Who ya gonna call? (Alerting Authorities): Measuring Namespaces, Web Certificates, and DNSSEC

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ABSTRACT
During disasters, crisis, and emergencies the public relies on online services provided by authorities to receive timely alerts, trustworthy information, and access to relief programs. It is therefore crucial for the authorities to reduce risks when accessing their Web services. This includes proper naming (e.g., against phishing attacks), name protection (e.g., against forged DNS data), adequate identification (e.g., against spoofing and impersonation), and transport security (e.g., against traffic manipulation).

In this paper, we take a first look on Alerting Authorities in the U.S. and measure the deployment of domain names, DNSSEC, and Web certificates related to their websites. Surprisingly, many do not take advantage of existing methods to increase security and reliability. Analyzing 1,388 Alerting Authorities, backed by the Federal Emergency Management Agency (FEMA), we are alarmed by three major findings. First, 50% of the domain names are registered under generic top-level domains, which simplifies phishing. Second, only 8% of the domain names are secured by DNSSEC and about 15% of all hosts fail to provide valid certificates. Third, there is a worrying trend of using shared certificates, which increases dependencies leading to instability in the future.

1 INTRODUCTION
Online media have been proven to be an effective channel to communicate with the public. An ever growing number of Americans prefer to get their news online [48], social media is being used for public health announcements [105], and authorities provide public disaster education and services via web portals [39]—to mention a few examples. Communication of critical information such as emergency response [10, Chapter 3] and provision of critical services are no exception to this trend. Research shows that in emergencies the public turns to official and authoritative sources especially when specific, precise, and trustworthy information is requested [21, 25, 35]. During the coronavirus pandemic outbreak in the U.S., for example, government institutions and health authorities were perceived as the most (social media being the least) trustworthy sources of information by the public [42, 91]: alone in the first month of the outbreak, nearly half a billion visits were registered on websites of Centers for Diseases Control and Prevention (CDC) and the National Institutes of Health (NIH) [5], while the high amount of visits on state unemployment websites brought many to a crash [17].

The ever-evolving landscape of web technologies, however, poses real operational challenges for organizations trying to maintain an up-to-date and secure online infrastructure. More than a decade after the introduction of the E-Government Act of 2002 [1] that lead to flourishing of government web portals [90], the federal government is investing two-thirds of its IT budget on maintaining legacy systems to mitigate existing operational and security risks [2]. To encounter spoofing attempts, data tampering, or disinformation
attacks, which are no exception to digital emergency communication (even during the coronavirus pandemic [109]), adequate security measures have to be taken. As minimal base, web-based emergency information and service provision should meet (i) data source identification, and (ii) data integrity and confidentiality. To this purpose, a domain name and its structural position within the domain namespace coupled with a digital certificate cater for data source identification (as an extension of authentication) given that the domain name itself is authenticated (DNSSEC). And transport layer security protocols (SSL/TLS) can be used for data integrity and confidentiality (see Figure 1).

In this paper, we aim to address the research blind spot of trustworthy and secure web-based emergency services. We systematically investigate the digital representation of emergency and disaster management organizations in the U.S. through the lens of DNS(SEC) and Web PKI. Our goal is to understand whether and how specific integration of these organizations in the domain namespace and their use of DNSSEC and X.509 certificates can mitigate threats against trustworthy communication.

Our key findings are: (i) only half of 1388 investigated organizations have their own dedicated domain names but depend on other entities for their online presence, (ii) about 80%, i.e., 1047 out of a total 1327 unique hosts, lack sufficient measures for unique identification (a requirement of trustworthiness), and (iii) throughout the past decade a rise of multitenancy structures and shared certificates has expanded the attack surfaces.

The point of departure for our study is the list of alerting authorities (AA) provided by the US Federal Emergency Management Angency (FEMA) [41], which comprises all entities (governmental and NGOs) on federal, state, territorial, tribal, and local levels authorized to dispatch alerts. In detail, in this paper we contribute:

1. **Method (Section 4).** Our method identifies common public alerting authorities in the U.S. and corresponding websites. The modular and configurable pipeline introduced here for data collection and analysis maintains a certain level of generality which makes it suitable to be extended to non-U.S. regions in future work.

2. **Analysis of namespace structure and protection (Section 5).** We map names of alerting authorities to fully qualified domain names (FQDN) and identify operational dependencies. We reveal that only 50% of unique domains names make use of designated namespaces (e.g., .gov, .ngo) and that only 8% use DNSSEC. Finally, respective implications of domain namespace and DNSSEC for trustworthy communication are discussed. We investigated whether there are discrepancies between organizations from various fields of operation (e.g., governmental, military, ...).

3. **Analysis of website protection (Section 6)** We analyze transport layer security protocols and certificates dedicated to protect websites of alerting authorities. On the one hand the historical and actual usage of X.509 is studied, and on the other hand it is investigated how widespread these technologies are, which certificate authorities are leading the market among AAs, and how (automated) domain-validation certificates affect source identification.

To the best of our knowledge, this is the first paper that investigates the security profile of official Alerting Authorities. After presenting background and our results, we discuss improving measures and conclude with an outlook.

## 2 Background

Emergency management (EM) can be understood as an ongoing cycle of mitigating, preparing for, responding to, and recovering from incidents that threaten life, property, operations, or the environment [11, 15]. The core objectives of emergency management, ranging from coordination efforts to raising awareness and critical service provision, are carried out by governmental agencies, NGOs, volunteer groups, and international organizations. The structure and organization of these entities differ in each country and even on local and regional levels. In the U.S., the list of Alerting Authorities regularly published by FEMA [41] provides a non-exhaustive overview of organizations which are (directly or indirectly) involved in the process of emergency management.

