TorPolice: Towards Enforcing Service-Defined Access Policies in Anonymous Systems

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1 ABSTRACT
Tor is the widely used anonymity network, currently serving millions of users each day. However, there is no access control in place for all these users, leaving the network vulnerable botnet abuse and attacks. For example, criminals frequently use exit relays as stepping stones for attacks, causing service providers to serve CAPTCHAs to exit relay IP addresses or blacklisting them altogether, which leads to severe usability issues for legitimate Tor users. To address this problem, we propose TorPolice, the first privacy-preserving access control framework for Tor. TorPolice enables abuse-plagued service providers such as Yelp to enforce access rules to police and throttle malicious requests coming from Tor while still providing service to legitimate Tor users. Further, TorPolice equips Tor with global access control for relays, enhancing Tor’s resilience to botnet abuse. We show that TorPolice preserves the privacy of Tor users, implement a prototype of TorPolice, and perform extensive evaluations to validate our design goals.

2 INTRODUCTION
In an era of mass surveillance, our online communications are being increasingly monitored by businesses and government entities to infer sensitive information. Technologies for anonymous communication aim to hide users’ network identity (IP address) from untrusted destinations, as well as third parties on the Internet [3, 9, 25, 57]. Counting almost two million daily users, the Tor network [9] is among the most popular digital privacy tools. As of May 2017, the network consists of over 7,000 volunteer-run relays, carrying nearly 100 Gbps of traffic [11]. Tor clients3 build a path (also known as Tor circuit) consisting of three relays (guard, middle and exit) to reach service providers such as Yelp or Wikipedia. Tor is used by law enforcement, intelligence agencies, political dissidents, journalists, whistle-blowers, businesses, and ordinary citizens to enhance their online privacy [12].

Today’s Tor network does not implement any access control mechanism, meaning that anyone with a Tor client can use the network without limitation. While the lack of access control fosters network growth, it has also caused various problems, most importantly botnet abuse [37]. In practice, botnets use Tor to attack third-party services, spam comment sections on websites, scrape content, and scan services for vulnerabilities [56]. In response, many service providers and content delivery networks (CDNs) have started to treat Tor users as “second-class” Web citizens [46], by either forcing Tor users to solve numerous CAPTCHAs [55, 56] or blocking Tor exit relay IP addresses altogether.

Another type of botnet-related abuse of Tor arises from command and control (C&C) servers run as Tor onion services (used to be known as hidden services) [21, 28, 32]. In the past, such events caused a rapid spike in the number of Tor clients [1, 38]. Besides the reputational issue of Tor “hosting” botnet infrastructure, the massive number of circuit creation requests from botnets is a heavy burden on Tor relays, causing significant performance degradation for legitimate Tor users (e.g., frequent Tor circuit failures). Other types of botnet abuse include paralyzing Tor relays via relay flooding attacks [14, 15] and performing large-scale traffic analysis via throughput or congestion fingerprinting [51, 53].

Contributions. In this paper, we present TorPolice, the first privacy-preserving access control framework for the Tor network. Leveraging cryptographically computed network capabilities, TorPolice enables service providers to define access policies for Tor connections, allowing them to throttle Tor-emitted abuse while still serving legitimate Tor users. Thus, TorPolice offers a more viable alternative to abuse-plagued service providers than simply blocking all Tor connections. Further, TorPolice improves the Tor network’s resilience to various botnet abuses by enabling global access control for Tor relays. Crucially, TorPolice achieves these benefits while still retaining Tor’s anonymity guarantees.

TorPolice’s design introduces a set of fully distributed and partially trusted access authorities (AAs) to manage and certify capabilities. To request capabilities from AAs, Tor clients must first obtain anonymous capability seeds which are types of resources that are costly to scale. Both service providers and the Tor network provide differentiated service to Tor clients that possess valid capabilities so to enforce self-defined access rules. The AAs generate capabilities using blind signatures [17] to break the linkability between capability requesting and capability spending. We conduct a rigorous security analysis to prove that TorPolice does not weaken privacy guarantees offered by the current Tor network.

We implement a prototype of TorPolice to demonstrate its practicality and evaluate the prototype extensively on our testbed, in the Shadow simulator [40], via simulations and over the live Tor network. Our results show that TorPolice can effectively enforce service-selected access policies and mitigate large-scale botnet abuses against Tor at the cost of negligible overhead.

We structure the rest of our paper as follows. We begin by outlining our problem statement in § 3, followed by a design overview in § 4. The details behind access authorities are in § 5. Next, § 6 discusses how TorPolice can control site access while § 7 discusses

3In this paper, we use the term client(s) to refer to the onion proxy (OP) software running on the Tor user’s machine.
how we can control access to the network itself. We analyze TorPolice’s effect on Tor’s anonymity in § 8, discuss its implementation in § 9, and evaluate it in § 10. Finally, we present related work in § 11 and conclude our work in § 12.

3 PROBLEM FORMULATION
In this section, we provide brief background on the Tor network (§ 3.1), outline TorPolice’s design goals (§ 3.2), and discuss our threat model (§ 3.3).

3.1 Tor Background
Tor clients anonymously connect to service providers (e.g., WikiLeaks) by building three-hop circuits consisting of a guard, middle, and exit relay. Tor’s use of layered encryption ensures that each relay only knows the identities of its direct neighbors (i.e., the previous and next hop in the circuit). Clients randomly select these relays, weighted by the relays’ bandwidth and their positions on the circuit. A list of all Tor relays—the network consensus—is published hourly by a set of nine globally-distributed directory authorities that are run by volunteers trusted by the Tor Project. While the directory authorities and guard relays learn a Tor client’s network identity (i.e., her IP address), they cannot observe the client’s online activity. Exit relays, however, can monitor the client’s activity, but do not know her identity. Tor’s anonymity stems from unlinking network identity from activity.

Besides client-side anonymity, Tor allows service providers to host their service anonymously over Tor onion services (OS). Once an OS is set up, it creates circuits to at least three relays severing as its introduction points (IPs). Then, the OS publishes its descriptor—which contains the IPs—to a distributed hash table that consists of a subset of all Tor relays. To connect to the OS, a Tor client first fetches the OS’s descriptor using its onion address, and then builds two circuits: one to an IP and another one to a randomly-selected relay called the rendezvous point (RP). The client instructs the IP to send the identity of the RP to the OS, which then creates a circuit to the RP to be able to finally communicate with the client.

3.2 Design Goals
TorPolice adds access control to the anonymous communication in Tor, benefiting both service providers and the Tor network. Different from prior capability based schemes [48, 49, 54, 65, 66], TorPolice’s design needs to address a unique combination of the following three challenges: (i) preserving Tor’s anonymity guarantees, (ii) avoiding central points of control, and (iii) being incrementally deployable.

Service-defined Access Policies. Project Honey Pot lists nearly 70% of all Tor exit relays as comment spammers [56], causing many service providers and CDNs to block and filter traffic originating from the Tor network. To reduce this tension between Tor users and service providers, TorPolice must allow service providers to define and enforce access rules for Tor connections, allowing them to throttle Tor-emitted abuse while still serving legitimate Tor users. TorPolice is a flexible framework that allows service providers to define self-desired access policies.

Mitigate Botnet Abuse Against Tor. Being a service provider itself, the Tor network is also subject to botnet abuse, such C&C servers hosted as onion services, and (D)DoS attacks against (selected) relays. TorPolice allows the Tor network to control the network usage of Tor clients, making it possible to throttle the abuse. In contrast to local rate limiting by each relay, TorPolice’s access control mechanism is global, meaning that an adversary cannot circumvent our defense by simply connecting to all relays.

Preserving Tor User Privacy. TorPolice must not degrade Tor’s anonymity guarantees. While we add a new layer of functionality to Tor (access control), this layer—like Tor itself—unlinks a client’s identity from its activity, and therefore preserves Tor users’ online anonymity.

Fully Distributed and Partially Trusted Authorities. In accordance with Tor’s design philosophy of distributing trust, TorPolice relies on a set of fully distributed and partially-trusted access authorities (AAs) to manage capabilities. An AA is operated either by the Tor Project, a service provider, or a trusted third party. Since Tor clients are free to choose any AA to request capabilities, no single AA has a global view on all Tor clients. Further, each AA is only partially trusted and a service provider can blacklist any misbehaving or compromised AA.

Incrementally Deployable. TorPolice must be incrementally deployable. Up-to-date Tor clients, relays, and service providers can benefit from a partially-deployed TorPolice immediately while outdated entities can continue their operations.

Elded Design Goals. Various attacks seek to break Tor’s unlinkability. For instance, an AS-level adversary may de-anonymize a Tor user’s Internet activities if the adversary is in a position to monitor both ingress and egress traffic [61]. TorPolice is not designed to mitigate those attacks on unlinkability. Instead, we preserve the unlinkability guarantees that the Tor network currently provides.

