummy rendezvous handshake right before the application data. Note that this defense only adds padding to clearnet connections, the onion traffic is not modified at all.

In contrast to previous experiments, using this defense both clearnet and onion connections have three circuits. As a consequence, in our experiments we evaluate the adversary’s ability to distinguish each of the three pairs of circuits independently. More precisely we employ three classifiers: first, a classifier which separates fake HSDir from real HSDir circuits. Second, a classifier which separates fake introduction from real introduction circuits, and third a classifier which separates padded exit from rendezvous circuits.

In terms of the feature space of this experiment, we focus on the entire cell sequence of the circuits involved (encoded as an array of -1 and +1 elements). Since all Tor cells have the same size, by using the entire cell sequence we also inherit any other features related to bandwidth.

Evaluation results We first evaluated these classifiers in a multi-open and a multi-closed dataset consisting of ten different websites (dataset sizes are shown in Appendix A). The results, displayed in Table 1, show that the defense was effective in completely hiding HSDir and introduction circuits in all scenarios. For rendezvous circuits, the defense was also successful in the open world scenario, where the classifier had not seen the same sites during training. In the closed world scenario, however, the adversary has non-negligible accuracy and precision (Appendix, Table 3).

To get a better understanding we then performed the same
Table 1: Accuracy results (delay-based defense)

|                | Fake-HSDir vs HSDir | Fake-Intro vs Intro | Padded-Exit vs Rend |
|----------------|---------------------|--------------------|---------------------|
|                | Dec. Tree | SVM | Dec. Tree | SVM | Dec. Tree | SVM |
| Multi-Closed   | 0.51      | 0.51 | 0.49      | 0.49 | 0.62      | 0.79 |
| Multi-Open     | 0.52      | 0.52 | 0.50      | 0.50 | 0.50      | 0.49 |

experiment in the single-site case, for each one of the same ten websites individually. The results, displayed in Fig. 5, highlight the same behavior: HSDir and introduction circuits are hidden, but rendezvous circuits can be distinguished from padded exit ones for most websites with high accuracy (reaching even 100%).

This behavior is quite surprising, since in principle the cell sequence of padded exit circuits is identical to those of rendezvous circuits. By examining the fingerprints used by our classifiers we managed to identify a surprising find that causes this behavior. In all experiments we tried to keep the application-layer data identical, by having identical content served from web servers with identical configurations. Still, the actual application-layer traffic did not seem to match in terms of cell sequences. We found the following two major issues that caused this unexpected phenomenon.

**Cell packing difference**  The biggest fingerprint exploited by our classifiers is the fact that cell packing is different between clearnet and onion connections. Specifically, in the onion case, the cell packing is done by the onion server, who typically receives the data from a web server running on the same machine. This means that the web server transmits application-layer data to the onion server via a high-bandwidth localhost connection, allowing the provider to optimally package that application-layer traffic into cells.

However, in the clearnet case, the cell packing is done by the exit node, who receives the data from the destination web server over a remote connection, possibly from a different continent. As a consequence, unpredictable networks delays are added to the application-layer traffic before it reaches the exit node, causing cells to be packed more loosely, but also a higher variance in the resulting number of cells.

The number of cells observed in our experiments for a specific website are shown in the Appendix (Fig. 14). Rendezvous circuits are clearly packed more densely, but also have less variance in their cell count.

**Latency influences the application-layer data**  Another, more subtle but present fingerprint was the fact that the inherent latency difference between exit and rendezvous circuits (due to the different number of hops) was creating fingerprintable patterns on application-layer cell sequences. In particular, we found that, for complex websites, the Tor Browser’s scheduling of the various page resources (images, scripts, etc) was sensitive to latency differences, causing, for instance, images to be predictably loaded in a different order over clearnet connections than over onion ones. Note that Tor Browser opens multiple TCP connections to fetch resources, which is important for this fingerprint to appear. However, the exact reason why the scheduling order is so predictably different is unclear and left as future work.

Finally, it should be noted that the two fingerprints described in the previous sections both lie in the application data, not the onion service protocol itself. As a consequence, they highly depend on the traffic patterns of each individual website, which is why the defense was effective in the open-world scenario, but ineffective in the closed-world (Table 1).

### 7.2 Bypassing the hurdles

The two fingerprints described in the previous paragraphs are fundamental, affecting the majority of onion service setups. Defending against them is possible but challenging.

With respect to the cell packing fingerprint, we believe that onion servers can work around it by placing the underlying service endpoint on a remote host. It is also possible to enhance our padding machines so that they emit additional padding cells on rendezvous circuits to simulate the non-optimal cell packing of exit circuits. With respect to the Tor Browser’s scheduling fingerprints, a defense could be to limit the number of concurrent connections to a single one (however that would negatively impact performance), or to improve the scheduling
algorithm to make it insensitive to latency differences.

Although such defenses are an interesting topic for future work, they are beyond the scope of this paper, which focuses on the onion service protocol itself and not on the application layer. For this reason, in the remaining of this paper we work around the above issues and evaluate our defenses under the assumption that such issues are not present. In particular, we employ a Tor network running completely on a single machine, using the Chutney Tor emulator, avoiding the problem of cell packing differences and ensuring that the application-layer cell length is the same in both clearnet and onion connections. Furthermore, we use wget instead of the Tor Browser to avoid the fingerprints caused by scheduling issues.