In each phase of EM cycle, communication (between and among authorities and the public) plays an integral role not just as a mere necessity but also in amounting to social resilience [70]. Beside using dedicated alerting systems, e.g., FEMA’s Integrated Public Alert & Warning System [40], social media, or similar channels for information dissemination, many of involved organizations have their own dedicated websites not only for informational purposes but also for services such as volunteer registry or disaster aid application (e.g., Homeland Security’s disasterassistance.gov).

The main challenge for the public during emergency and crisis is navigating through online service providers and evaluating their credibility and trustworthiness [71]. Specifically as people are most vulnerable and reliant on external aid, access to trustworthy infrastructure is necessary to refrain malicious actors from causing financial, political, or other societal harm. The global outbreak of the novel coronavirus (SARS-CoV-2) is an example of how desperate times pave the way for online disinformation, scam, and
measure names, web certificates, and DNSSEC of AA

fraud: the parallel infodemic [109], i.e., the over-abundance of information, which despite efforts from top tech companies [101] continued to grow and prevail [16], posed serious challenges both to politics and public health; and the growing number of individuals and business relying on unemployment insurance and governmental relief programs led to a boom in online fraud and scam. For example, a spoofing campaign in Germany managed to successfully impersonate the state government of North Rhine-Westphalia and redirect financial aid for businesses (comparable to U.S. PPP [82]) to illegitimate bank accounts. Instead of the original domain name soforthilfe-corona.nrw.de, scammers used two closely related names soforthilfe-corona-nrw.de and nrw-corona-soforthilfe.de and managed to register up to 4000 applications for relief funds before the State Criminal Police Office confiscated the domain names. It is noteworthy that these domains had DNSSEC enabled and were issued valid certificates from Let’s Encrypt. This and similar incidents are avoidable by having trustworthy TLDs that carefully verify delegation of their second-level domain names and certificates authorities that enforce rigorous authentication before certification. In the following a brief overview is given on how DNS namespace, DNSSEC, Web PKI, and SSL/TLS amount to trustworthy communication, specifically in case of emergency services with heightened security requirements.

DNSSEC. The global domain name system (DNS), a distributed key-value database with a hierarchical namespace and management scheme, is de facto the entry point to many (if not all) of Internet services. Respectively, for critical service providers, e.g., Alerting Authorities, it is indispensable to be represented within namespaces protected both in organizational and technical terms: TLDs with restricted naming and delegation policies protect domain name owners against name and trademark violations while assuring end users that the domain name owner has undergone some form of vetting; at the same time, DNSSEC [9] compensates the vulnerable client/server paradigm of DNS [12] and caters for authenticated delegation and protect DNS data against tampering.

Web PKI. To authenticate the content provider behind a domain name X.509 certificates [27] are used. The semantics of a certificate depends on its certification process: if the real-world entity behind a certificate is vetted by a certification authority (CA) and is respectively awarded with an organization or extended validation certificate (OV/EV), the certificate can used for identification. Otherwise, if the validation is limited to the ownership of a domain name, i.e., domain validation (DV), the certificate is only good for authenticated confidentiality and integrity. By presenting an OV or EV certificate bound to a real-world entity, an online service provider gives its clients the chance to verify with whom they are communicating, an issue which is at the heart of emergency communication as discussed above.

The certification ecosystem has been subject to criticism as the encompassing authority of each CA (due to lack of subordination rule [61]) poses a major threat to the global namespace if any of root CAs is compromised. Two noteworthy complementary technologies that can help against this threat are Certificate Transparency (CT) [67, 97], which allows monitoring certification to detect any misissuance, and DANE [52] which enables domain owners to put constraints on authorized certificates or CAs.

Transport Layer Security. The final step in trustworthy communication is securing data. SSL/TLS protocols enable two parties to negotiate communication parameters in terms of authentication (based on X.509 certificates), confidentiality through encryption, and integrity using message authentication codes (MAC). Specially critical data which is transmitted as part of emergency service provision, e.g., medical records or bank codes, pose a high risk to theft and needs to be protected with extra care.

3 THREAT ANALYSIS OF TRUSTWORTHY COMMUNICATION

The concept of trustworthy communication that we consider in this paper assumes preexisting trust relations in the real world and allows to apply these in online communication if the real-world entity behind a digital representation is uniquely identifiable. In this sense, spoofing and impersonation, and by extension tempering and data disclosure, are the main threats to trustworthiness. Here, we focus on technical, i.e., security, and organizational measures taken by a service provider which help to mitigate threats to aforementioned threats regardless of how a user, its communication client, e.g., browser, or other intermediate components, e.g., recursive resolvers, honor these measures. Respectively, we define assurance profiles and use these in our further analysis to evaluate Alerting Authorities.

To better understand how such threats can effectively be mitigated, we analyze actual cases of online fraud during the coronavirus pandemic as reported by news outlets, governmental and commercial security entities, and our own observations from a collected set of domain names including terms ‘corona’ or ‘covid’ from various public CT logs. We observed two conspicuous characteristics of phishing portals (comprising the majority of fraudulent websites): (i) the prevalent use of open namespaces and new gTLDs with no delegation restrictions, as for instance coronavirus.gov, us spoofing coronavirus.gov, and (ii) exclusive use of DV certificates as commonly issued by Let’s Encrypt. These characteristics, however, are not limited to malicious websites
Table 1: Interplay of DNS and X.509 certificate characteristics to provide different levels of assurance.

| Domain Name | Certificate | Auth | Assurance |
|-------------|-------------|------|-----------|
| Restricted  | Supports DNSSEC | DV O/EV | ✓ ✓ ✓ ✓ |
|              |              | Name | ✓   |
|              |              | Auth | ✓ |
|              |              | Assurance | Strong ● |
|              |              | Weak | ○ |
|              |              | Inadequate | ○ |

1 Name delegation reserved for eligible entities  
2 DV: domain validation, O/EV: organization or extended validation (implies domain validation as well)  
3 Authentication of DNS data and content provider identity  
4 ✓: support, ✗: no support, *: support or no support (entry value is immaterial)

and even legitimate ones, e.g., covid19responsefund.org (fundraising portal of World Health Organization), exhibit the similar profiles. Evidently, minimal organizational and financial costs are the main incentives for both malicious and legitimate websites.

