Abstract—Transport Layer Security (TLS) is the base for many Internet applications and services to achieve end-to-end security. In this paper, we provide guidance on how to measure TLS deployments, including X.509 certificates and Web PKI. We introduce common data sources and tools, and systematically describe necessary steps to conduct sound measurements and data analysis. By surveying prior TLS measurement studies we find that diverging results are rather rooted in different setups instead of different deployments. To improve the situation, we identify common pitfalls and introduce a framework to describe TLS and Web PKI measurements. Where necessary, our insights are bolstered by a data-driven approach, in which we complement arguments by additional measurements.

Index Terms—TLS, X.509, PKI, security, Internet measurement

I. INTRODUCTION

Many Internet applications and services use Transport Layer Security (TLS) to enable authentication, confidentiality, and integrity end-to-end on top of an otherwise insecure transport layer. Establishing a secure TLS connection involves specific protocol handshakes based on X.509 certificates, which are part of the Web PKI system. With the advent of QUIC, TLS principles are integral part of the transport layer, making a clear understanding of different TLS deployments even more important.

Due to the crucial role of TLS in securing Internet communication, the protocol itself as well as the different pieces such as X.509 certificates are popular subjects of Internet measurements. Research questions range from understanding general usage of TLS and Web PKI, (e.g., used algorithms and cryptographic material), deployment of related protocols (e.g., DANE [1]), impact of security of incidents (e.g., Heartbleed [2]), vulnerability to new attacks (e.g., Confusion Attacks [3]), adoption rate of TLS versions (e.g., TLS 1.3), to investigating nontechnical aspects such as market share of certification authorities.

Measuring and analysing TLS, X.509 certificates, and Web PKI is challenging due to (i) application-specific implementations, (ii) inherent flexibility of TLS, and (iii) different measurement setups. Applications may adapt TLS to their needs by defining further requirements and constraints. This leads to TLS implementations with different mandatory features. HTTP/2, for example, requires TLS to support Server Name Indication (SNI) and prohibits use of specific cipher suites [4, §9.], while such constraints are not given for SMTPS [5]. In terms of flexibility, TLS allows endpoints to negotiate parameters such as cryptographic algorithms during handshake. Finally, differences between measurement setups make measurements that aim for answering the same questions not comparable and their findings inconsistent in some cases.

In this paper, we address challenges and pitfalls when measuring the TLS ecosystem. To justify our arguments and illustrate pitfalls, we take a data-driven approach. In addition to surveying prior work, we thus conduct our own measurements and provide three independent datasets. Our main contributions are:

1) A survey of prior TLS measurement research to illustrate common data collection techniques and measurement features.
2) A framework to consistently exploring TLS and Web PKI deployments.
3) An evaluation of common tools and data sources.
4) Systematic guidance on how to prepare and perform measurements.
5) A summary of most common pitfalls when interpreting measurement data.

We hope that these insights help to guide and improve future
TLS measurements.

The remainder of this paper is structured as follows. We start by providing a comprehensive picture of TLS and Web PKI (Section II) and then introduce a simple framework to describe and compare measurements (Section III). In Section IV, we review common data sources and discuss their merits. Section V comprises a list of measurement tools and their capabilities. Subsequently, we discuss various aspects of preparing (Section VI) and performing (Section VII) measurements followed by pitfalls when interpreting measurement data (Section VIII). We conclude this paper in Section IX. Related work that is the base for this paper is summarized in Table I.

II. BACKGROUND

In this section we provide a brief overview of TLS, Web PKI, and DNS(SEC) and discuss related aspects. Figure 2 depicts technical components and non-technical entities involved in TLS and Web PKI ecosystems.

A. Transport Layer Security

TLS, the successor to Secure Sockets Layer (SSL), provides authenticated integrity and confidentiality over widely used transport layers of TCP, UDP, and QUIC [6]–[8]. In this paper, we limit ourselves to TLS versions 1.2 [9] and 1.3 [6] as TLS versions 1.0 and 1.1 have already been deprecated [10].

Components. TLS protocol is split into two layers: the higher layer includes TLS-specific messages (e.g., alerts and handshake messages), as well as applications data (e.g., HTTP), and the lower layer, the record layer, is responsible for fragmentation, encryption, and compression of higher-level messages before handing them to the transport layer. An overview of TLS components and their relation to application and transport layer is given in Figure 3.

Handshake. To establish a secure channel, peers perform a handshake to determine security parameters, establish a shared key, and authenticate each other. Server authentication in TLS 1.3 is mandatory, while in previous versions authentication is optional for both peers. Authentication is commonly realized using X.509 certificates [11] or through pre-shared keys (PSK) [6], [12].

Extensions. The functionality of TLS protocol can be extended using TLS extensions [13]. Server Name Indication (SNI), and Stapled Online Certificate Status Protocol (OCSP) are among the prominent extensions.

B. Web PKI and X.509

The most widespread approach to authentication on the Internet is based on the Web PKI: an ecosystem of certification authorities (CA), applicants and subscribers (e.g., website operators), and relying parties (e.g., users). A CA is a trusted third party (TPP) which validates the identity of an applicant and issues a corresponding X.509 certificate, i.e., binds a public key to a subject. The applicant then becomes a subscriber of the CA. A relying party can subsequently authenticate

1A list of registered extensions is made available by the Internet Assigned Numbers Authority (iana) [14].
the subscribers of its trusted CAs based on their presented certificates.

### Technical basis and governing entities

The technical basis of X.509 certificates is standardized by the International Telecommunication Union (ITU) and International Organization for Standardization (ISO) as part of the X.500 standard series [15]. This is further specified and adapted by IETF for the Web PKI in RFC5280 [11]. A set of common guidelines and policies (Baseline Requirements) are also defined by the CA/Browser Forum [16]. Additionally, each CA defines its own policies and procedures in Certificate Policy (CP) and Certification Practice Statement (CPS) documents. And finally, individual organizations such as browser and operating system vendors impose their own requirements on X.509 certificates (see for example Mozilla PKI Policy [17]). Figure 4 depicts this hierarchy.

#### Usage and semantics

A certificate is used for authentication and identification through its binding of a public key to a subject. Originally, a subject was meant to identify a natural or a legal person within a globally unique directory (X.500 [18]), which never came into existence. Alternative identities of the same subject from other namespaces (i.e., domain name space) are included as Subject Alternative Names (SAN). Within the Web PKI ecosystem, the most basic form of an identity is a domain name. Less common identities are IP and E-Mail addresses.