With these workarounds applied, we repeated the experiment of §7.1. The results for the multi-open and multi-closed scenarios, displayed in Table 2, show that the defense is now effective in hiding all types of circuits, with an accuracy close to 0.5 even in the multi-closed case. Similarly, the results for the 10 individual single-site scenarios, displayed in Fig. 6, also show low classification accuracy for all circuit types.

### 7.3 Fractional delay: exploiting the base rate

So far, our defense involved generating a dummy handshake triplet for every clearnet connection, while delaying the actual traffic. This strategy was successful in preventing circuit fingerprinting attacks, but introduces considerable latency to the vast majority of Tor traffic. We can, however, employ a simple trick to significantly improve the performance without sacrificing privacy: pad only a fraction of connections. For each clearnet connection we perform a probabilistic choice; with probability \( p \) we generate a dummy onion handshake while delaying the traffic, while with probability \( 1 - p \) we open the clearnet connection immediately without any padding.

This might appear as sacrificing privacy: the lack of an onion handshake immediately reveals that the connection is clearnet, while its existence provides evidence that the connection is onion. However, an accurate judgment requires taking into account the base rate \( c \), defined as the percentage of clearnet connections in the network. The number of clearnet and onion connections in Tor are far from equal; based on experimental measurements from 2018, the network saw about 216 million exit circuits [13], while 15 million successful rendezvous circuits daily [18], giving an approximate estimate of \( c = 0.93 \).

Let \( N \) denote the total number of onion handshakes (either dummy or real) and \( S \) denote the connection type which we wish to keep secret, namely \( S = 0 \) for clearnet and \( S = 1 \) for onion connections. Note that the base rate is equal to \( c = \Pr[S = 0] \) (prior probability). As already shown, the shape of an onion handshake can be easily observed by the adversary, but real and dummy handshakes are indistinguishable. As a consequence, in the following analysis we assume that \( N \) is the only information available to the adversary; since onion connections always produce a (real) handshake, while clearnet ones produce a (dummy) handshake with probability \( p \), we have that \( \Pr[N=1 \mid S=1] = 1 \) and \( \Pr[N=1 \mid S=0] = p \).

This leads us to the following result:

**Theorem 7.1.** The accuracy of the optimal classifier predicting \( S \) from \( N \) is equal to max \( \{c, 1 - cp\} \).

Note that \( c \) is the probability of being correct when guessing blindly. Essentially, when \( N = 0 \) the adversary has a clear choice (we must have \( S = 0 \)). The case \( N = 1 \) however, is harder: onion connections do produce \( N = 1 \) with higher probability, but they are far less likely to occur. If \( p \geq \frac{1}{c} - 1 \), it is in fact more likely that a connection is clearnet, even if we observe \( N = 1 \). As a consequence, the optimal adversary always believes that the connection is clearnet, regardless of \( N \), hence he has no advantage whatsoever over blind guessing.

**Tradeoff between privacy and latency/bandwidth** The tradeoff between privacy and latency is displayed in Fig. 7. Note that the adversary can achieve an accuracy of \( c \) simply by *blind guessing*; but having high accuracy simply because \( c = 0.9 \) is not really a problem of the system. As a consequence, we follow a standard approach from Quantitative Information Flow [30] and compute the system’s *leakage*, defined as “accuracy − prob. of blind guessing”. We see that for large values of \( c \), we can actually achieve zero leakage while padding only a small fraction of connections.

Regarding the latency overhead, our strategy adds a delay to each exit circuit equal to the time it takes to complete an onion service handshake. In our experiments (§6) we found that onion service handshakes have a mean time of around 3.34 seconds (with a median time of 2.8 seconds and standard deviation of 1.64 seconds). Since we dummy handshake is produced with probability \( p \), and only for clearnet connections, the expected latency overhead will be \( cp \cdot 3.34 \) seconds/connection, displayed in Fig. 7. Regarding bandwidth, a single

\[\text{Note that if we set } p = \frac{1}{c} - 1, \text{ the fraction of padded connections (wrt all) will be } cp = 1 - c, \text{ exactly equal to the fraction of onion connections.}\]

### Table 2: Multi site accuracy results (delay-based strategy over localhost)

|                  | Fake-Intro vs Intro | Fake-HSDir vs HSDir | Padded-Exit vs Rend |
|------------------|---------------------|---------------------|---------------------|
|                  | Dec. Tree | SVM     | Dec. Tree | SVM     | Dec. Tree | SVM     |
| Multi-Closed     | 0.49      | 0.49    | 0.49     | 0.49    | 0.48      | 0.48    |
| Multi-Open       | 0.50      | 0.50    | 0.50     | 0.50    | 0.50      | 0.50    |
Leakage
Circuit Padding (PCP).

