

ONIONS:
TOR-POWERED DISTRIBUTED DNS
FOR TOR HIDDEN SERVICES

by

Jesse Victors

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Computer Science

Approved:

Dr. Ming Li
Major Professor

Dr. Nicholas Flann
Committee Member

Dr. Daniel Watson
Committee Member

Dr. Mark R. McLellan
Vice President for Research and
Dean of the School of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2015

CONTENTS

	Page
LIST OF FIGURES	iii
CHAPTER	
1 INTRODUCTION	1
1.1 Onion Routing	1
1.2 Tor	3
1.3 Motivation	11
1.4 Contributions	11
2 PROBLEM STATEMENT	13
2.1 Assumptions and Threat Model	13
2.2 Design Objectives	14
3 CHALLENGES	16
3.1 Zooko's Triangle	16
3.2 Synchronization	17
4 SOLUTION	18
4.1 Overview	18
4.2 Definitions	19
4.3 Basic Design	21
4.4 Cryptographic Primitives	23
4.5 Data Structures	26
4.6 Protocols	30
4.7 Optimizations	41
5 ANALYSIS	44
5.1 Security	45
5.2 Performance	48
5.3 Reliability	48
REFERENCES	49

LIST OF FIGURES

Figure	Page
1.1 An example cell and message encryption in an onion routing scheme. Each router “peals” off its respective layer of encryption; the final router exposes the final destination.	3
1.2 Alice uses the encrypted cookie to tell Bob to switch to <i>rp</i>	10
1.3 Bidirectional communication between Alice and the hidden service.	10
3.1 Zooko’s Triangle.	16
4.1 A sample domain name: a sequence of labels separated by delimiters. In OnionNS, hidden service operators build associations between second-level domain names and their hidden service address.	20
4.2 The hidden service Bob uses a Tor circuit (guard, middle, and exit Tor routers) to anonymously upload a record to OnionNS. A client, Alice, uses her own Tor circuit to query the system for a domain name, and she is given Bob’s record in response. Then Alice connects to Bob by Tor’s hidden service protocol (section 1.2.4).	22
4.3 There are three sets of participants in the OnionNS network: <i>mirrors</i> , quorum node <i>candidates</i> , and <i>quorum</i> members. The set of <i>quorum</i> nodes is chosen from the pool of up-to-date <i>mirrors</i> who are reliable nodes within the Tor network.	22
4.4 An example <i>page</i> -chain across four <i>quorums</i> . Each <i>page</i> contains a references to a previous <i>page</i> , forming an distributed scrolling data structure. <i>Quorum</i> 1 is semi-honest and maintains its uptime, and thus has identical <i>pages</i> . <i>Quorum</i> 2’s largest cluster is likewise in agreement, but there are three nodes which are acting maliciously together and have changed their <i>pages</i> . Node 5 in <i>quorum</i> 3 references an old page in attempt to bypass <i>quorum</i> 2’s records, and nodes 6-7 are colluding with nodes 5-7 from <i>quorum</i> 2. Finally, <i>quorum</i> 3 has two nodes that acted honestly but did not record new records, so their <i>page</i> -chains differ from the others. However, across all four days the largest clusters are honest nodes and thus integrity remains in the <i>page</i> -chain. . . .	23
4.5 The hidden service operator uses his existing circuit (green) to inform <i>quorum</i> node Q_4 of the new record. Q_4 then distributes it via <i>snapshots</i> to all other <i>quorum</i> nodes. Each records it in their own <i>page</i> for long-term storage. The operator also confirms from a randomly-chosen <i>quorum</i> node Q_5 that the record has been received.	24

4.6	The hidden service operator Bob anonymously sends a record to the <i>quorum</i> (c_1 and c_2), informing them about his domain name. A node m_1 mirrors the <i>quorum</i> , which Alice anonymously queries for Bob's domain name.	25
4.7	Sample registration record from a hidden service, encoded in JSON and base64.	31
4.8	A sample empty <i>page</i> , encoded in JSON and base64.	32
4.9	A sample empty <i>snapshot</i> , encoded in JSON and base64.	33
4.10	A sample Create record has been merged into an initially-blank snapshot. .	37
4.11	A snapshot containing a single Create record has merged into Carol's page.	38

CHAPTER 1

INTRODUCTION

1.1 Onion Routing

As the prevalence of the Internet and other communication has grown, so too has the development and usage of privacy-enhancing systems. These are tools and protocols that provide privacy by obfuscating the link between a user's identification or location and their communications. Privacy is not achieved in traditional Internet connections because SSL/TLS encryption cannot hide IP and TCP headers, which must be exposed to allow routing between two parties; eavesdroppers can easily break user privacy by monitoring these headers. A closely related property is anonymity – a part of privacy where user activities cannot be tracked and their communications are indistinguishable from others. Tools that provide these systems hold a user's identity in confidence, and privacy and anonymity are often provided together. Following a general distrust of unsecured Internet communications and in light of the 2013-current revelations by Edward Snowden of Internet mass-surveillance by the NSA, GCHQ, and other members of the Five Eyes, users have increasingly turned to these tools for their own protection. Privacy-enhancing and anonymity tools may also be used by the military, researchers working in sensitive topics, journalists, law enforcement running tip lines, activists and whistleblowers, or individuals in countries with Internet censorship. These users may turn to proxies or VPNs, but these tools often track their users for liability reasons and thus rarely provide anonymity. Furthermore, they can easily voluntarily or be forced to break confidence to destroy user privacy. More complex tools are needed for a stronger guarantee of privacy and anonymity.

Today, most anonymity tools descend from mixnets, an early anonymity system invented by David Chaum in 1981. [1] In a mixnet, user messages are transmitted to one

or more mixes, who each partially decrypt, scramble, delay, and retransmit the messages to other mixes or to the final destination. This enhances privacy by heavily obscuring the correlation between the origin, destination, and contents of the messages. Mixnets have inspired the development of many varied mixnet-like protocols and have generated significant literature within the field of network security. [2] [3]

Mixnet descendants can generally be classified into two distinct categories: high-latency and low-latency systems. High-latency networks typically delay traffic packets and are notable for their greater resistance to global adversaries who monitor communication entering and exiting the network. However, high-latency networks, due to their slow speed, are typically not suitable for common Internet activities such as web browsing, instant messaging, or the prompt transmission of email. Low-latency networks, by contrast, do not delay packets and are thus more suited for these activities, but they are more vulnerable to timing attacks from global adversaries. [4] In this work, we detail and introduce new functionality within low-latency protocols.

Onion routing is a technique for enhancing privacy of TCP-based communication across a network and is the most popular low-latency descendant of mixnets in use today. It was first designed by the U.S. Naval Research Laboratory in 1997 for military applications [5] [6] but has since seen widespread usage. In onion routing with public key infrastructure (PKI), a user selects a set network nodes, typically called *onion routers* and together a *circuit*, and encrypts the message with the public key of each router. Each encryption layer contains the next destination for the message – the last layer contains the message’s final destination. As the *cell* containing the message travels through the network, each of these onion routers in turn decrypt their encryption layer like an onion, exposing their share of the routing information. The final recipient receives the message from the last router, but is never exposed to the message’s source. [3] The sender therefore has privacy because the recipient does not know the sender’s location, and the sender has anonymity if no identifiable or distinguishing information is included in their message.

The first generation of onion routing used circuits fixed to a length of five, assumed a

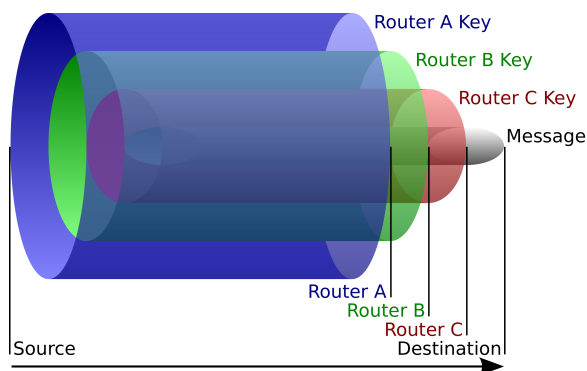


Figure 1.1: An example cell and message encryption in an onion routing scheme. Each router “peels” off its respective layer of encryption; the final router exposes the final destination.

static network topology, and most notably, introduced the ability to mate two circuits at a common node or server. This last capability enabled broader anonymity where the circuit users were anonymous to each other and to the common server, a capability that was adopted and refined by later generation onion routers. Second generation introduced variable-length circuits, multiplexing of all user traffic over circuits, exit policies for the final router, and assumed a dynamic network by routing updates throughout the network. A client, Alice, in second-generation onion routers also distributed symmetric keys through the cell layers. If routers remember the destinations for each message they received, the recipient Bob can send his reply backwards through the circuit and each router re-encrypts the reply with their symmetric key. Alice unwraps all the layers, exposing the Bob’s reply. The transition from public-key cryptography to symmetric-key encryption significantly reduced the CPU load on onion routers and enabled them to transfer more packets in the same amount of time. However, while influential, first and second generation onion routing networks have fallen out of use in favor of third-generation systems. [3]

1.2 Tor

Tor is a third-generation onion routing system. It was invented in 2002 by Roger Dingledine, Nick Mathewson, and Paul Syverson of the Free Haven Project and the U.S. Naval Research Laboratory [4] and is the most popular onion router in use today. Tor inherited many of the concepts pioneered by earlier onion routers and implemented several

key changes: [3] [4]

- **Perfect forward secrecy:** Rather than distributing keys via onion layers, Tor clients negotiate a TLS Diffie-Hellman-Merkle ephemeral key exchange with each of the routers in turn, extending the circuit one node at a time. These keys are then purged when the circuit is torn down; this achieves perfect forward secrecy, a property that ensures that the symmetric encryption keys will not be revealed if long-term public keys are later compromised.
- **Circuit isolation:** Second-generation onion routers mixed cells from different circuits in realtime, but later research could not justify this as an effective defence against an active adversary. [3] Tor abandoned this in favor of isolating circuits from each other inside the network. Tor circuits are used for up to 10 minutes or whenever the user chooses to rotate to a fresh circuit.
- **Three-hop circuits:** Previous onion routers used long circuits to provide heavy traffic mixing. Tor removed mixing and fell back to using short circuits of minimal length. With three relays involved in each circuit, the first node (the *guard*) is exposed to the user's IP address. The middle router passes onion cells between the guard and the final router (the *exit*) and its encryption layer exposes it to neither the user's IP nor its traffic. The exit processes user traffic, but is unaware of the origin of the requests. While the choice of middle and exits can be routers can be safely random, the guard nodes must be chosen once and then consistently used to avoid a large cumulative chance of leaking the user's IP to an attacker. This is of particular importance for circuits from hidden services. [7] [8]
- **Standardized to SOCKS proxy:** Tor simplified the multiplexing pipeline by transitioning from application-level proxies (HTTP, FTP, email, etc) to a TCP-level SOCKS proxy, which multiplexed user traffic and DNS requests through the onion circuit regardless of any higher protocol. The disadvantage to this approach is that Tor's client software has less capability to cache data and strip identifiable information out of a

protocol. The countermeasure was the Tor Browser, a fork of Mozilla’s open-source Firefox with a focus on security and privacy. To reduce the risks of users breaking their privacy through Javascript, it ships with the NoScript extension which blocks all web scripts not explicitly whitelisted. The browser also forces all web traffic, including DNS requests, through the Tor SOCKS proxy, provides a Windows-Firefox user agent regardless of the native platform, and includes many additional security and privacy enhancements not included in native Firefox. The browser also utilizes the EFF’s HTTPS Everywhere extension to re-write HTTP web requests into HTTPS whenever possible; when this happens the Tor cell contains an additional inner encryption layer.