Before issuing a certificate, a CA validates the identity of an applicant regarding its ownership of included domain name(s) (Domain Validation, DV). Additional validation procedures with higher identification assurances are Organization Validation (OV), Extended Validation (EV), and Individual Validation (IV) [16], [19]. For DV validation, an applicant proves its control over respective domain name(s) through automated methods (e.g., using ACME protocol [20]), or manually through e-mail or phone calls. OV and IV certificates include additional identification information regarding respective organization or individual as defined in CA/B Baseline Requirements [16]. EV certificates, originally introduced to make eCommerce more trustworthy, are subject to stricter requirements, audits, and lifecycle management [19]. Further validations types also exist for other purposes (e.g., S/MIME authentication) [21].

### C. DNS and DNSSEC

DNS is a hierarchical and distributed database with an eventual consistency model that maps domain names to Resource Records (RR) of various types, for example IPv4 and IPv6 addresses (A and AAAA records). DNSSEC [22] is a set of security extensions that address a number of DNS security shortcomings (see RFC4033 [23] §31).

In context of TLS and Web PKI, DNSSEC is utilized to counter various challenges. As such, the holistic measurement of TLS and Web PKI deployment must also regard its relation to DNS. In the following, we discuss three use cases of DNS(SEC) in context of TLS and Web PKI.

#### Removing ambiguity between CA and public keys

CAs are generally not restricted in their certificate issuance [11 §4.2.1.10.], i.e., a CA can issue a certificate for any arbitrary subject name (e.g., domain name). As such, a relying party cannot definitely determine if a given certificate was authorized by the entity denoted in the subject field or if it has been misissued.

The DNS-Based Authentication of Named Entities (DANE) for TLS [1] addresses this ambiguity between public keys and CAs by allowing the owner of an identity (e.g., a domain name or an e-mail address) to specify or characterize authorized certificates. DANE relies on DNSSEC [22] and TLSA RRs. An experimental TLS extension also enables embedding complete DNSSEC chains and TLSA records into the TLS handshake [24].

DANE can be an effective remedy against rogue or compromised CAs as well as CAs used by intelligence services and governments [25] such as the root certificates generated and forced by Kazakhstan Government [26] or TrusCore CA which recently was disclosed to have ties to ‘contractors for U.S. intelligence agencies and law enforcement’ [27].

#### Authorizing certificate issuance

Similar to relying party, CAs also need additional information to know if an applicant for an identity is actually authorized by identity owner (e.g., a domain name owner) to avoid misissuance. Domain name owners can use the CA authorization (CAA) resource record [28] to indicate which CAs are allowed to issue certificates for their domain names and also to report policy violation.

#### Upgrading opportunistic TLS

While browsers commonly lack DANE support for HTTPS [29], DANE has found popularity among SMTP servers [30] to address downgrade vulnerability of STARTTLS [31].

Mail server operators that are reluctant or unable to deploy DNSSEC, e.g., Google, alternatively use SMTP MTA Strict Transport Security (MTA-STS) [32]. In this approach a TXT resource record under a well-known subdomain is used to signal TLS support by respective mail servers. Related policies can then be fetched over HTTPS from a well-known URI (see RFC8615 [33]).

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**Figure 4:** Technical and political aspects shaping X.509 Certificates in Web PKI
III. PRINCIPLES FOR A TLS MEASUREMENT FRAMEWORK

The first step in measuring TLS and Web PKI is to decide on measurement aspects and choose a set of features. The next step is to choose the measurement frequency with regards to the measurement goal, and finally to collect data. In the following we discuss each aspect briefly and introduce a systematic approach to define and characterize TLS and Web PKI measurements. Finally, we survey related work (cited in this paper) in context of our approach (Table I).

A. Measurement Aspects and Features

We differentiate between two types of measurement aspects. Primary aspects can directly be measured and are quantifiable: X.509 public Key length, TLS session validity period, etc. are examples of this type. Secondary or derive ones can be inferred based on primary aspects or from raw data and might not be quantifiable: certificate policy statements, TLS stack in use by a server, and CA market share, for example. Derivative aspects might be useful in interpreting data such as explaining irregular observations (see Section VIII).

Here, we provide a set of primary aspects for TLS and Web PKI and limit our scope to study of TLS usage by Web servers, and X.509 certificates used for client or server authentication. Note that some TLS and Web PKI aspects are associated with DNS(SEC) records and require collecting respective records. We refer to related work \cite{34, 35} for methods of DNS and DNSSEC measurement.

**TLS.** TLS can be measured regarding each of its components (see Section II) and the integration of the protocol as a whole in context of an application:

**T1** Conformance to standards (e.g., proper implementation of TLS state machine \cite{36–38})

**T2** Handshake layer features (e.g., supported extensions \cite{13})

**T3** Record layer features (e.g., susceptibility to known vulnerabilities)

**T4** Integration with higher level application layer (e.g., TLS use by HTTP/2 \cite{4} §9.2.1)

**Web PKI.** As a complex ecosystem, Web PKI, can be studied regarding various aspects including its global structure, established trust stores, and CA certification policy and procedures. X.509 certificates, at the core of Web PKI, can further be analyzed regarding the following properties:

**X1** Conformance to existing standards (RFCs, CA/B baseline requirements, etc. \cite{39–42})

**X2** Validity (in time and within a trust chain or trust store)

**X3** Extensions and expected usage (e.g., validation method and key usage flags)

**X4** Revocation status (OCSP and CRL)

**X5** Relation to relevant DNS records (e.g., CAA and TLSA)

B. Frequency

In specific cases, it is desired or required to perform multiple measurements. If we are interested in observing temporal developments and discovering causal relations, \textit{e.g.}, in response to introduction of a new technology such as QUIC, we need to measure the whole sample set multiple times over a period of time. Such longitudinal measurements can be considered as regular repetition of snapshot measurements.

**Snapshot.** This type of measurement is based on probing a sample set on a set of features at a given point in time. Such measurements help to understand state of affairs at a single point in time. Shobiri \textit{et al.} \cite{43}, for example, investigate if CDN provides observe security hygiene when communicating to backend servers by monitoring incoming connections from CDN edge servers.

