Attacks on Onion Discovery and Remedies via Self-Authenticating Traditional Addresses

Paul Syverson
U.S. Naval Research Laboratory
paul.syverson@nrl.navy.mil

Saba Eskandarian
UNC Chapel Hill
saba@cs.unc.edu

Matthew Finkel
The Tor Project
sysrqb@torproject.org

Dan Boneh
Stanford University
dabo@cs.stanford.edu

ABSTRACT
Onion addresses encode their own public key. They are thus self-authenticating, one of the security and privacy advantages of onion services, which are typically accessed via Tor Browser. Because of the mostly randomly-looking appearance of onion addresses, a number of onion discovery mechanisms have been created to permit routing to an onion address associated with a more meaningful URL, such as a registered domain name.

We describe novel vulnerabilities engendered by onion discovery mechanisms recently introduced by Tor Browser that facilitate hijack and tracking of user connections. We also recall previously known hijack and tracking vulnerabilities engendered by use of alternative services that are facilitated and rendered harder to detect if the alternative service is at an onion address.

Self-authenticating traditional addresses (SATAs) are valid DNS addresses or URLs that also contain a commitment to an onion public key. We describe how the use of SATAs in onion discovery counters these vulnerabilities. SATAs also expand the value of onion discovery by facilitating self-authenticated access from browsers that do not connect to services via the Tor network.

CCS CONCEPTS
• Security and privacy → Browser security; Web protocol security; • Networks → Naming and addressing.

KEYWORDS
Contextual Trust, Onion Services, Web PKI, TLS Certificates

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1 INTRO TO ONION ADDRESSES AND SATAS
Our presentation of the attacks and countermeasures that are the subject of this paper assumes a familiarity with SATAs. The extremely brief description of these in this introduction is supported by a more detailed description in Appendix A. But first we give a similarly brief description of onion addresses.

Tor’s onion addresses are self-authenticating: the address encodes a public key used to authenticate the address. Onion addresses are an IETF standard [4] used by many Fortune 500 companies, government agencies, and major media and news organizations. They are generally only reachable via the Tor network, typically via Tor Browser. The Tor Project’s overview of onion services [1] provides a basic description, a list of some notable onion sites, and links to further documentation. Though self-authenticating, onion addresses are comprised only of an encoding of an ed25519 public key (plus a checksum and version number). They thus generally appear to be meaningless, random-looking 56-character strings, though some large sites commit significant computational resources to make a portion of the address meaningful, e.g., facebookwkhpilnemxj7asaniu7vnjbj1lt1xjqh9y3mbsbg7kx5tfyd.onion.

Self-Authenticating Traditional Addresses (SATAs), embed security into the nodes of the web in the same way that onion addresses do. Unlike onion addresses, they are also traditional addresses understood by DNS, by humans (to the extent registered domain names are), and by popular browsers that know only the protocols and standards of the (less-secure) web. A working example described in Appendix A is

https://selfauth.site/?onion=ixxuq4b4bsr3aggbokovydiys7rolq4ewqjva67qfmp3y55jxsi15yd.

Connecting to a SATA is authenticated by the traditional mechanisms of TLS and TLS certificates, but to support autonomy of site owners, it is also authenticated by a credential that attests to the binding of the domain name, the onion address, and optionally contextual labels about the type of site, e.g., that it is a news media site, or is a domain owned by Microsoft. We call such an attestation a satestation. Such satestations are made by a SATA, either a third-party SATA, or by a SATA about itself, in which case it also includes a fingerprint of the TLS certificate.

Currently a WebExtension we have implemented for Tor Browser and Firefox can recognize SATAs and checks satestations. Ultimately we expect this functionality to be in the browser itself, but a WebExt facilitates initial deployment, experimentation, and development. A SATA website will create a self-satestation, which is a signature using the onion private key over the following: the domain name and onion address, a fingerprint of the TLS cert, an issue date and most recent recheck date, and (optionally) a list of...
contextual labels. After completing the TLS handshake, a SATA-aware browser checks the self-sattestation and either succeeds and continues with the connection or returns an error and warning.

In Section 2 we describe various mechanisms for onion discovery that support routing to an onion address associated with a more meaningful URL. We also set out vulnerabilities that these mechanisms create or facilitate. Finally, in Section 3 we describe how SATAs and sattestation remediate these vulnerabilities.

2 ATTACKING ONION SERVICE DISCOVERY

Tor recently added mechanisms to make it easy for a Tor Browser client that connects to a registered domain to be easily (and mostly automatically) routed and connected to an associated onion site instead, when one is available. This follows a well-established tradition of automatically choosing a more secure option for the user, when one is available. HTTP Strict Transport Security (HSTS) is a classic example of such an automated choice. These automated Tor mechanisms are deployed and integrated into existing stable releases of Tor Browser. In this section we will describe novel attacks resulting from these Tor security deployments.