- **Directory servers:** Tor introduced a set of trusted directory servers to distribute network information and the public keys of onion routers. Onion routers mirror the digitally signed network information from the directories, distributing the load. This simplified approach is more flexible and scales faster than the previous flooding approach, but relies on the trust of central directory authorities. Tor ensures that each directory is independently maintained in multiple locations and jurisdictions, reducing the likelihood of an attacker compromising all of them. [3] We describe the contents and format of the network information published by the directories in section 1.2.3.
- **Dynamic rendezvous with hidden services:** In previous onion routers, circuits mated at a fixed common node and did not use perfect forward secrecy. Tor uses a distributed hashtable to record the location of the introduction node for a given hidden service. Following the initial handshake, the hidden service and the client then meet at a different onion router chosen by the client. This approach significantly increased the reliability of hidden services and distributed the communication load across multiple rendezvous points. [4] We provide additional details on the hidden service protocol in section 1.2.4 and our motivation for addition hidden service infrastructure in section 1.3.

As of March 2015, Tor has 2.3 million daily users that together generate 65 Gbit/s of traffic. Tor’s network consists of nine authority nodes and 6,600 onion routers in 83 countries. [9] In a 2012 Top Secret U.S. National Security Agency presentation leaked by Edward Snowden, Tor was recognized as the ”the king of high secure, low latency Internet anonymity”. [10] [11] In 2014, BusinessWeek claimed that Tor was “perhaps the most effective means of defeating the online surveillance efforts of intelligence agencies around the world.” [12]

1.2.1 Design

Tor’s design focuses on being easily deployable, flexible, and well-understood. Tor also places emphasis on usability in order to attract more users; more user activity translates to an increased difficulty of isolating and breaking the privacy of any single individual. Tor however does not manipulate any application-level protocols nor does it make any attempt to defend against global attackers. Instead, its threat model assumes that the capabilities of adversaries are limited to observing fractions of Tor traffic, that they can actively delay, delete, or manipulate traffic, that they may attempt to digitally fingerprint packets, that they may run onion routers themselves, and that they may compromise a fraction of other existing routers. Together, most of the assumptions may be broadly classified as traffic analysis attacks. Tor’s final focus is defending against these types of attacks. [4]

1.2.2 Circuit Construction

Overview

Let Alice be a client who wishes to enhance her privacy by using Tor but does not run a Tor router herself. Her basic procedure for initializing her own circuit is as follows:

1. Alice selects a Tor router R_1 and establishes an encrypted connection to it.
2. Alice selects a second router R_2 and tells R_1 to ensure that a TCP link is available to it.

3. Alice uses her link with R_1 to establish an encrypted connection with R_2 .
4. Alice selects an R_3 and uses the $Alice \leftrightarrow R_1 \leftrightarrow R_2$ tunnel to tell R_2 to connect to R_3 .
5. Alice establish an encrypted connection with R_3 over the $Alice \leftrightarrow R_1 \leftrightarrow R_2$ tunnel.

Following the successful circuit construction, she can then send messages out of R_3 through the $Alice \leftrightarrow R_1 \leftrightarrow R_2 \leftrightarrow R_3$ tunnel.

As a defense against traffic analysis using packet size, Alice packs and pads circuit traffic into equally-sized Tor *cells* of 512 bytes and changes R_2 and R_3 every 10 minutes. [13]

TODO: Tor chooses the guard carefully

TAP

The Tor Authentication Protocol (TAP) is a critical piece of Tor networking infrastructure as it allows Alice to verify the authenticity of the onion routers that she selects for her circuit while still remaining anonymous herself. Namely it prevents active spoofing attacks, which if successful would deanonymize Alice and compromise her privacy.

First, TAP assumes that the following is established:

- Alice has a reliable PKI that can securely distribute the identity, IP addresses, and public keys of all Tor routers. Tor accomplishes this through consensus documents from authority nodes, described in section 1.2.3.
- Let \mathcal{E}_B mean encryption and \mathcal{D}_B mean decryption under B 's public-private keypair for some party B .
- p is a prime such that $q = \frac{p-1}{2}$ is also prime and let g be a generator of the subgroup of \mathbb{Z}_p^* of order q .
- Let R_L be a generator that returns uniformly random L -bit values in the interval $[1, \min(q, 2^L) - 1]$.
- Define f as SHA-1 which takes input from \mathbb{Z}_p and returns a L_f -bit value.

Then TAP proceeds as:

1. Alice selects a Tor router, R_i .
2. Alice generates $x = R_L$ and computes $s = g^x \bmod p$.
3. Alice sends $c = \mathcal{E}_{R_i}(s)$ to R_i .
4. R_i computes $m = \mathcal{D}_{R_i}(c)$ and confirms that $1 < m < p - 1$.
5. R_i generates $y = R_L$ and computes $a = g^y \bmod p$ and $b = f(m^y \bmod p)$.
6. R_i sends (a, b) to Alice.
7. Alice confirms that $1 < a < p - 1$ and that $b = f(a^x \bmod p)$.
8. If the assertions pass, then Alice has confirmed R_i 's identity and now Alice and R_i can use $a^x = m^y$ as a shared symmetric encryption key and encrypt messages under AES.
9. Alice repeats steps 1 – 8 until the circuit is of the desired length.

Thus for each router in the circuit, Alice perform one public-key encryption and her half of a Diffie-Hellman-Merkle handshake, and each router in turn performs one private-key decryption and their half of a Diffie-Hellman-Merkle handshake. Under the assumptions that RSA is one way, AES remains unbroken, and f is strong and acts as a random oracle, an attacker has only a negligible chance of being able to impersonate R_i and read messages that she tunnels through the circuit. [14]

NTor

In 2013, TAP was superseded by “NTor”, a new protocol invented by Goldberg, Stebila, and Ustaoglu. [15] Compared to TAP, NTor requires less computational demand and uses stronger cryptographic primitives.

First,

- Let $H(x, t)$ be HMAC-SHA256, which accepts a message x and key t and returns a 32-byte output.
- Let K_{gen} yield a and A , the private and public halves, respectively, of the Curve25519 [16] keypair.
- Let each Tor router R_j generate a_j , $A_j = K_{gen}$ and publish A_j through the consensus document.

Then NTor proceeds as:

1. Alice selects a Tor router, R_i .
2. Alice generates x_i , $X_i = K_{gen}$.

1.2.3 Consensus Documents

The Tor network is maintained by nine authority nodes, who each vote on the status of nodes and together hourly publish a digitally signed consensus document containing IPs, ports, public keys, latest status, and capabilities of all nodes in the network. The document is then redistributed by other Tor nodes to clients, enabling access to the network. The document also allows clients to authenticate Tor nodes when constructing circuits, as well as allowing Tor nodes to authenticate one another. Since all parties have prior knowledge of the public keys of the authority nodes, the consensus document cannot be forged or modified without disrupting the digital signature. [17]

Here I plan to detail the consensus documents that I will be using, since I use them in my Solution section.

1.2.4 Hidden Services

Although Tor's primary and most popular use is for secure access to the traditional Internet, Tor also supports anonymous services, such as websites, marketplaces, or chat-rooms. These are a part of the Dark Web and cannot be normally accessed outside the context of Tor. In contrast to Tor-anonymized web requests where the client is anonymous

but the server is known, Tor hidden services provide bidirectional anonymity where both parties remain anonymous and never directly communicate with one another. This allows for a greater range of communication capabilities. [18]

Tor does not contain a DNS system for its websites; instead hidden service addresses are algorithmically generated by generating the SHA-1 hash of their public RSA key, truncating to 80 bits, and converting the remainder to base58. Ignoring the possibility of SHA-1 collisions, this builds a one-to-one relationship between a hidden service's public key and its address which can be confirmed without requiring any identifiable information or central authorities. The address is then appended with the .onion Top-Level Domain (TLD).

A hidden server, Bob, first builds Tor circuits to several random relays and enables them to act as *introduction points* by giving them its public key, B_K . He then uploads his public key and the fingerprint identity of these nodes to a distributed hashtable inside the Tor network, signing the result. He then publishes his hidden service address in a backchannel. When Alice obtains this address and enters it into a Tor-enabled browser, her software queries this hashtable, obtains B_K and Bob's introduction points, and builds a Tor circuit to one of them, ip_1 . Simultaneously, the client also builds a circuit to another relay, rp , which she enables as a rendezvous point by telling it a one-time secret, sec . During this procedure, hidden services must continue to use their same entry node in order to avoid leaking its IP address to possibly malicious onion routers. [7] [8]

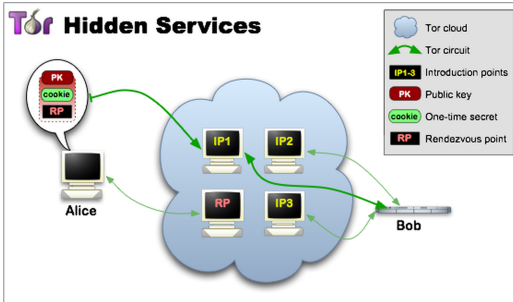


Figure 1.2: Alice uses the encrypted cookie to tell Bob to switch to rp .

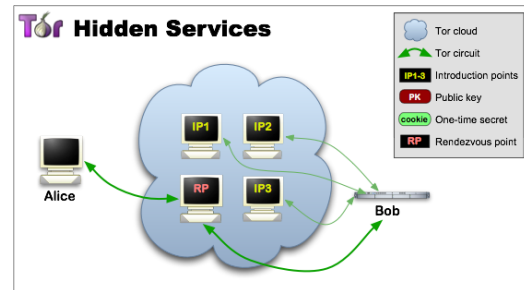


Figure 1.3: Bidirectional communication between Alice and the hidden service.

She then sends to ip_1 a cookie encrypted with B_K , containing rp and sec . Bob decrypts

this message, builds a circuit to *rp*, and tells it *sec*, enabling Alice and Bob to communicate. Their communication travels through six Tor nodes: three established by Alice and three by Bob, so both parties remain anonymous. From there traditional HTTP, FTP, SSH, or other protocols can be multiplexed over this new channel.