3.3 Adversary Model and Assumptions
We consider a Byzantine adversary that deviates from our protocol and abuses Tor in arbitrary ways. The adversary can use Tor to abuse third-party services, e.g., by scraping content, spamming comments, and scanning for vulnerabilities. The adversary may also abuse the Tor network directly, e.g., by using Tor OSes as C&C servers, performing traffic analysis, or launching (D)DoS attacks against Tor relays. The adversary may further control a large number of bots, and hence a significant amount of resources. The bots can act passively (e.g., monitor Tor traffic) or actively (e.g., spoof and manipulate packets).

We assume that the AAs are well-connected to the Internet backbone so that volumetric DDoS attacks against the whole set of AAs can be mitigated. Tor’s existing directory authorities are subject to the same assumption. In practice, one way to assure this assumption is relying on DDoS prevention vendors [49].

4 DESIGN OVERVIEW
In a nutshell, TorPolice is a generic access control framework based on capabilities. TorPolice enables both service providers and the Tor network itself to enforce access control on Tor clients to mitigate various types of botnet abuse caused by the lack of access control. To this end, we consider two types of capabilities: site-specific capabilities for accessing TorPolice-enhanced service providers through
Tor, and relay-specific capabilities for creating TorPolice-enhanced Tor circuits. Both types of capabilities are signed by a set of fully-distributed Access Authorities (AAs) that are deployed either by the Tor Project, service providers, or trusted third parties. To request capabilities from a particular AA, a Tor client is required to possess a capability seed—basically a costly-to-scale resource—accepted by the AA. Each AA accepts only a single type of capability seed. Since Tor clients are free to choose their AAs, no single AA has a global view on all Tor clients. TorPolice employs blind signatures [17] to unlink the requesting and spending of capabilities. When requesting capabilities from an AA, Tor clients express what kind of capability they request because the issuing process for two capability types differs. An AA maintains separate signing keys and rate limiters for two capability types.

Figure 1 illustrates the capability requesting and spending process. While both capability types have in common step one and two, the subsequent steps differ. A site-specific capability can only be spent at the service provider specified in the capability to request service while a relay-specific capability is spent at a specific Tor relay to build a TorPolice-enhanced circuit through the relay. A Tor client can use both capability types simultaneously by visiting a TorPolice-enhanced service provider through a TorPolice-enhanced Tor circuit. In Figure 1, we intentionally separate our two capability use cases for clear presentation.

5 THE ACCESS AUTHORITIES

TorPolice relies on a set of fully distributed and partially trusted access authorities (AAs) to manage network capabilities. We assume AAs to be honest-but-curious, meaning that they follow protocol, but seek to derive additional information about Tor clients. An AA can be deployed by the Tor Project, service providers (e.g., large CDNs like Cloudflare), or third parties. Each AA is a conceptually centralized entity. However, an AA can distribute its operations among multiple servers to achieve high availability.

5.1 Capability Seeds

AAs expect valid capability seeds from Tor clients to issue pre-capabilities, which are the basis for deriving spendable capabilities. For flexibility, we intentionally keep the definition of capability seeds broad: any resource that is readily available to Tor users, but costly to scale, can be adopted as capability seeds. Reasonable choices include proof-of-work schemes (e.g., solutions to CAPTCHAs or computational puzzles) and anonymous monetary resources. TorPolice does not assume that capability seeds can distinguish bots from humans. Rather, botnets can still obtain more capability seeds than legitimate Tor users. Instead, TorPolice employs capability seeds as a form of anonymous identities that enable both service providers and the Tor network to control access by each Tor client.

In this paper, we elaborate on two types of capability seeds (i.e., solutions to CAPTCHAs and computational puzzles) and further discuss how TorPolice can incorporate more types of seeds in §5.4. One key challenge of using anonymous capability seeds is to ensure that clients do not have to solve endless challenges while browsing the web and meanwhile ensure their activities are unlinkable. TorPolice proposes a capability renewal protocol to address this challenge (§6.1).

Although CAPTCHAs can be deployed using publicly available libraries like Google’s reCAPTCHA [31], TorPolice needs additional components to support computational puzzles. At a very high level, TorPolice’s puzzle system design is similar to Portcullis [54]. However, TorPolice’s puzzle system does make a great improvement over Portcullis: it can explicitly bound the percentage of CPU cycles that any client can spend on solving puzzles. As a result, the puzzle system can bring all bots down to the percentage that normal users prefer to use for puzzle computation, which significantly reduce the computation disparity between the normal clients and bots. For better readability, we defer detailed design for TorPolice’s puzzle system in §13.1.

5.2 Per-Seed Rate Limiting

Each AA accepts only one type of capability seed. The rate at which a seed can request pre-capabilities is limited. In particular, an AA publishes two rate limiters: one determines the maximum rate at which a capability seed can request pre-capabilities used for accessing TorPolice-enhanced service providers and the other one determines the maximum rate at which a seed can request pre-capabilities used for TorPolice-enhanced circuit creation. Based on these per-seed rate limiters published by all AAs, both service providers and Tor can configure a set of rules to fulfill their access policies. This paper presents two concrete examples. In §6.3, we elaborate on a design that enables a site to bound an adversary’s achievable service request rate through Tor using self-defined parameters. In §7.1, we present a design that allows Tor to prevent botnets from creating numerous Tor circuits to conduct various abuses. To improve readability, detailed settings of these rate limiters will be discussed when presenting these access policies.

5.3 Key Management

Each AA maintains two pairs of keys for signing pre-capabilities, and each of them is dedicated for one capability type. Each AA...
must publish the public key of both key pairs, for instance, via the Tor network consensus, to ensure other entities (e.g., Tor clients, relays and service providers) can verify the AA’s signatures. An AA can periodically renew its keys, but at any time only two key pairs from the AA are valid. After receiving signed pre-capabilities from an AA, Tor clients must verify that the AA uses proper keys before using the pre-capabilities for accessing service providers or Tor. This prevents a malicious AA from using more keys simultaneously to partition the anonymity set. Finally, each AA is associated with a long-term fingerprint to uniquely identity the AA, similar to the fingerprint of a Tor relay.

5.4 Extending the Access Authorities
Besides Tor, content delivery networks (e.g., Cloudflare or Akamai) also have direct incentives to deploy and control their own set of access authorities to mitigate Tor-emitted abuses while serving anonymous connections. In fact, Cloudflare is working on an independent implementation of a system whose design goals are similar to our AAs [20], although they focus on addressing the usability issues for Tor users when visiting Cloudflare-powered websites.

Finally, semi-trusted third parties such as social network operators (e.g., Google, Facebook, and Twitter), may also run access authorities (shown as TTP AA in Figure 1) based on pre-agreed terms. To prevent account information leakage to Tor and service providers, Tor users only authenticate themselves to the social network operators. Service providers or Tor only learn a single bit of information: whether a Tor client has a valid account (i.e., capability seed) or not.

6 TORPOLICE-ENHANCED SITE ACCESS
We now elaborate on the capability design for accessing TorPolice-enhanced service providers such as websites. To mitigate the tension between service providers and Tor users, our key observation is that service providers should not treat all connections from one Tor exit relay equally since each exit relay is shared by many Tor users. Instead, accountability should be enforced at the granularity of Tor clients so that each service provider can throttle malicious Tor clients without blocking legitimate Tor users. To this end, TorPolice designs site-specific capabilities that allows a service provider to enforce self-selected access rules on anonymous Tor connections.

6.1 Pre-capability Design
Before visiting a TorPolice-enhanced site, a Tor client must first request pre-capabilities from an AA. The client is free to choose any AA based on what capability seed the client prefers to give. To request a pre-capability, the client (i) provides a valid capability seed to its selected AA and (ii) provides blinded information for the AA to compute pre-capabilities. The client can hide its network identity from the AA, for instance, by using Tor.

Capability Seed Validation. Depending on the accepted type of capability seed, an AA performs corresponding seed verification. For instance, if an AA accepts proof-of-work schemes, it needs to verify that solutions to the presented challenge are correct. Further, an AA needs to ensure that the pre-capability request rates by any capability seed does not exceed the two rate limiters discussed in § 5.2. Since each AA maintains separate rate limiters and signing keys for two pre-capability types (i.e., either for TorPolice-enhanced service access or for TorPolice-enhanced Tor circuit creation), Tor clients must specify the pre-capability type in their requests (in this section, it is for accessing service providers). In § 6.3, we will explain how a site defines its access policies based on these pre-capability release rate limiters published by all AAs.

Information Required to Compute Pre-capabilities. To request pre-capabilities, the client provides its selected AA the following set of information \(\{S, n, T_e, F\}\), where \(S\) is the domain name of site that the client is going to visit, \(n\) is a 128-bit cryptographic nonce generated by the client, \(T_e\) is a universally agreed timestamp to indicate the freshness of the information and \(F\) is fingerprint of the selected AA. All information is blinded [17] by the client to avoid information leakage to the selected AA.