11% of traffic, leading to approximately 334 msecs of latency circuit where the third hop acts as the rendezvous point.

as an exit node; similarly, it can also be used as a rendezvous can be later used as an exit circuit, where the third hop acts until a proper use for them is found. The preemptive circuit performance, the Tor client continuously builds caused by extending the circuit to three hops. To optimize due to the use of public-key cryptography and the latency

Figure 7: Leakage (solid lines) and latency overhead (dotted lines) for the fractional-delay strategy.

onion handshake requires 44 cells (22.5 KB) to complete, leading to an expected overhead of $cp \cdot 22.5$ KB/connection.

As a realistic example, setting $c = 0.9$ (slightly lower than the 0.93 estimate from 2018), we can completely hide the connection type (zero leakage) by padding only $p = \frac{1}{c} - 1 \approx 11\%$ of traffic, leading to approximately 334 msecs of latency and 2.25 KB of bandwidth overhead per connection.

8 The zero-delay PCP strategy

In §6 we showed that we can construct dummy onion handshakes that perfectly match both the shape and the timing characteristics of real ones. The natural way to use these dummy handshakes is to inject them at the beginning of a clearnet connection while delaying the actual traffic; this strategy was shown in §7 to be an effective way of making clearnet connections indistinguishable from onion ones.

Although the delay can be significantly reduced via fractional delay (§7.3), one might wish to provide a defense without any delay whatsoever. If we are not allowed to delay traffic, by the time the clearnet request arrives it’s already too late for providing a defense. But how can we perform dummy handshakes before the application data even arrives? The key insight here is use preemptive circuits, a mechanism that already exists in Tor for performance reasons, but which can be exploited for defending against fingerprinting. In the following sections we detail a padding strategy we call Preemptive Circuit Padding (PCP).

Preemptive padding Creating circuits is a costly operation, due to the use of public-key cryptography and the latency caused by extending the circuit to three hops. To optimize performance, the Tor client continuously builds preemptive circuits, that are extended to three hops and then stay dormant until a proper use for them is found. The preemptive circuit can be later used as an exit circuit, where the third hop acts as an exit node; similarly, it can also be used as a rendezvous circuit where the third hop acts as the rendezvous point.

Tor’s preemptive circuit subsystem is not formally specified and depends on the current implementation. The current Tor client counts the number of available preemptive circuits every second, and creates new ones until a certain configurable threshold is reached. The client uses preemptive circuits both for clearnet and for onion connections.

The preemptive circuit mechanism presents a great opportunity to insert confusion in the time signature of onion services, since it blends the time of creation with the time of use of circuits. Using the preemptive circuit mechanism, Tor creates circuits before the actual usage of the circuit has been determined, and hence our machines can inject padding between the user and the middle node. An adversary observing the traffic will not be able to infer that this is a preemptive circuit still waiting to be used, and could confuse it with an active onion circuit that is completing its onion handshake. Of course, for this defense to be successful, the padding should be properly constructed, taking into account the actual traffic that will pass through the circuit after the preemptive phase.

In the following sections we detail the use of this technique to defend against circuit fingerprinting. Note that the use of preemptive padding is not limited to circuit fingerprinting; we envision that it could be useful for building defenses against guard discovery or traffic confirmation attacks [27].

The zero-delay PCP strategy This strategy involves injecting dummy onion handshakes (§6) in the preemptive phase. Since each handshake is in fact a triplet (HSDir, Intro and Rendezvous), we employ three preemptive circuits, each having a distinct role:

- **HSDir preemptive circuits** carry dummy and real HSDir handshakes.
- **Introduction preemptive circuits** carry dummy and real introduction handshakes.
- **Exit/Rendezvous preemptive circuits** carry dummy and real rendezvous handshakes, as well as (clearnet or onion) application data.

Upon creating these three preemptive circuits, we use padding machines (§6) to inject dummy onion handshakes in the corresponding preemptive circuits. At this moment, the actual user connection has not arrived yet, and we know neither when it will arrive, nor whether it will be a clearnet or onion connection. As a consequence, we keep repeating triplets of dummy handshakes in the preemptive circuits, using a random delay between them. When the user connection arrives, we proceed depending on its type.

- **Clearnet connections**: the HSDir and introduction preemptive circuits are terminated, and the Exit/Rendezvous preemptive circuit is used as an exit circuit.
- **Onion connections**: the preemptive circuits are used as HSDir, introduction and rendezvous circuits respectively, carrying the real handshakes and the application data.
We start with an analytic evaluation, obtaining an expression we can switch back to fractional-delay to reduce bandwidth to the adversary, PCP will only probabilistically produce such though the two connection instances appear indistinguishable, three dummy handshakes, or two dummy and a real one. Able traffic pattern (Fig. 3), but cannot tell whether we have three handshakes took place, since each one has a distinguish-able traffic pattern, so the probability to produce each one of them can be used to infer the type of connection.

Following the notation of §7.3, let $D$ denote the number of dummy handshakes sent on the circuits (whiled $N$ denotes the total number of handshakes, either dummy or real). The adversary cannot observe $D$ directly (dummy and real handshakes look identical), but can potentially observe $N$. In the case of a clearnet connection we have $N = D$, while for onion connection we have $N = D + 1$ (because of the additional real handshake), so after observing $N$ we can use the distribution of $D$ to infer which type of connection is more likely. In the example of Fig. 8, the adversary observes $N = 3$ but does not know whether we have a clearnet connection with $D = 3$ or an onion one with $D = 2$. So, the probabilities $Pr[D = 2]$ and $Pr[D = 3]$ need to similar; if we perform too few dummy handshakes, and $D = 3$ has negligible probability, the adversary can infer that we have an onion connection.