As of March 2015, Tor hosts approximately 25,000 unique hidden services that together generate around 450 Mbit/s of traffic. [9]

1.3 Motivation

As Tor’s hidden service addresses are algorithmically derived from the service’s public RSA key, there is at best limited capacity to select a human-meaningful name. Some hidden service operators have attempted to work around this issue by finding an RSA key by brute-force that generates a partially-desirable hidden service address (e.g. “example0uyw6wgve.onion”) and although some alternative encoding schemes have been proposed, (section) the problem generally remains. The usability of hidden services is severely challenged by the non-intuitive and unmemorable base58-encoded domain name. For example, 3g2upl4pq6kufc4m.onion is the address for the DuckDuckGo search engine, suw74isz7wqzpmgu.onion is a WikiLeaks mirror, and 33y6fjyhs3phzfjj.onion and vbmwh445kf3fs2v4.onion are both SecureDrop instances for anonymous document submission. These addresses maintain strong privacy as the strong association between its public key and its address significantly breaks the association between the service’s purpose and its address. However, this privacy comes at a cost: it is impossible to classify or label a hidden service’s purpose in advance, a fact well known within Tor hidden service communities. Over time, third-party directories – both on the Clear and Dark Internets – appeared in attempt to counteract this issue, but these directories must be constantly maintained and furthermore this approach is not convenient nor does it scale well. This suggests the strong need for a more complete and reliable solution.

1.4 Contributions

Our contribution to this problem is five-fold:

- We introduce a novel distributed naming system that enables Tor hidden service operators to choose a human-meaningful domain name and construct a strong association between that domain name and their hidden service address.
- We rely on the existing Tor network and other infrastructure, rather than introduce a new network. This simplifies our assumptions and reduces our threat model to attack vectors already known and well-understood on the Tor network.
- We introduce a novel protocol for proving the non-existence of any domain names.
- We enable Tor clients to verify the authenticity of a domain name against its corresponding hidden service address with minimal data transfers and without requiring any additional queries.
- We preserve the privacy of both the hidden service and the anonymity of Tor clients connecting to it.

CHAPTER 2

PROBLEM STATEMENT

2.1 Assumptions and Threat Model

The design of OnionNS on several main assumptions and threat vectors:

- Not all Tor nodes can be trusted. It is already well-known in the Tor community that some Tor nodes are run by malicious operators, curious researchers, experimenting developers, or government organizations. Nodes can be wiretapped, become semi-honest, or behave in an abnormal fashion. However, the majority of Tor nodes are honest and trustworthy: a reasonable assumption considering that Tor’s large userbase must make this assumption when using Tor for anonymity or privacy-enhancement purposes.
- Let us define an “honest node” to mean that the node does not log data, is stable, kept up-to-date, and acts according to specifications. Let “semi-honest” mean that the node acts properly but may be logging data and “dishonest” to mean that the node is run by an attacker, logs data, and may behave improperly. For an M -sized set chosen randomly from Tor nodes that have the stable and fast flags, $\lceil \frac{M}{2} \rceil$ or more of them are at least semi-honest. This assumption is very similar to the assumption made when Tor clients create circuits: that all three nodes in a circuit are honest and less than all of them are semi-honest. Relays with stable and fast flags are have more consensus weight are thus more likely to be chosen relative to other nodes during circuit construction.
- The amount of dishonest Tor nodes does not increase in response to the inclusion of OnionNS into Tor infrastructure. Specifically, that if an attacker Eve can predict the

next set of *quorum* nodes (section ??) that Eve does not have enough time to make those nodes dishonest. This is a reasonable assumption because regular Tor traffic is far more valuable to an attacker than DNS data is, so penetration of the Tor network would have occurred already if Eve meant to introduce disruption. OnionNS data structures are almost all public anyway.

- Adversaries have access to some of Tor inter-node traffic and to portions of general Internet communication. However, attackers do not have a global view of Internet traffic; namely they cannot always correlate connections into the Tor network with connections out of the Tor network. This assumption is also made by the Tor community and developers. No attempt is made to defend against a global attacker from either Tor or OnionNS.
- Adversaries are not breaking properly-implemented Tor circuits and their modern components, namely TLS 1.2, the AES cipher, ECDHE key exchange, and the SHA2 series of digests, and that they maintain no backdoors in the Botan and OpenSSL implementations of these algorithms.

2.2 Design Objectives

Tor's high security environment is challenging to the inclusion of additional capabilities, even to systems that are backwards compatible to existing infrastructure. Anonymity, privacy, and general security are of paramount importance. We enumerate a short list of requirements for any secure DNS system designed for safe use by Tor clients. We later show how existing works do not meet these requirements and how we overcome these challenges with OnionNS.

1. The registrations must be anonymous; it should be infeasible to identify the registrant from the registration.
2. Lookups must be anonymous or at least privacy-enhanced; it should not be trivial to determine both a client's identity and the hidden service that the client is requesting.

3. Registrations must be publicly confirmable; all parties must be able to verify that the registration came from the desired hidden service and that the registration is not a forgery.
4. Registrations must be securely unique, or have an extremely high chance of being securely unique such as when this property relies on the collision-free property of cryptographic hash functions.
5. It must be distributed. The Tor community will adamantly reject any centralized solution for Tor hidden services for security reasons, as centralized control makes correlations easy, violating our first two requirements.
6. It must remain simple to use. Usability is key as most Tor users are not security experts. Tor hides non-essential details like routing information behind the scenes, so additional software should follow suite.
7. It must remain backwards compatible; the existing Tor infrastructure must still remain functional.
8. It should not be feasible to maliciously modify or falsify registrations in the database or in transit though insider attacks.

Several additional objectives, although they are not requirements, revolve around performance: it should be assumed that it is impractical for clients to download the entirety or large portions of the DNS database in order to verify any of the requirements, a DNS system should take a reasonable amount of time to resolve domain name queries, and that the system should not introduce any significant load on client computers.

CHAPTER 3

CHALLENGES

3.1 Zooko's Triangle

One of the largest challenges is inherent to the difficulty of designing a distributed system that maintains a correlation database of human-meaningful names in a one-to-one fashion. The problem is summarized in Zooko's Triangle, an influential conjecture proposed by Zooko Wilcox-O'Hearn in late 2001. The conjecture states that in a persistent naming system, only two out of the three following properties can be established: [19]

- Human meaningfulness: the names have a quality of meaningfulness and memorability to the users.
- Securely unique: for any name, duplicates do not exist.
- Distributed: the naming system lacks a central authority or database for allocating and distributing names.

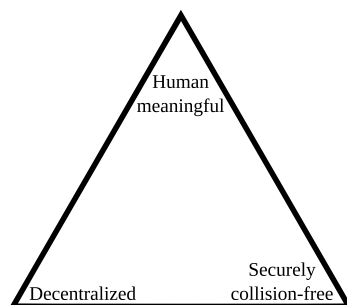


Figure 3.1: Zooko's Triangle.

Tor hidden service .onion domains, PGP keys, and Bitcoin addresses are secure and decentralized but are not human-meaningful; they use the large key-space and the collision-free properties of secure digest algorithms to ensure uniqueness, so no centralized database is needed to provide this property. Tradition domain names on the Clearnet are memorable and provably collision-free, but use a hierarchical structure and central authorities under the jurisdiction of ICANN. Finally, human names and nicknames are meaningful and distributed, but not securely collision-free. [20]

3.2 Synchronization

CHAPTER 4

SOLUTION

4.1 Overview

We propose the Onion Name Service, or OnioNS, a system which enables transparent translation of .tor domain names to .onion hidden service addresses. The system has three main aspects: the generation of self-signed claims on domain names by hidden service operators, the processing of domain information within the OnioNS servers, and the receiving and authentication of domain names by a Tor client.

First, a hidden service operator, Bob, generates an association claim between a meaningful domain name and a hidden service address. Without loss of generality, let this be `example.tor` \rightarrow `example0uyw6wgve.onion`. For security reasons we do not introduce a central repository and authority from which Bob can purchase domain names; however, domains are not trivially obtainable and Bob must expend effort to claim and maintain ownership of `example.tor`. We achieve this through a proof-of-work scheme. Proof-of-work systems are noteworthy for their asymmetry: they require the issuer to spend effort to find an answer to a moderately hard computational problem, but once solved can be easily verified correct by any recipient. The requirement of proof-of-work fulfils three main purposes:

1. Significantly reduces the threat of record flooding.
2. Introduces a barrier-of-entry that encourages the utilization of domain names and the availability of the underlying hidden services.
3. Increases the difficulty of domain squatting, a denial-of-service attack where a third-party claims one or more valuable domain names for the purpose of denying or selling

them en masse to others. In Tor’s anonymous environment, this vector is particularly prone to Sybil attacks.

Bob then digitally signs his association and the proof-of-work with his service’s private key.

Second, Bob uses a Tor circuit to anonymously transmit his association, proof-of-work, digital signature, and public key to OnioNS nodes, a subset of Tor routers. This set is deterministically derived from the volatile Tor consensus documents and is rotated periodically. The OnioNS nodes receive Bob’s information, distribute it amongst themselves, and later archive it in a sequential transaction database, of which each OnioNS node holds their own copy. The nodes also digitally sign this database and distribute their signatures to the other nodes. Thus the OnioNS Tor nodes maintain a common database and have each vouched for its authenticity.

Third, a Tor client, Alice, uses a Tor client to anonymously connect to one of these OnioNS nodes and request a domain name. Without loss of generality, let this request be `example.tor`. Alice receives Bob’s “`example.tor → example0uyw6wgve.onion`” association, his proof-of-work, his digital signature, and his public key. Alice then verifies the proof-of-work and Bob’s signature against his public key, and hashes his key to confirm the accuracy of `example0uyw6wgve.onion`. Alice then looks up `example0uyw6wgve.onion` in Tor’s hidden service distributed hashtable, finds Bob’s introduction point, and confirms that its knowledge of Bob’s public key matches the key she received from the OnioNS nodes. Finally, she finishes the Tor hidden service protocol and begins communication with Bob. In this way, Alice can contact Bob through his chosen domain name without resorting to use lower-level hidden service addresses. The uniqueness and authenticity of the Bob’s domain name is maintained by the subset of Tor nodes.

4.2 Definitions

Domain Name

A *domain name* is a case-insensitive identification string claimed by a hidden service

operator. The syntax of OnionNS domain names mirrors the Clearnet DNS; we use a sequence of name-delimiter pairs with the .tor Top Level Domain (TLD). The TLD is a name at depth one and is preceded by names at sequentially increasing depth. The term “domain name” refers to the identification string as a whole, while “second-level domain” refers to the central name that is immediately followed by the TLD, as illustrated in Figure . Domain names point to *destinations* – other domain names with either the .tor or .onion TLD.

