Designing a Global Authentication Infrastructure
(extended version)

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ABSTRACT

We address the problem of scaling authentication for naming, routing, and end-entity certification to a global environment in which authentication policies and users’ sets of trust roots vary widely. The current mechanisms for authenticating names (DNSSEC), routes (BGPSEC), and end-entity certificates (TLS) do not support a coexistence of authentication policies, affect the entire Internet when compromised, cannot update trust root information efficiently, and do not provide users with the ability to make flexible trust decisions. We propose a Scalable Authentication Infrastructure for Next-generation Trust (SAINT), which partitions the Internet into groups with common, local trust roots, and isolates the effects of a compromised trust root. SAINT requires groups with direct routing connections to cross-sign each other for authentication purposes, allowing diverse authentication policies while keeping all entities globally verifiable. SAINT makes trust root management a central part of the network architecture, enabling trust root updates within seconds and allowing users to make flexible trust decisions. SAINT operates without a significant performance penalty and can be deployed alongside existing infrastructures.

1. INTRODUCTION

Alice lives in the Republic of Mythuania and frequently travels around the world for business purposes. In her business dealings, she frequently communicates with her clients and with her banks, which are located all over the world. For the security of these communications to client and bank websites, Alice primarily relies on three mechanisms: DNSSEC [4, 5] to authenticate name-to-address mappings in DNS records, RPKI and BGPSEC [27, 28] to authenticate routes used to reach the sites, and TLS [15] to authenticate the public keys used to establish a confidential connection to the sites. These mechanisms rely on trust roots, which are assumed to be trustworthy, and follow one of two models: monopoly (the entire system has a single trust root) and oligarchy (users configure many trust roots of equal authority).

Unfortunately, these models both suffer from shortcomings that detrimentally affect Alice’s communication security. The monopoly model unrealistically expects users to trust a single global root, such as ICANN for DNSSEC. Alice must assume that ICANN correctly certifies DNS records if she wants to have confidence in DNSSEC. As a Mythuvian citizen, Alice may want to select a different set of trust roots from a citizen of Oceania, but under the monopoly model neither citizen has a choice of trust roots. Moreover, the global root is a single point of failure in the monopoly model, which is particularly worrying in light of recent state-level attacks [10, 14, 17, 18, 20, 40].

The oligarchy model, on the other hand, gives all trust roots equal, global authority, allowing every trust root to certify information all over the world (consider the example of root certificate authorities (CAs) in TLS). However, this unfettered global authority lacks an isolation property: any compromised trust root can affect authentication for any entity in the world, leading to weakest-link security. Under this model, Alice has difficulties evaluating the trustworthiness of the many trust roots, preventing her from effectively defending herself against compromised trust roots by ceasing to trust them. Together with the inability to choose trust roots, we say that Alice lacks trust agility [31], the ability to select and easily modify trust roots. Even if she can select trust roots in TLS, Alice may cut off access to some sites by deselecting certain trust roots, illustrating a need for global verifiability with trust agility.

Because Alice travels frequently, she faces additional problems with today’s authentication mechanisms. Due to the

\[1\] This is the fictional state in George Orwell’s novel 1984.
fact that some trust roots in systems such as TLS may only certify information in some parts of the world, Alice may have to trust these roots when in the respective parts of the world, requiring her to constantly change her set of trust roots. In contrast, she should have trust mobility, the ability to use the same set of trust roots wherever she is in the world. To evaluate her confidence in a chain of signatures authenticating a piece of information, she should have transparent authentication, knowing which trust roots are involved in certifying the information. Finally, in order to quickly obtain updated trust root information in the face of a compromise or change, Alice should be able to learn of any changes to her trust roots and obtain up-to-date information quickly and easily, a property we call update efficiency.

To address the above problems, we propose a Scalable Authentication Infrastructure for Next-generation Trust (SAINT), a series of architectural design changes to current authentication mechanisms (specifically DNSSEC, BGPSEC, and TLS). Using Alice’s example, we demonstrate how authentication in SAINT provides stronger guarantees and additional properties over today’s Internet. In designing SAINT, we make the following contributions:

- We propose isolation domains (ISDs), which partition the Internet into groups sharing common sets of trust roots, and scope trust root authority to these ISDs. The separation of ISDs allows Alice to select an ISD as a set of trust roots, enabling trust agility, and the scoped authority of each ISD’s trust roots enables isolated authentication.

- We design trust root configuration (TRC) files, network messages containing trust root information. The distribution channel of these files is the same as that of routing messages, providing update efficiency. Additionally, these files allow Alice to quickly obtain and use new trust root information, enabling trust agility.

- We require cross-signing of trust roots between ISDs sharing a routing link using special certificates. This requirement enables global verifiability, so that Alice can verify any entity to which she has a routing path. The certificates used for cross-signing allow Alice to see the ISDs through which she is authenticating her destination, enabling transparent authentication.

- We separate authentication for routing and service entities, preventing circular dependencies in authenticating routes. This separation also enables trust agility and mobility, allowing Alice’s trust decisions for service entities to apply anywhere in the world.

2. BACKGROUND

We provide a brief overview of existing authentication infrastructures relevant to this work and their shortcomings. DNSSEC [4][5] was created to authenticate DNS responses and thus to prevent cache poisoning and other attacks against DNS security. ICANN operates the DNSSEC root signing key, which authenticates the public keys associated with .com, .org, etc. In turn, these keys authenticate the next level of the DNS hierarchy. Clients can authenticate the DNS responses by starting from the root key and validating step-by-step the entire signature chain.

Shortcomings. The single root of trust in DNSSEC implies that the entire world is required to trust the root key, even though the world cannot agree on a single trusted entity. Furthermore, despite the measures taken to protect the root key from compromise, the key is still a single point of failure for DNSSEC.

BGPSEC [29] and RPKI [3] constitute a standard to protect BGP update messages against unwarranted modifications. BGPSEC relies on RPKI for prefix and router certificates. RPKI enables the authentication of AS numbers and IP address spaces. In RPKI, each Regional Internet Registry (RIR) serves as a trust anchor and signs certificates corresponding to resources, such as autonomous system (AS) numbers and IP addresses, issued by that regional registry. For example, ARIN signs a delegation for an address space provided to AT&T, which in turn signs a delegation to a customer of its subspace. The same process occurs with AS numbers. Verifiers use the trust anchor managed by each RIR to verify the delegation chain of certificates for AS numbers and address spaces. Before the owner of an address block advertises a prefix in BGPSEC, it can use the address block certificate to sign a Route Origin Authorization (ROA) to an initial AS. Each AS on the path adds a signature of its own and the following AS number, called a route attestation in S-BGP [23]. The route attestations, together with AS number and address block certificates, enable validation of the path in BGPSEC.

Shortcomings. RPKI’s validation process in BGPSEC suffers from circular dependencies. To transfer routing information, BGPSEC peers use the UPDATE message which contains signatures. The certificate chains for the signature validation are stored at each RIR’s RPKI server. Hence, validation of the UPDATE message requires each BGPSEC router to fetch the certificates directly from the RIRs or from its local server, resulting in slow update propagation.

SSL/TLS [15] were created to secure web connections between browsers and web servers. A web site is authenticated through an X.509 certificate that the web site obtains from a Certification Authority (CA). Each browser stores the public root key of each trusted CA, and uses one of these root keys to validate a server’s certificate.