The first step in our analytic evaluation is to study the distribution of $D$. Since dummy handshakes are repeated until the user connection arrives, $D$ crucially depends on the user’s think time, that is the time between consecutive handshakes for a new connection. As our user model, we assume that the think time follows an exponential distribution with rate $\lambda_u$; this is a commonly used model, although not always accurate [23]. Recall that the time between dummy handshakes is also sampled from an exponential distribution with rate $\lambda_d$; the question here is to compute how many dummy handshakes will be injected while waiting for the user connection to arrive.

Intuitively, this number $D$ depends on the relationship between $\lambda_u$ and $\lambda_d$. If $\lambda_d$ is much larger it means that we are generating dummies more quickly than the user is opening connections, so $D$ will be large; similarly, if $\lambda_u$ is much larger then $D$ will be small. In fact, we show that the distribution of $D$ solely depends on their ratio $\varphi = \lambda_d/\lambda_u$, which brings us to the following result (all proofs are in Appendix E).

**Theorem 8.1.** The number $D$ of injected dummy triplets follows a geometric distribution with parameter $1/1 + \varphi$, that is

$$Pr[D = k] = p(1 - p)^k \quad \text{for } p = \frac{1}{1 + \varphi}, k \geq 0.$$  

**Base rate and classification accuracy** As discussed in §7.3, the asymmetry in the base rate makes it harder for the adversary to produce confident guesses and classifications of onion circuits. In the example of Fig. 8, even if dummy handshakes are relatively sparse and $Pr[D = 3]$ is much smaller.

---

3We could alternatively use some heavy-tailed distribution (e.g., Pareto).
The accuracy of the optimal classifier predicting $S$ from $N$ is equal to $\max\{c, 1 - c \cdot \frac{\varphi}{\varphi + 1}\}$.

As discussed in §7.3, the adversary can achieve an accuracy of $c$ by simply blind guessing. In Fig. 9 we plot the system’s leakage, instead of the accuracy, which expresses how much worse the attack becomes due to the system’s output.

There are two main conclusions from these results: first, increasing $c$ decreases the system’s leakage, which is expected since it leads to more dummy handshakes. Second, the base rate $c$ works in our advantage: higher values require stronger evidence to support an accurate detection, meaning that we can achieve the same leakage with a smaller overhead $\varphi$.

These expressions are particularly useful for tuning the defense’s parameters. For instance, assuming $c = 0.7$ (much smaller than the $c = 0.93$ estimate from 2018), we see that setting $\varphi = 1$ is enough to make the system have zero leakage, meaning that the adversary is no better than blind guessing. Fixing $\varphi$ in turn allows us to configure the parameter $\lambda_d$, the one needed for implementing the defense, by estimating $\lambda_u$ from the user’s previous behavior and setting $\lambda_d = \varphi \cdot \lambda_u$.

**Avoiding $\lambda_u$ leaks** Although $\lambda_d$ is only known to the client, the middle node observes the times between dummy handshakes (i.e. samples from the distribution) and hence it can estimate $\lambda_u$, and thus $\lambda_u$, leading to potential fingerprinting issues. However, the middle node changes for every circuit and on average it only learns $\varphi$ samples, so for small $\varphi$ (e.g. $\varphi = 0.5$) the estimate will be very rough and this type of leakage could be tolerated. If we want to further protect $\lambda_u$, there are ways to do so: first, we can increase $\lambda_d$ by adding sufficient noise to it so that its initial value is obfuscated.

A different approach for bigger values of $\varphi$ would be to keep multiple preemptive circuits open for each type (with different middle nodes), and distribute the dummy handshakes randomly among them (in the extreme case send a single handshake per circuit) while sending the application traffic on the circuit with the most recent dummy handshake. Although this approach has worse performance because of the additional preemptive circuits, the security analysis of the defense is not affected. The advantages are twofold: first, we hide the $\lambda_u$ from individual middle nodes, and second, it works around the restrictions imposed by Tor’s RELAY_EARLY mechanism.

**Tradeoff between privacy and bandwidth** Although our PCP scheme does not increase latency at all, it does incur a bandwidth overhead due to the dummy handshakes. Since we inject an average of $\varphi$ handshakes per connection, the expected overhead will be $\varphi \cdot 22.5$ KB/connection. Hence, as expected, there is a tradeoff between privacy and bandwidth, displayed in Fig. 9. Note that the overhead does not depend on $\lambda_d$ or $\lambda_u$, but only on their ratio $\varphi$; moreover, in contrast to the fractional-delay strategy (§7), the overhead does not depend on $c$, since we pad both clearnet and onion traffic.