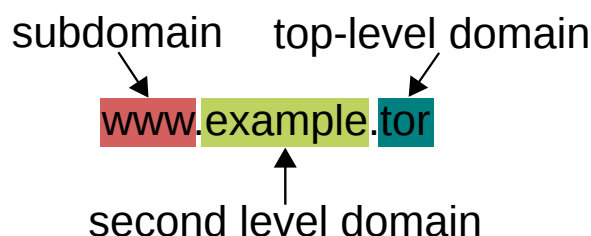


Figure 4.1: A sample domain name: a sequence of labels separated by delimiters. In OnionNS, hidden service operators build associations between second-level domain names and their hidden service address.

The Clearnet DNS defines a hierarchy of administrative realms that are closely tied to the depth of each name. By contrast, OnionNS makes no such distinction; we let hidden service operators claim second-level names and then control all names of greater depth under that second-level name. Hidden service operators may then choose to administer or sell the use of their subdomains, but this is outside the scope of this project.

Record

A *Record* is a small textual data structure that contains one or more domain-destination pairs, a proof-of-work, a digital signature, and a public key. Records are issued by hidden service operators and sent to OnionNS servers. Every Record is self-signed with the hidden service’s key. In section 4.5.1 we describe the five different types of Records: Create, Modify, Move, Renew, and Delete. A Create Record represents a registration on an unclaimed second-level domain name, Modify, Move, and Renew are operations on that domain name or its subdomains, and a Delete Record relinquishes ownership

over the second-level domain name and all its subdomains.

Page

A *Page* is textual database designed to archive one or more Records in long-term storage. Pages are held and digitally signed by OnioNS nodes and are writable only for fixed periods of time before they are read-only. Each Page contains a link to a previous Page, forming an append-only public ledger known as an *Page-Chain*. This forms a two dimensional distributed data structure: the chain of Pages grows over time and there may be redundant copies of each Page at any given time.

Mirror

A *Mirror* is any machine that has performed a synchronization (section 4.6.2) against the OnioNS network and now holds a complete copy of the page-chain. Mirrors do not actively participate in the OnioNS network and do not have the power to manipulate the central page-chain.

Quorum Candidate

A *Quorum Candidates* are *Mirrors* that have also fulfilled two additional requirements: 1) they must demonstrate that they are an up-to-date Mirror, and 2) that they have sufficient CPU and bandwidth capabilities to handle powering OnioNS in addition to their regular Tor duties. In other words, they are qualified and capable to power OnioNS, but have not yet been chosen to do so.

Quorum

A *Quorum* is a subset of Quorum Candidate Tor nodes who have active responsibility over maintaining the master OnioNS Page-Chain. Each Quorum node actively its own Page, which has a lifetime of that Quorum. The Quorum is randomly chosen from Quorum Candidates as described in section 4.6.3.

4.3 Basic Design

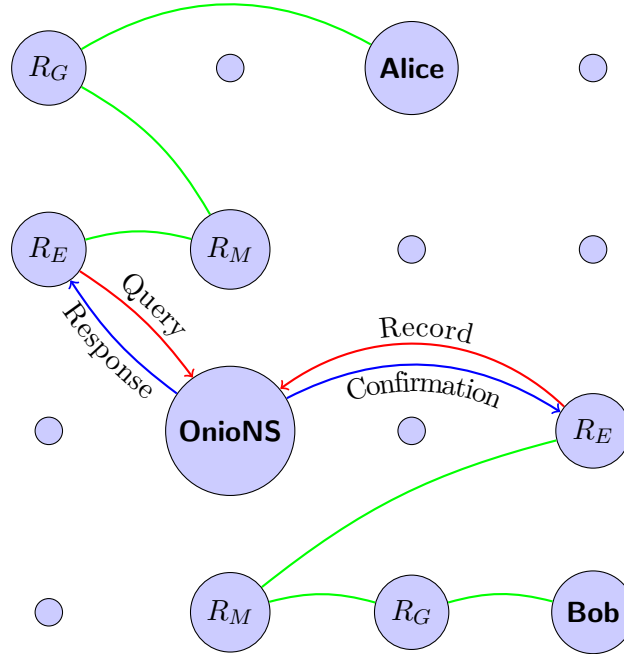


Figure 4.2: The hidden service Bob uses a Tor circuit (guard, middle, and exit Tor routers) to anonymously upload a record to OnionNS. A client, Alice, uses her own Tor circuit to query the system for a domain name, and she is given Bob’s record in response. Then Alice connects to Bob by Tor’s hidden service protocol (section 1.2.4).

4.3.1 Domain Name Operations

4.3.2 Page-Chain Maintenance

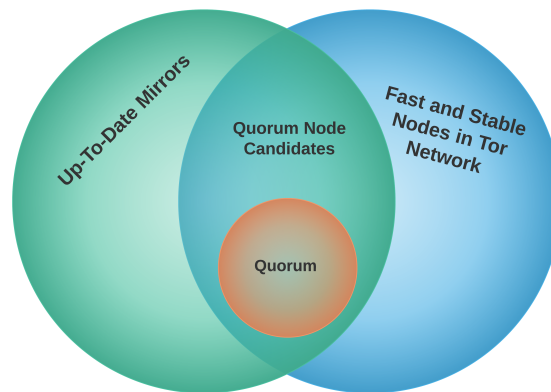


Figure 4.3: There are three sets of participants in the OnionNS network: *mirrors*, quorum node *candidates*, and *quorum* members. The set of *quorum* nodes is chosen from the pool of up-to-date *mirrors* who are reliable nodes within the Tor network.

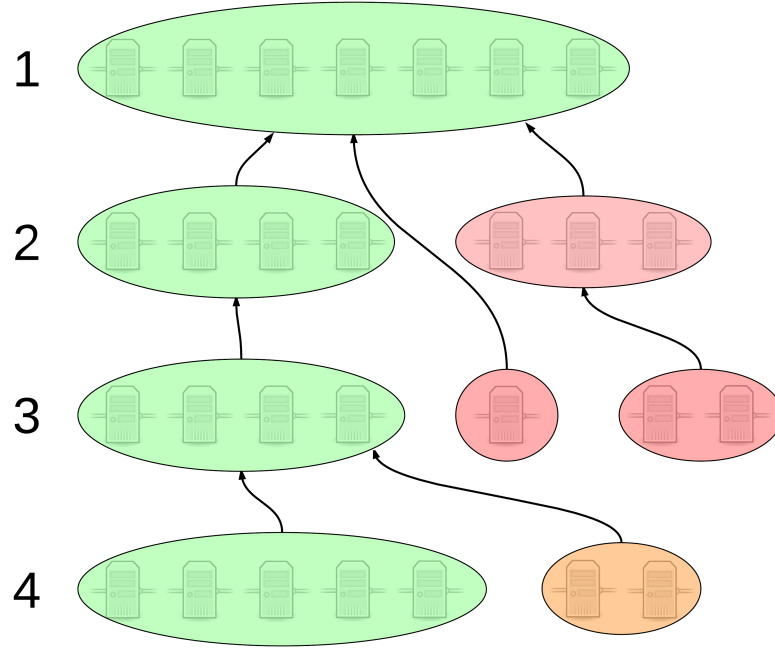


Figure 4.4: An example *page-chain* across four *quorums*. Each *page* contains a references to a previous *page*, forming an distributed scrolling data structure. *Quorums* 1 is semi-honest and maintains its uptime, and thus has identical *pages*. *Quorum* 2's largest cluster is likewise in agreement, but there are three nodes which are acting maliciously together and have changed their *pages*. Node 5 in *quorum* 3 references an old page in attempt to bypass *quorum* 2's records, and nodes 6-7 are colluding with nodes 5-7 from *quorum* 2. Finally, *quorum* 3 has two nodes that acted honestly but did not record new records, so their *page-chains* differ from the others. However, across all four days the largest clusters are honest nodes and thus integrity remains in the *page-chain*.

4.3.3 Client Request

4.4 Cryptographic Primitives

OnionNS makes use of cryptographic hash algorithms, digital signatures, proof-of-work, and a pseudorandom number generator.

TODO: symbols and letters for these to held distinguish them and make the paper fancier

- Hash function - We choose SHA-384 for applications in hash functions and message digests before digital signatures. SHA-384 is a derivative of SHA-512 and has greater

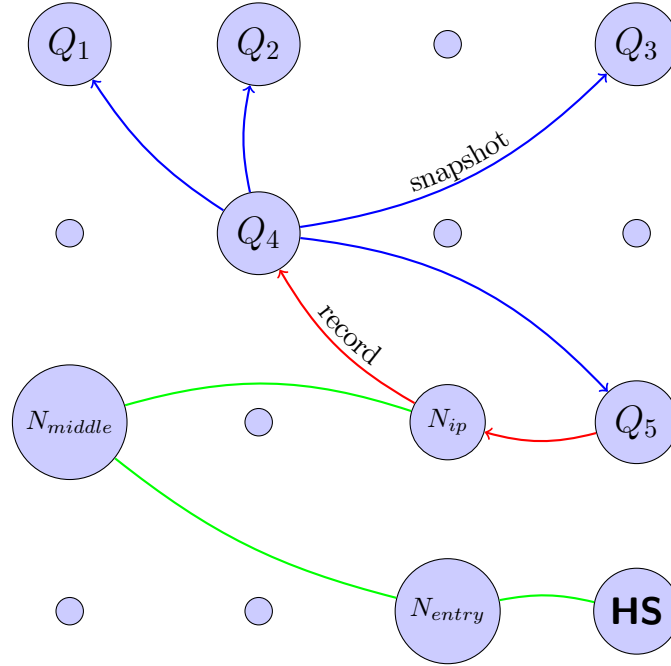


Figure 4.5: The hidden service operator uses his existing circuit (green) to inform *quorum* node Q_4 of the new record. Q_4 then distributes it via *snapshots* to all other *quorum* nodes. Each records it in their own *page* for long-term storage. The operator also confirms from a randomly-chosen *quorum* node Q_5 that the record has been received.

resistance to preimage, collision, and pseudo-collision attacks compared to SHA-256. Currently the best preimage attack of SHA-512 breaks 57 out of 80 rounds in 2^{511} time. [21] SHA-384 is included in the National Security Agency's Suite B Cryptography for protecting information classified up to Top Secret.