Based on these observations, we argue that the best method of mitigation is increasing the cost of spoofing and impersonation on two dimensions of name and identity authentication, thus making it unattractive (if not impossible) for malicious actors. On the one hand, legitimate actors should confine themselves to closed registries and enable DNSSEC to mitigate DNS hijacking. Stricter eligibility requirements of closed registries not only provides extra assurance regarding the owner, it also poses an additional organizational hurdle that cannot be fulfilled by illegitimate actors. Specially in the U.S., specific closed namespaces can be leveraged by various types of entities involved in emergency management, i.e., .gov or .us locality namespace for governmental, .mil for military, .edu for education, .ngo for non-governmental, and .int for international organizations (see §2). On the other hand, DV certificates should be avoided in favor of OV or EV certificates for adequate identity authentication. Table 1 enumerates different combination of measures that can be taken to cater for trustworthy web communication grouped by level of assurance:

**Strong (●):** combination of closed registry and secured domain name (DNSSEC) alongside an OV/EV certificate provides strong assurance against name and identity spoofing, phishing, and impersonation in general.

**Weak (○):** OV/EV certificates combined with open registries as well as lack of DNSSEC are considered as weak since the former lacks the extra vetting and assurance (easier spoofing), and the latter is susceptible to DNS hijacking and domain impersonation [98].

**Inadequate (○):** providing only a DV certificate defeats the purpose of identification and having no certificate at all poses the risk of tampering and information disclosure.

It should be noted that there is no single feature that can guarantee strong assurance. Even the presence of an OV/EV certificate alone is considered as weak if the respective domain name is not under a restricted namespace (see ID authentication column in Table 1).

The practical implications from an operational perspective is visualized in the dependency graph of Figure 2, from which two important insights can be taken: (i) both web PKI certificates and SSL/TLS are practically dependent\(^1\) on domain names, and (ii) transport layer security measures are indispensable in establishing trust.

4 METHOD AND DATA CORPUS

The subject of study in this paper are the U.S. organizations involved in EM. Due to lack of a central registry, we focus on the list of Alerting Authorities maintained by FEMA. Although this list might not include each and every entity involved in emergency management, it provides a decent, legitimate overview over this field comprising a wide spectrum of organizations ranging from local governments, law enforcement agencies, and military bases to NGOs and universities. Each entry represents an organization by a unique ID, a name, and a territory of operation (including unincorporated territories). Throughout this study, we use the AA list from September 11, 2019 comprising 1,388 entries, excluding a single duplicate entry.

\(^1\)Although certificates can directly be bound to IP addresses, it would reduce the usability and flexibility of both servers and clients. Furthermore, by waiving the use of certificates SSL/TLS protocols can technically provide confidentiality and integrity without authentication but would be susceptible to monkey-in-the-middle attacks.
Our method consists of three phases: (1) preparation phase in which AA names were mapped to their respective domain names, (2) domain namespace analysis, and (3) Web PKI analysis. Our measurements were carried out from October 2019 up to March 2020 with each measurement being executed at least twice from various vantage points in Europe and the U.S. to detect any possible vantage point dependent discrepancies, e.g., limited access due to geo-blocking. Figure 3 summarizes our methodology from preparation phase to data gathering and final analysis (see Sections 5 and 6).

(1) Preparation. In the preparation phase, we first retrieve and parse the AA list and then map each entity to one of the following fields of operation by matching the names against list of predefined keywords (see Appendix):

- **Public safety**: Fire departments, emergency management agencies, etc.
- **Governmental**: Governing authorities such as towns, counties, and councils
- **Law enforcement**: Police departments, sheriffs, homeland security, etc.
- **Military**: Army bases, forts, etc.
- **Educational**: Universities

It is worth noting that even though police and homeland security are also responsible for the broader task of public safety, we decided to assign them to law enforcement.

We will use this classification scheme to better understand whether there are any domain-specific operational practices, such as choices of names or certificate providers.

(2) Domain Namespace Analysis. In the second phase, we assign the domain name used for Web services for each organization. To identify the primary website of an alerting authority, we query and scrape Google search engine. For each entry in the AA list, the combination of name and territory of operation (e.g., Fresno Police Department CA) was used as query string. Each query yielded between 4 and 12 results. Since the results are not necessarily ranked to have the official URL first, we excluded results based on a list of inapt domain names (e.g., social media sites and yellow pages). The topmost remaining URL was then selected for the respective organization. Finally, the list of collected URLs was manually checked to remove any mismatches and falsely associated URLs which were not detected automatically, e.g., same URL for homonymous counties in different states. A total of 23 entries were removed: 11 entries with mismatched names, 11 associated with the wrong territory of operation, and 1 with no matching URL at all; leaving a total of 1,365 entries for further analysis.

The remaining URLs (e.g., https://www.fresno.gov/police) were parsed to extract the FQDNs (e.g., www.fresno.gov) and path segments (e.g., /police). The results of our analysis on domain names is presented in Section 5.