**Timing analysis** The PCP defense has potential timing fingerprints that are not present in our simpler delay-based defense. In particular, even though the timing patterns of onion handshakes can be imitated accurately (§6), the timing between the application-layer traffic and the padding could be used as a timing fingerprint. We believe that a relative large value of $\lambda_d$ will alleviate this issue (note that the low-latency of PCP is useful in busy periods when $\lambda_u, \lambda_d$ are large). Still, we consider that analyzing and evaluating more advanced defenses against such timing fingerprints to be beyond the scope of this paper and left as future work.

Note that the fractional-delay strategy from §7 does not suffer from such potential fingerprints, since the application-layer traffic immediately follows the handshake. We view the fractional-delay as trading latency for robustness with regards to timing fingerprints.

### 8.2 Experimental evaluation

To confirm our analytic evaluation, we performed a final experiment using the same single-site scenario as in §7.1. Implementing the defense in our deployed framework of §5 would require deploying further framework modifications to the network (e.g. finer control of preemptive circuits, and working around Tor’s restricting RELAY_EARLY mechanism) so we chose to simulate the PCP mechanism similarly to the experiments of §7.1.

![Figure 9: Leakage (solid lines) and bandwidth overhead (dotted lines) for the PCP strategy. Experimental results are also shown as individual crossed points.](image-url)
We used various values of $\varphi$ and $c$, and performed the following procedure: For each onion connection, we injected dummy handshakes in its three circuits as follows: we first sampled the user thinking time $t$ from an exponential distribution with a fixed rate $\lambda_u = 4 \text{ reqs/hour}$.\footnote{This choice is arbitrary, since $\lambda_u$ depends on the user behavior for which it is hard to obtain data. Still, since we keep $\varphi$ fixed (setting $\lambda_d = \varphi \cdot \lambda_u$), $\lambda_u$ only affects the bandwidth overhead and not the obtained privacy.} Then, we continuously sampled the time of each dummy handshake from an exponential distribution with rate $\lambda_d = \varphi \cdot \lambda_u$, injecting a triple of dummy handshakes in each of the three circuits (HSDir, introduction and rendezvous), until reaching the time $t$. The same procedure was followed to pad exit circuits, except that for each one of them two fake ones (fake HSDir and fake Intro) were created and added to the dataset.

The results for exit and rendezvous circuits (of a single website) are shown in Fig. 9, showing the accuracy for each combination of $\varphi, c$ are a data point over the analytic expressions. We see that the accuracy is identical to that predicted from Thm. 8.2, up to a small experimental error. This is in fact quite remarkable, since the classifier takes $N$ as its input, while in the experiments $N$ is not directly observable, but the classifier receives the direct cell sequences. The correspondence of the results means that the classifier in fact manages to learn $N$ (and use it to infer the connection type) but nothing more, since the traffic patterns are otherwise similar.

For other types of circuits we obtained the same results, omitted due to space restrictions. We also repeated the whole set of experiments with $\lambda_u = 8 \text{ reqs/hour}$, obtaining the same results, hence verifying the analytic conclusion that privacy depends on $\varphi$ alone, and not on the individual values $\lambda_d, \lambda_u$.

9 Discussion

We briefly discuss several new directions in both improving the attacks and exploring avenues for more effective defenses.

Defining circuit fingerprinting We believe that formalizing the circuit fingerprinting problem further can make defenses and evaluations more robust. We believe that a formal security game similar to IND-CPA where the adversary is asked to distinguish between onion and exit cell traces seems like a fruitful direction forward.

Furthermore, instead of doing classification on a per-circuit basis, it could prove more effective to do the classification on the global flow of connections. This way we could use the timing correlations between circuits of the onion service protocol as a feature for classification during experiments.

It is worth noting that previous works on website and circuit fingerprinting did classification on a per-circuit level because investigating timing correlations on a global level presents design issues and significantly increases the uncertainty of the classifier. Our goal with this work has been to push the circuit fingerprinting attacker into requiring access to precise timing information and not being able to do fingerprinting with simpler features like cell sequences.

Adversary capabilities As discussed in §2, it is common practice in the website fingerprinting literature to consider the network adversary being able to derive the precise cell contents of a circuit given raw TCP traces. However because of the importance of the precise cell sequence in the circuit fingerprinting world, we have a strong interest in weakening the network adversary.

We believe we can achieve this using Tor’s adaptive padding framework by increasing the number of simultaneous padding circuits to a point where a network adversary will find it hard to distinguish which circuit sends which cell. Combined with Tor’s move to a single guard per client [7] it makes the work of the network adversary much harder since there will always be simultaneous traffic to the single guard.

Future work While we implemented the initial padding machines into Tor, we did not implement our PCP defense and opted for a simulation due to the development effort required and the need for multiple iterations of the padding techniques. We believe that implementing PCP in upstream Tor should be a next step in the research against circuit fingerprinting.

Furthermore, our padding framework has room for improvement, since it currently lacks features like flow control, load balancing and probabilistic state transitions [6].

Finally, we believe that the advanced padding techniques introduced in this work can also be useful to hide the service-side onion service traffic from circuit fingerprinting adversaries. The main issue is that onion services can be distinguished by the great asymmetry between their incoming and outgoing traffic, which is not present in regular Internet connections. To emulate that volume of outgoing traffic using padding machines we would need realistic user traffic patterns that we could replay with padding machines.