1. Onion Alternative Services: Alternative Services (RFC 7838) present via an HTTP header an alternative (alt) URL to which a browser could connect instead of the one selected and displayed in the URL bar. This is entirely invisible to the user unless she examines the source code for this header. Cloudflare began offering onion alt services for its supported domains in April 2018\(^2\); Tor users could request connection to an HTTPS URL but be routed and connected to the domain through its onion address [17]. The URL address bar shows the requested HTTPS URL, even though the connection is through the onion address. No changes were needed to Tor Browser for these to function as intended.

An attacker who temporarily obtains a valid certificate for a victim domain can redirect browsers visiting (a spoof of) the victim domain to an alt service at the attacker’s onion address. Because browsers cache the alternate service response header for a period of time, all subsequent requests to the victim domain will go directly to the attacker’s onion site, without ever connecting to the victim website. Neither the user nor the victim website will detect this.

This vulnerability was previously discussed in [21]. As we will see in the next section, it can be elegantly mitigated using SAT addresses. As an aside, we point out that the caching behavior of alt services enables difficult to detect user tracking.

2. Onion location: Tor Browser 9.5 (released June 2020) introduced support for onion location. Owners of websites at traditional domains can provide a header over HTTPS that will cause a ”onion available” prompt to display in the URL bar. Clicking on this will allow redirection to an onion address, amounting to a kind of attestation by the site owner to its onion address. However, in case an attacker has a fraudulent or hijacked TLS certificate for some domain, they can set up a hijack site with onion location pointing to an onion site run by the attacker.

Tor Browser also allows users to click a radio button in their settings to always ”Prioritize onion sites when known”. (The default is ”Ask every time”) A client receiving any onion-location header (or onion-location meta tag) thus automatically redirects to the indicated onion address with no user input. This makes typo-squatting, domain impersonation, and similar attacks more likely to escape detection: when clicking on a link, the initial URL is visible for only a second before redirection to a random-looking onion address.

For example, suppose an adversary sets up a link:
\(<a href="https://fuii.com">full.com</a>\) where the adversary’s domain HTTPS Everywhere created a ruleset that the extension used to make the appropriate rewrite of URLs in the ruleset.

In 02016, Syverson and Boyce [20] suggested using an HTTPS Everywhere (H-E) is a browser extension originally intended to replace attempts to connect to a website via unencrypted HTTP with a TLS-encrypted connection to the same website [12]. Since some sites used a different URL for the secure version of the same webpage, or put different content at the same URL when an HTTPS connection was used, it was not enough to simply rewrite a request for http://example.com to https://example.com. To address this, HTTPS Everywhere created a ruleset that the extension used to make the appropriate rewrite of URLs in the ruleset.

In 02016, Syverson and Boyce [20] suggested using an HTTPS Everywhere ruleset as a way for users to type in a familiar, understandable domain name in an address bar that would automatically be converted to a connection to an onion address. Subsequent work noted that SATAs could address the problem of a user experiencing a surprising URL change to a completely different looking URL.

\(^2\)This paper uses 5-digit year dates in support of long-term thinking and awareness. Cf. https://longnow.org/.
The problem: Unfortunately the FPF H-E channel and described Tor Browser functionality are quite vulnerable to a compromised or malicious creator of a trusted channel. Such a creator can assign any onion address to example .con .securedrop .tor .onion. For H-E rulesets there is no specific infrastructure, like certificate transparency [8], to detect malicious or conflicting assignments of onion addresses to a domain name. Nor is there any current design or implementation that uses existing infrastructure for such detection.

To make matters worse, a rewrite from a ruleset takes place entirely in the browser before any external communication. Such an attack can thus succeed without any need to also succeed at a DNS hijack or to obtain a rogue TLS certificate. Further, a hijacked rewrite guarantees a successful attack: connection attempts never reach the correct destination during an H-E ruleset based attack.

Moreover, if Alice receives from someone she trusts at the CBC the address www .cbc .ca .securedrop .tor .onion, she must separately trust that the H-E channel maintained by FPF is mapping this address to the proper onion address. Further, the default URL displayed in Tor Browser is www .cbc .ca .securedrop .tor .onion. So, even if she knows the correct associated onion address, unless she does some separate additional checking, she will not have any indicators of (in)consistency with the address displayed to her. Perhaps more importantly, neither will her software. Hiding from the browser the mapping of recognizable names to onion addresses makes it harder to counter any unicode, doppelganger, or typo-squatting attacks on the ruleset.