Shortcomings. Numerous security issues exist with the key infrastructure since current browsers trust around 650 root CA keys [16]. Additionally, CAs have global jurisdiction and consequently any compromised CA can issue a fake certificate for any server in the entire Internet. Recent attacks on CAs have underscored the fact that even the most widely-used CAs suffer from such vulnerabilities, leading to Man-in-the-Middle (MitM) attacks on high-profile sites [32].

SCION [41] is an isolation architecture for inter-domain rout-
ing in the Internet. The provided isolation allows so-called trust domains (TDs) to distinguish between connections originating from inside or outside the domain, and can guarantee that the path of communication between two entities in a domain remains completely in that domain. TDs are formed from ASes that are naturally grouped along jurisdictional boundaries and who can agree on common roots of trust for routing information. These boundaries protect misbehavior in one TD from affecting routing in another TD.

**Shortcomings.** SCION does not provide authentication for name lookups or end entities, and does not specify mechanisms for the update or revocation of keys in the routing architecture. Additionally, SCION ties users to the TD in which they are located for all authentication, forcing them to trust their own TD core (which serve as routing authorities) for all authentication.

Additional related work is discussed in Section 13.

### 3. PROBLEM DEFINITION

Our goal is to design global infrastructures allowing a user (Alice) to authenticating routes, names, and EE certificates (such as TLS certificates) for a server (Bob) in the Internet. In a global environment such as the Internet, Alice does not trust all trust roots in the environment, and she and Bob may not even have any trust roots in common. The trust roots may differ in functionality and scope: some may authenticate routes and others names, and some may be global and some local. We want to minimize global authority, allow trust agility and mobility while maintaining global verifiability, and allow Alice to evaluate the trustworthiness of information being authenticated.

**Desired properties.** In order to effectively the above authentication problems, a network architecture should have the following properties:

- **Isolated authentication.** The compromise of a trust root should be limited in scope. In particular, if Alice and Bob share trust roots for some information, no other trust root should be able to affect authentication of that information.
- **Trust agility.** Alice should have a clear, understandable choice over her trust roots. This choice should be easily modifiable at any time, with changes taking effect immediately (within seconds).
- **Trust mobility.** Alice’s trust decisions should remain the same no matter where she is in the network. In other words, moving to different locations in the network should not require Alice to change her trust roots.
- **Global verifiability.** As in the current Internet, Alice should be able to authenticate any entity in the Internet that can be reached and has authentication information such as a name or EE certificate, even if its trust decision differs from hers.
- **Transparent authentication.** Alice should know when trust roots other than her own are certifying information that she verifies. In particular, for a chain of signatures Alice should be able to determine which trust roots are responsible for each signature.
- **Update efficiency.** Changes to trust root information (e.g., new keys and revocations) should take effect quickly (within minutes). In particular, Alice should be able to detect and obtain new information without requiring software updates.

**Adversary model.** Our adversary is an individual or organization whose goal is to convince Alice of false information for a route, name, or EE certificate. To achieve this goal, the adversary can actively suppress, change, replay, or inject messages into client-server communication, and might also gain access to the private keys of trust roots in one domain. However, besides these capabilities, the adversary cannot break cryptographic primitives such as public-key encryption and hash functions.

**Other assumptions.** In order for Alice to successfully verify authentication information, she must also be able to verify a set of trusted public keys which can then be used to bootstrap trust in other keys used during authentication. We therefore assume that users like Alice can verify an initial set of public keys through an out-of-band mechanism.

### 4. SAINT OVERVIEW

In this section, we highlight important features of SAINT. We provide intuitive explanations of how these features accomplish the desired properties mentioned in Section 3 and how they fit into the overall SAINT architecture.

#### 4.1 Isolation Domains (ISDs)

The Internet consists of a diverse assortment of groups, or domains, each with its own set of trusted parties and individual policies regarding routing, naming and EE certification. We make these differences a central part of the SAINT architecture in order to achieve isolated authentication. SAINT groups hosts, routers, and networks into isolation domains (ISDs), such as those shown in Figure 2. SAINT’s ISDs are inspired by SCION’s trust domains and leverage SCION’s routing infrastructure. However, SAINT’s ISDs provide additional authentication mechanisms for naming and EE certification.

An ISD is a collection of ASes with a common set of trust roots (see Figure 4). These trust roots manage authentication within their ISD, including management of routing, naming, and EE certification policies, but are not authorities outside of the ISDs. The structure of ISDs attempts to model existing trust relationships between humans by grouping those with similar trust decisions together and by protecting users from misconfigurations or breaches of trust outside these “circles of trust” where other trust decisions and policies hold. Thanks to ISDs, Alice can select her roots of trust and when communicating within her own ISD, she can stay protected from compromised trust roots outside of her ISD. Section 5 describes the structure of ISDs in more detail.
In practice, ISDs can represent groups of various scales, such as companies, conglomerates, or countries. ISD-level policies will vary greatly by the scale of the ISD, since corporate policies often contain much more detail than country-wide laws. In this paper we use countries as examples of ISDs for several reasons: (1) international boundaries approximately map to DNS naming boundaries, which are also separated in SAINT, (2) national data privacy laws provide a reasonable example of security policies in top-level ISDs, and (3) the resulting set of domains represents an easily-understood choice among possible sets of trust roots, since users can more easily understand what it means to evaluate and trust a country (representing a set of trust roots) rather than doing so with individual trust roots.

4.2 Trust Root Configuration (TRC) Files

Trust root management in SAINT is handled by TRC files, which contain information about an ISD’s trust roots, such as their public keys (see Section 6.2 for more details). TRC files are disseminated as network messages along the same channels as routing messages and DNS responses (see Section 6.3), providing update efficiency. Because routing messages are required to maintain connectivity, new TRC files can quickly propagate throughout the network in case a trust root is compromised. This mechanism allows Alice to quickly obtain up-to-date trust root information.

In addition to the above distribution mechanisms, TRC files can also be downloaded and chosen by the users as a new set of trust roots. Since a TRC file contains all of the necessary trust root information, a user like Alice can easily switch to a different set of trust roots by simply obtaining and selecting a different TRC file. In essence, SAINT provides trust agility by allowing users to easily modify their trust decisions at any time.

TRC files contain trust root information for a given ISD and thereby enable transparent authentication. Namely, when a trust root signs the information of another ISD’s trust root (as explained below), it does so by signing the TRC file of the other ISD. Thus a chain of signatures clearly indicates domain boundaries by design. Alice can use this knowledge of ISD boundaries to evaluate the trustworthiness of this signature chain and determine whether or not to accept the authenticated information.

4.3 Cross-Signing Trust Roots

If we consider ISDs as countries, then we can clearly see that not all ISDs’ trust roots will cross-certify one another, and it is unrealistic to expect countries to do so. Rather, we only require the trust roots of two ISDs to cross-certify one another if they share routing links, that is, if they are physically connected and route traffic through one another. This requirement ensures that the existence of a routing path implies the existence of a chain of signatures for a name or EE certificate, providing global verifiability by allowing Alice to verify this information for any entity she can reach (see Section 7 for more details).