10 Conclusion

In this work we introduced novel padding-based techniques that can be used to protect Tor onion service clients against circuit fingerprinting attacks. In the process of doing so, we demonstrated new fingerprints that can be used to distinguish onion service circuits. We also built and deployed a versatile adaptive padding framework based on WTF-PAD that can be used to implement such padding-based defenses.

Our work shows that adaptive padding defenses that utilize preemptive circuits can be fruitful to thwart circuit fingerprinting adversaries with no additional latency cost.
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A Dataset sizes

In this section we present the number of circuits in each dataset for each experiment. These circuits describe the multi site scenarios of our tests. The number of circuits are shown below:

**Delay-based strategy experiment**

|                  | HSDir     | Fake HSDir |
|------------------|-----------|------------|
| Introduction     | 15536     | 15536      |
| Rendezvous       | 15508     | 15508      |
|                  | 14955     | 15008      |

**Delay-based strategy over localhost experiment**

|                  | HSDir     | Fake-HSDir |
|------------------|-----------|------------|
| Introduction     | 15000     | 15000      |
| Rendezvous       | 15000     | 15000      |

**PCP zero-latency strategy experiment**

|                  | HSDir     | Fake-HSDir |
|------------------|-----------|------------|
| Introduction     | 15000     | 15000      |
| Rendezvous       | 15000     | 15000      |

B Onion service cell sequence diagrams

In this section we present cell sequence diagrams for all onion circuits. Fig. 10 shows the cell flow of HSDir circuits, and Fig. 11 shows the cell flow of rendezvous circuits.
C Padding Machines

In this section we provide the source code and state machine of padding machines for creating dummy introduction handshakes.

C.1 Client-side introduction machine

The source code below specifies a client-side padding machine that creates dummy introduction handshakes. The state diagram of the padding machine can be seen in Fig. 12.

```
cirpad_machine_spec_t* client_machine = tor_malloc_zero(sizeof(cirpad_machine_spec_t));
client_machine->name = "client_intro_circ";
client_machine->conditions.apply_state_mask = CIRPAD_CIRC_OPENED;
client_machine->start_state = 2;
/* This is a client machine */
client_machine->is_starting_side = 1;
/* Start the machine when the preemptive phase ends */
client_machine->conditions.apply PURPOSE_mask =
cirpad_circ_PURPOSE_to_mask(CIRPAD_PURPOSE_C_PREEMPTIVE);
/* Keep the machine around if it is in the CIRPAD Padding purpose (but do not try to take over other machines in that purpose). */
client_machine->conditions.keep PURPOSE_mask =
cirpad_circ_PURPOSE_to_mask(CIRPAD_PURPOSE_C_CIRCUIT_PADDING);
/* Two states: EXTEND, INTRODUCE (and END) */
cirpad_machine_states_init(client_machine, 2);
/* We transition from EXTEND to the next step (INTRODUCE) after receiving a PADDING_NEGOTIATED (which replaces EXTENDED) */
client_machine->states[0].next_state[CIRPAD_EVENT_NON_PADDING_RECV] = 1;
/* We transition from INTRODUCE state to END, when we receive a padding cell */
/* (INTRODUCE_ACK) from the other side */
client_machine->states[1].next_state[CIRPAD_EVENT_PADDING_RECV] = CIRPAD_STATE_END;
/* During INTRODUCE phase we need to send a single padding cell (INTRODUCE) */
client_machine->states[0].length_dist.type = CIRPAD_DIST_UNIFORM;
/* client_machine->states[0].length_dist.param1 = 1; */
/* We send padding at as soon as possible */
client_machine->states[0].last_dist.type = CIRPAD_DIST_UNIFORM;
client_machine->states[0].last_dist.param1 = 0;
/* Register the machine */
client_machine->machine_num = smartlist_len(machines_sl);
cirpad_register_padding_machine(client_machine, machines_sl);
```