We now turn to the use of SATAs and sattestation to counter the attacks described in this section.

3 ATTACK REMEDIATION

Onion location, discussed in the previous section, was introduced to provide a simple way for Tor Browser users to connect to a more secure onion site for the current webpage when one is available. Note that if onion location redirects to a SATA rather than to a simple onion address, it would make the self-authentication protections of onion addresses available to users of every browser that has our extension installed, not just Tor Browser. Before describing how SATAs better secure onion location, however, we recall a previously published mitigation that SATAs provide to vulnerabilities facilitated by onion alt services.

3.1 Remedies via SATA

Trusted alt services: Onion alt services have been discussed in the context of SATAs in previously published work [21]. We do not revisit the full discussion here and simply recall that (1) neither the user nor the browser itself can readily tell whether the connection is actually to an onion address or not (so not actually self-authenticating in a practical sense), and (2) onion alt services provide easy to implement and hard to notice tracking of users. As described in [21], however, the WebExtension, keeps track of alternate headers it sees, indicates if there is a self-sattestation provided for an onion alt service, and also permits blocking of alt services unless they are trusted. This provides a basic interface for user visibility and control over the alternative services accepted.

Self-authenticating onion location: if onion location always redirects to a SATA address, then the redirected connection can still be an HTTPS connection using the same TLS certificate as the original connection (recall that the SATA is included in the TLS certificate for the domain). This has two advantages.

First, there is no switch to HTTP for the onion connection. This is primarily a UI rather than a security benefit (onion connections are always encrypted). It ensures that the browser does not show any HTTP warnings.

Second, since the onion address is incorporated in the certificate, a CT log will have promised to include it using a signed certificate timestamp (SCT). Neither Firefox nor Tor Browser natively supports checking SCTs at time of writing. But even before that changes, e.g., as described in [10], SATAs are accessible to other popular browsers that do check SCTs. Using them thus raises the bar for attacks intended to avoid such checks.

With SATAs, onion location as a separate feature can be abandoned altogether and we can still have both of these advantages. If a site is provided as a SATA, a ”.onion available” prompt is not needed. If a requested URL is available as a SATA, then the browser should be redirected to the SATA automatically. Since both the registered domain and the onion address of the SATA are represented in the TLS certificate, the browser can safely reach the requested site over HTTPS using the SATA. And, as we have newly implemented, if using Tor Browser the WebExtension will now automatically reroute to the onion site without touching DNS or otherwise exiting the Tor network. The URL bar will, nonetheless, continue to display the SATA rather than switching the displayed URL to the onion address. Since SATA use for improved authentication does
not automatically imply a site is generally accessible via onion service protocols, it would make sense to add a field or bit to the SATA header indicating whether or not it is onion-service accessible.

Another advantage of SATAs over onion location is that, since a SATA is a fully qualified domain name (FQDN), the destination can have a free domain-validated (DV) certificate right now, rather than depending on Let’s Encrypt to implement cert issuance of DV certificates for onion addresses. HARICA does issue DV certificates for onion addresses. Since issuance involves both the usual checks for control of the registered domain and possession of the private onion key, this amounts to an implicit structural sattestaton from HARICA. In addition, using SATAs, site owners do not need to set up and maintain two versions of the site, one with addresses based on the registered domain name and one with onion addresses.

**Reflecting domain authentication decisions in CT logs:** Onion location does not incorporate into CT logs any association between the traditional domain and the onion address. CT logs are primarily meant to provide a record of certificate authority (mis)behavior, but more generally they provide a public record of the certificates that underlie authentication on the web. Onion location significantly affects that authentication but does not have any associated components that change this public record in any way. Thus, it not only engenders the attacks we describe but also this secondary vulnerability. But, in addition to counting the attacks those mechanisms engender, SATAs are reflected in certificates and CT logs in ways that provide relevant evidence if attacks do occur. Third-party CT log inspectors exist that site owners can use to check for the existence of certificates they did not authorize. Adding a check for any claimed association of their onion addresses with other registered domain names should be straightforward. These would not fool the WebExt or Tor Browser since the attacker would not have the onion private key, but it would reveal attempts to use their SATAs and onion addresses to attack less-secure browsers in some way.

**Self-authenticating SecureDrop:** Like onion location, the FPF SecureDrop H-E ruleset is about discovery rather than authentication, and it enables attacks on authentication if the ruleset is controlled by the adversary. For example, suppose a user connects to https://www.cbc.ca/ and finds on that page a link to http://www.cbc.ca.securedrop.tor.onion. Tor Browser converts this to an onion address using the H-E ruleset channel maintained by FPF, and then connects to that onion address. Thus, if the FPF ruleset is compromised, the user will end up at the wrong SecureDrop location.