This cross-signing requirement also helps to provide mobility: no matter where users are located, they can authenticate service information (names and EE certificates) starting from their own trust roots (named in their “home” TRC file) to the ISD of the entity whose information they are verifying. Thus as long as Alice can reach her home ISD from the ISD in which she is located, she can use her existing trust decision for authentication anywhere in the world.

4.4 Separation of Authentication Types

SAINT separates routing authentication from service authentication (which certifies names and EE certificates). Because authentic routes are required to fetch necessary information during name lookups and EE certificate handshakes, we treat routing as a separate authentication mechanism. Moreover, we note that authentication of routes cannot rely on fetching external information, as this would itself require authentic routes and thus create a circular dependency.

The separation of routing and service authentication also helps provide trust mobility in SAINT. We observe that users’ physical locations indeed influence their routing authentication; in particular, a route from Alice to Bob must be authenticated by trust roots of the ISDs in which Alice and Bob are located. However, this requirement does not hold for service authentication; thus Alice can use the trust roots of an ISD of her choosing to completely bypass the ISD in which she is located to authenticate names or EE certificates, providing trust mobility and greater resilience against MitM attacks.

5. ISOLATION DOMAINS

We now discuss isolation domains in more detail. We begin by describing the physical layout of ISDs along with the structure of the namespace and the address space in SAINT. We then present the concept of trust anchor ISDs, which provide starting points for the authentication of routes, names, and EE certificates.

5.1 ISD Structure

An ISD is made up of multiple networks, or ASes, as shown in Figure 2, with ISDs connecting to one another to
We structure SAINT’s global namespace as a collection of several hundred core ASes in total. Therefore, in running such a protocol we do not worry about significant overhead or scalability.

5.2 DNS Namespace

Each ISD has the autonomy to manage its own namespace. We structure SAINT’s global namespace as a collection of top-level domains (TLDs) bound by an inter-domain web of trust [42] (as shown in Figure 3), rather than by a global root zone as is done in DNSSEC. However, SAINT’s name resolution process is similar to that of DNSSEC.

Each SAINT DNS root server answers queries for hosts within its ISD. An ISD’s namespace supports one of two top-level domain types:

- **Regional TLDs** in SAINT correspond to a specific ISD. In the example of Figure 3, the TLD .us represents the United States ISD, whereas .uk represents the United Kingdom ISD. In order to provide transparency, the DNS server responsible for a regional TLD guarantees that any address record (similar to A records in DNS) maps to an address within the corresponding ISD.

- **Generic TLDs** such as .com and .org, by contrast, are not bound to any specific ISD, and can thus name an entity located anywhere in the world. However, a name in a generic TLD can only map a redirection to another name, thereby ensuring that only names under regional TLDs map to addresses (and only within the TLD’s corresponding ISD). This guarantee provides domain transparency during DNS lookups. Details about name resolution for generic TLDs are in Appendix [13].

We expect that today’s ccTLDs such as .us and .uk will continue to operate as regional TLDs under SAINT. Countries such as Tuvalu (whose ccTLD is the popular .tv) may choose to operate as a generic TLD and continue to sell names that map all over the world, but must do so through redirections to other names.

5.3 Address Space

We define an address in SAINT as a 3-tuple of the form \((I, A, e)\), where \(I\) represents an ISD identifier, \(A\) represents an AS identifier (ASID), and \(e\) represents an endpoint identifier (EID). For example, if Alice wants to reach Bob, who has the EID 42ac6d in AS 567 and ISD \(I\), she would contact the address \((I, 567, 42ac6d)\). In contrast to the current Internet, AS numbers and EIDs do not have significance outside of their respective ISDs and ASes, and thus can have any format. An EID, for example, can be an IPv4, IPv6, MAC, or self-certifying address.

Registry servers in ISDs (described in Section 6.1) assign ASIDs to ASes, and similar servers in each AS issue EIDs to endhosts. Due to the local significance of ASIDs and EIDs, \((I, A, e)\) and \((J, A, e)\) are distinct addresses even though both have the same ASID and EID. This addressing scheme allows full address to be globally unique while giving ISDs and ASes the autonomy to manage addressing as well as names within their own realm of control.

The above addressing system also allows for interoperability with the current IP addressing and AS numbering schemes while simultaneously enabling local deployments of other proposed addressing schemes. For example, some ISDs may choose to retain the current AS numbering and IP addressing schemes, while others may opt to provide ASes with human-readable identifiers and endpoints with IPv6 addresses.

Similarly to ASIDs, endpoint addresses (since only used locally in intra-AS routing) do not need to be globally allocated like the current IP address space. Since the routing authentication infrastructure only handles inter-AS routes, SAINT does not bind the endhost address space to public keys as RPKI does. Instead, forwarding from an edge router to an endpoint address is resolved and handled entirely within an AS.

5.4 Trust Anchor ISDs

Trust anchors in the current Internet, such as IANA for RPKI and BGPSEC, ICANN for DNSSEC, and root CAs in TLS, represent starting points for authenticating information. Similarly, trust anchor ISDs are starting points for authenticating routes, names, and EE certification in SAINT. Due to the separation of authentication by type, Alice can anchor her trust for authenticating routing and service information in

![Figure 3: Namespace structure in SAINT. Solid lines indicate hierarchical relations, and dashed lines indicate redirections.](image-url)
As discussed in Section 4.4 for routing purposes the trust roots of the ISD’s in which Alice is currently located must certify all of her routes. However, Alice can select the trust roots of any ISD to authenticate service information (names and EE certificates). We call this ISD Alice’s trust anchor ISD. Alice choice of this ISD can be easily changed at any time (as described in Section 6.3). An example of such trust bootstrapping is provided in Section 9.

6. TRUST ROOTS

In this section, we cover what entities serve as trust roots and how trust roots are configured for an ISD. We also discuss how we update trust root information using network-level messages, and how this incorporation of trust management into the network allows for fast updates of trust root information. Finally, we describe our scheme of separating trust roots by ISD, and how separated categories of authentication enable trust agility.

6.1 Trusted Parties

Trust roots sign authentication information for routes, names, or EE certificates, and set policies governing the ISD. These policies may include information such as preferences for certain encryption or signature algorithms or constraints on certificate validity. A trust root is an authority for either routing or service authentication (see Figure 4).

Because a trust root is only an authority in its own ISD, a compromised trust root cannot enable the impersonation of servers in other ISDs. Scoping trust root authority to the ISD level protects Alice and Bob’s communication from many compromises in other ISDs and provides guarantees to Alice about authentication in her trust root ISD.

We classify trust roots into routing and service trust roots. The routing trust roots consist of the following parties:

- The core ISPs are responsible for sending out route announcements, which are propagated from providers to customers and establish cryptographically signed paths from the recipient to the core.
- The path server stores and provides a lookup service for mappings between an ASID and the AS’s downstream paths. These paths are registered by the ASes at the core. The path server is co-located with and operated by the core ISPs.
- The registry server issues and stores AS certificates binding an ASID to its public key (called its AS key), which are used to verify the signed paths provided by the path server. Like the path server, the registry server is co-located with and operated by the core ISPs.