(3) Web PKI Analysis. Finally, domain names were used to investigate the current and historic adaption of Web PKI certificates and SSL/TLS protocols by respective hosts. To study the current state, OpenSSL version 1.1.1d CLI was leveraged to fetch complete certificate chains, perform validation, and verify revocation status using stapled Online Certificate Status Protocol (OCSP) [3], manual OCSP [96], or Certificate Revocation Lists (CRL) [27], depending on availability. We also leveraged testssl.sh\(^2\), a command line penetration testing tool, to gather information and perform tests on SSL/TLS enabled hosts. We collected data of 1,185 unique hosts comprising information about server configuration (e.g., supported SSL/TLS protocols and cipher suites) and susceptibility to known vulnerabilities.

\(^2\)https://testssl.sh/
For our historical analysis, we used CT logs [67, 97]. To this end, we leveraged the publicly accessible database provided by Sectigo under crt.sh, which audits 79 log servers from 12 organizations (at the time of writing). For any given host name, the database was queried for certificates which have the host name or a wildcard covering the host name as their subject name or have it included in the list of subject alternative names (SAN). From a total of 28,370 retrieved unique certificates, 10,826 were pre-certificates and are omitted from further analysis. The remaining 17,544 certificates were then limited to those issued in the past decade (2009–2019), leaving a total number of 17,477 certificates which are analyzed as described in Section 6.

5 DNS NAMESPACE ANALYSIS

By studying the domain names of alerting authorities, we aim to answer the following questions:

1. Does each AA have its own dedicated domain name?
2. How do AAs integrate in the global DNS namespace?
3. Do AAs secure their names using DNSSEC?

The first question is concerned with how Alerting Authorities maintain their online presence, and avoid unnecessary dependencies. Lack of a dedicated name, for example, leads to dependence on someone else for authentication and data security as X.509 certificates are bound to domain names (see Figure 2). The second question aims to investigate whether AAs prefer specific TLDs to take advantages of recognizability (e.g., governmental organization under .gov) and security (restricted vs. non-restricted TLDs). Finally, the last question regards measures taken in securing names against threats such as spoofing or DNS hijacking which can also lead to impersonation and phishing.

5.1 Dedicated Domain Names

We consider an AA to have a dedicated DNS name either if it has its own name directly under a top-level domain [53], or has been assigned a sub-domain under the namespace of its parenting organization or any generic service provider, which is not shared. For example, the Tehama County Sheriff (tehamaso.org) has its own dedicated name whereas Apache County Sheriff's Office (www.co.apache.az.us/sheriff/) does not.

To measure dedicated domain names we divided the set of AA URLs into two groups depending on whether the URL path segment is empty (674 entries) or not (691 entries); the group with empty path segments was then regarded as having dedicated names. To prevent false positives of non-dedicated names, we manually examined all these websites and verified that the landing page does not relate to the Alerting Authority. We found only 25 false positives (e.g., http://www.franklincountyema.org/db/ with /db path being the start page), which leads to overall ≈ 51% AAs with dedicated names while the rest represents common names of parent organizations or other service providers. We also observed three emergency management agencies with dedicated names which are redirected (using HTTP 301/302 response codes) to web pages under county or state websites. Out of the total 1,365 collected URLs 1,327 unique names for designated organizations or purposes, e.g., different agencies all under the domain name of a single state.

The data also shows that all educational entities (total of 4) and over 90% of governmental entities (467 out of 503) such as state and local governments own dedicated names in contrast to only ≈ 25% of public safety entities (164 out of 669), and less than half of military organizations (8 out of 19) which nearly all are represented under home.army.mil.

5.2 Namespace Structure

The point of departure for our analysis are various top-level domains (TLDs) and country code second-level domains (ccSLDs) in use by alerting authorities, which we group as follows:

- **gTLD [58]**: generic top-level domains, e.g., .org
- **ccTLD [57]**: country code top-level domain, e.g., .us
- **ccSLD [59]**: country code 2nd-lvl domain, e.g., .ny.us
- **sTLD [60]**: sponsored top-level domains, e.g., .mil

Each TLD group features different properties. In general, there are little to no delegation limits and naming conventions for names under gTLDs or ccTLDs except for the .us namespace. Under .us ccTLD more than 3,000 names are reserved and unavailable for public registration [76] and the namespace has a rigorous structure with domain names at second, third, or fourth levels. This structuring reflects the “political geography” [26] and defines a number of reserved names for designated organizations or purposes, e.g., county or city, and territory of operation (see Figure 4). Finally, sponsored TLDs (.edu, .gov, and .mil) impose stricter eligibility requirements and thus have an advantage over gTLD names.

Figure 4: Excerpt of .us namespace structure [26, 77]
so that it can be made sure that only eligible registrants are granted the ownership of respective domain names [28, 88], given that such policies are adequately enforced by respective registries.

As summarized in Table 2, whereas half of domain names are registered under generic TLDs, the remaining majority (≈ 45%) makes use of sponsored TLDs and names within the .us state-code namespace, and the rest 5 percent opts for country code top-level domains. It is noteworthy that the .us locality namespace exhibits a relatively low penetration among AAs. For example, the usage of canonical forms [ci, co].<locality>.<state-code>.us for cities or counties: we observe that for every 5 city which have the term city in its domain name there exists only 1 city which uses the foreseen naming pattern, and for every 4 county choosing to have the term county in its domain name, there is only one county opting for the canonical form.

Finally, it is examined if the specific choice of top-level domains for an organization correlates with the organization’s field of operation. Figure 5 depicts how widespread various TLD types are in use in different fields of operation. It is noteworthy that educational and military organizations make exclusive use of restricted TLDs (.edu and .mil respectively), whereas gTLDs remain the more popular choice among the others. This figure also confirms the previous observations that the majority of remaining organizations, regardless of field of operation, opt for generic TLDs instead of taking advantage of special namespaces within the well-organized structured of .us namespace.