**Longitudinal.** When the same set of features for a constant sample set is probed over a period of time, we speak of longitudinal measurements. In contrast to snapshots, longitudinal data are suitable for understanding causal relations. Probing same targets over time enables capturing temporal changes, \textit{e.g.}, in response to an incident. Durumeric \textit{et al.} \cite{2}, for example, analyze (among others) the patch rate of HTTPS servers vulnerable to Heartbleed by probing Alexa Top 1M sites and a sample set of IPv4 address space every 8 hours for a period of ca 3 months. Similarly, Zhang \textit{et al.} \cite{44} study revocation and reissuance of certificates for vulnerable hosts at the wake of the Heartbleed.

C. Data Collection

Raw data can be collected by intercepting network (passive) or through initiation of purposeful transactions (active).

**Passive.** In passive measurements, data in transit, \textit{i.e.}, passing through the network, is captured without further modification. This presupposes access to special network nodes, \textit{e.g.}, routers. Passive measurements are useful for studying traits that cannot actively be measured, \textit{e.g.}, actual cipher suites used by users.

In context of TLS, the main challenge of passive monitoring regards relevant data that might be encrypted and cannot be dissected, \textit{e.g.}, after the handshake concludes or upon TLS session resumptions. To address this issue, data can be collected directly at endpoints instead of in transit. Oakes \textit{et al.}
al. [45], for example, collect data from a web monitoring tool installed directly on user devices.

Active. In active measurements purposefully generated or manipulated data packets are exchanged with hosts. Both request and response data are then recorded for further analysis. Active measurement is suitable to investigate the behavior of a counterpart in presence of a concrete condition or data packet. Hebrik et al. [46], for example, analyze security of TLS sessions by generating special handshake messages and testing these against TLS servers.

IV. DATA SOURCES

Here, we introduce various sources for data collection and discuss their merits: subsections IV-A to IV-D regard active measurements and the remainder are related to passive measurements. In Section VI we dig deeper into the ramifications of choosing specific data sources for measurements, and in Section VIII we discuss pitfalls when interpreting data from specific sources.

A. IP Address Space Scanning

A straightforward and commonly used approach to TLS and Web PKI measurement is first to scan the IP address space (or a selected subnet) for ports reserved for TLS-enabled protocols (e.g., 443 for HTTPS) and then to establish a TLS connection with matching hosts. It should, however, be noted that since presence of an open port on its own is not a guarantee that respective protocol is also available at that endpoint [39], [54], false positives need then be discarded during the actual measurement. In Section V we discuss tools that address both IP scanning and service detection.

A disadvantage of IP scanning is the lack of intrinsic ordering among IP addresses, e.g., in terms of popularity or usage, so that at first glance the IP address of a home router (possibly accessed by a single individual) has the same weight as an IP address of a critical or high-traffic router (possibly accessed by a single individual). Additionally, detecting cases of opportunistic TLS, e.g., STARTTLS over SMTP, require scanners to perform protocol handshakes to determine if a security upgrade is supported. And finally, virtual hosts on the same server, i.e., behind the same IP address, cannot individually be addressed in this approach, e.g., using SNI extension [57] (see Section II).

Research [39], [47] shows how IP scanning can skew measurement results and result in an incomplete picture of TLS and Web PKI landscape, partly due to virtual hosting and required usage of Server Name Indication (SNI). Although SNI is an optional TLS extension [13 §3], its use is mandated by some higher-level applications protocols. HTTP/2 [4] §9.2.] and HTTP/3 [77] §9.3.], for example, require clients to use SNI for the TLS connection if server is identified by a domain name. Respectively, web servers behavior vary depending on existence of SNI. Cloudflare, for example, aborts the TLS handshake (alert 40) if no SNI is provided, whereas Firebase (Google) and Wordpress return wildcard certificates (*.firebaseapp.com and *.wordpress.com) that would match the free subdomains allocated for their customers. The possibility of encountering such cases can be elaborated by Figure 6, which depicts the distribution of the number of DNS SAN in certificates from our TRASCO dataset (see Section A).

We observe that only about 17% of all certificates enlist a single SAN entry and among the rest about 16% contain at least two unique eSLDs signalling that the certificate might be shared among two different subjects but served under the same IP.

B. Hit Lists

We refer to a set of curated or purposefully collected domain names that fulfill specific criteria as a hit list. Related work has already evaluated different aspects, such as reliability, reproducibility, and fluctuation, of such lists and the implications of their use in research [78]–[80]. Here, we only consider actively maintained and publicly available lists. Table I provides an overview.

Tranco List. An aggregation of various popularity-based top lists with the aim of being consistent, manipulation-resistant, reliable, and reproducible [79]. By default, domain names in the Tranco List are trimmed at the effective second level domain name (eSLD) and contain only the public suffix (effective TLD; eTLD [81]) plus the next label (referred to as pay-level domains by list maintainers). For example city.ofunato.iwate.jp (an actual entry) consists of the public suffix ofunato.iwate.jp and city as its effective SLD. This default structure can be modified through Tranco website where registered users can apply additional filters such as setting the combination algorithm or removing domains marked as unsafe by Google Safe Browsing database.

It should be noted that not all entries in this list resolve to IP addresses: at the time of this writing, for example, 74 listed domain names out of the top 500 and 83,519 (8.3%) of the top 1M do not resolve to an IP address (i.e., have no DNS A records). The main reason for this is the trimming behavior mentioned above that causes the list to include domain names belonging to CDNs, cloud service providers, or infrastructure operators, e.g., akamaiedge.net, which do not resolve to IP addresses at that level. Creating a custom list with subdomains beyond the eSLD partly solves this issue but...
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<tr>
<th>Year</th>
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<td></td>
<td>TLS over domains in Common Crawl</td>
<td>Facility</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>X.509 ICSI over research net</td>
<td>Facility</td>
</tr>
<tr>
<td>2018</td>
<td>Scheitle et al.</td>
<td>CT Logs</td>
<td>TLS from UC Berkley net</td>
<td>Facility</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TLS over 423M domain names</td>
<td>Facility</td>
</tr>
</tbody>
</table>

†‡ Year, Authors, Context, Data collection: Year and Authors are the year of publication and the authors of the work, respectively. Context describes the context of the work, such as generic, CDN, or Heartbleed. Data collection includes specific data collection methods and time frames.

Measurement Features: Fundamental features include CA share and CA market share. Derivative features might include CA ownership and market share, shared certificates, and CRL sizes. Time frames for data collection and measurement are also provided.
results in inclusion of public suffixes such as gob.es or ca.us. Beside a few exceptions (e.g., gov.uk), public suffixes do not resolve to IP addresses and some browsers (e.g., Chromium based) even consider them as a search query (and not a URL) when entered in the address bar.