The routing trust roots include the routing root CAs, which consist of the trust roots for naming and for EE certification. The DNS root is the starting point for verifying all names in the ISD’s namespace. The DNS root also sets ISD-wide naming policies such as reserved or forbidden domain names and allowed signature algorithms to sign records. Because the failure of the DNS root can block user connectivity in an ISD, the DNS root should be highly robust and available, using mechanisms such as distributed anycast schemes and placing servers in the ISD core where they can be reached through highly available top-tier ASes.

The root CAs are the starting points for verifying EE certification information in an ISD. Root CAs in SAINT serve the same purpose as they do in today’s PKIs by signing TLS public-key certificates. However, they are restricted to only signing EE certificates in ISDs in which they are root CAs. They can also sign intermediate CA certificates as in today’s TLS PKI. If the ISD uses other public-key infrastructures such as CT or AKI (see Section 12), then the trust roots for EE certification also include public logs and auditors/validators.

6.2 Trust Root Configuration (TRC) Files

As mentioned in Section 4.2 a TRC file specifies the trust roots for an ISD, the public keys of those trust roots, and the authentication policies of the ISD. It also specifies the locations of the DNS root and TRC servers (described in Section 6.3) to allow users to reach these servers without performing DNS lookups. TRCs are created and managed by an ISD’s trust roots and distributed through the routing mechanism. Specifically, a threshold of trust roots is required to sign a new or updated TRC file, and the core ISPs distribute the TRC file within the ISD through a broadcast mechanism that we describe below.

The quorum of trust roots required to update the TRC file is specified in the TRC file itself, providing the trust roots with the autonomy to set their own threshold for altering the TRC file. A higher threshold is more secure to a compromise of multiple trust roots, but also reduces the efficiency in updating TRC files. The TRC file also specifies a quorum of trust roots that must sign a cross-signing certificate to authenticate another ISD’s trust roots. Cross-signing certificates are described in more detail in Section 7.

TRC format. A TRC file is encoded as an XML file with the fields shown in Figure 5. The version number and timestamp ensure that users can verify information using recent policies and trust root information. The public keys of the ISD’s trust...

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**Figure 4:** Logical and physical placements of trust roots in an ISD.
we envision that Alice will also use group signatures [12] or threshold signatures [37] to provide a quorum of trust roots signs the TRC file. The trust roots can most commonly obtain an initial TRC file of her provider’s ISD when forming a service agreement. If Alice wants to obtain a different ISD’s TRC file, she can contact the TRC server of that ISD, a server that stores the TRC files and cross-signing certificates (see Section 7) of other ISDs. The TRC server’s address is in the TRC file of the ISD, allowing Alice to directly query the server for other TRC files. In an extreme case where Alice does not trust the provider or ISD, she may download a TRC file from a publicly-accessible mirror site or obtain one in person from a trusted colleague or organization. Alice can also obtain a TRC file a priori if she plans to join such an ISD with a new device.

### Obtaining updated TRC files.
ASes and users in an ISD are informed of the latest version of the TRC file with each routing announcement and DNS response. Thus, as long as Alice has an Internet connection and performs DNS lookups, she can quickly detect and obtain a new TRC. The version number is part of each routing announcement, and a timestamped message signed by the trust roots accompanies each DNS answer (to avoid re-signing every DNS record in the ISD upon updating the TRC file). When Alice detects a new TRC file, she can fetch the new file from the provider or DNS root (see Figure 6).

### Changing trust anchor ISDs.
Besides the ability to select trust roots as described in Section 5.4, trust agility also provides the ability to easily and quickly modify this selection. The above methods of obtaining TRC files provide this notion of trust agility, as Alice can change trust anchor ISDs by simply obtaining a new TRC file. Under normal circumstances Alice can simply download a new TRC file from her trust anchor ISD’s TRC server, but if for example she discovers that her trust anchor ISD has been conducting state-level surveillance, she can instead obtain the TRC file manually or from an external server as described above.

#### 7. CROSS-SIGNING
In this section, we provide a detailed discussion of cross-signing in SAINT. We begin by describing cross-signing certificates, and then detail how these are used to enable inter-ISD authentication and global verifiability. We then discuss the tradeoff between global verifiability and the trustworthiness of authenticated information, and how the authentication policies expressed in an ISD’s TRC file fits in this tradeoff.

##### 7.1 Cross-Signing Certificates
In order to enable global verifiability, we require ISDs to issue cross-signing certificates for its neighboring ISDs, that is, ISDs with which they share routing links. The resulting web of cross-signing between ISDs ensures that by following a route from Alice’s ISD to Bob’s ISD, a corresponding chain of signatures from Alice’s trust roots to Bob’s trust roots will exist, forming a chain of signatures from Alice’s trust roots to Bob’s trust roots without direct routing connections can also issue cross-signing certificates to one another, forming further chains of signatures to enable authentication be-

| Field   | Description                                                                 |
|---------|-----------------------------------------------------------------------------|
| isd     | ISD identifier                                                              |
| version | Version of TRC file                                                         |
| time    | Timestamp                                                                   |
| coreISPs| List of core ISPs and their public keys                                      |
| registryKey | Root registry server’s public key                                           |
| pathkey | Path server’s public key                                                    |
| rootCAs | List of root CAs and their public keys                                      |
| rootDNSkey | DNS root’s public key                                                      |
| rootDNSaddr | DNS root’s address                                                          |
| trcServer | TRC server’s address                                                      |
| quorum  | Number of trust roots that must sign new TRC                               |
| policies| Additional management policies for the ISD                                  |
| signatures | Signatures by a quorum of trust roots                                      |

**Figure 5:** Fields in a TRC file.

**Figure 6:** Distribution mechanism for updated TRCs. Arrows indicate sent network messages.
between different ISDs directly.

A cross-signing certificate issued by \( I \) for \( J \)'s trust roots contains (a) a timestamp, (b) \( I \), (c) the current version number of \( T_J \), (d) \( J \), (e) the current version number of \( T_J \), (f) a hash of \( T_J \), and (g) a signature by a quorum of \( I \)'s trust roots (see [Figure 7] for an explanation of notation). The version numbers of the TRC files ensure that the trust roots’ public keys can be checked against the appropriate versions of the TRC files.

The ISD stores these certificates in its TRC server for its users and also propagates the certificates along its inter-ISD routing links to provide each ISD with the necessary information to form a chain of signatures to a given destination ISD. Alice can then query her trust anchor ISD to obtain these chains of signatures and select one to authenticate information in Bob’s ISD.

### 7.2 Inter-ISD Authentication

When Alice, whose trust anchor ISD is \( K \), wants to authenticate Bob, who is in another ISD \( M \), she needs to obtain cross-signing certificates to form a chain of signatures from \( K \) to \( M \). While verifying Bob’s routes, name, and EE certificate, she obtains the appropriate cross-signing certificates from \( K \)'s TRC server. If Alice is in an ISD \( I \), then every route from her to Bob will have a chain of signatures starting at \( K \), proceeding to the trust roots of \( I \), then to the trust roots of \( M \), and finally to Bob’s AS.

If \( K \) and \( M \) do not share routing links but have issued cross-signing certificates to each other, Alice can verify Bob’s name and EE certificate using \( K \)’s cross-signing certificate for \( M \). These cross-signing “shortcuts” allow Alice to authenticate Bob’s information with fewer ISDs authenticating information “in transit,” providing fewer opportunities for a compromised trust root to disrupt authentication.