Addresses like www.cbc.ca.securedrop.tor.onion are human-meaningful extensions of traditional, registered domains. They are easy enough even to type by hand, given a known domain name. Unfortunately, they are not proper domain names themselves, so cannot have TLS certs. Fortunately, due to implementation decisions, when routing to an onion address based on a SecureDrop H-E rule, Tor Browser performs TLS certificate validation based on the underlying onion address, instead of the human-meaningful name. And, the onion address for the CBC SecureDrop site, [onion].onion, can be included as an alt name in the TLS cert for www.cbc.ca, as some journalism sites have done. The cert could also contain as alt name the SATA [onion].www.cbc.ca. Thus, if the URL bar contains www.cbc.ca.securedrop.tor.onion/?onion=[onion], e.g., as linked from www.cbc.ca, then the SecureDrop rewrite can induce a connection to [onion].onion, and the WebExtension can then check the returned TLS cert and SATA header against the result of removing .securedrop.tor.onion from www.cbc.ca.securedrop.tor.onion/?onion=[onion].

### 3.2 Remedies via trusted sattestors

Given the ability to hijack a certificate, an adversary can obtain a TLS cert for some SATA for the registered domain, one that she can hijack and authenticate to a SATA WebExtension—because she has herself created the onion address component for the certificate. This is what sattestaton counters. (If the certificate contains the onion address as a SAN and the CA checks possession of the private onion key, as HARICA currently does, then an external attacker cannot hijack a SATA’s certificate issuance. A malicious CA still could.) If an extension is configured to require sattestaton from trusted sattestors from which the adversary is not able to obtain a sattestaton, then such a hijack against onion location (or against onion alt services or the SecureDrop H-E ruleset) will not succeed.

Browsers can be configured to expect third-party sattestations with corresponding labels for specific domains. For example, large enterprises can cooperate with browser vendors so that labels for their domains with SATAs are correct. To limit the need for specific enterprise/browser interactions, industry consortia (e.g., software alliance BSA) can further provide sattestations that indicate sattestors and labels for member entities. If a sattestor SATA and label for a domain is on this list, the specific SATA for the domain need not be on it: the browser will expect, e.g., some SATA for live.com with label microsoft and a sattestaton from the BSA that labels a Microsoft SATA with sattestor(microsoft). In this way the only SATA that must be trusted in advance for any consortium member is that of the consortium.

The existing WebExt does not support automated trust decisions for onion alt services. Contextual sattestations could underly such automation, however, which would counter third-party hijack via alt services but not first-party tracking (without additional checks).

Sattestaton uses the same mechanism for trust at the scale of personal associations as for trust at the scale of a large corporation or a certificate authority. Clients are assumed to reflect contextual trust that users attach to specific domain names or to sattestaton labels. For sites that have no such context, sattestaton provides no more trust than a TLS certificate issued by a generic CA. But, clients can be configured with some default contextual labels and trusted sattestors for those labels. They can then trust the binding of a SATA with a particular label for a domain, e.g., journalism, even if they are completely unfamiliar with the domain.

### 4 CONCLUSION

We have described novel vulnerabilities engendered by onion discovery mechanisms recently introduced by Tor Browser that facilitate hijack and tracking of user connections as well as previously known hijack and tracking vulnerabilities. We described how the use of SATAs and sattestaton in onion discovery counters these
vulnerabilities. SATAs also expand the value of onion discovery by facilitating self-authenticated access from browsers that do not connect to services via the Tor network and by making onion addresses visible in CT logs and making SCT checks of associated certificates visible in other browsers.

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A APPENDIX: SATAS AND SATTESTATION

This appendix provides an overview of SATAs and sattestation. Though many of the core concepts are revisited from [21], we also describe novel content introduced here. This includes the query-string format for SATAs, sattestation credentials and contextual labels, and an improved implementation including both these and Tor Browser connections to SATAs via onion service protocols.

Self-Authenticating Traditional addresses, introduced in [19, 21], are designed to enhance traditional certificate based authentication widely used on the web. In particular, they reduce the reliance on certificate authoritities (CAs) to provide domain validation by properly binding a DNS domain name to a public key.