- Digital signatures - Our default method is EMSA-PSS, (EMSA4) a probabilistic signature scheme defined by PKCS1 v2.1 and republished in 2003's RFC 3447. We note that this choice is flexible and with can be substituted for another signature algorithm minimal effort.
- Proof-of-work - We select script, a password-based key derivation function which is notable for its large memory and CPU requirements during its operation. The script function provides significantly greater resistance to custom hardware attacks and massively parallel computation primarily due to its memory requirements. This limits attackers to the same software implementation and asymptotic cost as legitimate

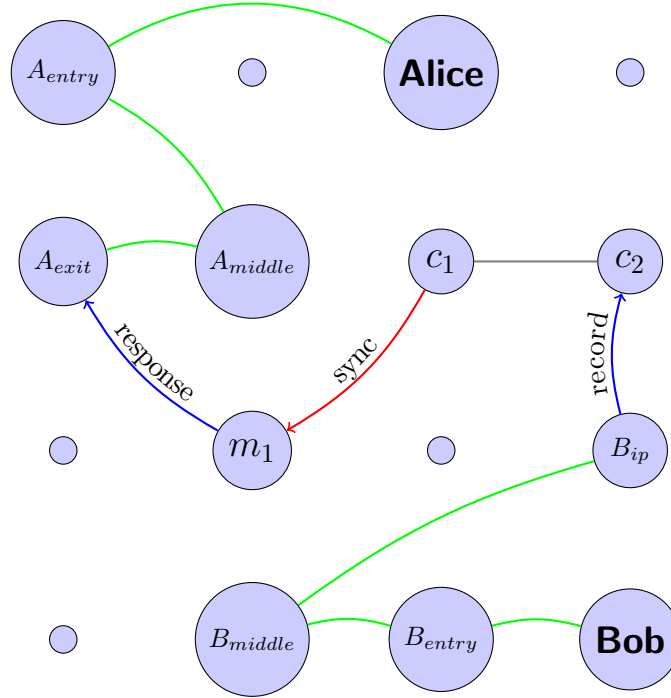


Figure 4.6: The hidden service operator Bob anonymously sends a record to the *quorum* (c_1 and c_2), informing them about his domain name. A node m_1 mirrors the *quorum*, which Alice anonymously queries for Bob's domain name.

users. [22] [23] We choose script because of these advantages over other key derivation functions such as SHA-256 or PBKDF2. For these reasons script is also common in some cryptocurrencies such as Litecoin. In the context of proof-of-work, we rely on EMSA-PKCS1-v1.5, (EMSA3) defined by 1998's RFC 2315; this choice allows our proof-of-work algorithm to be deterministic.

- Pseudorandom number generation - In applications that require pseudorandom numbers from a known seed, we use MT19937, commonly known as the Mersenne Twister. This generator is widely used throughout most programming languages and is well known for its speed, long period, and the high quality of its pseudorandom output, although it is not cryptographically secure. [24]

We use the JSON format to encode records and databases of records. JSON is significantly more compact than XML, but retains readability. Its support of basic primitive

types is highly applicable to our needs. Additionally, we consider the JSON format safer than byte-level encoding.

4.5 Data Structures

4.5.1 Record

There are five different types of Records: Create, Modify, Move, Renew, and Delete. The latter four Records mimic the format of the Create Record with minor exceptions.

Create

A Create record consists of nine components: *type*, *nameList*, *contact*, *timestamp*, *consensusHash*, *nonce*, *pow*, *recordSig*, and *pubHKey*. Fields that are optional are blank unless specified, and all fields are encoded in base64, except for *nameList* and *timestamp*, which are encoded in standard UTF-8. These are defined in Table 4.5.1.

Field	Required?	Description
type	Yes	A textual label containing the type of record. In this case, <i>type</i> is set to “Create”.
nameList	Yes	An array list of up to 24 domain names and their destinations. Domain names can be up to 16 levels deep and each name can be up to 32 characters long, though the full domain name cannot exceed 128 characters in length. This field must also contain second-level domain names, which must match any subdomains (names at level < 2) claimed by the issuer. In this way, records can be referenced by their unique master second-level domain names and issuers cannot claim ownership of domain names that they do not own.

contact	No	The final 16, 24, or 32 characters in the issuer's PGP key fingerprint, if he has a key chooses to disclose it. If the fingerprint is listed, clients may query a public keyserver for this fingerprint, obtain the PGP public key, and contact the owner over encrypted email.
timestamp	Yes	The UNIX timestamp of when the issuer created the registration and began the proof-of-work to validate it. This timestamp cannot be more than 48 hours old nor in the future relative to the recipient's clock.
consensusHash	Yes	The SHA-384 hash of a consensus document published at 00:00 GMT no more than 48 hours before the record was received by the recipient.
nonce	Yes	Four bytes that serve as a source of randomness for the proof-of-work.
pow	Yes	16 bytes that store the result of the proof-of-work.
recordSig	Yes	The digital signature of all preceding fields, signed using the issuer's private key.
pubHSKey	Yes	The issuer's public key in PKCS.1 DER encoding. When the SHA-1 hash of the decoded key is converted to base58 and truncated to 16 characters the resulting hidden service address must match at least one <i>nameList</i> destination.

Table 4.1: A Create record, which contains fields common to all records. Every record is self-signed and must have verifiable proof-of-work before it is considered valid.

Modify

A Modify record allows an owner to update his registration with updated information. The Modify record has identical fields to Create, but *type* is set to “Modify”. The owner corrects the fields, updates *timestamp* and *consensusHash*, revalidates the proof-of-work, and transmits the record. Modify records have a difficulty of $\frac{\text{difficulty}_{\text{Create}}}{4}$. Modify records can be used to add and remove domain names but cannot be used to claim additional second-level domains.

Move

A Move record is used to transfer one or more second-level domain names and all associated subdomains from one owner to another. Move records have all the fields of a Create record, have their *type* is set to “Move”, and contain two additional fields: *target*, a list of domain-destination pairs, and *destPubKey*, the public key of the new owner. Domain names and their destinations contained in *target* cannot be modified; they must match the latest Create, Renew, or Modify record that defined them. Move records also have a difficulty of $\frac{\text{difficulty}_{\text{Create}}}{4}$.

Renew

Second-level domain names (and their associated domain names) expire every L days because (as explained below) the page-chain has a maximum length of L pages. Renew records must be reissued periodically at least every L days to ensure continued ownership of domain names. Renew records are identical to Create records, except that *type* is set to “Renew”. No modifications to existing domain names can be made in Renew records, and the domain names contained within must already exist in the page-chain. Similar to the Modify and Move records, Renew records have a difficulty of $\frac{\text{difficulty}_{\text{Create}}}{4}$.

Delete

If a owner’s private key is compromised or if they wish to relinquish ownership rights over all of their domain names, they can issue a Delete record. Aside from their *type* field

set to “Delete”, Delete records are identical in form to Create records but have the opposite effect: all second-level domains contained within the record are purged from local caches and made available for others to claim. There is no difficulty associated with Delete records, so they can be issued instantly.

4.5.2 Snapshot

originTime

Unix time when the snapshot was first created. This must be less than Δs minutes ago and not in the future relative to a recipient’s clock.

recentRecords

A array list of records in reverse chronological order by receive time.

fingerprint

The hash of the public key of the machine maintaining this snapshot.

snapshotSig

The digital signature of the preceding fields, signed using the machine’s private key.

4.5.3 Page

Each page contains five fields, *prevHash*, *recordList*, *consensusDocHash*, *fingerprint*, and *pageSig*.

prevHash

The SHA-384 hash of *prevHash*, *recordList*, and *consensusDocHash* of a previous page.

recordList

An array list of records, sorted in a deterministic manner.

consensusDocHash

The SHA-384 of *cd*.

fingerprint

The hash of the public key of the machine maintaining this page.

pageSig

The digital signature of the preceding fields, signed using the machine's private key.

the page-chain is publicly confirmable by anyone participating in or using the Tor network.

4.6 Protocols**4.6.1 Hidden Services****Record Generation**

Issuers must complete the proof-of-work before transmitting the record to the recipient. Let the variable *central* consist of all fields except *recordSig* and *pow*. The issuer must then find a *nonce* such that the SHA-384 of *central*, *pow*, and *recordSig* is $\leq 2^{\text{difficulty} * \text{count}}$, where *difficulty* specifies the order of magnitude of the work that must be done and *count* is the number of second-level domain names claimed. For each *nonce*, *pow* and *recordSig* must be regenerated. When the proof-of-work is complete, the valid and complete record is represented in JSON format and is ready for transmission.

Broadcast

Operation records, such as Create, Modify, Move, Renew, and Delete must anonymously transmitted through a Tor circuit to the *quorum* by a hidden service operator. First, the operator uses a Tor circuit to fetch from a *mirror* the consensus document on day $\lfloor \frac{i}{\Delta i} \rfloor$ at 00:00 GMT, which he then uses to derive the current *quorum*. Secondly, he asks the *mirror* for the digitally signed hash of the *page* used by each *quorum* node. Third, he randomly selects two *quorum* nodes from the largest cluster of matching *pages* and sends his record to one of them. For security purposes, the operator should use the same entry

```

0 {
1   "names": {
2     "example.tor": "exampleruyw6wgve.onion"
3   }
4   "contact": "AD97364FC20BEC80",
5   "timestamp": 1424045024,
6   "consensusHash": "uU0nuZNNPgilLlX2n2r+sSE7+N6U4DukIj3rOLvzek=",
7   "nonce": "AAAABw==",
8   "pow": "4I4dzaBwi4AIZW8s2m0hQQ==",
9   "recordSig": "KSaOfzrXIZclHFcYxI+3jBwLs943wxVv3npI5ccY/
    kBEpyXRSopzjoFs746n0tJqUpdY4Kbe6DBwERaN7ELmSSK9Pu6q8QeKzNAh+
    QOnKl0fKBN7fqowjkQ3ktFkR0Vuox9WrrbNTMa4+
    up0Np52hlbKA3zSRz4fbR9NVlh6uuQ=",
10  "pubHsKey": "MIGhMA0GCSqGSib3DQEBAQUAA4GPADCBiwKBgQDE7CP/
    kgwtJhTTc4JpuPkvA7Ln9wgc+
    fgTKgkyUp1zusxgUAn1c1MGx4YhO42KPB7dyZO3pcRk94XsYFY1ULkF2+
    tf9KdNe7GFzJyMFCQENnUcVXbcwLH4vAeiGK7R/nScbCbyc9LT+
    VE1fbKchTL1QzLVBLqJTxhR+9YPi8x+QIFAdZ8BJS="
11 }

```

Figure 4.7: Sample registration record from a hidden service, encoded in JSON and base64.

node for this transmission that their hidden service uses for its communication. Fourth, he constructs a circuit to the second node and polls the node 15 minutes later to determine if it has knowledge of the record. If it does, he can be reasonable sure that the record has been properly transmitted and recorded. If the record is not known the next day, the operator should repeat this procedure to ensure that the record is recorded in the *page-chain*.

This process is illustrated in figure 4.5.

4.6.2 OnionNS Servers

Initialization

This following description assumes that Alice is maintaining a local page-chain in synchronization with a Faythe, a trusted second party. The functionality described here is extended to distributed environments in ?? – Application Within Tor.

```

0 {
1   "prevHash": 0,
2   "recordList": [],
3   "consensusDocHash": "uU0nuZNNPgilLiLX2n2r+sSE7+N6U4DukIj3rOLvzek=",
4   "fingerprint": "2FC06226AE152FBAB7620BB107CDEF0E70876A7B",
5   "pageSig": "KSaOfzrXIZclHFcYxI+3jBwLs943wxVv3npI5ccY/
               kBEPyXRSopzjoFs746n0tJqUpdY4Kbe6DBwERaN7ELmSSK9Pu6q8QeKzNAh+
               QOnKl0fKBN7fqowjkQ3ktFkR0VuoX9WrrbNTMa4+
               up0Np52h1bKA3zSRz4fbR9NVlh6uuQ="
6 }

```

Figure 4.8: A sample empty *page*, encoded in JSON and base64.