The set of information is designed to prevent abuse. In particular, \(S\) is used to make the capability site-specific to prevent capability double-spending at different sites. The nonce \(n\) is added to ensure the uniqueness of each pre-capability, which in turn ensures the uniqueness of each capability. The \(T_e\) indicates the freshness of pre-capabilities so that expired ones are nullified automatically. The client is required to use Tor’s daily generated fresh random number [33] as \(T_e\) such that at any time all valid capabilities have the exact same timestamp. This design eliminates the possibility of information leakage cased by timestamp abuse. \(F\) is added to allow other entities (i.e., clients, Tor relays and service providers) to use correct public keys to verify signatures.

Computation. Upon validation of the client’s pre-capability request, the AA computes pre-capabilities using the blinded information provided by the client. Pre-capabilities computed by an AA \(A_i\) are denoted by \(P_{A_i}\). Then we have

\[
P_{A_i} = \{S | n | T_e | F_{A_i}\}^b | S_{A_i}^b,
\]

where \(F_{A_i}\) is \(A_i\’)s fingerprint, \(S_{A_i}^b\) is \(A_i\’s blind signature over the set of blinded information \(\{S | n | T_e | F_{A_i}\}\), and \(b\) represents concatenation throughout the paper.

Pre-capability Renewal. One key challenge for designing pre-capabilities is to ensure that Tor clients do not have to repeatedly solve challenges when browsing the web. A strawman design is that an AA can issue many (i.e., a few hundred) pre-capabilities for each solved challenge. However, this strawman design has at least two shortcomings: (i) it breaks the site-specific pre-capability design since the client may not be able to forecast the sites that it is going to visit so as to provide these blinded information immediately after solving challenges; (ii) the design makes it easier for automated bots to accumulate pre-capabilities, weakening the entire system.

To combat these problems, we propose a pre-capability renewal protocol. In particular, when a client first presents its challenge solution (i.e., capability seed) to an AA, the AA issues the client a forgettable pseudonym \(I = \{r | \phi\}\) where \(r\) is a random 128-bit nonce and \(\phi\) is the AA’s signature over \(r\). Later on, the client presents \(I\) as a proof of validation when requesting new pre-capabilities from the AA, allowing the client to bypass future challenges. Not only does the site-specific pre-capability design hold with this design, but also the AA can account each pre-capability request on a specific solved challenge (i.e., capability seed) to enforce the per-seed
rate limiting described in § 5.2. Each pseudonym has a validation period determined by the AA. Clients with expired pseudonyms are required to solve new challenges to obtain new pseudonyms that are unlinkable to previous ones.

**Impact of the Pseudonym on Anonymity.** Different from the prior pseudonym-based anonymous blacklisting systems [18, 19], in which a user interacts with a service provider using a persistent pseudonym, the pseudonym in our pre-capability renewal protocol is transient and never presented to both service providers and Tor relays. The pseudonym in our protocol is only linked with a specific challenge solution served as an anonymous capability seed. Since a Tor client presents its pseudonym to an AA through Tor, the AA cannot link the pseudonym with the client. Further, since all site-related information sent to the AA is blinded, the pseudonym is unlinkable with any site access as well. Thus, using pseudonym in our protocol does not impact Tor users’ anonymity.

### 6.2 Site-specific Capability Design

After obtaining \( P_{\mathcal{A}_i} \), the Tor client *unblinds* the signature using its secret blind factor to produce the unblinded version of the pre-capability, which is the capability spendable at a specific site. In particular,

\[
C = S | n | T_c | F_{\mathcal{A}_i} | S_{\mathcal{A}_i} \tag{2}
\]

The capability \( C \) contains a set of unblinded information that allows the site \( S \) to perform capability verification when the client presents \( C \) to access the site, as detailed in § 6.3.

Employing blind signature is the key to ensure that TorPolice preserves Tor’s privacy guarantee. First, signatures from the AAs prevent unauthorized entities from issuing capabilities. Second, using blind signature avoids disclosing any site-related information to the AAs since the blinded information sent to the AAs is unlinked with the “plain” information produced by the client. Such unlinkability further ensures the unlinkability between the client and its capability spending even if the AAs could collude with the site, which preserves online anonymity of Tor users. We provide a formal security proof in § 8.

### 6.3 Site-Specific Capability Spending

**Capability Validation.** Tor clients spend site-specific capabilities at TorPolice-enhanced sites to request services. Upon receiving capabilities, a TorPolice-enhanced site first validates them before subsequent processing. A site-specific capability is valid if (i) it encloses an authentic signature from an AA; (ii) it encloses a domain name that is consistent with the site; (iii) the capability is not expired (i.e., \( T_c \) is the fresh random number released by Tor); and (iv) the capability is not nullified by the site. If any of these conditions does not hold, the site rejects this capability to deny access. If a CDN provider (e.g., Cloudflare) processes capabilities on behalf of its powered sites, the second rule is passed as long as the enclosed domain is owned by one of the CDN provider’s customers. In the fourth rule, whether a capability is nullified or not is decided by the site’s access policies, as detailed below.

**Site-Defined Access Policies.** Once a site-specific capability is validated, the site accepts the Tor client’s service request. Since the major form of Tor abuse is that automated bots use Tor to conduct various malicious activities against the site [56] (e.g., content scraping, vulnerability scanning, comment spamming and so forth), the site needs to further control the number of service requests (e.g., HTTP requests) allowed by each capability. We clarify that each site can have its own definition of service requests. Once a Tor client’s service request count exceeds a threshold, the site nullifies the current capability and requires a new site-specific capability for subsequent service requests. Recall that the pre-capability request rate by each client is limited by the AAs through the per-seed rate limiting design in § 5.2. Thus, together with these rate limiters, it is possible for the site to design access policies so as to bound a strategic adversary’s service request rate using self-selected parameters, as detailed below.

**Policy Definition.** Assume the following set of access authorities \( \{ A_0, A_1, ..., A_n \} \) are deployed, and each authority accepts one type of capability seed. In this context, the site defines its access policy as \( \{ w_0, w_1, ..., w_n \} \) where \( w_j \) is the number of service requests allowed by one valid site-specific capability issued by the access authority \( A_j \).

We now formulate \( \{ w_0, w_1, ..., w_n \} \) mathematically. We denote the set of capability seeds by \( \{ s_0, s_1, ..., s_n \} \) and authority \( A_j \) accepts seed \( s_j \). Let \( c_j \) denote the cost of obtaining a capability seed \( s_j \). We denote the cost of obtaining one network identity (i.e., IP address) by \( \lambda \). Let \( r_j \) denote the maximum rate at which a seed \( s_j \) can request pre-capabilities (for accessing service providers) from authority \( A_j \). Assume that for any client connecting to the site directly without using Tor, the site allows a maximum service request rate \( O \) before either blocking the client or forcing the client to solve challenges. Then to bound a strategic adversary’s service request rate by using Tor, the site derives \( \{ w_0, w_1, ..., w_n \} \) to ensure that the following condition is satisfied for any set of parameters \( a_0, a_1, ..., a_n \) where \( a_i \in [0, 1] \) and \( \sum_{i=0}^{n} a_i = 1 \).

\[
\sum_{i=0}^{n} a_i \cdot \lambda \cdot r_j \cdot w_i \leq \epsilon \cdot O, \tag{3}
\]

where \( \epsilon \) is a site-defined parameter.

**Policy Correctness.** The parameters \( a_0, a_1, ..., a_n \) represent the adversary’s strategy of purchasing various types of capability seeds. Thus, if formula (3) holds for any strategy, the site can guarantee that the maximum Tor-emitted service request rate achieved by an adversary when spending \( \lambda \) on purchasing capability seeds is no greater than \( \epsilon \cdot O \). Thus, if an adversary that spends a certain amount of resources on obtaining network identities can access the site with rate \( O \) without using Tor, then the maximum rate that the adversary can request service from the site by using Tor is no greater than \( \epsilon \cdot O \), given that the adversary spends the same amount of resources on acquiring capability seeds. Equivalently, in order to achieve the same service request rate, the adversary has to spend \( 1/\epsilon \) times as many resources when launching attacks through Tor as it spends when launching attacks natively without using Tor. To ensure that formula (3) holds for any attacker strategy, we choose

\[
w_i \leq \epsilon \cdot \frac{c_j \cdot O}{\lambda \cdot r_j}, \quad \forall i \in [0, n] \tag{4}
\]

**Policy Enforcement.** If \( w_i = 1 \), then each capability is usable for exactly one service request. The site can enforce this by suppressing service requests with duplicate capabilities, for example,
through the use of a Bloom filter. If $w_i > 1$, then statistically more than one service request should be allowed for each capability. To enforce this, the site stops accepting a capability with probability $1/w_i$, and then adds the capability to the duplicate suppressor. However, multiple service requests carrying the same capability can trivially be linked by the site. We discuss how to address this issue through system parameterization below. Finally, if $w_i < 1$, then each capability is accepted with probability $w_i$, and exactly one service request is allowed for each accepted capability.