A simple example of a SATA is a DNS domain name where the site’s public TLS key is included as a subdomain. A site bank.com could advertise its domain name as [HashedPubTLSKey].bank.com, for example. A user who searches for the bank on a trusted search engine, or bookmarks the bank’s homepage, would reach the bank through this domain name. A SATA-aware browser will verify the bank’s certificate, as browsers do today, and will also check that the public key in the bank’s certificate matches the [HashedPubTLSKey] in the subdomain. We stress that SAT addresses are intended to enhance the current PKI trust model, not supplant it.

This hashed-TLS-certificate-public-key approach is unworkable for a site that has multiple certificates for a single domain, and it can be inconvenient with regular certificate rotation if keys are changed upon obtaining a new certificate. In Section A.1.1 we will consider other options for creating SATAs. Most notably we will use Tor onion addresses [11] to mitigate the shortcomings of the above approach. An onion address contains the public key of the onion service to which it belongs. Therefore, [onion-address].bank.com is a viable way to form a SAT address for bank.com, as explained in Section A.1.1. As we will see, a single SAT address can be used to authenticate many TLS certificates. Note that here we focus on the authentication that onion addresses provide, rather than privacy.

This paper introduces a number of new techniques to make SATAs compatible with the modern web and demonstrates that adoption of SATAs can solve security issues in deployed systems, supporting a traditional trusted internet connection (TIC) [9] use case, simplify certificate revocation, and strengthen the web’s PKI, all while maintaining backwards compatibility and interoperability with existing infrastructure. We summarize these contributions in more detail below after providing necessary background on SATAs.

Useful and easy to deploy SATAs must satisfy three properties:

- **Authority-independence:** Once a domain owner creates a SATA for its domain, a misbehaving CA cannot bind a rogue public key to that SATA. The SATA binds the domain to its public key.
- ** Dirt Simple Trust:** Learning a SATA from a trusted party suffices to ground assurance that a connection is to the intended site.
- ** Synergistic Backwards Compatibility:** SATAs should be fully backwards compatible with existing internet and web infrastructure, without having to duplicate content or links on sites.

SATAs are most useful when the user has a way to obtain the correct address for the domain that she wants to interact with. This
could be through a trusted search engine, a friend, a previously created bookmark, etc. The existing web PKI also functions this way: a user needs to know the full name of the domain that she wants to connect to, otherwise the subject name validation in an X.509 certificate is meaningless. To illustrate this point, consider the secure operating system Qubes OS which is served from the domain qubes-os.org. Users looking to download the operating system often find its domain via a search engine query. If instead a user guesses the address and connects to qubes.com or qubesos.com, she will end up at a site that has a valid X.509 certificate, but is unrelated to the qubes-os project. That site could serve a backdoored version of the OS, and the user will never know. The same applies to banking sites, shopping sites, etc.

Self-authentication does not automatically guarantee an intended address either. sik5n1gfc5qyj1nnsr57qrbe642bdx6t41reyhpon3y chmxnie7tioad.onion is a self-authenticating address that encodes its own public key, but unless told by a trusted source that this is the onion address associated with qubes-os.org, which it is, the user could not tell that this address is correct. The trusted source can attest to this association by signing a statement for the user asserting a binding of these addresses. We describe a means to effectively do that, sattestation, in Section A.2. We will also see in Section A.1.1 that the query-string format for SATAs introduced in this paper allows a response of https://bank.com/?onion=[onion-address] to a request for https://bank.com. A client can learn about a SATA simply by being redirected to it from its parent domain, but the query string format allows this to happen without any change to the domain name in the URL bar.

The SATA threat model: SATAs are designed to defend against an adversary whose goal is to fool the user into connecting to a fraudulent copy of a victim site (e.g., a copy of bank.com) without the user’s knowledge. To do so, the adversary can do the following:

- **Network attacks**: the adversary can manipulate DNS for a targeted class of users, and can potentially mount a BGP hijack of traffic to an IP range covering an intended destination. In particular, this ability enables the attacker to obtain a certificate for a victim site from some existing CAs [5, 6].

- **CA compromise**: We explicitly give the adversary the ability to obtain a valid TLS certificate for the victim site from a reputable CA. However, the adversary cannot compromise the certificate transparency (CT) infrastructure [8], and in particular, cannot forge a signed certificate timestamp (SCT).

SATAs are designed to fail-closed in the presence of such adversaries. See Section A.1.2 and [21] for additional details on this point.