Finally, the advertised options of filtering domains that resolve to an IP address, have a specific HTTP status, or return a minimum amount of HTTP content (see original publication[79]) were not available at the time of writing.

**CISCO Umbrella.** This is a popularity ranked list based on passive measurements of DNS queries over CISCO Umbrella network[1] (formerly OpenDNS services). Similar to Tranco, reproducibility is provided (by date), but in contrast to the Tranco list entries are not trimmed to their functional SLD.

This list suffers from three handicaps. First, about every fifth entry in the top 500 list (total of 118) does not resolve to an IP address. Second, multiple subdomains of the same company or domain names sharing the same eSLD can cause measurement data skew. For example, more than half of the top 25 entries (14 in total) are related to netflix.com or netflix.org. Finally, opaque ranking and normalization algorithms used to generate this list are also among the drawbacks of this list.

**Cloudflare Radar.** Similar to Cisco Umbrella, Radar statistics by Cloudflare are based on observations at own DNS resolvers (1.1.1.1). The data can be fetched over Cloudflare website or through its API which provides more detailed information. Beside a global ranking (over 1M domains), top 100 domains per country are also available. Domain names in this set are

https://umbrella.cisco.com

---

**TABLE II: Comparison of various hit lists**

<table>
<thead>
<tr>
<th>Name</th>
<th>Source Description</th>
<th>Scoped</th>
<th>Ordered</th>
<th>Entities</th>
<th>Entries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tranco</td>
<td>List Aggregation</td>
<td></td>
<td>✓</td>
<td></td>
<td>≈ 3.6M</td>
</tr>
<tr>
<td>CISCO Umbrella</td>
<td>Passive DNS measurements</td>
<td></td>
<td>✓</td>
<td></td>
<td>1M</td>
</tr>
<tr>
<td>Cloudflare Radar</td>
<td>Passive DNS measurements</td>
<td></td>
<td>✓</td>
<td></td>
<td>≥ 1M</td>
</tr>
<tr>
<td>Majestic Million</td>
<td>Active Web crawls</td>
<td>Web</td>
<td>✓</td>
<td></td>
<td>1M</td>
</tr>
<tr>
<td>Chrome Report</td>
<td>Browser telemetry</td>
<td>Web</td>
<td>✓</td>
<td></td>
<td>1M</td>
</tr>
<tr>
<td>HSTS Preload</td>
<td>Zone owner submissions</td>
<td></td>
<td></td>
<td></td>
<td>126k</td>
</tr>
</tbody>
</table>

†: active measurement; ‡: passive measurement; † includes only TLS and X.509 datasets; ‡ Irregular measurement

In combination with active and ICSI scans of the same study.
trimmed at effective second level domain.

The downside of this list is twofold. First, much like Tranco, trimming names at eSLD leaves a non-negligible portion of entries without a respective IP address. And second, similar to CISCO umbrella, we observe high ranking names that are never directly visited by users, e.g., doubleclick.net (advertising company).

Majestic. The Majestic Million [82] top list is a ‘link-level backlink index’ (popularity ranked) list based on data gathered from web crawls. The domain rank here (trimmed at eSLD) relates to (i) the number of its ‘External Inbound Links’, and (ii) counts of referring domain, IP, and subnets which are calculated during the crawl [83].

Among the top 500 domains in this list only 16 entries do not resolve to an IP address. Invalid entries are either public suffixes (e.g., go.id), private suffixes (e.g., azurewebsites.net), or simply miss a label (e.g., miit.gov.cn without www label).

The main drawback of this list is its limited scope to the Web. Using this as a point of departure to measure TLS in other contexts, such as SMTP, would require further steps (e.g., query MX records) and would defeat the ranking: facebook.com (rank 1) is only popular as a website and not necessarily as a mail server.

Chrome UX Report. As part of its user experience report, Google provides a popularity ranking of domain names based on data collected from Chrome browser users. The ranking is further divided by country, platform, and popularity metric [84]. In contrast to Tranco, host names are not trimmed at eSLD and Ranking is only provided ‘on a log10 scale with half steps’.

The main advantage of this list is having browser data as its main source which leads to a better accuracy compared to other top lists [89]. For example, only 10 out of the top 1000 names in this list do not resolve to an IP address at the time of this writing.

HSTS Preload List. Curated by Google as part of the Chromium Project, the ‘HTTP Strict Transport Security (HSTS [85] Preload List’ is a collection of domain names that supporting browsers contact only through HTTPS. At the time of writing more than 120k names are listed including public and private suffixes (e.g., .zip, and .now.sh), eSLD domains, and individual domain names including all subdomains (e.g., www.aclu.org). In contrast to the aforementioned hit lists, the entries here are not ordered and do not fulfill any specific criteria except supporting TLS. Moreover, not every domain name in this list is delegated (NXDOMAIN) or carry an A record.

C. Certificate Transparency Logs

To address the problem of ‘misissued certificates’, Certificate Transparency (CT) Logs [60], [86] were introduced. These are publicly available and auditable data structures that are modified in an append-only manner. CAs commonly log issued X.509 certificates in multiple CT logs allowing identity (e.g., domain name) owners or CA subscribers to detect misissued certificates for their identities by monitoring CT logs. Similarly relying parties, e.g., browsers, make use of CT logs. For example, Chrome and Safari browsers, with a combined global market share of over 90% [87], validate server certificates only if they are logged in multiple CT logs [88]–[90]. It is, thus, safe to assume that any certificate exchanged during a TLS handshake in a browser can be found in at least one CT log. Even certificates that are used for purposes other than server and client authentication (e.g., code signing) can partly be found in CT logs. The corollary to this observation is that CT-logged certificates, or more specifically their Subject Alternative Names (of type DNS or IP), can be used as point of departure for TLS measurements.

Note that due to wildcard certificates, it is not possible to discover every viable domain name from CT logs. In our TRANCO dataset (see Section A), for example, about 40% of all valid certificates have at least one wildcard SAN while less than 1% solely include wildcard names. Figure 7 depicts the frequency of certificates in our TRANCO dataset based on number of wildcard SAN entries and the total number of SANs in each certificate.

Finally, it should be noted that not every logged certificate is deployed on a TLS server. Cloudflare, for example, vicariously applies for two certificates for its customers: a production and a backup certificate to instantly replace it in emergency cases (e.g., key compromises) [91]. Furthermore, it is not possible to infer which service actively use a logged certificate (e.g., HTTPS or SMTP). Finally, for a given logged certificate (even if not expired or revoked) it is not guaranteed that the domain names that it covers is still delegated or resolves to an IP address.