**Policy Parameterization.** We now discuss the parameterization of $w_i$. First, to compute $w_i$, the site does not need to exactly know $c_i$. Instead, the site simply needs to assign specific weights to these capability seeds based on its policies. Further, with an ideal parameterization, $w_i$ should be exactly one since (i) no capability is spendable on more than one service request to ensure unlinkability and (ii) no additional capabilities are required for a single service request to avoid extra computation and networking overhead. However, it is difficult to reach the ideal parameterization since $r_i$ is chosen by the authority $A_i$ that is unaware of the site’s configurations $c$ and $\bar{O}$. In addition, configurations can vary greatly among different sites so that an ideal parameterization for one site could be undesirable for others.

To address the problem, TorPolice sets $r_i$ such that (with high probability) a Tor client can obtain enough capabilities so that it is feasible for the client to present a unique capability for each TCP connection to the site. This ensures that the client can achieve the highest level of unlinkability offered by Tor, i.e., service providers only see TCP connections from Tor exit relays. We clarify that it is the client who determines how to spend its capabilities across TCP connections (as described below). The above parameterization is adopted only to ensure that spending a unique capability for each TCP connection is a feasible strategy for the client. A reasonable setting of $r_i$ can be estimated based on the live Tor measurement in [42], which finds that during a 10-minute interval, each Tor client opens about 24 web streams. In practice, the authority $A_i$ should enforce $r_i$ over a longer period of time (e.g., few hours) to accommodate usage burst.

Note that when an AA $A_k$ is deployed by the site itself, system parameterization for $A_k$ is easier since the site determines the rate limiters for issuing pre-capabilities.

**Capability Spending by Tor Clients.** Given $r_i$, some sites may end up with rules $w_i > 1$, i.e., one capability is allowed for multiple service requests. In this case, the site needs to send a response to indicate whether a capability is nullified or not. Tor clients are free to determine their capability spending strategies. For instance, a Tor client can send $w_i$ service requests using the same capability within a single TCP connection (due to HTTP keep-alive), which still ensures the highest level of unlinkability. Or the client may choose to spend one capability across multiple TCP connections to allow trans-TCP linkability. We note that if a Tor client uses the default setting of Tor Browser, it already allows trans-TCP linkability since the Tor Browser uses session cookies. For a site that has $w_i$ less than 1, it can enforce such policies by accepting one capability with probability $w_i$ and for each accepted capability, the site allows only one service request.

### 7 TORPOLICE-ENHANCED TOR ACCESS

In this section, we detail the capability design for accessing the TorPolice-enhanced Tor network. The current Tor network suffers from a variety of botnet abuses such as large scale C&C abuse [21, 28, 32, 37, 38], relay flooding attacks [14, 15] and traffic analysis [51, 53]. These abuses lead to various bad results, including poor system performance for legitimate Tor users, de-anonymization threats and bad reputation for Tor. The root cause of these attacks is that botnets can create an arbitrary number of Tor circuits without any limitation. Enforcing local rate limiting for circuit creation at each relay is unlikely to stop these attacks since a strategic botnet can instruct each bot to enumerate all relays to circumvent the local rate limiting.

With TorPolice, Tor can globally control circuit creations by any client using our capability scheme. In particular, when TorPolice is activated, clients are required to possess valid capabilities in order to create TorPolice-enhanced circuits (to be incrementally deployable, circuit creation requests without valid capabilities are de-prioritized in case of congestion). Then, by controlling the rate at which a Tor client can obtain capabilities, TorPolice can explicitly limit the client’s circuit creation rate.

#### 7.1 Relay-Specific Capability Design

To create a three-hop TorPolice-enhanced circuit, a Tor client $U$ needs to obtain three capabilities, each of them being specific to a relay on the circuit. The design of relay-specific capabilities is identical to that of site-specific capabilities, except for the following.

(i) During pre-capability requesting, the client needs to specify the proper pre-capability type, i.e., it is for Tor-enhanced circuit creations. Further, to request a pre-capability specific to a relay $R$, the client encloses the fingerprint of relay $R$ (rather than any site domain) in the set of blinded information sent to its selected AA.

(ii) Relay-specific capabilities are spendable at TorPolice-enhanced relays (not at any sites) for creating Tor-enhanced circuits through the relays. The relays first validate received capabilities (based on a set of rules similar to those defined in § 6.3) before extending circuits.

We clarify that to request pre-capabilities, Tor clients do not have to use TorPolice-enhanced circuits to reach the AAs. Thus, there is no deadlock for bootstrapping TorPolice. Another alternative is pre-installing few relay-specific capabilities on Tor clients so that using TorPolice-enhanced circuits to bootstrap the system is viable.

**Policy Definition.** Similar to site-specific capabilities, relay-specific capabilities enable Tor to enforce access rules for its relays. In this paper, we propose to use capabilities to control the circuit creation rate by any Tor client so as to mitigate those aforementioned botnet abuses against Tor. In particular, assume the following set of AAs $\{A_0, A_1, \ldots, A_n\}$ are deployed and authority $A_i$ accepts a type of capability seed $s_i$. In this context, Tor defines its access policies as $\{q_0, q_1, \ldots, q_n\}$, where $q_i$ is the maximum rate at which a capability seed $s_i$ can request pre-capabilities (for creating Tor-enhanced circuits) from authority $A_i$. Then in order to bound a Tor client’s circuit creation rate, $\{q_0, q_1, \ldots, q_n\}$ should satisfy the following condition for any attacker strategy $\{\alpha_0, \alpha_1, \ldots, \alpha_n\}$ where $\alpha_i \in [0, 1]$ and $\sum_{i=0}^{n} \alpha_i = 1$. 

\[ \alpha_0 q_0 + \alpha_1 q_1 + \ldots + \alpha_n q_n \leq 1 \]
\[ \sum_{i=0}^{n} \frac{a_i \cdot \lambda \cdot q_i}{3 \cdot e_i} \leq T, \]  

(5)

where \( \lambda \) is the cost of getting one network identity, \( c_i \) is the cost for obtaining one capability seed \( s_i \) and \( T \) is the maximum circuit creation rate allowed for a client, which is a parameter controlled by Tor. We note that the constant 3 appears in above formula since a standard Tor circuit contains 3 relays and each of them consumes a relay-specific capability.

To ensure the correctness of formula (5) for any attacker strategy, we choose

\[ q_i \leq \frac{3 \cdot c_i \cdot T}{\lambda}, \quad \forall i \in [0, n] \]  

(6)

**Parameterization.** Similar to how sites determine its access rules using Equation (4), to compute \( q_i \), the Tor Project needs to assign certain weights to these capability seeds. Further, a proper configuration of \( T \) can be determined based on the live Tor measurements in [42]. In particular, during an 10-minute interval, PrivCount [42] estimates that a Tor client opens about 4 Tor circuits. Thus, the maximum rate \( T \) at which one Tor client can create circuits should be close to 4 per ten minutes. In practice, each AA should enforce \( q_i \) over a longer period of time (e.g., few hours) to accommodate usage bursts and relay churn.

### 7.2 Capability Exchange for Tor OSes

The design of relay-specific capabilities needs to be augmented with a capability exchange protocol to better support Tor onion services (OSes). In particular, a Tor onion server (itself runs a Tor client) needs to open many Tor circuits in order to serve all its clients (referred to as OS-clients). Although a Tor hidden server can continue to use legacy Tor circuits to serve its OS-clients, we do design a capability exchange protocol to enable onion servers to use TorPolice-enhanced circuits as well.

The design intuition is that an OS-client requests a new type of capability, i.e., trans-capability, from the AAs, and sends it to the OS, which subsequently redeems the trans-capability at the AAs for new pre-capabilities. The trans-capability, accounted on the capability seed of the OS-client, anonymously informs the AAs that the hidden server needs to create a new TorPolice-enhanced circuit to serve the OS-client. For better readability, the detailed design of the protocol is deferred in § 13.2.

### 8 SECURITY ANALYSIS

In this section, we perform a formal security analysis for the impact of TorPolice on Tor users’ anonymity. Let \( N_T \) denote the set of Tor clients that request pre-capabilities from the AAs, and subsequently present capabilities to access service providers or Tor relays. We first present two useful lemmas on unlinkability.

#### 8.1 Lemmas

**Lemma 8.1.** Consider any client \( U \in N_T \). By colluding with each other, both the AAs and a service provider \( W \) gain only negligible advantage over random guessing when trying to link a specific Tor-emitted site access with the client \( U \).

**Proof.** We first specify the notations used in the proof. Let \( V \) denote a Tor-emitted site access to \( W \) initiated by the Tor client \( U \). Note that the definition of a site access is decided by \( W \). Let \( C \) denote the service-specific capability that \( U \) sends to \( W \) to support the site access \( V \). Let \( P \) denote the pre-capability used by \( U \) to compute \( C \).