5.3 DNSSEC Deployment

We used drill to chase DNS signatures and verify if a domain has properly activated DNSSEC. All TLDs in use by AAs (see Table 2) support DNSSEC except a number of .us ccSLD domains: out of 50 total state ccSLDs under .us namespace, 32 have been used by AA organizations with only 18 supporting DNSSEC. Figure 6 depicts the state ccSLDs, which support DNSSEC (blue), which do not support (red), and those which are not used by any of organizations in our data set (white).

Although ≈ 57% of TLDs in use support DNSSEC, less than 8% of AA domain names have DNSSEC enabled. To our surprise even among .gov second-level domains which are mandated to implement DNSSEC [83] less than 10% (30) have support for DNSSEC. Lack of DNSSEC, as mentioned in Section 3, specifically in combination with DV certificates, jeopardizes the identification of the domain name owner.

6 WEB PKI ANALYSIS

The ecosystem of Web PKI evolves around X.509 certificates and SSL/TLS protocols. We investigate the deployment of both techniques in the context of Alerting Authorities to answer the following questions:

(1) To which extent do AAs adapt web PKI?
(2) Do hosts use up-to-date SSL/TLS protocols and secure libraries?
(3) How is the landscape of X.509 shaped among AAs?

6.1 Current Deployment of Certificates

To have a better understanding of the current deployment of web certificates, we gathered a snapshot of SSL/TLS deployment on public servers of Alerting Authorities. Out of the total 1327 unique names, 1187 hosts (≈ 89%) support SSL/TLS with 1130 hosts (≈ 95%) delivering valid X.509 certificates. Within the remaining 57 hosts, 17 use expired certificates, 9 use self-signed certificates, and 1 has self-signed certificates in its certificate chain. The validity of certificates provided by the remaining 30 hosts could not be verified due to some kind of misconfiguration, e.g., use of invalid certificates or certificates with missing issuer information. Recall that we use OpenSSL trusted root certificates for validation.

Table 3 combines our findings from this Section and Section 5 to reveal different combinations of DNS and X.509 certificate characteristics, linked to different levels of assurance according to Table 1. In Table 4, we group our results by organization types. Due to low penetration of DNSSEC, popularity of open TLDs, and pervasiveness of DV certificates among AAs (§ 5), only 20% of AA are considered to
be best equipped against common threats to trustworthy communication.

### 6.2 SSL/TLS Implementations

From our sample set of 1187 SSL/TLS hosts, we had to remove 3 hosts; one due to redirection to an already examined host, one due to sever misconfiguration making further analysis futile, and one due to domain drop catching during our analysis. It should be noted that SSL/TLS analysis given here has been carried out regardless of the validity of provided X.509 certificate.

#### 6.2.1 Supported Protocol Versions

Security flaws, outdated algorithms, or broken cryptography are among the reasons for introducing newer TLS protocols while deprecating the older ones. SSLv2 and SSLv3 [47] are inherently considered insecure (see RFC 6176 [104] and POODLE attack [75]), in contrast to TLS protocols [30–32, 92], which are considered vulnerable if implemented or configured improperly. Consequently, SSL versions 2 and 3 are deprecated [14, 104], and TLS versions 1.0 and 1.1 are planned to be deprecated in the future [74].
Whenever authentication is required, it is crucial for hosts to avoid ciphers with anonymous authentication as this defeats the purpose of source identification and opens the doors for monkey-in-the-middle attacks. In our analysis, only 2 hosts (≈ 0.1%) provide ciphers with anonymous authentication, whereas the majority of 1150 (≈ 97%) hosts cater for ciphers with RSA authentication, 68 (≈ 5%) ECDSA, and 249 (≈ 21%) the newest TLS 1.3 suites which allow for ad hoc selection of RSA, ECDSA or pre-shared keys for authentication.

### Key Exchange

For key exchange, i.e., establishing a shared symmetric key for further efficient encryption, two factors should be noted: (i) weak keys during exchange should be avoided, and (ii) perfect forward secrecy (PFS) should be provided. Here, we follow the NIST recommendation [13] of at least 112 bit security strength for key exchange algorithms and key sizes, while considering everything below as weak, i.e., 1024 bit key size for Diffie-Hellman (DH) and RSA key exchange and 160-223 bit keys for elliptic curve DH (ECDH). Perfect forward secrecy guarantees that session keys are not compromised even if the asymmetric key-pairs used to create those keys are (retrospectively) compromised. Among analyzed hosts, none is limited to only weak key exchange, one still supports deprecated insecure export cipher suites, 120 (≈ 10%) provide weak (EC)DH key exchange cipher suites alongside non-weak suites, and five only support RSA key exchange (no PFS). Moreover, a total of 1180 hosts (≈ 99%) provide cipher suites which support PFS. It is noteworthy that RSA key exchange alone (without ephemeral DH) does not support PFS so if the server is compromised (and in turn its private keys), the session keys can also be considered compromised as well.

### Encryption and Message Authentication

For data encryption, our data shows that weak, broken, or deprecated ciphers (RFC 7225 [100]), e.g., DES [36], 3DES [13, 78], RC2 and RC4 [87], and even NULL-encryption ciphers are still offered. Nonetheless, nearly all hosts offer suites with strong AES (128 and 256) ciphers and none offers only weak or broken ciphers. Respectively, although weak message authentication codes, e.g., MD5 and SHA1, are still in use, the majority of hosts give clients the possibility of choosing ciphers with stronger MACs such as AEAD, which is the default in TLS 1.3.