![Fig. 7: Frequency of valid certificates in our Tranco dataset based on the number of wildcard and total SAN of type DNS in each certificate (capped at 100)](https://developer.chrome.com/docs/crux/)

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[https://www.chromium.org/hsts/](https://www.chromium.org/hsts/)
D. DNS Zone Files

The Internet Corporation for Assigned Names and Numbers (ICANN) allows interested parties to directly request generic TLD (gTLD) registries for their zone files through the Centralized Zone Data Service (CZDS). Zone files for TLDs are commonly used in DNS and DNSSEC measurements [29], [35], [75] but are also suitable in context of TLS and Web PKI (see, for example, Holz et al. [65]).

The downside of using DNS zone files is twofold: (i) not every TLD is part of CZDS and not every request is granted, and (ii) the massive amount of names in .com alone is estimated to have 160M delegations [92]—in no specific order poses a challenge for both the measurement procedure and interpretation. Merits of using DNS zone file as point of departure have been discussed in related work [29].

E. Indexing Services

Numerous commercial companies in the field of Internet measurement and scanning provide access to their data which can be used as a point of departure for TLS and Web PKI measurements. Two prominent examples are Censys Search [7] and Rapid7 Open Data [8]. Censys performs daily scans of the IPv4 address space and provides an API to query and search collected data. Data by Rapid7 is limited to its Open Data repository containing artifacts of regular scans by Project Sonar [93] and lacks search and query features.

Downside of using such services as data sources is lack of control and transparency on underlying scanning procedures. Wan et al. [67], for example, discuss how regular scans by Censys (using ZMap; see Section V) leads to its source IP addresses being blocked and consequently missing up to 4.6% of all HTTPS hosts. A similar phenomenon is also observed by Chung et al. [53] for datasets from Rapid7 and University of Michigan, suggesting that data from regular scanners are susceptible to being incomplete due to blacklisting.

F. Internet Traffic Monitors

Instead of collecting data, we could rely on data collected by traffic monitors. Passive measurements present an authentic snapshot of Internet usage but are usually limited in their scope, e.g., traffic on a university network, and require access to special network nodes.

Note that although using passive measurements for TLS and Web PKI analysis is widespread [47], [54], [58], [59], [62], [94], such data might not be suitable for specific use cases [29].

V. TOOLING

To draw a holistic picture of TLS and Web PKI numerous aspects need to be measured. Nearly all general-purpose programming languages offer implementations of common Internet protocols, e.g., TLS and HTTP. However, not all are appropriate for measurement purposes. For example, the standard crypto library of Node.js, a JavaScript engine, is limited to parsing selected fields from an X.509 certificate, and implementing client-side session tickets is a tedious task over its TLS API.

In this section we introduce some widely established tools for measuring TLS and Web PKI and discuss their merits regarding features introduced in Section III Table III provides an overview.

OpenSSL. An open source implementation of a wide variety of cryptographic algorithms and protocols, OpenSSL is used in client (e.g., curl) and server software (e.g., NGINX) alike and lends itself as an appropriate tool to collect and analyze TLS and Web PKI data.

It can be used programmatically through its C API or any of its CLI tools, such as s_client (a TLS client), or x509 (an X.509 certificate parser). However, manipulating low level details, e.g., of handshake (T2) and record layers (T3) or X.509 extensions (X3), is limited to its API. OpenSSL is capable of validating signed certificate timestamps (CT) (related to X2) and DANE records as well as revocation status over CRL, OCSP, and stapled OCSP (X4) if required resources, e.g., DNS resource records, are provided additionally.

OpenSSL suffers from four shortcomings: (i) low level API (e.g., manual memory management), (ii) non-machine-readable CLI output, (iii) partial nonconformity with RFCs (T1), e.g., OSCP response is not validated if signed by a designated entity and a complete certificate chain is missing (see RFC2560 guidelines [95, §4.2.2.2]). Standard distributions of OpenSSL also do not contain weak cipher suites which are relevant for (T2) and (T3). And (iv) higher level protocols are not implemented (T4).

curl. A command-line tool and library (libcurl) that implement various Internet protocols. curl is extensive in terms of configuration and protocol support (T4) but has its focus mainly on transferring data. As such, the CLI only provides a rudimentary option to print data in machine-readable format: either by selecting from a set of predefined keys or by printing all the keys in JSON format.

The drawbacks are as follows: (i) specific data, e.g., raw certificates, as well as granular access to handshake and record layers are (T2 and T3) not given over the CLI but only through libcurl. This API, however, is not as extensive as the underlying TLS engine, i.e., provides limited callbacks to OpenSSL functions or available cipher suites. And, (ii) curl is limited in parsing X.509 certificates and provides unstructured data over the CLI and uses its own structure over the API (X3). (iii) it does not support validation of SCT and OCSP (X4), and finally (iv) it cannot be configured to validate DANE (X2). By default, curl distributions are based on OpenSSL and inherit all respective shortcomings as discussed above. It is, however, possible to manually build curl with other TLS engines.

ZMap Project. ZMap is a network scanner similar to nmap but with a focus on modularity and speed [39]. It can be used both programmatically and over the CLI. Since its introduction, ZMap has been grown into a software suite including, among others, an application-layer scanner (ZGrab), a DNS lookup tool (ZDNS), and an X.509 certificate parser (ZCertificate) and linter (ZLint).
ZMap CLI tools produce machine-readable output in JSON format and can be combined using standard Linux pipes. For example combining `zmap`, `zls`, and `zgrab2` allows scanning hosts for various ports, detect services, and finally perform an application layer handshake.

ZMap accepts custom client hello handshakes and allows modifying record layer through cipher suites selection (T2) and (T3). It also supports various application layer protocols using (opportunistic) TLS (T4). X.509 certificates can be checked against standards, such as RFCs and ETSI, as well as other relevant policies, such as CA/B baseline requirements and browser PKI/CT policies (X1). It also implements certificate validation similar to common browsers but without integrating proprietary CRL lists (X2).

The shortcoming of ZMap Suite is twofold: (i) it only supports OCSP and not OCSP or CRL (X4), and (ii) it lacks built-in means to correlate DNS and X.509 to relevant DNS records (X5).