Since the client \( U \) can use Tor to connect to the AAs when requesting the pre-capability \( P \), in the ideal case, \( U \) is unlinkable with \( P \). However, to ensure that our lemma still holds in the worst case when Tor’s unlinkability is broken by adversaries, we assume the AA \( \mathcal{A} \) that issues \( P \) can link \( P \) with the client \( U \). Thus, the service provider \( W \) and other AAs can have such linkability as well by colluding with \( \mathcal{A} \).

Next, we prove the lemma by contradiction. Assume that the AAs and \( W \) can design an algorithm \( K \) that enables the AAs and \( W \) to link the site access \( V \) with the client \( U \). Since the site access \( V \) is linkable with the capability \( C \) (as \( C \) is presented to the site to support the access \( V \)) and the client \( U \) is linkable with the pre-capability \( P \) (based on the above worst-case assumption), designing the algorithm \( K \) is equivalent to designing another algorithm \( K' \) that enables the AAs and \( W \) to link the capability \( C \) with the pre-capability \( P \).

In TorPolice’s design, \( P \) is the blinded message signed by the AA \( \mathcal{A} \) (i.e., the blind-signer), and \( C \) is the unblinded version of \( P \) produced by the client \( U \) using a secret factor unknown to the blind-signer. Thus, the problem of designing \( K' \) to link \( P \) with \( C \) is the same as designing an algorithm \( K'' \) that allows a blind-signer to link the blinded message it signs to the unblinded message without knowing the secret factor, which is impossible in a blind signature [13, 17]. This contradiction proves that the hypothetical algorithm \( K \) does not exist, indicating both AAs and \( W \) gain only negligible advantages of linking an specific site access \( V \) with client \( U \) via collusion. We clarify this lemma does not claim that colluding among multiple entities does not pose a risk for Tor; it only proves that TorPolice does not introduce any further risk even if multiple entities collude with each other. \( \square \)

Using the similar reduction proof as Lemma 8.1, we can prove the following lemma.

**Lemma 8.2.** Consider any client \( U \in N_T \). By colluding with each other, both the AAs and Tor relays gain only negligible advantage over random guessing when trying to link a specific relay access (i.e., TorPolice-enhanced circuit creation) with client \( U \).

### 8.2 Information Leakage Analysis

Given the above two lemmas, we now analyze the impact of TorPolice on Tor user anonymity. We measure the possible information leakage to an arbitrary service provider \( W \) based on degree of anonymity [23, 58]. Our analysis uses information-theoretic entropy [59] as the measure of information contained in a probability distribution. Recall that \( N_T \) denote the set of TorPolice-upgraded Tor clients. Given an arbitrary capability-enhanced site access (i.e., an access supported by a valid capability), \( W \) believes that with probability \( p_i \), the access originates from client \( i \in N_T \). Thus, \( W \) maintains a probability distribution \( I \) for all anonymous accesses.
Then, the entropy (i.e., the information contained in the distribution $I$) is defined as $H_W = -\sum_{i \in \mathbb{N}_T} p_i \cdot \log_2(p_i)$.

Based on the unlinkability proven in Lemma 8.1, we have $p_i = 1/N_T$, where $N_T$ is the size of the anonymity set $\mathbb{N}_T$. Thus, the entropy after introducing TorPolice is

$$H_W = \log_2 N_T. \quad (7)$$

Next, we analyze the system entropy before introducing TorPolice. Let $\mathbb{N}$ denote the entire set of anonymous Tor clients. Notice that the current Tor network protects $\mathbb{W}$ from linking a (native) site access with a specific Tor client. Thus, given the entire anonymous client set $\mathbb{N}$, the maximum entropy $H_M$ of the system $k$ is $H_M = \log_2 N$, where $N$ is the size of the anonymity set $\mathbb{N}$.

Thus, based on the definition in [23, 58], the degree of anonymity $d$ after introducing TorPolice is

$$d = 1 - \frac{H_M - H_W}{H_M} = \frac{\log_2 N_T}{\log_2 N}. \quad (8)$$

Anonymous Set Analysis. Given Equation (8), the information leakage is determined by the size of the anonymous client set before and after TorPolice is introduced. Therefore, once all Tor clients are upgraded to support TorPolice, there is no information leakage at all. Thus, eventually, TorPolice completely preserves the privacy guarantee offered by the Tor network. To mitigate the one-time privacy issue during the early deployment phase of TorPolice, the Tor Project can require mandatory client upgrades from a certain time point to “force” all active clients to serve as TorPolice initiators.

9 IMPLEMENTATION

In this section, we present the full implementation of TorPolice.

9.1 Capability Implementation

We implement capability-related computation using C, Python and JavaScript to consider various usage scenarios. For instance, the capability design can be directly built into the Tor software written in C (as shown in § 9.4), or it can be implemented as a plugin for the Tor browser, which executes capability-related computation in JavaScript (as shown in § 9.2). Websites may compute capabilities using any language. Thus, we use Python as an example due to its popularity in web applications.

We use the RSA algorithm to perform capability-related cryptographic operations such as blind signing. The C implementation uses the OpenSSL library [5] and the Python implementation imports the PyCrypto module [6]. Since no standardized JavaScript library for computing blind signatures is available, we develop our own library based on crypto-js [4] and BigInt [2], two libraries that allow us to perform computation (e.g., modulo) for very large prime numbers in JavaScript. We benchmark the capability computation overhead in § 10.1.

9.2 Implementation of the Access Authority

For an AA accepts CAPTCHAs as capability seeds (referred to as CAA), we implement it as a web server that deploys Google’s reCAPTCHA [31] service. For an AA accepts computational puzzles (referred to as PAA), it accepts puzzle solutions over HTTP (or HTTPS) requests. These AA servers define a customized HTTP header (X-Capability) to carry TorPolice-related cryptographic tokens such as pseudonyms and pre-capabilities. To make the implementation transparent to clients (i.e., no client-end network stack modifications are required), the AA servers add X-Capability in the Access-Control-Allow-Headers HTTP header option.

Although Tor clients can access PAA using native HTTP libraries, the CAA needs to be accessed using browsers. Thus, we implement a Firefox add-on (referred to as CapJS) to execute TorPolice-related cryptographic operations in browsers. In real-world deployment, the add-on should be developed by trusted entities (e.g., the Tor project) and signed by Mozilla so that Tor users can install it on their Tor browsers.

CapJS Design. When a Tor client connects to a CAA server, CapJS checks cookies to determine whether a pseudonym $I$ issued by the same CAA server is locally cached. If so, CapJS then puts $\{I | \{S | n | t_s | F\}^b\}$ into the X-Capability header, where $\{S | n | t_s | F\}^b$ is the set of blinded information described in the pre-capability design (§ 6.1). If no pseudonym issued by the same CAA is available, CapJS only puts the set of blinded information into the X-Capability header. With this customized HTTP header, CapJS sends an AJAX GET to the CAA server.

After receiving the AJAX request, the CAA server inspects the X-Capability header. If a valid pseudonym is retrieved, the CAA server computes a pre-capability for the client using the blinded information carried in the header. Otherwise, the CAA server loads a reCAPTCHA challenge page for the client. Once the challenge is successfully solved, the CAA server computes a pre-capability by signing the blinded information, as well as a pseudonym for the client. These tokens are returned to the client in a JSON object responding to the client’s AJAX GET request.

After receiving a response from the CAA server, CapJS inspects the received data object to retrieve the pre-capability and the pseudonym (if applies). The pre-capability is then unblinded to produce a capability, and the pseudonym is cached for future use.

9.3 TorPolice-enhanced Site Access

To serve TorPolice-enhanced Tor clients, the deployment required at service providers is lightweight. In particular, a site simply needs to add X-Capability in its Access-Control-Allow-Headers HTTP header option to allow CapJS to pass site-specific capabilities in the header. CapJS is responsible for sending capabilities to corresponding sites if the client visits multiple TorPolice-enhanced service providers.
and potentially enforcing the capability spending policies discussed in § 6.3. Upon receiving capability-enhanced service request, the site verifies the received capability using the rules discussed in § 6.3 to enforce its desired access policies. Figure 2 depicts the workflow of a site access by a client with CapJS installed on its browser.

9.4 TorPolice-enhanced Tor Circuit

We now discuss the implementation of TorPolice-enhanced Tor circuit creation.

Tor Source Code Modification. We modify the Tor software source code to integrate our capability design into Tor circuit creation. The native Tor circuit creation proceeds as follows. The onion proxy (OP) on a Tor client first sends a CREATE cell containing the first half of the Diffie-Hellman handshake to a guard relay, which responds with a CREATED cell containing the second half of the handshake. To extend the circuit to a new relay $R_e$, the OP sends a RELAY_EXTEND cell (specifying the address of $R_e$ and a new secret) to the last relay $R_m$ on the partially-created circuit. $R_m$ copies the received information into a new CREATE cell, and forwards the cell to $R_e$.