### Susceptibility to Vulnerabilities

How aforementioned weaknesses or misconfiguration in authentication, key exchange, encryption, MAC algorithms, or other server configurations can practically impact the communication is studied here on the basis of known vulnerabilities that affect confidentiality, data integrity, or service availability (see CIA-triad [108]). We tested known hosts against a set of select vulnerabilities and summarized the results in Table 5. The Common Vulnerability Scoring System (CVSS) [72] used here is an open and standardized mean of quantifying the severity of vulnerabilities based on base, temporal, and environmental metric groups which characterize the vulnerability. It can
Table 6: Count of unique hosts with at least 1 publicly logged certificate per issuer

| CA          | '09 | '10 | '11 | '12 | '13 | '14 | '15 | '16 | '17 | '18 | '19 |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Comodo      | 3   | 7   | 15  | 21  | 29  | 62  | 92  | 238 | 304 | 299 |
| DigiCert    | 31  | 53  | 70  | 83  | 92  | 105 | 120 | 135 | 146 | 263 | 281 |
| Entrust     | 7   | 13  | 22  | 25  | 34  | 32  | 33  | 39  | 40  | 44  | 48  |
| GeoTrust    | †   | 0   | 5   | 29  | 49  | 54  | 59  | 63  | 67  | 68  | 61  | 29  |
| GoDaddy     | ††  | 25  | 54  | 80  | 109 | 141 | 183 | 215 | 249 | 290 | 330 | 347 |
| LetsEncrypt | †‡  | 0   | 0   | 0   | 0   | 0   | 0   | 29  | 102 | 210 | 335 |
| Sectigo     |     | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 228 |
| Verisign    | ‡   | 18  | 45  | 49  | 43  | 43  | 42  | 35  | 27  | 17  | 6   | 0   |

All Hosts‡‡ 122 244 298 356 398 458 517 630 830 1012 1109

† Rebranded to Sectigo in 2018. †† Acquired by DigiCert in 2017.
†‡ Beta in 2015; public launch in 2016.
‡‡ Denotes the # of unique hosts per year with at least one logged certificate.

It can be seen that the majority of hosts are resilient to our tested attacks and although more than half are potentially vulnerable to BREACH attack, the risk of such attack is relatively low (a score of 2.6).

6.3 Historic X.509 Certificate Landscape

The historic analysis of X.509 certificates collected from Certificate Transparency logs (§ 4) helps us to gain a better understanding of security policy changes related to Alerting Authorities and CAs. We span ten years. It should be noted that the total number of organizations with publicly logged certificates changes for each year. We consider this in the following and normalize the results either with respect to the number of organizations or total number of certificates valid per year.

6.3.1 Certificate Authorities. In addition to common regulations, certificate authorities implement and follow their own set of policies. From the perspective of relying parties, i.e., web users, such policies are transparent and as long as a CA is included in a user’s trust store, it is considered trustworthy. For the subscribers, however, these policies among other factors such as annual fees, offered certificate types, and operation costs are decisive in choosing an appropriate CA.

The list of top CAs with an average of yearly 20 unique subscribers (hosts) in the last decade and the number of respective covered hosts per year is given in Table 6. We use the term cover to differentiate from issuance: if a host, for example, is issued a certificate by a CA valid from 2010 to 2013, we consider this host to be covered by that CA for 2010, 2011, 2012, and 2013. Respectively, if a CA issues multiple short-lived certificates (e.g., 90 days) for a host within a given year, we only count that host as covered once in that year by the issuing CA. This would avoid the data skew in favor of issuers with lower certificate validity windows and higher certification rate per year. It also should be noted that a single host can have certificates issued from different CAs. The bottom row puts the above number in relation to the total number of CA subscribers for each year and for all observed CAs. For example, in 2019, a third of 1109 hosts with at least one logged certificate made use of Let’s Encrypt DV certificates. Figure 8 depicts these findings in terms of relative market share development in the past decade.

Table 6 and Figure 8 highlight two factors evidently decisive for AAs in their choice of CA: convenience and cost factors. GoDaddy, for example, which has been the market leader among AAs for about two thirds of the past decade, provides web hosting and domain name registration beside certification services in convenient packages; and Let’s Encrypt [4], which has surged to the top in the short period after its public offering, offers automated DV certification at no cost.

6.3.2 Validation types and assurance profiles. In Section 6.1, we showed that currently only 20% of AAs honor security profiles that are strongly resilient against threats to trustworthy communication (see Tables 3 and 4). Historically, however, as depicted in Figure 9, a higher share of alerting authorities provisioned for such measures. When compared with the share of various certificate validation types (DV, OV, and EV), it becomes evident how the decreasing usage of OV certificates is directly proportional to the reduction of preferred assurance profiles. At the same time the surging popularity of DV certificates has led to an increase in cases of what we consider as inadequately trustworthy (no identification).

It should be noted that due to lack of historic data regarding DNSSEC penetration among AAs, we made a simple assumption that historic support for DNSSEC among AAs equals to its current penetration state (see Section 5.3).
6.3.3 Certificate Sharing. Except EV certificates, both DV and OV certificates allow wild card names as subject alternative names (SAN) to avoid enumerating all fully qualified domain names (FQDN) under the control of the certificate holder. In practice, the SAN extension also allows sharing a certificate among different hosts. For example, in 2019 the federal government was issued OV certificates with more than 600 SAN entries each. Sharing certificates among various hosts expands the attack surface and increases operational costs since if one of the hosts is compromised or the certificate is revoked, every other host also need to configure a new certificate.