Alice creates an initial OnionNS database by the following procedure. Let i be the current day, and let Δi be the lifetime in days of a individual page.

1. Download a copy of the consensus document cd published at at 00:00 GMT on day $\lfloor \frac{i}{\Delta i} \rfloor$.
2. Create an empty AVL tree, an initial hashtable bitset, an empty trie, a blank snapshot, and an empty page.
3. Sets the snapshot's *originTime* field to the current Unix time, *recentRecords* to an empty array, and *fingerprint* to the hash of her public key.
4. Digitally sign $originTime + recentRecords + fingerprint$ and save the signature in *snapshotSig*.
5. Set the page's *prevHash* field to zeros, *recordList* to an empty array, *fingerprint* to the hash of her public key, and *consensusDocHash* to the SHA-384 of cd .
6. Digitally sign $prevHash + recordList + consensusDocHash + fingerprint$ and save the signature in *pageSig*.

Page Selection

To do...

```

0 {
1   "originTime": 1426507551,
2   "recentRecords": [],
3   "fingerprint": "2FC06226AE152FBAB7620BB107CDEF0E70876A7B" ,
4   "snapshotSig": "KSaOfzrXIZclHFcYxI+3jBwLs943wxVv3npI5ccY/
                    kBEPyXRSopzjoFs746n0tJqUpdY4Kbe6DBwERaN7ELmSSK9Pu6q8QeKzNAh+
                    QOnKl0fKBN7fqowjkQ3ktFkR0Vuox9WrrbNTMa4+
                    up0Np52h1bKA3zSRz4fbR9NVlh6uuQ="
5 }

```

Figure 4.9: A sample empty *snapshot*, encoded in JSON and base64.

Synchronization

Rather than continue to query Alice, Bob may wish to become his own resolver. Bob may also become a resolver for others that trust Faythe. The procedure to clone Alice's databases is simple:

1. Bob downloads Alice's $\min(i, L)$ most recent pages in her page-chain.
2. Bob obtains the consensus documents published every Δi days between days $i - \min(i, L)$ and i at 00:00 GMT. Bob may download these from Alice, but Bob may also download them from any other source. These documents may be compressed beforehand: : very high compression ratios can be achieved under 7zip.
3. Bob verifies the authenticity of the consensus documents and then verifies the signatures on each page in the page-chain.
4. Bob constructs his own AVL tree, hashtable bitset, and trie and confirms that Faythe's signatures on her bitset and Merkle collision tree root match his copy. If so, there has been no corruption and Bob has an authentic copy of the database.

Once the synchronization is complete, Bob can confirm the integrity, authenticity, and uniqueness of domain names.

Quorum Qualification

To meet the first requirement, Tor nodes must demonstrate their readiness to accept new records. The naïve solution is to have Tor nodes and clients simply ask the node if it was ready, and if so, to provide proof that it's up-to-date. However, this solution quickly runs into the problem of scaling; Tor has ≈ 7000 nodes and $\approx 2,250,000$ daily users [9]: it is infeasible for any single node to handle queries from all of them. The more practical solution is to publish information to the authority nodes that will be distributed to all parties in the consensus document. Following a full synchronization, a *mirror* publishes this information in the following manner:

1. Let *tree* be its local AVL Tree, described in section 4.7.2.
2. Encode $\text{SHA-384}(\text{tree})$ in Base64 and truncate to 8 bytes.
3. Append the result to the Contact field in the relay descriptor sent to the authority nodes.

While ideally this information could be placed in a special field set aside for this purpose, to ease integration with existing Tor infrastructure and third-party websites that parse the consensus document (such as Globe or Atlas) we use the Contact field, a user-defined optional entry that Tor relay operators typically use to list methods of contact such as email addresses and PGP keys. OnionNS would not be the first system to embed special information in the Contact field; onion-tip.com identifies Bitcoin addresses in the field and then sends shares of donations to that address proportional to the relay's consensus weight.

One weakness with this approach is that because this hash is published in the 00:00 GMT descriptor, an adversary could very easily forge the hash for the 01:00 GMT descriptor and onward and thus broadcast the correct hash without ever performing a synchronization. One possible solution is to combine this hash publication with a Time-based One-time Password Algorithm (TOTP) at a 1 hour time interval. Although this would not thwart collusion or the publishing of the hash elsewhere, it would make the attack non-trivial.

Of all sets of relays that publish the same hash, if *mirror* m_i publishes a hash that is in the largest set, m_i meets the first qualification to become a quorum node *candidate*. Relays must take care to refresh this hash whenever a new *quorum* is chosen. Assuming complete honesty across all *mirrors* in the Tor network, they will all publish the same hash and complete the first requirement.

The second criteria requires Tor nodes to prove that has sufficient capabilities to handle the increase in communication and processing. Fortunately, Tor’s infrastructure already provides a mechanism that can be utilized to prove reliability and capacity; Tor nodes fulfil the second requirement if they have the *fast*, *stable*, *running*, and *valid* flags. These demonstrate that they have the ability to handle large amounts of traffic, have maintained a history of long uptime, are currently online, and have a correct configuration, respectively. As of February 2015, out of the 7000 nodes participating in the Tor network, 5400 of these node have these flags and complete the second requirement.

Both of these requirements can be determined in $\mathcal{O}(n)$ time by anyone holding a recent or archived copy of the consensus document.

Record Processing

Alice then listens for new records from herself or from third-parties. Let p_i be Alice’s current page and s_x the current snapshot.

For each received record, Alice

1. Rejects the record if the fields are invalid, the signature does not validate, or the proof-of-work cannot be confirmed.
2. Checks for the second-level domain name in s_x , p_i , the hashtable bitset, and then the AVL tree.
3. If Alice received a Create record, rejects the record if the domain was found.
4. If a Modify, Move, Renew or Delete record was received, rejects the record if the domain was not found.

5. Adds the record into s_x 's *recentRecords* and regenerates *snapshotSig*.

Every Δs minutes, Alice

1. Generates a new snapshot, s_{x+1} .
2. Sets its *originTime* to the current time, creates *snapshotSig*, and sets s_{x+1} to be the currently active snapshot for collecting new records.
3. Sends s_x to Faythe and accepts Faythe's snapshot if one is offered.
4. Merge all records in *recentRecords* from s_x and Faythe's snapshot into the *recordList* field of p_i .
5. Regenerates *pageSig*.
6. Increments x .

Every Δi days, Alice

1. Creates a new page p_{i+1} and sets its *prevHash* to $\text{SHA-384}(\text{prevHash} + \text{recordList} + \text{consensusDocHash})$ from p_i .
2. Sets p_{i+1} 's *consensusDocHash* to the SHA-384 of the consensus document at 00:00 GMT.
3. Deletes page p_{i-L} if it exists.
4. Regenerates her local AVL tree and hashtable bitset from records in the page-chain using the pages in reverse chronological order. The leaves of the AVL tree at each second-level domain name point to the latest record containing that domain. Deletion records mark that domain as available and invalidate any Create, Modify, Move, or Renew that contain that domain earlier in the page-chain.
5. Regenerates the trie with the .onion addresses in the page-chain such that each leaf in the trie is mapped to the record that immediately resolves it.

```

0 {
1   "originTime": 1426507551,
2   "recentRecords": [{
3     "names": {
4       "example.tor": "exampleruyw6wgve.onion"
5     }
6     "contact": "AD97364FC20BEC80",
7     "timestamp": 1424045024,
8     "consensusHash": "uU0nuZNNPgilLILX2n2r+sSE7+N6U4DukIj3rOLvzek=",
9     "nonce": "AAAABw==",
10    "pow": "4I4dzaBwi4AIZW8s2m0hQQ==",
11    "recordSig": "KSaOfzrXIZclHFcYxI+3jBwLs943wxVv3npI5ccY/
    kBEpyXRSopzjoFs746n0tJqUpdY4Kbe6DBwERaN7ELmSSK9Pu6q8QeKzNAh+
    QOnKl0fKBN7fqowjkQ3ktFkR0Vuox9WrrbNTMa4+
    up0Np52h1bKA3zSRz4fbR9NVlh6uuQ=",
12    "pubHsKey": "MIGhMA0GCSqGSIb3DQEBAQUAA4GPADCBiwbKbgQDE7CP/
    kgwtJhTTc4JpuPkvA7Ln9wgc+
    fgTKgkyUp1zusxgUAn1c1MGx4YhO42KPB7dyZO3pcRk94XsYFY1ULkF2+
    tf9KdNe7GFzJyMFCQENnUcVXbcwLH4vAeiGK7R/nScbCbyc9LT+
    VE1fbKchTL1QzLVBLqJTxhR+9YPi8x+QIFAdZ8BJs="
13  }],
14  "fingerprint": "2FC06226AE152FBAB7620BB107CDEF0E70876A7B",
15  "snapshotSig": "KSaOfzrXIZclHFcYxI+3jBwLs943wxVv3npI5ccY/
    kBEpyXRSopzjoFs746n0tJqUpdY4Kbe6DBwERaN7ELmSSK9Pu6q8QeKzNAh+
    QOnKl0fKBN7fqowjkQ3ktFkR0Vuox9WrrbNTMa4+
    up0Np52h1bKA3zSRz4fbR9NVlh6uuQ="
16 }

```

Figure 4.10: A sample Create record has been merged into an initially-blank snapshot.

6. Asks Faythe for an updated signature on her hashtable bitset, which should verify against Alice's bitset.
7. Increments i .

4.6.3 Tor Clients

Quorum Derivation

```

0 {
1   "prevHash": 0,
2   "recordList": [{
3     "names": {
4       "example.tor": "exampleruyw6wgve.onion"
5     }
6     "contact": "AD97364FC20BEC80",
7     "timestamp": 1424045024,
8     "consensusHash": "uU0nuZNNPgILiLX2n2r+sSE7+N6U4DukIj3rOLvzek=",
9     "nonce": "AAAABw==",
10    "pow": "4I4dzaBwi4AIZW8s2m0hQQ==",
11    "recordSig": "KSaOfzrXIZclHFcYxI+3jBwLs943wxVv3npI5ccY/
    kBEpyXRSopzjoFs746n0tJqUpdY4Kbe6DBwERaN7ELmSSK9Pu6q8QeKzNAh+
    QOnKl0fKBN7fqowjkQ3ktFkR0Vuox9WrrbNTMa4+
    up0Np52h1bKA3zSRz4fbR9NVlh6uuQ=",
12    "pubHsKey": "MIGhMA0GCSqGSIb3DQEBAQUAA4GPADCBiwbKbgQDE7CP/
    kgwtJhTTc4JpuPkvA7Ln9wgc+
    fgTKgkyUp1zusxgUAn1c1MGx4YhO42KPB7dyZO3pcRk94XsYFY1ULkF2+
    tf9KdNe7GFzJyMFCQENnUcVXbcwLH4vAeiGK7R/nScbCbyc9LT+
    VE1fbKchTL1QzLVBLqJTxhR+9YPi8x+QIFAdZ8Bjs="
13  }],
14  "consensusDocHash": "uU0nuZNNPgILiLX2n2r+sSE7+N6U4DukIj3rOLvzek=",
15  "fingerprint": "2FC06226AE152FBAB7620BB107CDEF0E70876A7B",
16  "pageSig": "KSaOfzrXIZclHFcYxI+3jBwLs943wxVv3npI5ccY/
    kBEpyXRSopzjoFs746n0tJqUpdY4Kbe6DBwERaN7ELmSSK9Pu6q8QeKzNAh+
    QOnKl0fKBN7fqowjkQ3ktFkR0Vuox9WrrbNTMa4+
    up0Np52h1bKA3zSRz4fbR9NVlh6uuQ="
17 }

```

Figure 4.11: A snapshot containing a single Create record has merged into Carol's page.