Ghost domains: To demonstrate the potential benefits of SATAs, we begin with an example: ghost domains. Consider a web page at a.com that points to a URL at b.com. If the domain b.com is later abandoned by its owner, and is taken over by someone else, then a user visiting a.com will be fooled into going to the wrong page. This is a common occurrence on the web. For example, in 20015, bottles of Heinz ketchup in Germany carried a label that included a QR code pointing to a domain for a recently expired promotion, sagsmtheinz.de (translation, “say it with Heinz”). While bottles were still in circulation, this domain registration expired, and a German pornography company registered the name, surprising some ketchup customers who followed the address on their bottles [3]. Similarly, abandoned banking domains have been used to target users who attempted to connect to those banks [13]. More recent research has shown how stale NS records for an active domain can serve as reactivated zombies in a resolver’s cache [2].

SATAs are a solution to ghost domains. If a different entity takes over an expired domain name, that entity will not be able to authenticate as the associated SATA to any browser that checks knowledge of the private key associated with the SATA. In the ketchup example above, users who try to connect to the expired SATA domain in the QR code will get an error. Likewise for a server incorrectly reached through an attack on DNS or BGP. Of course, a domain should be allowed to rotate its SATA address. This can be done by the domain publishing a new SAT address, and is further simplified by the sattestation process we describe in Section A.2.

### A.1 SAT Addresses in Practice

#### A.1.1 Backwards Compatible SAT Addresses

Previous work on SAT addresses [19, 21] proposed the subdomain format discussed in the previous section, but using an onion address for authentication. The SAT address for bank.com is then [onion-address].bank.com, where “[onion-address]” represents an onion address in the format used by Tor onion services [11]. Recall that this is 56 characters long and comprised of a base-32 encoding of the tuple (ed25519 public key, checksum, version number, “.onion”). A browser that understands SAT addresses, such as one using our WebExtension, will authenticate the TLS certificate for bank.com using the onion address, as explained in Section A.1.2 below. (Implementation in an extension allows for both easy experimentation and configuration on initial rollout, and it facilitates quicker initial adoption. Once the value add is well-established, the functionality provided by the extension can be moved into the browser itself.) If the browser was given the correct SAT address, then the user is assured that the connection is to the correct bank.com, even in the presence of malicious CAs or ghost domains. As an example, we set up the following SATA for the domain selfauth.site:

https://ixxuq4b4b53ragbokovydiiys7rolq4ew qjva67qfmp35y55jsx15ydonion.selfauth.site

This entire string can be used as a Subject Alternative Name (SAN) in a domain validation (DV) certificate issued for selfauth.site. This means that a no-cost certificate for this SATA can be obtained from Let’s Encrypt through a relatively simple automated process. These self-authenticating traditional domains are the only form of SATA set out in prior work. This format is fully backwards compatible: browsers that know nothing about SAT addresses will handle TLS authentication as they do for any other site. In this paper we introduce another SATA format with additional advantages.

**SAT addresses using query strings**: To be a SATA, the onion addresses need not appear in the domain itself. We can put the onion address elsewhere too, e.g., in a query string. Using a query-string-formatted SAT address, a link to the above address becomes

https://selfauth.site/?onion=ixxuq4b4b53ragbokovydiiys7rolq4ewqjva67qfmp35y55jsx15yd.
Our WebExtension recognizes this SATA format and uses the SATA to authenticate the TLS certificate, as in Section A.1.2. A SATA-unaware browser will connect to selfauth.site and authenticate it using only its TLS certificate.

One benefit of this SATA format is that it is not necessary to deploy the subdomain SATA on a reachable site, except possibly during certificate issuance. It may also simplify SATisfaction of an existing site by permitting a simple front end to handle new authentication tasks, no change of internal links or content should be needed. Perhaps most importantly, this SATA format is less likely to cause user confusion. As Reynolds et al. recently observed [14], “when examining confusing URL transforms, we found that users were least able to understand URLs with long subdomains/FQDNs.” There are thus usable security advantages to adopting a query-string format for SATAs.

A.1.2 Authentication using a SAT address. Validating the certificate received during TLS session establishment is critical, especially in a zero-trust architecture [16]. If the browser fails to identify a misissued or revoked cert, the entire session can be compromised.

If the server’s address is a SATA, browser-side certificate validation can be greatly strengthened. A SATA-aware browser will use the server’s SATA to authenticate the received TLS certificate. For a SATA with the domain bank.com authentication works as follows:

- **Preparation:** Once every few days, a backend server at bank.com uses the onion private key associated with the SATA to sign the fingerprints of all the TLS certificates at bank.com (one signature per certificate). Let S be the resulting signature data for one such certificate.

- **Server sends signature:** When a browser and a server at bank.com establish a TLS connection, the server sends appropriate signature data S to the browser. This signature is either embedded in a new HTTP header called a SATA header, or is sent in a TLS server-hello extension. Our WebExtension uses the header method because it cannot read server-hello data. This header is a form of sattestation, about which more will be said presently.