Multitenancy web hosting and security service providers (both public or government exclusive) are making use of shared certificates as depicted in Figure 10 (Note that Let’s Encrypt certificates only allow up to 100 DNS type SAN). In our analysis, we also noticed an increasing number of certificate sharing among hosts which do not belong to the same logical entity. Most critically also among OV certificates where a service provider obtains a certificate under its name and lists the host name of its customers as SAN, practically defeating the identification purpose of the certificate. As the time of writing, for example, we observe cases of such certificates listing subject alternative names that obviously do not belong to the same entity, e.g., mo.gov, asap.farm, and incapsula.com under the same certificate. In this very specific case, records from the Wayback Machine (by the Internet Archive) show that asap.farm has previously belonged to Missouri Department of Agriculture [81] but it was never removed from certificate as the ownership was transferred to another entity.

6.3.4 Certificate Validity. A certificate is presumed valid if, among others, it is deployed within its validity period, is issued by a trustworthy CA, carries a valid signature, bound to the correct subject name, and is not revoked (see RFC 5280 [27]). Checking revocation status is the most expensive operation among aforementioned factors, thus in many cases it is either performed inadequately or ignored altogether by browsers (partly in favor of proprietary solutions) [69]. Consequently, in the past years both CAs and browser vendors have been negotiating to cap and reduce certificate lifetimes [44–46] as an effort to reduce security risks due to misissued or revoked certificates.

As depicted in Figure 11, the lifetime of certificates utilized by AAs has been constantly decreasing. This trend can partly be attributed to consensus among CAs and browser vendors to reduce certificate lifetimes, but also due to rising popularity of CAs which are specialized on gratuitous and automated DV certificates such as Let’s Encrypt (fixed lifetime of 90 days).

7 RELATED WORK
To the best of our knowledge, this is the first study investigating how Alerting Authorities in the U.S. (as part of broader
critical infrastructure) implement measures to cater for trustworthy Web-based communication and service provision. Previous research on trust in online emergency service provision mainly focuses on form and content and its relation to the perception of trustworthiness [18, 35, 56], conception of trustworthy emergency communication and collaboration systems [19, 85] or simply best practices in building trust [10, 70]. Although previous research has already highlighted how knowing who is behind an online emergency service impacts the trustworthiness of their respective services [35, 70, 86], we observe a research gap when it comes to evaluating the measures at one’s disposal to reach this goal. More specifically, the interplay of domain names, X.509 certificates, and transport layer security protocols has not been investigated to our best knowledge. Respectively, in this section we limit ourselves to an overview of related work which studies these technologies on their own.

**Domain Namespace and DNSSEC.** The influence of a domain name on authenticating or at least recognizing the real-world entity behind that name has been investigated in terms of general trustworthiness associated with TLDs and impersonation of trusted entities through domain name masquerading. Walther, Wang, and Loh [106] examine how choice of TLD can positively impact the credibility of health websites. Seckler et al. [99] investigate how a relevant domain name, e.g., a known TLD, can positively enforce familiarity and in turn increase trust. Similarly, a yearly report commissioned by the Public Internet Registry (responsible for .org, .ngo, and .ong TLDs) examines the trustworthiness of select TLDs among NGO donors.

A closely related topic is how the domain namespace of malicious websites is structured and operated. Hao et al. [49] studies the registration behaviors, e.g., naming patterns, of spammers for .com TLD. Korczynski et al. [63] show how low pricing and registration barriers alongside the possibility of bulk registration is an enabler for malicious actors to migrate to new gTLDs. In a longitudinal study of typosquatting, Agten et al. [6] reveals how registration fees and registry policies can attract or deter malicious actors; practically determining the credibility of such TLDs (the top three most abused TLDs in the world are new gTLDs [89]). And Antonakakis et al. [8] introduce a reputation system for DNS to detect malicious domain names. Different studies show how scammers try to impersonate other entities by partly or fully integrating legitimate domain names in their own domain names [6, 62, 94, 103] or even by using homonymous names using internationalized domain names [102].

With regard to namespace security, studies in the past pinpoint a relatively low DNSSEC penetration due to various factors ranging from lack of support by local resolvers to server misconfigurations [23, 50, 68, 84] despite more than 90% of all TLDs being signed and supporting DNSSEC [93]. The prevalence of DNSSEC among various types of organizations, such as educational, military, commercial, etc. has not been subject of study to determine if there is a correlation between field of operation and sensibility for DNS security measures. The only exception is the fine-grained, i.e., including second level domains, regular analysis of DNSSEC deployment among U.S. governmental agencies within the .gov namespace [79, 95].

**Web PKI.** Throughout the years, various measurements have characterized X.509 certificates in use over the Internet in terms of validity, issuing CAs, key strength, etc. [22, 33, 55, 73] Among these, Mishari et al. [73] investigates the difference between certificates of legitimate and fraudulent websites. The study by Holz et al. [55] has the advantage of being performed from different vantage points spread over the world. The measurements by Durumeric et al. [33] is noteworthy as it goes beyond mere X.509 certificate analysis and investigates the dependencies among root and intermediate CAs, their market share, and the characteristics of respective certificates. And finally, the measurements performed by Chung et al. [22] aim to understand why a majority of certificates advertised over IPv4 are invalid. It should be noted that except the last study, the others have been carried out before the public launch of Let’s Encrypt [4] (2016), and antedate various mergers and rebrandings which has changed the Web PKI landscape ever since.

Specifically related to the topic of our work are studies which investigate the trustworthiness of CAs in general and their policies specially in enabling fraud and impersonation. Delignat-Lavaud et al. [29], for example, investigate the conformance of CAs to the CA/Browser Forum guidelines, which in turn can influence trustworthiness of a CA. Others have defined various metrics to qualify [20, 37] or quantify trustworthiness of CAs [51] beyond technical measures. In a recent study Schwittmann, Wander and Weis [98] exhibit how various CAs are susceptible to attacks on DV certification processes that can practically lead to domain impersonation. Similarly, Roberts et al. [94] studies which CAs are responsible for issuing DV certificates to malicious target-embedded domains.