C.2 Relay-side introduction machine

The source code below specifies a relay-side padding machine that creates dummy introduction handshakes. The state diagram of the padding machine can be seen in Fig. 13.

```
cirpad_machine_spec_t* relay_machine = tor_malloc_zero(sizeof(cirpad_machine_spec_t));
relay_machine->name = "relay_intro_circ";
relay_machine->conditions.apply_state_mask = CIRPAD_CIRC_OPENED;
relay_machine->start_state = 2;
/* This is a relay machine */
relay_machine->is_starting_side = 0;
/* Two states: EXTENDED, INTRODUCE_ACK (and END) */
cirpad_machine_states_init(relay_machine, 3);
/* For the relay-side machine, we need to transition from EXTENDED to INTRODUCE ACK upon receiving the first padding cell by the relay-side machine (INTRODUCE) */
relay_machine->states[0].next_state[CIRPAD_EVENT_PADDING_RECV] = 1;
/* We transition from INTRODUCE_ACK state to END, when we send the first padding cell (INTRODUCE_ACK) */
relay_machine->states[1].next_state[CIRPAD_EVENT_PADDINGSENT] = CIRPAD_STATE_END;
/* During EXTENDED phase we need to send a single padding cell (EXTENDED) */
relay_machine->states[0].length_dist.type = CIRPAD_DIST_UNIFORM;
relay_machine->states[0].length_dist.param1 = 1;
relay_machine->states[0].length_dist.param2 = 1;
relay_machine->states[0].max_length = 1;
/* We use the LogLogistic(alpha=3.19, beta=0.14) distribution that simulates the round-trip delay to the introduction purpose */
relay_machine->states[0].last_dist.type = CIRPAD_DIST_LOG_LOGISTIC;
/* param1 is alpha, param2 is 1.0/beta */
relay_machine->states[0].last_dist.param1 = 3.19;
relay_machine->states[0].last_dist.param2 = 0.313;
/* During INTRODUCE_ACK phase we need to send a single padding cell */
/* (INTRODUCE_ACK) using the same delay distribution as above */
relay_machine->states[1].length_dist.type = CIRPAD_DIST_UNIFORM;
relay_machine->states[1].length_dist.param1 = 1;
relay_machine->states[1].length_dist.param2 = 1;
relay_machine->states[1].max_length = 1;
/* We use the LogLogistic(alpha=3.19, beta=0.14) distribution that simulates the round-trip delay to the introduction purpose */
relay_machine->states[1].last_dist.type = CIRPAD_DIST_LOG_LOGISTIC;
/* param1 is alpha, param2 is 1.0/beta */
relay_machine->states[1].last_dist.param1 = 3.19;
relay_machine->states[1].last_dist.param2 = 0.313;
/* Register the machine */
relay_machine->machine_num = smartlist_len(machines_sl);
cirpad_register_padding_machine(relay_machine, machines_sl);
```

D Delay-based strategy experiment

Similarly with the metrics of Table 4, in this section we present metrics for the delay-based strategy experiment on this section. The metrics are TPR and FPR, alongside with Precision for the interested circuit in each case. Combined with accuracy results on Table 1, they describe the classification performance for both Decision Tree and SVM classifiers for our multi site scenario.
Table 3: True Positive and False Positive Rates in comparison with Precision (delay-based strategy) (A positive result means that the classifier thought that a circuit is a real onion circuit)

|                      | Fake-HSDir vs HSDir | Fake-Intro vs Intro | Padded-Exit vs Rend |
|----------------------|---------------------|---------------------|---------------------|
|                      | Dec. Tree | SVM | Dec. Tree | SVM | Dec. Tree | SVM |
| Multi-Close          | TPR       | FPR | Precision | TPR | FPR | Precision |
|                      | 0.03      | 0   | 1.00      | 0.03 | 0 | 1.00 |
|                      | 0        | 0   | 0          | 0.31 | 0 | 0.72 |
|                      | 1.00      | 1.00 | 1.00      | -   | 0.73 | 0.56 |
| Multi-Open           | TPR       | FPR | Precision | TPR | FPR | Precision |
|                      | 0.04      | 0   | 1.00      | 0.04 | 0 | 0.49 |
|                      | 0        | 0   | 0          | 0.99 | 0 | 0.50 |
|                      | 1.00      | 1.00 | -         | -   | 0.49 | 0.49 |

Table 4: True Positive and False Positive Rates in comparison with Precision (delay-based strategy over localhost) (A positive result means that the classifier thought that a circuit is a real onion circuit)

|                      | Fake-HSDir vs HSDir | Fake-Intro vs Intro | Padded-Exit vs Rend |
|----------------------|---------------------|---------------------|---------------------|
|                      | Dec. Tree | SVM | Dec. Tree | SVM | Dec. Tree | SVM |
| Multi-Close          | TPR       | FPR | Precision | TPR | FPR | Precision |
|                      | 0        | 0   | 1.00      | 0.04 | 0 | 1.00 |
|                      | 0        | 0   | 1.00      | 0.64 | 0 | 0.88 |
|                      | 0.49      | 0.49 | 0.49      | 0.47 | 0 | 0.48 |
| Multi-Open           | TPR       | FPR | Precision | TPR | FPR | Precision |
|                      | 0        | 0   | 1.00      | 1.00 | 1.00 | 1.00 |
|                      | 0        | 0   | 1.00      | 1.00 | 1.00 | 1.00 |
|                      | 0.50      | 0.50 | 0.50      | 0.50 | 0 | 0.50 |

E Proofs of §8.1

Theorem 8.1. The number \( D \) of injected dummy triplets follows a geometric distribution with parameter \( \frac{1}{1+\varphi} \), that is

\[
\Pr[D = k] = p(1 - p)^k \quad \text{for} \quad p = \frac{1}{1+\varphi} \quad k \geq 0 .
\]

Proof. Let \( T \) be a random variable modelling the time when the user's request arrives. \( T \) is assumed to follow an exponential distribution with rate \( \lambda_u \), with pdf:

\[
f_T(t) = \lambda_u e^{-\lambda_u t} . \tag{1}
\]