No matter where \( M \) is, Alice is guaranteed to find a chain of signatures to \( M \) and to Bob if she can find a route to Bob. Since she must be able to contact \( K \) from \( I \) to obtain the appropriate cross-signing certificates, she has a route between \( K \) and \( I \) and can thus obtain cross-signing certificates from \( K \) to \( I \), and similarly for \( I \) and \( M \). Though a chain of signatures may cross many ISDs, Alice is guaranteed to find at least one such chain.

Note that cross-signing certificates do not necessarily indicate a trust relationship between ISDs; a cross-signing certificate instead only states: “These are the public keys of the trust roots for the following ISD.” It is therefore up to Alice to determine the trustworthiness of a chain of signatures before accepting the information it certifies as authentic.

### 7.3 Authentication Policies

The above cross-signing requirement ensures that Alice can authenticate Bob’s information regardless of which ISD he is in. While a compromised trust root on a chain of signatures from Alice to Bob can adversely affect authentication by certifying false information, Alice’s trust anchor ISD \( K \) can mitigate this risk through the use of ISD-wide policies in the TRC file. These policies can also blacklist public keys, such as those contained in known unauthorized certificates or those of compromised trusted authorities. Using such policies, \( K \) can protect Alice from compromises in other ISDs. If others with \( K \) as their trust anchor ISD frequently contact Bob or other destinations in \( M \), then \( K \) may form a cross-signing relationship with \( M \) to minimize the risk of compromised trust roots in other ISDs.

ISDs face a tradeoff between enabling global verifiability and protecting their users from compromises in other domains. The default behavior in SAINT is to provide global verifiability. As illustrated above, an ISD must explicitly state any exceptions to this behavior in the policy field of its TRC file. The ability to restrict the authentication of known false information through policies provides a mechanism by which an ISD can protect not only its own users, but also users for whom a chain of signatures passes through the ISD.

## 8. SEPARATED AUTHENTICATION

In this section, we describe how SAINT separates routing and service authentication. We first describe our motivation for separating these two types of authentication, and then discuss how this separation provides Alice with trust mobility.

### 8.1 Routing and Service Authentication

Authentication in SAINT is classified and separated into routing and service authentication (see [Figure 1]). We make this separation in part because we observe that the authentication of route information fundamentally differs from the authentication of service information. In particular, routing authentication cannot assume the existence of secure routes to obtain any external information, and therefore an entity must rely on pre-verified paths or be able to verify paths without fetching external information. By contrast, service authentication assumes the existence of authentic routes and thus allows contacting external entities to obtain authentication information.

Routing messages in SAINT propagate beginning from the ISD core and follow provider-customer AS links. Unlike in RPKI and BGPSEC, all necessary information (e.g. AS certificates) are sent with the routing message, allowing an AS to verify routing messages upon arrival. Moreover, information such as AS certificates are short-lived, eliminating the need to propagate revocation information for AS keys.

By contrast, a DNS lookup, which falls under service authentication, must use a route to reach one or more name-servers and fetch the appropriate information for verifying a name-to-address mapping. TLS features such as OCSP also require contacting an external entity to determine the validity of an EE certificate. Due to this dependence, Alice must verify routes to the ISD core of her current ISD \( I \), and form and verify routing paths from \( I \) to Bob’s ISD \( M \) before she can authenticate Bob’s service information.
### 8.2 Trust Mobility

Separating routing and service authentication also enables trust mobility. Suppose that Alice checks into a hotel in Oceania, a known surveillance state, and attempts to connect to her hotel’s wireless Internet. If the Oceanian trust roots are compromised by the government, then it is inevitable that the government can see her packets themselves, as her physical location in Oceania enables the government to examine her packets. In other words, Oceanian trust roots must certify her routes out of the Oceanian ISD and thus these trust roots must be on the chain of signatures for routes from Alice to any destination in the Internet.

With SAINT, however, Alice can choose $K$ as her trust anchor ISD for service authentication, since SAINT separates routing and service authentication. Moreover, this choice does not depend on Alice’s current location and thus applies wherever Alice is in the Internet. In our example, this means that Alice does not have to rely on signatures from the Oceanian trust roots to verify Bob’s name or EE certificate, even if she is connecting to the Internet from an Oceanian hotel.

### 9. AUTHENTICATION EXAMPLE

We now discuss the complete authentication process in SAINT. We first describe setup steps for a server, such as joining an ISD and registering domain names, routing paths, and EE certificates. We then describe how Alice (the client) checks the information that she receives about Bob (the server). We use $a$ to denote Alice and $b$ to denote Bob. As previously mentioned, Alice’s trust anchor ISD is $K$. Bob is part of the AS $B$ in Mythuania $M$, whose ccTLD is .my.

#### 9.1 AS Setup

Figure 8 depicts the steps of the AS setup process for AS $B$ in the Mythuvian ISD $M$:

1. $RS_M$ assigns the ASID $B$ to Bob’s AS.

#### 9.2 Server Setup

Figure 9 shows the steps of the server setup process for Bob:

1. $AS$ assigns Bob the EID $e_b$, making his address $(M, B, e_b)$.
2. Bob chooses the name $b.my$ and creates a domain-name key pair $(DK_b, DK_b^{-1})$.
3. Bob sends $b.my$ and $DK_b$ to the .my operator to register his name and key.3
4. The .my operator creates a delegation signer (DS) record to point to $DK_b$ from the .my zone, as well as a record mapping $b.my$ to Bob’s nameserver.
5. Bob creates a mapping of $www.b.my$ to $(M, B, e_b)$, $DK_b$, and resource record signature (RRSIG) record of the mapping signed with $DK_b^{-1}$.
6. Bob creates an end-entity key pair $(EK_b, EK_b^{-1})$.
7. Bob sends $\{b, EK_b\}$ to a CA in $M$.
8. The CA issues Bob an EE certificate $EC_b = \{b, EK_b\}^{K_{CA}}$.
9. Bob creates a certificate $DC_b = \{b.my, DK_b\}^{EK_b^{-1}}$ and stores $DC_b$ along with $EC_b$ as a CERT record in his nameserver.

#### 9.3 Client Setup

In practice, Bob will create multiple key pairs and use one of the private keys to sign the others, but for simplicity we assume here that Bob uses $DK_b$ both to sign his DNS zone information and to self-sign $DK_b$. 

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1. Figure 7: Notation.
2. Figure 8: Diagram for AS setup steps (Section 9.1).
3. Figure 9: Diagram for server setup steps (Section 9.2).
In order for Alice to verify information, she must first possess a TRC file to configure her set of trust roots. Even if she does not have a TRC file, we assume that she can verify a TRC file from her trust anchor ISD $K$. In fact, she can verify this TRC file in any ISD $I$—even if she does not trust $I$. As illustrated in Figure 10 after connecting to the Internet in $I$, Alice does the following to obtain and verify a TRC file:

1. Alice’s ISP (AS C) assigns her the EID $e_a$, making her address $(I, C, e_a)$. C also sends her the latest TRC file $T_I$ for the ISD $I$.

2. Alice requests from $PS_C$ a path to the TRC server $TS_I$ of $I$ or $TS_K$ of $K$ (if she knows the address).

3. $PS_C$ returns to Alice the path she requested.