To create a capability-enhanced circuit, in addition to these original cells, the OP further sends a valid relay-specific capability to each hop. In our prototype, the OP prepends a capability to the payload of the CREATE cell when connecting to the guard relay. Capabilities for subsequent relays are prepended to corresponding RELAY_EXTEND cells. Figure 3 illustrates the modified cell structure. Each relay first verifies the received capability based on the rules defined in § 7.1 before processing the onionskin carried in the remaining payload. Since capability verification is much cheaper than the onionskin processing, this design saves the relay considerable compute resources for processing bogus circuit creations without valid capabilities. Alternatively, a relay-specific capability can be carried via a customized cell. In this case, the cell should be sent together with the CREATE cell (or RELAY_EXTEND cell) to avoid additional RTTs.

To validate our implementation, we test the modified Tor source code in Shadow [40], a safe development environment to run real Tor source code in a private Tor network. Via log analysis, our evaluations center around the following.

10 EVALUATION

10.1 Capability Computation Overhead

In this section, we benchmark the overhead of capability-related cryptographic operations in C, Python and JavaScript on our testbed. All results are obtained using a single 3.30GHz Intel i3-3120 core. We perform 10,000 runs to learn the mean, median, and standard deviation of the computation times for a single capability generation, verification, information blinding and unblinding. We perform experiments for various RSA key lengths. Results shown in Table 1 are obtained when the RSA key length is 1024. The overall computational overhead is small. For instance, it takes an AA (performed by Tor clients) in the order of 300 microseconds in C to compute a pre-capability. And a single capability verification takes ~25 microseconds in C. A blinding and an unblinding operation by Tor clients can be finished in ~3 and ~2 microseconds, respectively, in C. The implementations in C and Python have comparable performance since PyCrypto internally wraps C code. Although it is more expensive to perform signing and verifying in JavaScript, the overhead of blinding and unblinding operations (performed by Tor clients) in JavaScript is comparable with other languages. The AAs, relays and service providers can adopt more efficient languages such as C and Python to perform capability generation and verification.

Table 1: The computational time (in microseconds) for capability-related cryptographic operations.

| Operation     | Mean      | Median     | Std. Dev. | Language |
|---------------|-----------|------------|-----------|----------|
| Generation    | 232.0     | 232.0      | 0.1       | C        |
|               | 253.7     | 253.6      | 0.3       | Python   |
|               | 27,320.0  | 27,240.0   | 245.5     | JavaScript |
| Verification  | 25.6      | 25.6       | 0.0       | C        |
|               | 32.0      | 32.0       | 0.1       | Python   |
|               | 355.5     | 354.3      | 5.3       | JavaScript |
| Blinding      | 3.5       | 3.5        | 0.0       | C        |
|               | 46.3      | 46.3       | 0.1       | Python   |
|               | 18.1      | 18.1       | 0.3       | JavaScript |
| Unblinding    | 2.4       | 2.4        | 0.0       | C        |
|               | 7.0       | 7.0        | 0.0       | Python   |
|               | 64.8      | 64.7       | 6.8       | JavaScript |
10.2 Deployment Overhead of the AAs

In this section, we evaluate the deployment overhead of the AAs. We first estimate the compute resources needed by the AAs to support the pre-capability computation for all Tor users. Then we evaluate the pre-capability issuing latency using the AAs deployed on our testbed.

Collective Compute Resources Needed. To estimate compute resources required from the AAs, we need to estimate the amount of pre-capability requests from all Tor clients. Recall that each AA server maintains two rate limiters for issuing pre-capabilities: \( r \) for issuing site-specific pre-capabilities and \( q \) for issuing relay-specific pre-capabilities (§ 5.2). We estimate \( r \) and \( q \) using the live Tor measurement results in [42]. In particular, during a 10-minute interval, PrivCount [42] estimates that each Tor client opens about 24 TCP streams and 4 circuits. Further, PrivCount [42] counts about 710, 000 unique clients during a 10-minute interval. Combing these, we estimate the collective pre-capability request rate from all Tor clients is about 44, 000 per second. Since it takes one core 0.23 milliseconds to issue one pre-capability, the AAs collectively need about 11 cores to support the entire set of current Tor users.

In practice, the AAs should be over-provisioned to prevent an adversary from overwhelming them via massive pre-capability requests. We clarify that such flooding attack aims to exhaust the AAs’ compute resources rather than their network bandwidth (bandwidth-oriented volumetric DDoS attacks can be prevented by hosting the AAs on well-provisioned cloud [49]). Figure 4(a) plots the number of cores required in order to withstand different-sized botnets. The results show that the AAs need about 100 cores to withstand a 5-million node botnet.

Pre-Capability Release Latency. We now evaluate pre-capability release latency using the AAs deployed on our testbed (§ 9.2). We define the pre-capability release latency as the time required for an AA server to process a pre-capability request, excluding networking latency and other user-introduced latency (e.g., the time required for solving challenges). We provision eight servers on our physical testbed as AA servers in this experiment. We double-threaded each AA server so that the eight AA servers collectively have 16 cores. To emulate pre-capability requests from the entire set of Tor users, we develop a requester that generate requests at the rate of 44, 000 per second. To send each request, the requester randomly picks one of the 8 AA servers. The results, plotted in Figure 4(b), show that the pre-capability release latency is less than few milliseconds, which is over 2 orders of magnitude smaller than the typical circuit creation time (0.7s based on our live Tor measurements in § 13.3).

10.3 Enforcing Site-Defined Policies

In this section, we demonstrate that TorPolice enables a site to enforce site-defined access policies for anonymous Tor connections. As a result, a site can explicitly bound a strategic adversary’s service request rate using self-defined parameters.

Access Policies. For evaluation purpose, we assume that the site assigns equal weights to both types of capability seeds, i.e., \( c_0 \) (for CAPTCHA solutions) and \( c_1 \) (for puzzle solutions) in Equation (4) are the same. However, the actual costs, denoted by \( c'_0 \) and \( c'_1 \), can be different from \( c_0 \) and \( c_1 \). Further, base on the measurements in [27, 52], we assume \( c'_0 \) is close to \( \lambda \) (the cost for obtaining one network identity).

We evaluate three strategies that a site may use to define its access policies. The first strategy (referred to as basic strategy) is that the site accepts all Tor-emitted requests with valid capabilities. In the second strategy (referred to as rate limiting strategy), the site enforces a maximum service request rate \( r_{\max} \) for all Tor-emitted requests with valid capabilities. In the third strategy, besides rate limiting, the site further performs weighted fair queuing (WFQ) to serve requests: rather than serving all valid Tor-emitted requests in one FIFO queue, requests with capabilities obtained using CAPTCHA solutions and puzzle solutions are served in two separate FIFO queues weighted equally. The third strategy (referred to as WFQ strategy) prevents one type of seed from overwhelming the other one.

Policy Enforcement. We now study an adversary’s service request rate through Tor when it invests a certain amount of money on acquiring capability seeds. Define \( k = c'_0/c'_1 \). We first present the evaluation results for \( k = 0.5 \) in Figure 5 and then extend our discussion to arbitrary \( k \). For any amount of investment, the adversary’s service request rate through Tor (denoted by \( r_a \)) is normalized to the service request rate obtained when the adversary connects to the site directly without using Tor.

Since \( c'_0 < c'_1 \) given \( k=0.5 \), the adversary’s optimal strategy is spending all investment on solving CAPTCHA. Thus, we have...
\( r_a = \epsilon \), where \( \epsilon \) is the site-configurable parameter defined in Equation (3). When the site adopts the basic strategy, \( r_a \) remains the same as the adversary increases its investment. However, for the other two strategies, \( r_a \) will reach a point of diminishing returns as the adversary’s investment further increases (as shown in Figure 5). In particular, when the site adopts the rate limiting strategy, the point of diminishing returns is reached when the collective service request rate from the adversary and all legitimate Tor clients exceeds \( r_{\text{max}} \). In Figure 5, we denote the adversary’s cost at this point by \( 2E_\epsilon \). After that, further increasing investment actually reduces \( r_a \) since no more Tor-emitted requests are allowed by the site.

When the WFQ strategy is adopted, \( r_a \) experiences two points of diminishing returns as the adversary’s cost increases, as shown in Figure 5. The first one happens when the collective service request rate from all Tor clients using the optimal seed (CAPTCHA seed in this evaluation) exceeds \( \frac{r_{\text{max}}}{2} \). After this point, the adversary has to use sub-optimal seeds in order to further get services. As a result, \( r_a \) starts to decline from the optimal rate \( \epsilon \). The second point of diminishing returns is reached when the collective Tor-emitted service request rate exceeds \( r_{\text{max}} \).

**General Results.** Our further analysis (deferred in § 13.4) proves that for any \( k \), \( r_a \leq \epsilon \) if \( k \leq 1 \) and \( r_a \leq k \epsilon \) if \( k \geq 1 \). Thus, regardless of the actual cost of obtaining capability seeds, the adversary’s service request rate is bounded by \( \Theta(\epsilon) \). This result holds no matter which strategy the site adopts and how many types of capability seeds are accepted by TorPolice.