Quorum are randomly chosen from the set of quorum node *candidates*. The *quorum* perform the main duties of the system, namely receiving, broadcasting, and recording DNS records from hidden service operators. The *quorum* can be derived from the pool of *candidates* by performing by the following procedure, where i is the current day:

1. Obtain a remote or local archived copy of the most recent consensus document, cd , published at 00:00 GMT on day $\lfloor \frac{i}{\Delta i} \rfloor$.

2. Extract the authorities' digital signatures, their signatures, and verify cd against $PK_{authorities}$.
3. Construct a numerical list, ql of quorum node *candidates* from cd .
4. Initialize the Mersenne Twister PRNG with $\text{SHA-384}(cd)$.
5. Use the seeded PRNG to randomly scramble ql .
6. Let the first M nodes, numbered $1..M$, define the *quorum*.

In this manner, all parties — in particular Tor nodes and clients — agree on the members of the *quorum* and can derive them in $\mathcal{O}(n)$ time. As the pages and the *quorum* both change every Δi days, *quorum* nodes have an effective lifetime of Δi days before they are replaced by a new *quorum*.

Domain Query

Alice can optionally act as a resolver for other parties. Let Bob be a client and Faythe a third-party trusted by both Alice and Bob. Assume that Bob does not trust Alice, Bob has Faythe's public key, and that Bob has obtained a copy of the Tor consensus document published on day $\lfloor \frac{i}{\Delta i} \rfloor$ at 00:00 GMT. Faythe has divided her bitset into Q sections, digitally signed each section, digitally signed the root hash of the Merkle tree, and send the signatures to Alice.

Bob enters “sub.example.tor” into his Tor Browser. As this TLD is not used by the Clearnet DNS, his client software directs the request to Alice. Bob must recursively resolve the .tor domain name into a .onion address and it is more efficient if Alice returns back to Bob all the necessary information that he needs to perform this resolution. Along with the domain name, Bob also sends to Alice one of the two verification levels, each providing progressively more verification that the record Bob receives is authentic, unique, and trustworthy. The default verification level is 0 for performance reasons.

At verification level 0, Alice first checks the hashtable bitset to confirm that the record exists. If it does, Alice then queries the AVL tree to find the latest record that contains

the requested domain name. Alice resolves the requested domain and repeats this lookup up to eight times if the resulting destination uses the .tor TLD. Once a .onion TLD destination is encountered, Alice returns to Bob all records containing the intermediate and final destinations. If a lookup fails, Alice returns to Bob records containing any intermediary destinations, and the Faythe-signed section of the bitset. If the hash maps to a “1” bucket, Alice also returns the Faythe-signed root of the Merkle collision tree, the leaves of the branch containing neighbouring second-level domain names that alphabetically span the failed domain, and all other hashes at the top level of the branch in the Merkle tree.

Bob receives from Alice the data structures containing the domain name resolutions. Bob confirms the resolution path and confirms the validity, signature, and proof-of-work of each record in turn. Finally, Bob looks up the .onion hidden service in the traditional manner. If the resolution was unsuccessful, Bob also verifies the signed section of the bitset. If the domain maps to a “0”, Bob’s client software returns that the DNS lookup failed, otherwise Bob confirms that no such second-level domain name exists in the Merkle tree branch returned by Alice. Since the leaves of the branch alphabetically span the requested domain and would otherwise contain it if it existed, Bob knows that it does not exist. Finally, Bob hashes the leaves to reconstructs the branch, and constructs the rest of the tree by combining the root of that branch with the other hashes returned by Alice at that level, and verifies the root hash against Faythe’s signature. If this validates, Bob’s software also informs the Tor Browser that DNS lookup failed. The resolution can also fail if the service has not published a recent hidden service descriptor to Tor’s distributed hash table. End-to-end verification (relative to the authenticity of the hidden service itself) is complete when *pubHKey* can be successfully used to encrypt the hidden service cookie and the service proves that it can decrypt *sec* as part of the hidden service protocol.

At verification level 1, in addition to returning all record and supplementary data structures in level 0, Alice also returns the page that contained each record and the *pageSig* field from Faythe’s page. Since Alice and Faythe are maintaining a common page-chain, both Alice and Faythe will be signing the same data. Bob verifies the authenticity of the

page against both Alice and Faythe’s public keys and proceeds with his steps in level 0.

Onion Query

Bob may also issue a reverse-hostname lookup to Alice to find second-level domains that directly resolve to a given .onion hidden service address. This request is an Onion Query. Unlike on the Clearnet (under RFCs 1033 and 1912) not every .onion name has a corresponding domain name, so these queries may also fail. When Bob sends a Onion Query to Alice, Alice finds in her trie the record that contains a second-level .tor domain name that immediately maps to that .onion, and returns the domain name. Bob can optionally perform additional verification by issuing a Level 1 Domain Query on that domain name which should resolve to the original requested .onion hidden service address, a forward-confirmed reverse DNS lookup.

4.7 Optimizations

4.7.1 Snapshot

A *Rnapshot* is textual database designed to hold collections of Records in a short-term volatile cache. Snapshots are used to

as a short-term and volatile cache. When two or more machines are maintaining a common page-chain, snapshots are used as a buffer that is flushed to the other parties every Δs minutes. Individually, they are flushed to a local page every Δs minutes. Snapshots contain four fields: *originTime*, *recentRecords*, *fingerprint*, and *snapshotSig*.

4.7.2 AVL Tree

A self-balancing binary AVL tree is used as a local cache of existing records. Its nodes hold references to the location of records in a local copy of the page-chain and it is sorted by alphabetical comparison of second-level domain names. As a page-chain is a linear data structure that requires a $\mathcal{O}(n)$ scan to find a record, the $\mathcal{O}(n \log n)$ generation of an AVL tree cache allows lookups of second-level domain names to occur in $\mathcal{O}(\log n)$ time.

4.7.3 Hashtable Bitset

A hashtable bitset is a special and highly compact adaptation of a traditional hashtable. Unlike its AVL tree counterpart, its purpose is to prove the non-existence of a record. As an extension of an ordinary hashtable, the hashtable bitset maps keys to buckets, but here we are interested in only tracking the existence of keys and have no need to store the keys themselves. Therefore each bucket in the structure is represented as a bit, creating a compact bitset of $\mathcal{O}(n)$ size. The hashtable bitset records a “1” if a second-level domain name exists, and a “0” if not. In the event of a hash collision, all second-level domains that map to that bucket should be added to an array list. Once the bitset is fully constructed, the array is sorted alphabetically and the result is converted into the leaves of a Merkle tree.

Let Alice and a trusted authority Faythe maintain a common page-chain, and let Alice be a resolver for a third-party Bob. In the event that Bob asks Alice to resolve a domain name to a hidden service and Alice claims that the domain name does not exist, Bob must be able to verify the non-existence of that record. Demonstrating non-existence is a challenge often overlooked in DNS: even if existing records can be authenticated by Bob, Alice may still lie and claim a false negative on the existence of a domain name. Bob may choose to query Faythe to confirm non-existence, but this introduces additional load onto Faythe. Bob cannot easily determine the accuracy of Alice’s claim without downloading all of the records and confirming for himself, but this is impractical in most environments.

The hashtable bitset efficiently resolves this issue. Faythe periodically generates a timestamped hashtable bitset for all existing domain names, digitally signs it, and publishes the result to Alice. As described in section 4.6.3, Alice then includes this bitset along with any non-existence responses sent back to Bob. Since Bob knows and trusts Faythe, he can verify Alice’s claim by verifying the authenticity of the bitset and confirming that the domain he requested does not appear in the hashtable or in the Merkle tree in $\mathcal{O}(1)$ time on average. The hashtable also serves as an optimization to Alice: she can check the bitset for Bob’s request in $\mathcal{O}(1)$ time, bypassing the $\mathcal{O}(\log n)$ lookup if the second-level domain

name does not exist.

Note that a Bloom filter with k hash functions could be used instead of a compact hashtable, but a Bloom filter would require sending up to k sections of buckets to the client. Therefore, we use a simple hashtable scheme, which is effectively a Bloom filter with $k = 1$.

4.7.4 Trie

A trie, also known as a digital tree, is used for efficiently resolving Onion Queries (section 4.6.3). Each node in the trie corresponds to a base58 digit of the .onion hidden service address. These addresses are currently defined at 16 characters, so the trie has a maximum depth of 16 and up to 58 branches per node.

CHAPTER 5

ANALYSIS

We have designed OnionNS to meet our original design goals. Assuming that Tor circuits are a sufficient method of masking one’s identity and location, hidden service operators can perform operations on their records anonymously. Likewise, a Tor circuit is also used when a client lookups a .tor domain name, just as Tor-protected DNS lookups are performed when browsing the Clearnet through the Tor Browser. OnionNS records are self-signed and include the hidden service’s public key, so anyone — particularly the client — can confirm the authenticity (relative to the authenticity of the public key) and integrity of any record. This does not entirely prevent Sybil attacks, but this is a very hard problem to address in a distributed environment without the confirmation from a central authority. However, the proof-of-work component makes record spoofing a costly endeavour, but it is not impossible to a well-resourced attacker with sufficient access to high-end general-purpose hardware.

Without complete access to a local copy of the database a party cannot know whether a second-level domain is in fact unique, but by using an existing level of trust with a known network they can be reasonably sure that it meets the unique edge of Zooko’s Triangle. Anyone holding a copy of the consensus document can generate the set of *quorum* node and verify their signatures. As the *quorum* is a set of nodes that work together and the *quorum* is chosen randomly from reliable nodes in the Tor network, OnionNS is a distributed system. Tor clients also have the ability to perform a full synchronization and confirming uniqueness for themselves, thus verifying that Zooko’s Triangle is complete. Hidden service .onion addresses will continue to have an extremely high chance of being securely unique as long the key-space is sufficiently large to avoid hash collisions.