4. Alice now contacts either $TS_I$ (4a in Figure 10) or $TS_K$ (4b) and requests $T_K$. In the case of 4b, Alice also requests a cross-signing certificate for $I$ from $TS_K$ to ensure that all authentication (even for routes) begins from $T_K$.

5. If Alice contacted $TS_I$, she receives $T_K$ (5a). Otherwise, she receives $T_K$ and the cross-signing certificate for $I$ from $TS_K$ (5b).

We assume that Alice verifies the authenticity of $T_K$ through an out-of-band mechanism, e.g., if she makes plans to travel to $I$ and considers it a “hostile” ISD, then Alice can obtain a hash of the public keys of $K$’s trust roots a priori, or she can obtain this information in an embassy of $K$ within $I$.

### 9.4 Client Verification

Figure 11 illustrates the complete process that Alice executes to authenticate Bob. We assume that Alice has completed the client setup process and thus has $T_K$ to use as the starting point for authenticating Bob. The authentication process is as follows:

1. Alice begins by looking up www.b.my, and thus first obtains $T_M$. She contacts $PS_C$ to obtain a path to $TS_K$.
2. $PS_C$ returns to Alice a set of paths that she can use to reach $TS_K$.
3. Alice contacts $TS_K$ to request $T_M$.
4. $TS_K$ returns $T_M$ and a cross-signing certificate for $M$.
5. Alice contacts $PS_C$ to request a path to the DNS root of $M$, whose address she has from $T_M$.
6. $PS_C$ returns to Alice a set of paths to $M$’s DNS root.
7. Alice contacts $M$’s DNS root to query www.b.my.
8. Alice performs DNSSEC resolution to obtain $(M, B, e_B)$ as well as Bob’s domain and EE certs $DC_b$ and $EC_b$.
9. Alice requests a path to Bob’s address from $PS_C$.
10. $PS_C$ returns to Alice $B$’s AS certificate $AC_B$ and a set of paths $P_B$ to reach $B$.
11. Alice contacts Bob to initiate the TLS handshake.
12. Bob sends Alice his EE certificate $EC_B$.

Alice verifies that Bob’s EE public key $EK_B$ contained in the EE certificate she obtained from $M$’s DNS root matches the EE public key she receives during the TLS handshake. If the keys match, she proceeds with the TLS handshake to establish a secure end-to-end connection with Bob.

Throughout this process, Alice verifies that valid authentication paths exist for each entity she contacts: $PS_C$, $TS_K$, $M$’s DNS root, $B$, and Bob. When she receives information signed by the trust roots of an ISD other than $K$, Alice uses the appropriate cross-signing certificate to verify the public keys of the ISD’s trust roots, thus ensuring that all authentication ultimately begins with trust roots listed in the TRC of her trust anchor ISD $K$.

**Error handling.** A verification failure at any stage in the authentication process will prevent Alice from authenticating and establishing a connection to Bob. In the event that the verification of a routing path fails, Alice will not be able to reach Bob or entities such as DNS roots and TRC servers. However, Alice likely cannot detect this failure from her browser. In the event that the verification of Bob’s name-to-address mapping fails, Alice will not know the address at which she can reach Bob. While most modern browsers indicate such a failure, Alice cannot proceed with verification after such a failure. From the perspective of Alice’s browser, a failure to verify Bob’s EE certificate is the most informative, as most modern browsers display the type of error that occurred and in some cases provide the option to continue with the connection anyway.

### 10. IMPLEMENTATION AND EVALUATION

In this section, we describe our prototype implementation of SAINT. We used this implementation to evaluate the performance of authentication and trust root management functions; we also discuss our evaluation results here.
We implemented the endhost side of SAINT (see Figure 12). The main component of our implementation is the SAINT daemon, which acts as a gateway between applications and the network. The SAINT daemon includes SCION layer support for packet encapsulation and decapsulation, a path engine for route management and verification, a name lookup engine for SAINT name queries, and a TRC engine, which allows users to obtain and verify TRC files.

Traffic generated by the applications is delivered to the SAINT daemon by the NetFilter queue, allowing legacy applications to deploy SAINT without requiring any changes. We ran our simulation on an Intel Core i5-3380M CPU at 2.90 GHz, 16 GB of RAM, Python 3.4, and gcc 4.8.2. We used ed25519 [8] as our signature scheme for name and path verification, and RSA-2048 for TLS certificates.

We measured the efficiency of TRC distribution and updates by simulating the propagation through the current AS topology. We used the CAIDA inferred AS relationships dataset from October 2014 [2] as our model of the current topology, and used traceroutes from iPlane datasets to estimate inter-AS latency. From each of iPlane’s vantage point ASes (distributed throughout the world), we identified the latency (half of the RTT) to each of the top-tier ASes identified using the CAIDA-based topology.

Our evaluation demonstrates that more than half of our vantage point ASes receive a new TRC file within 100 ms of the file being sent from the core ISPs (see Figure 13). Moreover, all vantage point ASes receive the new TRC file within 600 ms. Our vantage point ASes included stub ASes (that is, ASes with no customer ASes), demonstrating that end users around the world can quickly receive updated TRC files. These results show that our TRC propagation mechanism is significantly more efficient than the current trust root update mechanisms in browsers (which typically occur on the order of days).

### 10.3 Authentication Overhead and Performance

To test the actual latency of authentication in SAINT, we measured 300 end-to-end secure connection establishments on a sample SCION topology of virtual machines. Figure 14 shows the timing results, which only reflect the cryptographic verifications and do not take into account network delay, since a full network deployment of SCION is not available at this time. However, our results give us an insight into the overhead of SAINT. In particular, all functions take less than 1 ms on average, which is significantly less than the end-to-end round trip time in an actual connection establishment.

As a baseline, we measured end-to-end connection establishments to 100 HTTPS sites on the current Internet randomly selected from httpsnow.org. We observed 418 separate TLS connection establishments. Using DNSSEC, BG-PSEC, and TLS, we measured the latency of the total page loading time, which included blocking of the connection request, the DNS lookup, the connect, send, and wait, and receive times, and the TLS handshake. The observed latencies ranged from 15 ms to 7969 ms, with an average of 534 ms and a median of 1811 ms. For SAINT, we assumed that a path lookup has an equivalent latency to a DNS query (one round trip), fast cryptography is used in verification (ed25519), and an average of 8 keys are authenticated during the DNS and routing lookups. In this setting, we observed latencies ranging from 19 ms to 7974 ms, with an average of 586 ms and a median of 1863 ms. These latencies are not based on a full deployment of SAINT, but indicate a reasonable 10% increase in connection latency on average as compared to the current Internet.
yet joined a SAINT ISD. For example, suppose that a.com maps to the IP address 1.2.3.4 in the current Internet, which is located in AS 567, which has not yet deployed SAINT. The domain a.com would then correspond to the address \((L, 567, 1.2.3.4)\). The security guarantees for names, routes, and EE certificates in the legacy ISD are only as strong as they are in today’s Internet.