### 10.4 Mitigating Botnet Abuse Against Tor

In this section, we perform Tor-scale evaluations to demonstrate the following.

**Mitigating Botnet C&C Abuse in Tor.** Based on the real data collected from the large scale botnet C&C abuse against Tor happened during Aug-Sep 2013, we show that Tor clients suffered from very high circuit failure rates (~40%) during the abuse. Then we demonstrate that TorPolice effectively mitigates the abuse by reducing failure rates by ~74% (§ 10.4.1).

**Mitigating Tor-targeted DDoS Attacks.** We demonstrate that TorPolice significantly increases Tor’s resilience against cell flooding attacks that aim to paralyze the Tor network via excessive circuit creation requests (§ 10.4.2).

**Tor-scale Simulator.** We aim to show that TorPolice is able to mitigate the harm that a multi-million botnet can do to Tor. While we do have a TorPolice implementation that runs on Shadow [40] (see § 9.4), we would run into scalability issues with simulating millions of Tor clients. Further, Shadow is unable to help us simulate the cryptographic overhead that botnets would impose on Tor relays [39]. Due to these shortcomings, we developed our own simulator. We faithfully implement Tor’s path selection algorithm [24] and validate the correctness of our implementation by comparing relays’ selection probability with the ones published by Tor Atlas [10]. We sampled the computational capacity of relays from Barbera et al.’s work that was based on live Tor measurements [14].

#### 10.4.1 Mitigating Botnet C&C Abuse.

In this section, we study the botnet C&C abuse that happened during Aug-Sep 2013, when Tor’s daily estimated users rapidly increased from 1 million to 6 million. We first show that Tor clients experienced very high circuit creation failure rates when Tor was under this abuse. Then we show TorPolice effectively mitigates such abuse.

**Circuit Creation Failure Rate.** We use the data collected by Tor to estimate the amounts of circuit creations initiated by the botnet during the C&C abuse. To improve readability, we defer the detailed mathematical modeling to § 13.5. Due to the massive circuit creations by the botnet, compute resources of many relays are exhausted, resulting in very high circuit creation failure rates, as depicted in Figure 6. Such high failure rates are caused by the following vicious cycle. When the abuse starts, Tor relays begin to drop requests due to the lack of compute resources. These initial failures force the bot clients to continuously send requests until their circuits are successfully created, which further increases the network load. The resulting consequences are that the botnet still managed to use Tor as its primary C&C channel after numerous trials whereas Tor is less usable for legitimate Tor users since it could require tens of trials before a circuit is finally created, resulting a high user-perceived latency.

**Mitigating Botnet Abuse in Tor.** The root cause of such high circuit creation failure rates is that bot clients deviate from typical Tor usage pattern, i.e., they initiate numerous circuit creation requests without any limitation. As described in § 7.1, TorPolice allows Tor to explicitly control the circuit creation by any Tor clients. Thus, to counter this abuse, Tor sets its access policies such that the maximum rate at which a client can create circuit is 4 per ten minutes (aligned with live Tor measurements in [42]). We plot the resulting circuit creation failure rates after enforcing the access policies in Figure 6. Clearly, TorPolice effectively eases the network load and reduces the average failure rate from ~41% to ~10%, a ~74% reduction.

In response to the C&C abuse, the Tor project released a new version (0.2.4.17-rc) that prioritizes the processing of onionskins using the ntor [30] protocol since the bot clients used an older version without ntor support. Tor’s countermeasure reduced the circuit failure ratio to about 20% [38]. We clarify that a strategic botnet could circumvent Tor’s defense by changing adaptively (e.g.,
As noted in [37], a general concern of attacking a botnet by Tor in case of abuse (e.g., by blacklisting its hidden servers) is that it may lead to retaliation. For instance, a botnet can easily paralyze Tor via excessive circuit creation requests. According to Tor design [24], a Tor client drops its current guard relay when circuit failure rate measured by the client is above 30%. Via massive circuit creation requests, an adversary can easily exhaust computation resources of the entire set of relays, driving circuit failure rates much higher than this threshold. Figure 7 demonstrates this vulnerability: a moderate-sized botnet with hundreds of thousands of bots is enough to cause very high circuit failure rates. When Tor is protected by TorPolice, however, even a multi-million node botnet can only cause very limited failure rates for the current Tor network (represented by the consensus published on May 1st, 2017).

11 RELATED WORK

In this section, we discuss closely related work.

Capabilities in the Internet. Capability schemes ([48, 49, 54, 65, 66]) have been proposed to protect the Internet from DDoS attacks. In these approaches, capabilities specify certain traffic policing rules and meanwhile carry cryptographic signatures to ensure correctness. Victims (e.g., servers or congested routers) police traffic based on received capabilities to stop attacks. Different from TorPolice, Internet capability designs do not consider privacy. Further, some of these capability schemes are difficult to deploy since they require modification of Internet core and client network stack. On the contrary, TorPolice is readily deployable in Tor with small overhead.

Anonymous Blacklisting Systems. Anonymous blacklisting systems [35] allow service providers to maintain a “blacklist” to explicitly block abusive users while serving non-abusive users without breaking anonymity. Anonymous blacklisting systems can be categorized into three broad groups: the pseudonym systems [18, 19, 22, 50, 60], the Nymble-like systems [34, 36, 45, 47, 64], and the revocable anonymous credential systems based on zero-knowledge proofs [16, 62, 63]. These systems either offer pseudonymity instead of full anonymity or require a trusted or semi-trusted authority to provide anonymity. TorPolice is not designed to be a new anonymous blacklisting system. Rather, TorPolice is explicitly designed for Tor, focusing on proposing a capability-based access control framework that allows service providers and Tor to enforce access rules to throttle various botnet abuses while still serving legitimate Tor users properly. Further, TorPolice’s trust is more distributed since its AAs are fully distributed and each of them only has a partial view of the entire system.

12 CONCLUSION

In this paper, we present TorPolice, the first privacy-preserving access control framework that allows service providers and Tor to enforce self-selectable access policies on anonymous Tor connections so as to throttle various botnet abuses while still providing service to legitimate Tor users. TorPolice leverages blindly signed network capabilities to preserve the privacy of Tor users. We implement a prototype of TorPolice, and perform extensive evaluations to validate TorPolice’s design goals.
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centralization, and meanwhile it does not need to include all DAs to be fault-tolerant, similar to how the Tor network consensus is released. Specifically, each DA contributes its part for puzzle seed by generating a random nonce signed by its public key along with a timestamp, as formulated below:

\[ s_i = n_i | t_s | S_{D,i} \]

where \( n_i \) is the nonce, \( t_s \) is the timestamp set to the starting time of the current \( P^*_{sr} \) (e.g., \( t_1 \) in Figure 8) to indicate the freshness of the \( s_i \), and \( S_{D,i} \) is the \( i \)th DA’s signature to prove the integrity of \( s_i \). To construct a puzzle seed for the current \( P^*_{sr} \), clients need to concatenate at least \( n \) authentic seed pieces issued by \( n \) distinct DAs. We note that Tor’s existing random value generator [33] does not fit for TorPolice since it computes a fresh value every day whereas TorPolice’s puzzle seeds need to be released more frequently to improve usability, as explained in § 13.1.4.

13 APPENDIX

13.1 Distributed Puzzle Systems

To support puzzle solutions as capability seeds, TorPolice introduces a distributed puzzle system for distributing computational puzzles. Compared with prior systems (e.g., Portcullis [54]), the novelty of TorPolice’s puzzle system is that it can explicitly bound the CPU usage by any client for solving puzzles. In particular, legitimate clients do not prefer to use all their CPU cycles to compute puzzles. However, automated bots do. To enable access control, prior systems (e.g., Portcullis [54]) would need to prioritize requests based on the difficulty level of puzzles since otherwise the bots could overwhelm the system by solving easy puzzles. Thus, to compete with automated bots, legitimate clients are forced to use all their CPU cycles to compute puzzles. As a result, the percentage of CPU cycles allowed for solving puzzles, TorPolice’s can bring all automated bots down to the percentage that normal clients prefer to use for puzzle computation, which significantly reduces the computation disparity between legitimate clients and automated bots.

13.1.1 Puzzle System Overview.

All computational puzzles are computed based on a series of puzzle seeds that are released periodically. Tor’s existing directory authorities (DAs), for instance, can be used for releasing puzzle seeds. The puzzle system works on the basis of two periods, as illustrated in Figure 8. In each puzzle seed release period (\( P^*_s \)), one fresh puzzle seed is released at the beginning of the period and no more puzzle seeds will be further released in this period. The seed release algorithm (§ 13.1.2) ensures that the puzzle seeds cannot be pre-computed and each valid seed requires the participation from a majority of all DAs. In each \( P^*_s \), all puzzles are computed based on the puzzle seed released in the current \( P^*_s \). Thus, it is impossible to pre-compute solutions for future puzzles even if the puzzle generation algorithm (§ 13.1.3) is public. Similarly, solutions to previous puzzles cannot be used as valid capability seeds in the current \( P^*_s \). To bound a client’s CPU usage for solving puzzles, all puzzle solutions have to be returned to the AAs within the puzzle solution acceptance period (\( P^*_a \)). Late solutions will not be accepted. Thus, the percentage of CPU usage for solving puzzles is bounded by \( P^*_a/P^*_s \).