**TL.S-Attacker Suite.** A collection of tools and libraries in Java with a focus on security analysis of TLS servers and clients. Similar to ZMap it is capable of performing Internet-wide TLS scanning and vulnerability detection (T1). It also allows for fine-grained manipulation of TLS handshakes and exchanged messages (T2 and T3), and provides tools to parse and generate X.509 certificates (X3). Support for Web PKI aspects, however, are rather limited (see Table III).

**Testssl.sh.** A portable script to analyze security of SSL/TLS servers, `testssl.sh` checks for known TLS vulnerabilities (T2 and T3), and simulates TLS handshakes for a variety of known clients (e.g., Firefox 100 on Win 10). It also supports automatic certificate validity checking over CRL and OCSP endpoints (X4), and looks for DNS CAA records (without matching however).

This tool is rather suitable for administrators than performing measurement at large while lending itself as a good alternative for debugging single noticeable observations from measurement datasets. Disadvantages of `testssl.sh` can be summarized as follows: (i) its lack of an API, and its monolithic design that does not support modification without changing the core codebase, (ii) insufficient certificate information (X3) and lack of an option to store the full certificate chain, and finally (iii) file storage for results causes slow-downs in high concurrency measurements due to file system operation overhead (see Section VII).

**Goscanner.** This is command line tool written in Go language. It has the ability of fingerprinting TLS handshake using various methods [97], [98] (T2), validating and storing X.509 certificate chains (X2), and using custom handshakes when contacting servers. The output is stored in multiple files in CSV format.

**Puppeteer.** A Node.js library (JavaScript) that enables programmatic control of browsers which support Chrome DevTools Protocol (CDP). Although limited to the Web, measurements using Puppeteer can precisely simulate user experience (see Section VIII). It can, for example, properly follow redirects of various types (e.g., HTML and JavaScript) and extract certificates as presented by the browser to users. Puppeteer, however, is limited in scope by four factors: (i) the CDP protocol does not provide access to lower level API and many features are still experimental (e.g., retrieving certificates), (ii) Chromium configuration flags that define its behavior upon initiation are not well-documented, (iii) page navigation (equivalent to opening a tab in browser) spawns multiple processes and consumes a relatively high amount of resources (computation and memory). As the number of concurrent Puppeteer jobs increases, Puppeteer fails to properly kill Chromium process and free up memory. Finally, (iv) underlying browsers used by Puppeteer might exhibit non-standard behavior. Chrome, for example, artificially generates an HTTP redirect (status code 307) when encountering an HSTS header even if the server does not explicitly indicate a redirect.

<table>
<thead>
<tr>
<th>Tool</th>
<th>API</th>
<th>Command Line Interface</th>
<th>TLS†</th>
<th>X.509‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>OpenSSL</td>
<td>C</td>
<td>✘</td>
<td>O</td>
<td>✘</td>
</tr>
<tr>
<td>curl</td>
<td>C</td>
<td>✘</td>
<td>(JSON)</td>
<td>✘</td>
</tr>
<tr>
<td>ZMap Suite</td>
<td>GO</td>
<td>✘</td>
<td>O</td>
<td>✘</td>
</tr>
<tr>
<td>TLS-Attacker Suite</td>
<td>Java</td>
<td>✘</td>
<td>DB</td>
<td>✘</td>
</tr>
<tr>
<td>testssl.sh</td>
<td>✘</td>
<td>✓</td>
<td>CSV / JSON</td>
<td>✘</td>
</tr>
<tr>
<td>goscanner</td>
<td>✘</td>
<td>✓</td>
<td>CSV</td>
<td>✘</td>
</tr>
<tr>
<td>Puppeteer</td>
<td>Node.JS</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

† T1: verifies conformity to TLS standards / T2: can manipulate handshake layer messages / T3: can manipulate record layer messages / T4: implements relevant application layer protocols
‡ X1: verifies conformity to X.509 standards / X2: can manipulate certificate similar to a browser (except proprietary CRL lists) / X3: can fully parse certificate / X4: can evaluate revocation status / X5: can relate the certificate to DNS records

https://chromedevtools.github.io/devtools-protocol/
VI. PREPARING MEASUREMENTS

Depending on the measurements goals, we need to take different aspects into considerations before initiating the actual measurement. Here we address getting familiar with best practices, and choosing appropriate vantage point and measurement features, and subsequently provide a brief discussion on proper documentation for reproducibility, and software/hardware validation in advance.

A. Best practices

Performing measurements, specifically large-scale or Internet-wide, can be a source of disturbance, e.g., can be regarded as malicious attacks to infrastructure operators. Here we discuss two aspects that must be considered before performing a measurement.

Ethical considerations. Durumeric, Wustrow, and Halderman [39 §5] recommend 7 practices that address ethical aspects of Internet-wide measurements ranging from coordinating with local network admins to information provision at source DNS and IP addresses, and catering for simple opt-outs. Partridge and Allman [99] go beyond technical means and discuss ‘tangible harm to people’ that can be caused by active measurements. In a recent paper, Pauley and McDaniel [100] provide an overview of previous work of ethical measurement, summarize existing community guidelines, and discuss recommendations to establish an ‘ethical framework’ for Internet measurements.

Responsible disclosure. If security vulnerabilities are detected during measurements, researchers are encouraged to inform affected entities through Coordinated Vulnerability Disclosure (aka Responsible Disclosure), Governmental organization (e.g., US CISA or Germany’s BSI), standardization institutes (e.g., NIST or ETSI), and other relevant entities have their own guidelines and procedures to document and submit vulnerabilities. The CERT Guide to Coordinated Vulnerability Disclosure [101] is, for example, a comprehensive guide by Carnegie Mellon University.

B. Vantage Points

The physical location where measurements are performed can have a twofold impact on the results in terms of reachability, and consistency. As such, same measurement (method and target) from different vantage points can lead to different results.

Reachability. Wan et al. [67] discuss how host reachability can vary depending on the vantage point. They show how the origin location in single-probe IPv4 address space scans can lead to missing around 5% of all HTTPS hosts in the worst case (See Censys in Section IV). Reachability itself, however, can be subject of measurement instead of being a mere measurement artifact, e.g., in censorship studies (see, for instance, Raman et al. [68], [102]). In such cases it is desired to measure data from specific vantage points to study reachability, even by crowd-sourcing the measurements through platforms such as OONI [103] or RIPE Atlas [104] to avoid detection or blocking.

Consistency. Depending on the vantage point, the same domain name can be resolved and routed to different IP addresses, e.g., to the nearest point of presence of a cloud provider. Lee et al. [69] show how different edge servers hosting content for the same domain name can be configured differently with respect to TLS security.