Just as traditional Clearnet DNS lookups occur behind-the-scenes, OnionNS Domain Queries require no user assistance. Client-side software should filter TLDs to determine

which DNS system to use. We introduce no changes to Tor’s hidden service protocol and also note that the existence of a DNS system introduces forward-compatibility: developers can replace hash functions and PKI in the hidden service protocol without disrupting its users, so long as records are transferred and OnionNS is updated to support the new public keys. We therefore believe that we have met all of our original design requirements.

5.1 Security

5.1.1 Quorum-level Attacks

The quorum nodes hold the greatest amount of responsibility and control over OnionNS out of all participating nodes in the Tor network, therefore ensuring their security and limiting their attack capabilities is of primary importance.

Passively Malicious Quorum

In section 2.1, we assumed that an attacker, Eve, already controls a fraction of Tor routers. For a dynamic network size, a fixed fraction of dishonest nodes, and a fixed quorum size, every time a quorum is selected there is a probability that more than half of the quorum is dishonest and is colluding together. If this occurs, records may be dropped rather than archived. *Here we explore the optimal quorum rotation rate, given the balance between high overhead and high security risk if the quorum is rotated quickly, and long-term implications and possible stability issues associated with very slow rotation.*

Active Malicious Quorum

If Eve controls some Tor nodes (who may be assumed to be colluding with one another), the attacker may desire to include their nodes in the quorum for malicious manipulation, passive observation, or for other purposes. Alternatively, Eve may wish to exclude certain legitimate nodes from inclusion in the quorum. In order to carry out either of these attacks, Eve must have the list of qualified Tor nodes scrambled in such a way that the output is pleasing to Eve. Specifically, the scrambled list must contain at least some of Eve’s malicious

nodes for the first attack, or exclude the legitimate target nodes for the second attack. We initialize Mersenne Twister with a 384-bit seed, thus Eve can find k seeds that generates a desirable scrambled list in 2^{192} operations on average, or 2^{384} operations in the worst case. The chance of any of those seeds being selected, and thus Eve successfully carrying out the attack, is thus $\frac{2^{384}}{k}$.

Eve may attempt to manipulate the consensus document in such a way that the SHA-384 hash is one of these k seeds. Eve may instruct her Tor nodes to upload a custom status report to the authority nodes in an attempt to maliciously manipulate the contents of the consensus document, but SHA-384's strong preimage resistance and the unknown state and number of Tor nodes outside Eve's control makes this attack infeasible. The time to break preimage resistance of full SHA-384 is still 2^{384} operations. This also implies that Eve cannot determine in advance the next consensus document, so the new quorum cannot be predicted. If Eve has compromised at least some of the Tor authority nodes she has significantly more power in manipulating the consensus document for her own purposes, but this attack vector can also break the Tor network as a whole and is thus outside the scope of our analysis. Therefore, the computation required to maliciously generate the quorum puts this attack vector outside the reach of computationally-bound adversaries.

OnionNS and the Tor network as a whole are both susceptible to Sybil attacks, though these attacks are made significantly more challenging by the slow building of trust in the Tor network. Eve may attempt to introduce large numbers of nodes under her control in an attempt to increase her chances of at least one of the becoming members of the *quorum*. Sybil attacks are not unknown to Tor; in December 2014 the black hat hacking group LizardSquad launched 3000 nodes in the Google Cloud in an attempt to intercept the majority of Tor traffic. However, as Tor authority nodes grant consensus weight to new Tor nodes very slowly, despite controlling a third of all Tor nodes, these 3,000 nodes moved 0.2743 percent of Tor traffic before they were banned from the Tor network. The Stable and Fast flags are also granted after weeks of uptime and a history of reliability. As nodes must have these flags to be qualified as a *quorum candidate*, these large-scale Sybil attacks

are financially demanding and time-consuming for Eve.

5.1.2 Non-existence Forgery

As we have stated earlier, falsely claiming a negative on the existence of a record is a problem overlooked in other domain name systems. One of the primary challenges with this approach is that the space of possible names is so vast that attempting to enumerate and digitally sign all names that are not taken is highly impractical. Without a solution, this weakness can degenerate into a denial-of-service attack if the DNS resolver is malicious towards the client. Our counter-measure is the highly compact hashtable bitset with a Merkle tree for collisions. We set the size of the hashtable such that the number of collisions is statistically very small, allowing an efficient lookup in $\mathcal{O}(1)$ time on average with minimal data transferred to the client.

5.1.3 Name Squatting and Record Flooding

An attacker, Eve, may attempt a denial-of-service attack by obtaining a set of names for the sole purpose of denying them to others. Eve may also wish to create many name requests and flood the *quorum* with a large quantity of records. Both of these attacks are made computationally difficult and time-consuming for Eve because of the proof-of-work. If Eve has access to large computational resources or to custom hardware she may be able to process the PoW more efficiently than legitimate users, and this can be a concern.

The proof-of-work scheme is carefully designed to limit Eve to the same capabilities as legitimate users, thus significantly deterring this attack. The use of script makes custom hardware and massively-parallel computation expensive, and the digital signature in every record forces the hidden service operator to resign the fields for every iteration in the proof-of-work. While the scheme would not entirely prevent the operator from outsourcing the computation to a cloud service or to a secondary offline resource, the other machine would need the hidden service private key to regenerate *recordSig*, which the operator can't reveal without compromising his security. However, the secondary resource could perform the script computations in batch without generating *recordSig*, but it would always perform

more than the necessary amount of computation because it would could not generate the SHA-384 hash and thus know when to stop. Furthermore, offloading the computation would still incur a cost to the hidden service operator, who would have to pay another party for the consumed computational resources. Thus the scheme always requires some cost when claiming a domain name.

5.2 Performance

bandwidth, CPU, RAM, latency for clients to be determined...

5.2.1 Load

demand on participating nodes to be determined...

Unlike Namecoin, OnionNS' *page-chain* is of L days in maximal length. This serves two purposes:

1. Causes domain names to expire, which reduced the threat of name squatting.
2. Prevents the data structure from growing to an unmanageable size.

5.3 Reliability

Tor nodes have no reliability guarantee and may disappear from the network momentarily or permanently at any time. Old *quorums* may disappear from the network without consequence of data loss, as their data is cloned by current *mirrors*. So long as the *quorum* nodes remain up for the Δ_i days that they are active, the system will suffer no loss of functionality. Nodes that become temporarily unavailable will have out-of-sync *pages* and will have to fetch recent records from other *quorum* nodes in the time of their absence.

REFERENCES

- [1] D. Chaum, “Untraceable electronic mail, return addresses and digital pseudonyms,” in *Secure electronic voting*. Springer, 2003, pp. 211–219.
- [2] M. Edman and B. Yener, “On anonymity in an electronic society: A survey of anonymous communication systems,” *ACM Computing Surveys (CSUR)*, vol. 42, no. 1, p. 5, 2009.
- [3] P. Syverson, “A peel of onion,” in *Proceedings of the 27th Annual Computer Security Applications Conference*. ACM, 2011, pp. 123–137.
- [4] R. Dingledine, N. Mathewson, and P. Syverson, “Tor: The second-generation onion router,” DTIC Document, Tech. Rep., 2004.
- [5] P. F. Syverson, D. M. Goldschlag, and M. G. Reed, “Anonymous connections and onion routing,” in *Security and Privacy, 1997. Proceedings., 1997 IEEE Symposium on*. IEEE, 1997, pp. 44–54.
- [6] M. G. Reed, P. F. Syverson, and D. M. Goldschlag, “Anonymous connections and onion routing,” *Selected Areas in Communications, IEEE Journal on*, vol. 16, no. 4, pp. 482–494, 1998.
- [7] K. Bauer, D. McCoy, D. Grunwald, T. Kohno, and D. Sicker, “Low-resource routing attacks against tor,” in *Proceedings of the 2007 ACM workshop on Privacy in electronic society*. ACM, 2007, pp. 11–20.
- [8] L. Overlier and P. Syverson, “Locating hidden servers,” in *Security and Privacy, 2006 IEEE Symposium on*. IEEE, 2006, pp. 15–pp.

- [9] T. T. Project, “Tor metrics,” <https://metrics.torproject.org/>, 2015, accessed 4-Feb-2015.
- [10] S. Landau, “Highlights from making sense of snowden, part ii: What’s significant in the nsa revelations,” *Security & Privacy, IEEE*, vol. 12, no. 1, pp. 62–64, 2014.
- [11] R. Plak, “Anonymous internet: Anonymizing peer-to-peer traffic using applied cryptography,” Ph.D. dissertation, TU Delft, Delft University of Technology, 2014.
- [12] D. Lawrence, “The inside story of tor, the best internet anonymity tool the government ever built,” *Bloomberg BusinessWeek*, January 2014.
- [13] D. McCoy, K. Bauer, D. Grunwald, T. Kohno, and D. Sicker, “Shining light in dark places: Understanding the tor network,” in *Privacy Enhancing Technologies*. Springer, 2008, pp. 63–76.
- [14] I. Goldberg, “On the security of the tor authentication protocol,” in *Privacy Enhancing Technologies*. Springer, 2006, pp. 316–331.
- [15] I. Goldberg, D. Stebila, and B. Ustaoglu, “Anonymity and one-way authentication in key exchange protocols,” *Designs, Codes and Cryptography*, vol. 67, no. 2, pp. 245–269, 2013.
- [16] D. J. Bernstein, “Curve25519: new diffie-hellman speed records,” in *Public Key Cryptography-PKC 2006*. Springer, 2006, pp. 207–228.
- [17] L. Xin and W. Neng, “Design improvement for tor against low-cost traffic attack and low-resource routing attack,” in *Communications and Mobile Computing, 2009. CMC’09. WRI International Conference on*, vol. 3. IEEE, 2009, pp. 549–554.
- [18] S. Nicolussi, “Human-readable names for tor hidden services,” 2011.
- [19] M. S. Ferdous, A. Jøsang, K. Singh, and R. Borgaonkar, “Security usability of petname systems,” in *Identity and Privacy in the Internet Age*. Springer, 2009, pp. 44–59.

- [20] M. Stiegler, “Petname systems,” *HP Laboratories, Mobile and Media Systems Laboratory, Palo Alto, Tech. Rep. HPL-2005-148*, 2005.
- [21] J. Li, T. Isobe, and K. Shibutani, “Converting meet-in-the-middle preimage attack into pseudo collision attack: Application to sha-2,” in *Fast Software Encryption*. Springer, 2012, pp. 264–286.
- [22] C. Percival, “Stronger key derivation via sequential memory-hard functions,” *Self-published*, pp. 1–16, 2009.
- [23] C. Percival and S. Josefsson, “The scrypt password-based key derivation function,” 2012.
- [24] M. Matsumoto and T. Nishimura, “Mersenne twister: a 623-dimensionally equidistributed uniform pseudo-random number generator,” *ACM Transactions on Modeling and Computer Simulation (TOMACS)*, vol. 8, no. 1, pp. 3–30, 1998.