One challenge we face in practice is that names in SAINT’s generic TLDs may already exist in the legacy ISD. Not only do such collisions cause a problem for name resolution, but they also create vulnerabilities to downgrade attacks in SAINT’s name lookup mechanism, since an adversary could simply return an unsecured DNS response in the legacy ISD for a query with a name collision. We therefore require SAINT name resolvers to query the legacy ISD as a last resort, and only with a proof of the name’s absence in the SAINT namespace (such as an NSEC3 record).

Interoperability. SAINT is designed with a focus on incremental deployability. ISDs can be deployed among individual networks, since the remainder of the Internet that has not yet deployed SAINT joins the legacy ISD. The naming infrastructure is interoperable with that of the current Internet in that it can query the legacy DNS nameservers as is done today. Routing between two physically separated domains in SCION can utilize IP tunneling to communicate over the legacy ISD.

In order to maintain connectivity to the current Internet, servers and clients must support legacy authentication. In particular, clients and servers must continue to support DNSSEC, BGPSEC, and TLS. Additionally, when servers receive incoming connections from the legacy ISD, they should not respond with SAINT-specific messages such as signed path sets or cross-signing certificates. However, TRC files will be made available through the legacy ISD in order to support the initial bootstrapping of trust roots.

ISD Deployment. SAINT offers benefits even for early deployers of ISDs. A single-ISD deployment of SAINT provides isolation of compromises within that ISD. Additionally, the legacy ISD will be protected from compromised trust roots in every ISD deploying SAINT. Moreover, ISDs deploying SAINT enjoy greater flexibility in their choice of alternative PKIs by enabling the benefits of the PKIs without requiring their global deployment. In the policy field of the TRC file, an ISD would specify its choice of the underlying PKI, which would prevent protocol downgrade attacks.

If using countries as ISDs, then a newly-deploying ISD can simply attach to the existing namespace at its corresponding ccTLD. This construction allows the DNS to provide a scaffolding during the deployment of SAINT and also allows the DNS in SAINT to distribute TRC files.

However, we recognize the challenges that come with using countries as ISDs. In particular, the deployment of such a scheme would require the core ISPs, root CAs, and Internet registries in each country to create a federation of trust roots. In practice, we may see corporations rather than countries form ISDs. In this case, ISDs would have to form IP tunnels in order to form inter-ISD routing relationships. Additionally, since there are far more corporations than countries, cross-signing relationships may not scale to this number of ISDs. However, because most corporations do not form many business relationships relative to the number of corporations that exist, we do not expect that the number of cross-signing relationships will grow to an unsustainable scale.

TRC Distribution. The initial distribution of TRCs must occur securely since TRCs are the starting point for all authentication in SAINT. Many trust roots in the current Internet may continue to serve as trust roots in SAINT, and thus may be able to “inherit” user trust in SAINT that they already have in the current Internet. However, SAINT will likely result in the creation of new trust roots, and thus must have a mechanism for bootstrapping trust in the initial public keys of these roots.

To address this challenge, we suggest to perform the initial distribution of SAINT TRC files through DNSSEC. Since ISDs can deploy by attaching to specific ccTLDs in the current DNS namespace, an ISD can create a reserved domain name such as trc.us, whose DNS record contains the TRC (e.g., in a TXT record). Clients can then fetch the TRC by looking up the appropriate domain name. Additional work has been done in distributing authentication information through out-of-band means such as over public radio \[36\], but these strategies are beyond the scope of this paper.

12. DISCUSSION

Feasibility of country-based ISDs. In order to determine the feasibility of having countries as ISDs in SAINT as described in Section 4.1, we mapped AS numbers to countries and examined the resulting inter-ISD relationships. We used the AS relationships database from CAIDA \[2\] and Team Cymru’s IP to AS number mapping tool \[3\] to map AS numbers to countries. We identified 188 “countries” in total, including the EU and ZZ (indicating that the AS’s country was unknown). We identified 2 636 unique country pairs between which an inter-AS link existed. These links signify direct routing connections, and thus we expect cross-signing for each ISD pair. The most prolific cross-signing ISDs were the US (196), the EU (135), and the UK (124), but half of the ISDs cross-sign on the order of tens of other ISDs.

Political Concerns. Given concerns over governmental nationwide surveillance, readers may worry about centralizing trust roots in a large ISD. While we acknowledge that states may compromise these entities on a large scale, SAINT’s trust agility allows users to protect themselves from the interception of sensitive connections. Additionally, our efficient method of updating trust root information allows ISDs to quickly recover from a compromised CA.

\[\text{http://www.team-cymru.org/Services/ip-to-asn.html}\]
Another concern we anticipate is that SAINT encourages fragmentation in the Internet. While this is true, SAINT is designed to preserve global reachability while simultaneously protecting users through the use of ISDs and trust agility. We thus structure inter-ISD authentication to provide users with the best of both worlds.

Sub-ISDs. To add further scalability to SAINT, we propose the use of sub-ISDs, i.e., ISDs being completely contained in other ISDs. A sub-ISD can be used to provide additional policies and finer-grained control of trust roots in an ISD, and can additionally enable isolated authentication within an ISD. For example, governments or medical organizations may use their own network within a country ISD to ensure data privacy and further scope the authority of their trust roots.

A sub-ISD structurally resembles a top-level ISD, but authenticates to other sub-ISDs in the same parent ISD using the core of the parent ISD, and has its trust roots of a certified by its parent ISD via a cross-signing certificate. Connections within an ISD could then be negotiated using the lowest-level common ISD. For example, two hospitals in an ISD would share data about a patient using the medical sub-ISD rather than the general ISD.

Some details regarding authentication for sub-ISDs still remain, however. For example, compromised trust roots could also affect authentication entirely within a sub-ISD due to the requirement that parent ISDs certify the trust roots of their sub-ISDs. Furthermore, users cannot select sub-ISDs as their trust anchor ISDs without also trusting the corresponding parent ISDs. We hope to investigate these challenges in future work.

Optimizations. As described in Section 9, the authentication process involves six round-trip connections from Alice. Each communication with the path server requires verification of the path server’s signature, the signed set of routing paths returned by the path server, the destination AS certificate, and possibly cross-signing certificates for the path server and destination AS’s ISDs. To contact a destination outside her trust anchor ISD, Alice must also obtain and verify a cross-signing certificate. Contacting the DNS server requires verification of the at least the DNS root key, server DNS key, and signed DNS record, and contacting the server (Bob) requires verification of at least the server certificate.

However, in practice many of these verifications may not be necessary. Caching cross-signing certificates, for example, eliminates the need to reach a TRC server and to verify a cross-signing certificate with each end-to-end connection establishment. Additionally, some of these verifications can be handled by entities other than the client; for example, paths can be verified by the client’s AS, and DNS records by a trusted DNS stub resolver. Since ASes and stub resolvers serve multiple clients, caching verification results can further reduce the connection latency, especially for popular names, routes, and EE certificates.

In order to further decrease the size of messages sent in the network, we can also split the TRC file into routing and a service TRC files. The routing TRC can then be propagated along AS links, and the service TRC can be obtained from the TRC server. This scheme ensures that users only receive the portion of the TRC that they need for a particular type of authentication, thus reducing the size of TRC files sent in the network.

13. RELATED WORK

This section provides related work supplemental to the work mentioned in Section 2. Many such works propose mechanisms to authenticate network entities. We review these works with regards to domain-centric proposals as well as authentication for naming, routing, and EE certification.