C. Measurement Features

We need to define the feature sets that we want to record for each host when performing a measurement. For example, if we are only interested in X.509 certificates, TLS record messages and any application layer data can be ignored while further information such as DANE records or CRL and OCSP data needs to be fetched in addition.

These features are related to entities depicted in Figure 2 and can roughly be categorized as technical and non-technical. The former category is summarized in Section III and comprises (i) TLS handshake and record layer features, e.g., supported cipher suites, (ii) DNS related resource records, e.g., TLSA records and DNSSEC chain, and (iii) Web PKI entries, e.g., X.509 chains and OCSP signer certificates. We categorize other features that are not manifested in technical terms but might be relevant for analysis, interpretation of data, or reproducibility of results as non-technical. For example, applicable CP/CPS documents of CAs or government regulations at the time of study belong to this category (see Section VIII).

D. Documentation for Reproducibility

To establish measurement results, it should be reproducible, i.e., it should be possible to reach to the same results using the same procedure or artifacts [105]. We refer to related work [106]–[109] for an extensive discussion of best practices and challenges of reproducibility. Here, we confine ourselves to a brief overview regarding software and data.

Software. When using off-the-shelf software (see Section V), the exact version must be noted. For open source software a reference to specific state, e.g., a git branch or commit, is preferable. Any modification to the software must also be documented, e.g., using inline comments, accompanied by a short reason, e.g., bug in original software.

Hard coding configurations should be avoided, and measurement parameters should be externalized in dedicated files. Similarly, the list of dependencies (software and system alike) should be documented and provided in a readily installable format, e.g., pip freeze and pip install -r for Python software. Optimally, a configure script (e.g., generated by GNU Autotool) can help other researchers to check their systems for missing libraries and other dependencies.

Instruction should be provided on how to start, configure, and optimize each program for measurement. Respectively, structure and content of generated output and error codes must be disclosed. A step-by-step manual to execute a complete measurement must also be available. To reproduce a specific measurement exact configuration and input parameters through platforms such as OONI [103] or RIPE Atlas [104] to avoid detection or blocking.
(e.g., list of measured hosts) alongside deployment settings (e.g., vantage point) are to be provided.

Source code, configurations, and even dependencies can be bundled together, e.g., in a container image, to cater for easier and faster bootstrapping. Some tools also define virtual environments that can be exported and imported on any arbitrary system.

Data. A measurement might consist of multiple phases where output from one phase is fed as input to another. Moreover, utilized software might implicitly (e.g., due to convention over configuration) rely on files that differ from one execution environment to the other. For example, OpenSSL is shipped with a set of default configurations (e.g., path to trusted CAs) that impact certificate validation and other operations. Both implicit and explicit data (files) are required for reproducibility. Each piece of information should be accompanied by metadata describing its content, structure, timestamps, etc.

The granularity of data is also relevant. Instead of providing only end results, having interim data for each step of the measurements allows others to verify correctness of the overall procedure. For example, in place of stating if a host supports stapled OCSP, TLS handshake containing OCSP response alongside the CA certificates (from local trust store) used to validate it should be provided.

E. Validation of Software and Hardware

The final step in preparing measurements is to validate the software and hardware before executing the complete measurement. Wan et al. [67], for example, runs their measurement in small scale (1% or IPv4 address space) from all selected vantage points to confirm that both software and hardware can reach desired scanning speed while avoiding extraordinary packet drops.

VII. Performing Measurements

After we have determined our source and a set of features, the actual measurement can be started. In this section, we discuss the importance of maintaining temporal integrity while collecting data from different sources, different types of stateful measurements, detecting and handling errors during measurement, and finally how to best store data.

A. Temporal Integrity

There are numerous pieces of temporally bound data that we might collect during our measurement from various sources: Table IV provides an overview. To make sure that our measurements capture a correct snapshot, we must make sure that we measure these features with short temporal discrepancies. That is to reduce the time distance between probing related features, for example by querying DNS A records and establishing the TLS connection, or fetching certificates and validating OCSP response. Nawrocki et al. [74], for example, notes how a short time difference between two measuring X.509

<table>
<thead>
<tr>
<th>Type</th>
<th>Source</th>
<th>Collected at</th>
<th>Temporal indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNS RR</td>
<td>Auth. NS</td>
<td>DNS resolution</td>
<td>TTL field(^\d)</td>
</tr>
<tr>
<td>DNSSEC</td>
<td>Auth. NS</td>
<td>DNS resolution</td>
<td>Inception / expiration fields(^\d)</td>
</tr>
<tr>
<td>X.509 cert</td>
<td>Server</td>
<td>TLS handshake</td>
<td>Not before / not after fields(^\d)</td>
</tr>
<tr>
<td>TLS session</td>
<td>Server</td>
<td>TLS handshake</td>
<td>Lifetime hint(^\d)</td>
</tr>
<tr>
<td>Stapled OCSP</td>
<td>Server</td>
<td>TLS handshake</td>
<td>This update / next update(^\d)</td>
</tr>
<tr>
<td>OCSP</td>
<td>CA</td>
<td>CA OCSP endpoint</td>
<td>This update / next update(^\d)</td>
</tr>
</tbody>
</table>

\(^\d\) Relative / \(^\d\) Absolute

TABLE IV: Selected measurement features which are temporally bound and are collected at various sources

certificates can result in collecting different certificates for the same host due to key roll-overs. Zirngibl et al. [110] observe in their analysis of QUIC how Google rotates certificates for googlevideo.com even before these are expired. Finally, in their study of DANE use by SMTP servers, Lee et al. [75] notes the necessity of maintaining temporal integrity and collects DANE records and X.509 in an atomic operation. Figure 8 depicts temporal values for different records that we collected for our TRANCO dataset.

B. Stateful Measurement

Some aspects of TLS cannot be analyzed based on one-off and stateless measurements. In the following we discuss cases that require measuring same servers multiple times or measuring different servers in the same context and with respect to each other.

Same host and settings. Here, for each host in the sample set multiple measurements are performed. For example, Liu et al. [52] observe that some servers deliver stapled OCSP only if it has already been cached locally [52 §4.3], so to determine if Stapled OCSP is supported, multiple successive measurements are to be performed. In a later study [63], the authors expand

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\(^\d\) Can be printed using openssl version -d command

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their scope to investigation of OCSP responders using hourly measurements in a longitudinal study (4 months period) from multiple vantage points, practically forcing servers to always query and cache OCSP responses.