Now fix some value \( T = t \), and consider the number of dummies generated before time \( t \). Since the inter-arrival time between dummies follows an exponential distribution with rate \( \lambda_d = \varphi \lambda_u \), it is well known that the number of dummies generated before time \( t \) follows a Poisson distribution with parameter \( \lambda_d t \), in other words

\[
\Pr[D = k \mid T = t] = e^{-\lambda_d t} \frac{(\lambda_d t)^k}{k!} . \tag{2}
\]

Letting \( p = \frac{1}{1+\varphi} \), note that

\[
p = \frac{\lambda_u}{\lambda_d + \lambda_u} \quad \text{and} \quad 1 - p = \frac{\lambda_d}{\lambda_d + \lambda_u} . \tag{3}
\]

Finally, we have that:

\[
\Pr[D = k] = \int_0^\infty \Pr[D = k \mid T = t] \cdot f_T(t) \, dt
\]

= \int_0^\infty e^{-\lambda_d t} \frac{(\lambda_d t)^k}{k!} \lambda_u e^{-\lambda_u t} \, dt

= \frac{\lambda_d^k \lambda_u}{k!} \int_0^\infty t^k e^{-(\lambda_d + \lambda_u)t} \, dt

= \frac{\lambda_d^k \lambda_u}{(\lambda_d + \lambda_u)^{k+1}}

\int_0^\infty x^k e^{-ax} \, dx = \frac{a^k}{a^{k+1}} . \tag{4}

Theorem 8.2. The accuracy of the optimal classifier predicting \( S \) from \( N \) is equal to \( \max \{ c, 1 - c \frac{\varphi}{\varphi + 1} \} \).

Proof. The Bayes classifier (which is well known to be optimal) maps an observation \( k \) to the label \( s \) with the highest posterior probability \( \Pr[S = s \mid N = k] \). Note that this is equivalent to selecting the label \( s \) with the highest joint probability \( \Pr[S = s, N = k] \). This classification is correct for all pairs \( (s,k) \) such that \( s \) is the one with the highest \( \Pr[S = s, N = k] \), for that \( k \). Hence the classifier’s accuracy is equal to the probability of such a pair appearing, which is given by

\[
\text{Accuracy} = \sum_{k=0}^{\infty} \max_{s \in \{0,1\}} \Pr[S = s, N = k] . \tag{5}
\]

To compute the joint probabilities, note that when \( S = 0 \) (exit circuit), the adversary only observes the generated dummy triplets, that is \( N = D \). On the other hand, when \( S = 1 \) (onion circuit), the adversary observes the dummy triplets plus the real one, that is \( N = D + 1 \). Since \( D \) follows a geometric
distribution with parameter \( p = \frac{1}{1 + \phi} \) (Thm. 8.1), and (by definition) \( c = \Pr[S = 0] = 1 - \Pr[S = 1] \), we get the following expressions for the joint probabilities:

\[
\begin{align*}
\Pr[S = 0, N = k] &= c \cdot p(1 - p)^k \\
\Pr[S = 1, N = k] &= \begin{cases} 0 & \text{if } k = 0 \\ (1 - c)p(1 - p)^{k-1} & \text{if } k > 0 \end{cases}
\end{align*}
\]

We now need to find which label \( s \in \{0, 1\} \) gives the max for each observation \( k \) in (4). For \( k = 0 \), the max is clearly given by \( s = 0 \) since \( \Pr[S = 1, N = 0] = 0 \) (intuitively, onion circuits produce at least one triplet). For \( k > 0 \), on the other hand, the max is given by \( s = 0 \) iff

\[
\Pr[S = 0, N = k] \geq \Pr[S = 1, N = k] \Leftrightarrow c \cdot p(1 - p)^k \geq (1 - c)p(1 - p)^{k-1} \Leftrightarrow c \geq 1 - c(1 - p)
\]

Note that (5) does not depend on \( k \), in other words either \( s = 0 \) or \( s = 1 \) give the max for all \( k > 0 \) simultaneously. We consider the two cases.

Case \( c \geq 1 - c(1 - p) \): in this case the max in (4) is given by \( s = 0 \) for all \( k \geq 0 \), hence the accuracy becomes

\[
\text{Accuracy} = \sum_{k=0}^{\infty} \Pr[S = 0, N = k] = \Pr[S = 0] = c.
\]

Case \( c < 1 - c(1 - p) \): in this case the max in (4) is given by \( s = 0 \) for \( k = 0 \) and by \( s = 1 \) for \( k > 0 \), hence the accuracy becomes

\[
\text{Accuracy} = \Pr[S = 0, N = 0] + \sum_{k=1}^{\infty} \Pr[S = 1, N = k]
= \Pr[S = 0, N = 0] + (\Pr[S = 1] - \Pr[S = 1, N = 0])
= cp + (1 - p)
= 1 - c(1 - p).
\]

Finally, combining the two cases we get:

\[
\text{Accuracy} = \begin{cases} c & \text{if } c \geq 1 - c(1 - p) \\ 1 - c(1 - p) & \text{otherwise} \end{cases}
= \max\{c, 1 - c(1 - p)\}
= \max\{c, 1 - c\frac{\phi}{1 + \phi}\}.
\]

Figure 14: Cell packing difference between rendezvous and exit circuits

\[
p = \frac{1}{1 + \phi}
\]