- **Validation by browser:** The browser parses the SATA HTTP header and verifies the embedded signature data using the public key encoded in the SAT address. If valid, it learns that the TLS certificate is a valid certificate for bank.com, as required. Otherwise, the browser raises an error. This is done in addition to the standard browser-side TLS certificate validation checks.

Note that the browser need not use the public key for lookup of and connection to an onion service. The browser may not even be capable of invoking connections via the Tor network. The browser uses the public key embedded in the SATA only to verify a signature.

This SATA validation process ensures that an attacker who wants to masquerade as bank.com must obtain a fake certificate for bank.com and must obtain a valid SATA header for that fake certificate signed by the private onion key for this SATA for bank.com.

A few more comments about this approach. First, the SATA for bank.com should be embedded in the bank.com TLS certificate. The TLS certificate thus authenticates the SATA, and vice versa. This also ensures that the SATA for bank.com is included in CT logs that list this TLS certificate, enabling bank.com to detect invalid SATAs. Second, because the backend server used in the preparation step is mostly offline, access to it can be more tightly controlled.

Third, the signature data S sent to the browser in the SATA header needs to be specified more precisely. This signature data is a special case of a new credential format, sattestation, that is presented in Section A.2. This data contains the following fields:

- version number,
- issued date,
- refresh rate (e.g., seven days),
- domain name,
- TLS certificate fingerprint(s), and optionally, a comma-separated list of labels, along with an ed25519 signature on these data fields. The resulting data is less than 800 bytes, without compression.

Our Webextension running on the client checks if the attempted connection is to a SATA. If not, it does nothing and returns control to the browser. If the URL is a SATA, it makes sure that the SATA is present in the TLS certificate from the server. It then validates the SATA header by verifying that (i) a valid signature is present, (ii) that it is currently valid, namely that the absolute value of the difference between the current date and the issued date is less than the refresh rate, and (iii) that one of the certificate fingerprints in the SATA header matches the TLS certificate from the server. If all checks succeed, then the connection completes. Otherwise an appropriate error message is produced.

A.2 Sattestation

A sattestation is a new credential format, defined in this paper, that is designed for relatively short-lived assertions by sites about themselves (self-sattestations), as well as for contextual trust assertions by third parties that scale both up and down. In simplest form, a sattestation binds two values D and O to each other, where:

- D is a domain name (e.g., nytimes.com), and
- O is a self-authenticating name, such as a hashed public key or an onion address.

Sattestations also have two optional values

- L is a set of labels (e.g., (news)), and
- C is a hash of a TLS Certificate.

A sattestation is an assertion issued by a sattester indicating that D, O, (and possibly L, C) are bound to each other. Labels are used to reason about the trust properties of the sattestation. A sattester can be as large as a CA that generates sattestations for the public, as small as an individual who is sending an attested SATA to a friend, or anything in between.

A single sattestation can include multiple bindings such as \{(D_1, O_1), \ldots, (D_n, O_n), L\}, indicating that O_i is a self-authenticating name for D_i, for all i = 1, \ldots, n. This lets a sattester issue a single sattestation for multiple related domains (e.g., multiple news sites or multiple domains owned by the same company).
Figure 1: An example sattestation in JSON format

```
{ "sattestation": {
  "sattestation_version":1,
  "sattestor_domain":"sattestora.info",
  "sattestor_onion":"..." // sattestor's addr.
  "sattestor_refresh_rate":"7 days",
  "sattestees": [ 
    { // bind domain to a self auth. address
      "domain":"domain1.info",
      "onion":"...", // onion address
      "labels":"news",
      "issued": "2020-06-01",
      "refreshed_on": "2020-08-25"
    },
    { // bind domain to a self auth. adress
      "domain":"domain2.info",
      "onion":"...", // onion address
      "labels":"union",
      "issued": "2020-06-01",
      "refreshed_on": "2020-08-25"
    } ],
  // signature by sattestor
  "signature": "...
```

Fig. 1 gives an example sattestation in JSON format that can be sent as a credential in a header. The sattestation includes the sattestor’s (issuer’s) SATA, the refresh rate indicating how often the sattestor verifies the bindings and reissues the sattestation, and the list of domain-address bindings. Each binding indicates the date it was first issued, and when it was last refreshed. Finally, the sattestation is signed by the sattestor. Notice that the sattestor is identified by its SATA (in the sattestor_domain and sattestor_onion fields), and not only by its domain. This sattestation does not bind any TLS certificate, typical for a third-party sattestation.