13.1.2 Puzzle Seed Release.

The puzzle seed release process requires the participation of at least \( n \) of Tor’s DAs. \( n \) should include the majority of DAs to avoid

Figure 8: TorPolice’s puzzle system works on the basis of \( P^*_a \) and \( P^*_s \). One fresh puzzle seed is released in each \( P^*_s \) and puzzle solutions are redeemable at AAs for pre-capabilities only within \( P^*_a \) in each \( P^*_s \).
based on the fresh puzzle seed released in the current $P_r$. (iii) The puzzle stub encloses its own fingerprint. (iv) The puzzle solution is valid, as defined in §13.1.3. (v) The puzzle stub has not been spent before. To enforce the fifth rule, the AA needs to cache all spent puzzle stubs. The cache space is bounded as the AA can erase the puzzle stubs received in previous periods since they are no longer spendable.

13.1.6 Puzzle System Analysis.
In each $P_r$, the number of puzzles solved by a client follows the following binomial distribution

$$ G_{\text{seed}} \sim B\left(p_p, \left[ \frac{p_a}{t_p} - \frac{P_c}{t_p} \right] \right), \quad (11) $$

where $G_{\text{seed}}$ denotes number of solved puzzles, $p_p$ is the probability that one attempt (i.e., a hash computation) produces a valid puzzle solution according to the rule in §13.1.3, $t_p$ is the amount of time it takes for the client to attempt a single hash computation and $\left[ \frac{p_a}{t_p} - \frac{P_c}{t_p} \right]$ is the number of attempts $U$ can make within the allowed time period.

TorPolice can control $p_p$ and $P_a$ to affect the numeric values of $G_{\text{seed}}$. In particular, $p_p$ should be chosen such that with high probability (i.e., 0.99) a client with slow computation speed (e.g., a mobile device released few years ago) and slow network connection (e.g., 99th percentile of the RTT measured by CAIDA [8]) can correctly solve one puzzle so as to produce a valid capability seed. In particular, given that the slow device’s computation speed is $t_p$ and the 99th percentile network latency is $P_c^{99th}$, $p_p$ is selected such that $1 - (1 - p_p)^N_c > 0.99$, where $N_c = \left[ \frac{p_a - \frac{P_c}{t_p}^{99th}}{t_p} \right]$.

13.2 Trans-Capability Design Design
In this section, we detail the capability exchange protocol discussed in §7.2. Since a Tor orion server (itself runs a Tor client) needs to open many Tor circuits in order to serve all its clients (i.e., OS-clients) via TorPolice-enhanced circuits, enforcing per-seed rate limiting for pre-capability release may limit the availability of Tor OSes. To address this issue, we design the following capability exchange protocol.

In particular, a OS-client needs to request a new type of capability, i.e., trans-capability, from the AAs. During the hidden service setup process, along with the information about Rendezvous Point, the OS-client sends a trans-capability to one of the OS’s Introduction Points. The OS subsequently redeems the trans-capability at the AAs for new pre-capabilities, which can be used for generating new relay-specific capabilities. The trans-capability, accounted on the capability seed of the OS-client, anonymously informs the AAs that the OS needs to create a new circuit to serve the OS-client.

Trans-capability Computation. Each trans-capability is computed based on pre-trans issued by the AAs. By default, all Tor clients request pre-trans to prevent the AAs from knowing whether a client has the intention to visit OSes. Clients that do not visit any OS simply ignore the received pre-trans. To request pre-trans, the OS-client sends $\{ z, n, t_s \}$ to the AAs, where $z$ is a pre-defined system value for trans-capability. No information about the OS is enclosed to protect the OS’s privacy. The AAs then compute blind signatures over the information to produce a pre-trans. Finally, the OS-client unblinds the received pre-trans to produce a trans-capability.

Redeeming Trans-capability. The process of redeeming trans-capability is identical to how a Tor client requests relay-specific pre-capabilities using its capability seed (the trans-capability now serves as a new capability seed). The AAs reject all unauthentic, expired or spent trans-capabilities.

13.3 Live Tor Interaction
In this section, we continue our discussion in §9.4 for live Tor network interactive.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{relay_manager.png}
\caption{The design of RelayManager.}
\end{figure}
that since the capability verification is offloaded from live Tor relays to the OP, there could be some marginal errors in our latency measurements since live Tor relays may simultaneously process multiple circuits requests.

### 13.4 Enforcing Site-Defined Policies

In this section, we continue the analysis in § 10.3 to prove that an adversary’s service request rate \( r_a \) is always bounded by \( \Theta(\varepsilon) \). In particular, when \( k \leq 1 \), CAPTCHA solutions are the optimal seeds since \( c_0' < c_1' \). Therefore, the optimal \( r_a \) is obtained when the adversary spends all investment on purchasing CAPTCHA solutions. Thus we have \( r_a = \varepsilon \). When \( k \geq 1 \), solutions to computational puzzles become the optimal seeds. In this case, the adversary’s optimal \( r_a \) is \( k \cdot \varepsilon \) which is obtained by investing all money on solving computational puzzles.

When the site adopts the basic strategy (i.e., accepts all Tor-emitted requests with valid capabilities), the adversary can continuously use optimal capability seeds to maintain its optimal \( r_a \) as its investment increases. However, if either the rate limiting strategy or the WFQ strategy is adopted, the adversary will reach a point of diminishing returns when the site no longer accepts service requests using capabilities that are obtained via the optimal seeds. As a result, the adversary’s \( r_a \) starts to drop from the optimal value.

Thus, regardless of \( k \) and the site’s strategy, \( r_a \) is always bounded by \( \Theta(\varepsilon) \). The above analysis can be easily extended to more types of capability seeds.

### 13.5 Modeling for Botnet C&C Abuse

In this section, we continue the discussion in § 10.4.1 to detail the mathematical modeling for estimating the amount of circuit creation requests in Tor when Tor was under the large scale C&C abuse happened in September 2013.

We collect the Tor network consensus published from September 1 to September 30, 2013 when the number of estimated daily Tor users ranged from 4 million to 6 million. Since one consensus file is published in each hour, we use the average statistics from all 24 consensus files published in a day to represent the Tor status in that day. We model the relay computation capacity based on the live Tor relay measurements in [14] by uniformly sampling their measurement numbers, excluding the samples with low confidence (as defined in their paper).

The number of circuit creation requests received by Tor is modeled by a Poisson Process with arrival rate \( \lambda \). To compute \( \lambda \), we first estimate the number of unique Tor clients in a time interval and then estimate the number of circuits opened by each client in the same interval. Mathematically, we have

\[
\lambda = \frac{N_1 + N_2}{t_1 - t_2},
\]

where \( N_1 \) and \( N_2 \) are the number of unique legitimate clients and bot clients, respectively, over the time interval \( t_0 \); \( r_1 \) and \( r_2 \) are the average number of circuit creations requested by a legitimate client and a bot client, respectively, over the same interval \( t_0 \). \( N_1 \) and \( N_2 \) can be estimated using the metric inferred from live Tor measurements in [42]. In particular, over a 10-minute interval, PrivCount [42] counts 710 unique clients when Tor’s daily estimated user count is 1.75 million, which indicates the client population turnover rate \( \rho \) is about 2.5. Since the methodology used by Tor to estimate its daily user has not changed since 2013, we assume that \( \rho \) obtained in 2016 is also applicable in 2013. Thus, over a 10-minute interval, we have \( N_1 = N^{T}/\rho \) and \( N_2 = (N^{T} - N^{L})/\rho \), where \( N^{T} \) and \( N^{L} \) are the number of legitimate daily users and total daily users estimated by Tor, respectively. We estimate \( N^{L} \) as 1 million, which was the estimated daily Tor user number right before the abuse started in August 2013. \( N^{T} \) can obtained directly from the data published by Tor [11]. Further, PrivCount [42] counts about 4 circuits opened for each Tor client over a 10-minute interval, thus we estimate \( r_2 \) is about 4 in a 10-minute interval, assuming that legitimate Tor clients had the same usage pattern in 2013 as they have in 2016.

However, the above usage pattern inferred from [42] cannot be applied to determine \( r_2 \) since bot clients may have different usage patterns from legitimate clients. Thus, we estimate \( r_2 \) using historical data. In particular, we find that the highest circuit creation failure rate on September 27 2013 is about 35% [38]. Then using the network consensus of the same day, \( r_1 \) is estimated at about 150 over a 10-minute interval.

Based on the above mathematical modeling, we study the circuit creation failure rates using our Tor-scale simulator. The results are plotted in Figure 6.