Finally, regarding transport layer security protocols, Kotzias et al. [64] characterize both the deployment of SSL/TLS by web hosts and its usage by various applications with respect to relevant security issues.

**8 KEY FINDINGS AND DISCUSSIONS**

Our results draw a rather alarming picture of the current online emergency management landscape regarding trustworthy communication. Along the line of our key findings,
we briefly discuss the possible reasons for the observed deficiencies and suggest alternatives.

Only about half of AAs use dedicated names. An organization without a dedicated domain name depends on its hosting entity, i.e., parent organization or other service provider, for authentication and data security. From a user perspective, there is no viable way of discriminating the organization from its hosting entity. Even if organizations are reluctant to acquire their own second-level domain names, they should at least be assigned with their own subdomains instead of being subsumed in the path segment of a URL.

The majority of organizations opt for generic TLDs. This poses a major threat of phishing and typosquatting by not taking the advantage of closed registries and restricted namespaces such as the .us locality namespace. In contrast to gTLDs, higher registration fees, bureaucratic hurdles, and longer delegation processing times are among discouraging factors, which call for governmental support and can effectively be addressed by policy-makers through price caps and easier access for eligible organizations which fulfill the strict requirements.

Only a fraction of AAs care for DNSSEC. Securing domain names is seemingly a non-priority for investigated organizations as the low penetration rate of DNSSEC suggests. Although DNSSEC suffers low deployment on the global scale, it is an indispensable component in securing emergency communication as part of the broader critical infrastructure. Yet, it should be noted that in some cases due to lack of support registrants are forced to abandon DNSSEC in favor of other factors, e.g., registering under a .us locality name for which there is, surprisingly, no DNSSEC support (see Figure 6).

We also note that although domain names under .gov namespaces are mandated to use DNSSEC [83], the low support for DNSSEC has its roots in operational and organizational mismanagement rather than technical issues.

Convenience and cost factors have a high impact on CA preferences. Our study shows that currently about 15% of alerting authorities provide either none or invalid certificates. This can be traced back to carelessness regarding the Web PKI trust model (self-signed certificates) or additional (not only financial) configuration [65] and certification costs. Rapid growth of Let’s Encrypt with its fully automated certificate issuance and renewal is an indication of how the aforementioned factors influence the decision for choosing an appropriate CA.

A rising trend, which we consider as rather worrisome for critical infrastructure, is the usage of domain validation (DV) or shared certificates in multitenancy settings. As both cannot cater for identification, they remain inappropriate for trustworthy communication (Section 3). In case of domain validation, we encourage the stakeholders to reconsider semantically equivalent alternative of TLSA domain issued certificates (DANE EE) as they provide higher resilience against spoofing in contrast to DV certificates [98]. In general DANE can be used to remove ambiguity regarding public keys and responsible CAs for a domain name. Regarding shared certificates, we suggest abandoning them completely to minimize attack surface. We also encourage CAs to avoid issuing OV certificates for service providers without ensuring that all the listed subject alternative names belong to the same organization.

Security measures for critical infrastructure should not be guided by convenience or cost factors. In an ideal setting certification of specific organizations would be limited to dedicated CAs (similar to InCommon Certificate Service for higher education institutes) and subordination rules [61] are enforced by all other trusted CAs to avoid issuing certificates for these protected organizations and namespaces.

Responsibility beyond Alerting Authorities. The scope of trustworthy communication goes beyond our investigations and extends to consumers as well as infrastructure operators such as CAs, ISPs, and browser vendors. There is still a gap between CA practices and guidelines [29], some automated DV certification services are susceptible to impersonation attacks [94, 98], and not all root CAs restrict certification scope for their intermediate CAs [33]. DNS registrars do not offer DNSSEC by default or free of cost [24] and ISPs often do not bother to operate DNSSEC-aware recursive resolvers that properly verify signed DNS records [23, 107]. Browser vendors should also provide better security usability by avoiding confusing SSL/TLS warnings [7], improve instead of abandoning visual cues for different certificate types [38, 54, 80], and start offering alternative CA trustworthy assessment measures beyond the standard binary trust model [20, 37, 51].

9 CONCLUSION AND OUTLOOK

In this paper we provided an overview of how alerting authorities (AA) in the U.S. are structured within the domain namespace, how widespread is DNSSEC in securing their domain names, and how Web PKI and transport layer security protocols are used for authentication and data security. We uncovered deficiencies and discussed alternatives while emphasizing that respective solutions are not necessarily technical but operational as well as political. Protecting critical infrastructure for emergency communication and public safety entails addressing operational and policy challenges on national and international levels and calls for commitment of all stakeholders from service providers to intermediate infrastructure operators and browser vendors alongside policy-makers.
In the future this work can be extended beyond the U.S. territory while providing a comparison basis for other countries. Furthermore, the role of intermediate infrastructure and further dependency structures can be investigated in depth.

**Data Disclosure.** We will make our analysis toolchain as well as all measurement data (i.e., domain names, Web certificates etc. of alerting authorities) publicly available.

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APPENDIX

Table 7: Regular expressions applied on an AA name to categorize its field of operation (in order of application).

| Category          | Regular expression                                      |
|-------------------|----------------------------------------------------------|
| Military          | ^[[:alnum:]]fort|^fort|army|missile|base|pfpa                        |
| Governmental      | county|counties|city|commission|borough|town|village|authority|council|government|national|aviation|parish|correction |
| Educational       | university                                 |
| Law Enforcement   | police|sheriff|investigation|law enforcement'|patrol|'homeland|security'|intelligence |
| Public Safety     | 911|9-1-1'|emergency|ema|eom|ohsep|fire|safety|communication|dispatch |