Domain-centric proposals. The idea of aggregating hosts and routers into an abstracted routing entity has been previously proposed. The Nimrod routing architecture [11] describes a hierarchy of “clusters” of hosts, routers, or networks that can reach each other via a path contained within the cluster. FARA [13] generalizes the notion of an “entity” to also include clusters of computers that can be reached as a network communication endpoint. ISDs in SAINT fit the criteria for clusters in Nimrod, but add a set of common trust roots as well as the constraint that all intra-domain paths must be contained within the ISD.

Name authentication. Previous work has addressed authentication in a distributed, large scale network without any global trust infrastructure. Birrell et al. [9] propose to use an authenticated path through the name space to make explicit trust relationships among entities, and Lampson et al. [25] describe an authentication theory based on the name space or the communication channel from which the other entity’s authority can be deduced. Gligor et al. [19] define a policy for inter-realm authentication trust based on trust hierarchies that can support transparent name authentication.

Routing authentication. AIP [7] provides accountability for network entities based on self-certifying names, where the name of an entity is its public key [33,35,39]. AIP groups an independent administrative network into an accountability domain (AD) and assigned globally unique self-certifying names to ADs and hosts. Consequently, at the AD granularity, AIP not only supports routing and forwarding authentication, but also domain authentication without relying on an external PKI. However, key discovery in AIP relies on DNSSEC, and key revocations always force entities to change their names.

IPA [50] focuses on incremental deployment in the current Internet and leverages DNSSEC as a lightweight PKI to enable host authentication. IPA distributes AS certificates via S-BGP routing update messages, avoiding circular dependencies. However, it relies in a single global root of trust.

End-entity authentication. Several proposals raise issues with the current domain authentication schemes based on
X.509 and propose enhancements. For example, CAge [22] proposes to restrict CAs to signing domains in a small number of TLDs and treat other certificates as suspicious, and the US government has also recently considered this proposal [1]. Abadi et al. suggest a policy engine to empower clients or ISPs to specify acceptance criteria for certificates [6]. Although the authors outline a promising user-oriented entity authentication policy, its integration in the end-user system is still in question.

DANE [21] leverages the DNSSEC infrastructure to authenticate TLS public keys. Its goals are to tie TLS public keys to DNS names, use DNS to distribute these public keys, and to leverage the hierarchical authentication structure of DNSSEC to restrict the scope of CAs’ authority. However, the security of DANE relies on the security of DNSSEC. A compromised DNSSEC key can be used to specify arbitrary trust anchors and bypass X.509 certificate validation.

Certificate Transparency (CT) [26] and the Accountable Key Infrastructure (AKI) [24] expose all CA operations to the public to improve the security of SSL/TLS PKIs. Neither CT nor AKI define how misbehavior should be disseminated to users and other parties, but both can be deployed in ISDs, which leverage TRC files to quickly remove a compromised trust root and update users’ trust root information.

14. CONCLUSIONS

By explicitly separating and scoping trusted authorities in the Internet, we allow users to choose their trust roots and protect users from compromises throughout the Internet. By distributing trust root information as network messages, we allow users to quickly obtain up-to-date information about compromised or updated trust roots. By mandating cross-signing relationships based on routing connections, we ensure that users can authenticate information throughout the Internet. By separating routing and service authentication, we allow users’ trust root decisions to apply anywhere in the world. These ideas address fundamental shortcomings of current authentication and secure Alice’s communications throughout the world regardless of her choice of trust roots.

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As stated in Section 5.2, for reasons of transparency and security, each domain name with a generic TLD is resolved to a regional domain name (rather than to an address). Assume, for example, a company \( r \) wants to register the domain \( r.com \). Instead of registering a DNS tuple \( (r.com, IP) \), the company registers one or more CNAME-like records \( \{r.com\} \rightarrow \{r.us, r.de, r-swiss.ch, r-italia.it\} \) (1)

Upon a DNS resolution request for a generic domain \( D \) from a client, the DNS server for \( .com \) returns all regional names for \( D \) in the order specified by the registrant \( r \). The client then either chooses a domain name that is within its own ISD, or it chooses any other domain name in the provided list.

In order to ensure the authenticity of generic DNS records, SAINT requires a minimal setup as follows: any registrant \( r \) must first register its DNS public key \( DK_r \) with the generic DNS server \( S \).

\[
\begin{align*}
S & \xrightarrow{DK_r} r \\
S & \xrightarrow{\{r.DK_r\}_{K_s^{-1}}} \{D, \ldots\} \\
\end{align*}
\]

After this initial step, registrant \( r \) registers its domain name \( D \) by providing the list of regional domain names \( \{D, \ldots\} \) together with a signature \( \{D, \ldots\}_{DK_r^{-1}} \).

\[
\begin{align*}
D & \xleftarrow{DK_r} S \\
D & \xleftarrow{\{r.DK_r\}_{K_s^{-1}}} \{D, \ldots\} \\
\end{align*}
\]

The client verifies the signature \( \{r.DK_r\}_{K_s^{-1}} \) and caches the public verification key \( DK_r \) of the registrant \( r \) of domain \( D \). The client then verifies the authenticity of the record \( \{D, \ldots\} \) using the registrant’s public key \( DK_r \).

If the verification was successful, the client choses one of the specified regional domain names and resolves its actual address \( T.A.E \).

**Performance.** As in the current DNSSEC, the DNS server \( S \) for generic TLDs does not sign the stored CNAME-like records itself; rather, it signs the public keys of the registrants. The reasons include performance considerations: whenever a registrant \( r \) wants to register a new generic domain or whenever \( r \) wants to extend an existing record, the DNS server has minimal effort in that it does not need to validate or sign the new records. Using CNAME-like records also keeps the performance close to existing lookups: CNAME records add only 13% latency to a DNS name resolution on average.\[^6\]

**Availability.** Whenever a client needs to resolve a generic domain name, the client first contacts its local DNS server. If the local DNS server has no cached entry for the generic domain, the request is redirected to the DNS server of the generic TLD. This one step of indirection is at least as robust as today’s DNS system: in case the DNS server for a generic domain is unavailable, then only the availability of that single TLD is constricted. There is hence no single point of failure for the entire DNS system. As today, caching of generic domain name records by local DNS servers further increases the robustness and performance for generic DNS lookups.

**Security.** The record for a generic domain \( D \) is signed by the owner of \( D \) (i.e., the registrant \( r \)) using an asymmetric signature scheme and the private signing key of \( r \). The public verification key of \( r \) is signed by \( r \)’s ISD and by the DNS server for \( .com \). Client \( C \) can hence base its trust on the ISD of \( r \) or (in case \( C \) does not trust this ISD) on the DNS server for \( .com \).

Another positive aspect of this design is the fact that a key compromise of \( .com \)’s DNS server does not directly affect the security of an end-to-end connection: an attacker would additionally need to

\[^3\] CNAME records cannot point to multiple names, but the general idea of our records is the same.

\[^6\] This result is based on our private discussions with Verisign Labs.
compromise the DNS server of a regional ISD, which is used for the second lookup, the regional lookup for the actual address \((I,A,E)\). Despite being unlikely, this attack only works under the assumption that a client uses the verification key of \(.com\) (rather than the verification key of the resolved regional CNAME domain).