The SATA header described in Section A.1.2 is an example of a self-sattestation, thus it does bind a TLS certificate. Self-sattestations can only include a single (D, O) binding, but may bind multiple certificates for the domain. For example, in a self-sattestation, the sattestees part of Fig. 1 (below) could look like:

```
"sattestees": [ { // only one entry
  "domain":"sattestora.info",
  "onion":"...", // same as sattestor
  "cert_fingerprint": ["632B119944 ...", "23964A1368 ..."],
  "issued": "2020-06-01",
  "refreshed_on": "2020-08-25"
} ],
```

Because a single signature certifies multiple certificate, this will reduce the work to generate self-sattestations for a domain that has a large number of certificates (say, when every machine in the data center has a different certificate).

Self-sattestations are relatively short-lived (e.g., 3.5 days). For this reason, and unlike certificates, there is no need for accompanying revocation information, such as a CRL distribution point, or an OCSP responder address.

Rotation of self-authentication keys: If a new self-authentication key is chosen for a SATA, sattestation permits a simple means to rotate a SATA: like rotation of PGP keys, that a new key has been adopted can be signified by having oldSATA and newSATA provide sattestations for each other. Anyone visiting a SATA site that uses the old address can be redirected to newSATA. Provided the mutual authentication checks are passed, this can occur automatically as can the propagation of trust to the new address without any user interaction. Updates for browser bookmarks can be handled similar to any change of domain, although here the WebExtension can rely on the persistence of the domain name if it is only the self-authenticating portion of the address that is changing to, e.g., suggest a change to bookmarks. Search engines and links in websites will also need updating, but these should have no special issues versus existing URL updates.

It is important that the new SATA provide sattestation for the old SATA, not merely the reverse, to avoid framing attacks. How long to maintain such rotation information is a matter of individual policy, which can vary depending on circumstances. Once the old SATA is considered expired, it should only be maintained with a self-sattestation that has a single label sattestor({newSATA}) to support redirection and validation for clients with dated information.

An attacker that has compromised a SATA’s onion key and is capable of obtaining a TLS cert could perform such a rotation itself. Nothing in the above would prevent that or detect any misbehavior. Here, too, sattestation plays an important role. Sattestations for oldSATA from other sattestors trusted by a client will not automatically propagate to newSATA. The attacker would also have to trick a trusted sattestor to attest to newSATA for the attack to succeed.

Implementing Contextual Trust: Previous work mentioned the idea of sattestation [21] but had only a toy representation and implementation via downloadable lists of sattestee addresses: unlike the sattestations introduced in this paper there were no sattestation credential mechanisms, no means to cope with any transitivity (as permitted by a sattestor label), and no means to validate or even describe labels or context. Thus it had no means to provide sattestations for a particular corporation, industry group, societal category, government agency, etc.

A.3 Implementation

We developed a prototype implementation of our contributions by extending the prototype Firefox WebExtension already publically available [21]. The extension is available for download².

Our implementation adds support for query-string formatted SATAs, creation of sattestation credentials at a well-known address on a server, and verification on a client of valid sattested SATAs via credentials. We re-implemented the server-side component in Rust, allowing for easier testing and deployment than would be possible by directly modifying the Tor source code. This server-side program produces SATA headers and sattestations. Then an Apache

²https://selfauthdomain.info/sata.xpi?onion=hmfakusa1uamqi46u4luncnred
cpsjks46en7mzbah12x3en1gpkh3ad
or at https://github.com/sysrqb/satis-selfauth-domains.
web server configuration is modified so the correct HTTP headers are sent to clients. We also implemented a custom serialization format for sattestation lists and credentials due to the lack of an existing web standard for cryptographic signatures using ed25519.

Tor’s onion services do not rely on DNS for address lookup. Instead a DHT comprised of thousands of Tor relays stores network location information to access onion services. Descriptors with this and other information are encrypted so that, unless a DHT relay already knows the onion address, it will not know for what onion service it is holding descriptors. Descriptors are also regularly reassigned to unpredictable nodes within the DHT. For these and other reasons, it would thus be advantageous when Tor Browser attempts to connect to a SATA if lookup and connection uses onion service protocols. We have now implemented this.

Also, a SATA in the URL bar prompting such an onion service connection is not rewritten to the corresponding .onion address. Amongst other things, this means that sites with SATAs can now easily have a certified TLS connection when contacted in this way via Tor Browser. Though DV certificates for .onion addresses have been approved by CA/Browser Forum guidelines since March 02020, almost all CAs have only issued EV certificates for .onion addresses to date. (Recently HARICA became the only exception.) Since SATAs can have DV certificates, with our implementation the security advantages of onion services, SATAs, and TLS certificates can all occur together for connections to SATAs from Tor Browser.