**Same host with different settings.** In other cases, we might need to alternate measurement settings and parameters. For example, discovering how TLS sessions are implemented and deployed requires performing multiple handshakes with and without session IDs or tickets. In a study from 2018, Sy et al. [6] regularly establish TLS connections to Alexa Top 1M sites and show how TLS resumption can be used to track visitors. Hеброк et al. [46] examine cryptographic issues of TLS resumptions by executing 10 TLS handshakes for every (virtual) host while storing session keys alongside session tickets. Furthermore, collected session tickets were modified to check for server-side authentication vulnerabilities.

**Different hosts with same settings.** In some cases, we need to perform subsequent measurements based on information retrieved during an initial measurement of a sample. For example to study TLS sessions that are shared among virtual hosts at the same or among different servers. Sy et al. [11] show performance advantages of sharing session among domain names given that they are all controlled by the same entity. Similarly, Springall, Durumeric, and Halderman [55] study shared TLS session among different domain names but set the focus on security ramifications instead of performance. For this, session tickets were collected regularly over a period of 9 weeks and finally compare with each other to detect, among others, security risks of servers reusing session cache, session ticket, and Diffie-Hellman parameters.

**Different hosts with different settings.** Finally, there are cases that an initial measurement of a single sample is used to define and perform measurements on related samples but under different settings. An example is the family of TLS confusion attacks. This is an umbrella term referring to a type of MitM attacks where an attacker manages to divert TLS traffic from intended server to another without the client noticing.

Delignat-Lavaud and Bhargavan [3] show how a TLS terminating proxy server can be tricked into redirecting HTTPS traffic meant for a virtual server to another. The anecdotal examples of this study are extended by the systematic analysis of Zhang et al. [66] where for a set of host names sharing an X.509 certificate TLS connections are made to different IP addresses and ports. Brinkmann et al. [70] introduces a cross protocol variation of TLS confusion attacks where traffic is diverted from one protocol to another, e.g., HTTPS to SMTPS.

C. Failure handling

Misconfigurations, blackouts, deficient workflow, and software bugs are among causes for measurement errors and failures. It is, thus, integral to detect errors early on and subsequently be capable of resuming measurements without having to start atop.

**Detecting sources of error.** Nearly all tools discussed in Section IV support debug mode which can be used to print extra operational information to standard error stream. Debug and error messages, however, are not always in machine-readable format or include necessary information (e.g., passed arguments) to detect causes for failure. Another (complimentary) approach is to dump data packets in transit during measurements, e.g., using Wireshark, and to dissect them in case of failures that cannot be debugged otherwise.

**Detecting measurement artifacts.** In addition to technical failures, such as software bugs, that manifest themselves in error logs, software crashes, etc., deficiencies in measurement techniques can lead to measurement artifacts. This kind of error is harder to detect and commonly materialize itself after inspecting measurement results. For example consider the measurement agent being marked as bot by cloud providers or having a TLS connection terminated due to lack of SNI. In both cases the logs will not indicate any failures, but the software has practically failed to capture a truthful snapshot. Although not all measurement artifacts can be avoided, it is important to monitor measurement for any cases that might serve as an indication.

**Resuming measurements.** Specially in case of large-scale measurements or limited resources, it is desirable to be able to resume failed measurements, i.e., skip successful measurements, rerun failed ones, and continue with the rest. None of the tools with built-in batch process (see Table III) supports measurement resumtion. To address this shortcoming, tools can be wrapped inside process managers, e.g., GNU Parallel [112], that are able to parallelize and monitor processes and cater for resumption in cases of failures.

D. Data Storage

Measurement data can are commonly stored in traditional databases (e.g., TLS-Attacker), flat-file databases (e.g., Z-Map suite), or simple files (e.g., per certificate, per TLS handshake, etc.). Storing each feature in a single file simplifies searching and filtering but the added overhead due to file system and disk I/O operations can lead to throttling measurement speed and parallelization.

In practice, a mixture of all strategies might be chosen. Holz et al. [54], for example uses Z-Map to discover viable hosts, collects data using OpenSSL and stores the result in a database.

VIII. INTERPRETING DATA

After designing and performing measurements, we need to interpret data. In this section we discuss a number of pitfalls that can skew measurement-based conclusions and insights.

A. Certificate Subjects

It might be useful to detect the subject of a certificate, for example, to detect if a certificate is being shared among distinct service providers [49], [56]. Depending on validation type (DV, OV, IV, and EV; see Section II) corroborating data might be needed to uniquely identifying a certificate owner.

For EV certificate, the subject name explicitly denotes the entity running a website, i.e., the organization responsible for its content [19] §2.1.] and is sufficient to extract the
certificate owner. In contrast, OV and IV certificates identify the certificate applicant [16 §3.2.2.]. In case of delegated services [49], e.g., when a CDN operator vicariously applies for a certificate, the subject might actually identify the delegator and not the delegator and cause a misinterpretation of the certificate. Cloudflare, for example, uses OV certificates with its own identity information for its free-tier customers—a marketing stunt that can be avoided by upgrading to paid plans [113].

DV certificates pose the biggest challenge, as the only subject information is provided in form of SANs (domain name, IP addresses, etc.) and cannot be used to identify the certificate owner. Although SAN entries are supposed to be alternative names of the same subject, there is no guarantee that all entries actually denote the same owner. Multitenant infrastructure operators, e.g., Google and Imperva, list domain names of different customers as SANs of the same certificate. To address such issues, Cangialosi et al. [50 §4.1], for example, devise a method based on e-mail addresses included in DNS WHOIS data to infer if two domain names belong to the same organization. This method, however, might be less fruitful for future measurements as information in WHOIS databases are more restricted nowadays due to privacy concerns and regulations such as EU GDPR.

B. Certificate Issuers

Each certificate denotes its issuing and signing CA in its issuer field. Understanding the role of CAs in the Web PKI has also been part of research. Durumeric et al. [48], for example, give a detailed overview of CAs (e.g., country of origin and market share) alongside an analysis of which type of organizations (e.g., libraries, museums) are awarded with unconstrained intermediate CA certificates (see Section II). Fadai et al. [114] go further and investigate CAs in terms of corruption, human rights, etc. at their respective country of origin.

Identifying the operator of a CA using only its (subject) name is, however, a non-trivial task as Ma et al. [73] notes. The authors show, for example, how a given root CA does not refer to its operator, DigiCert, in its subject name (CN=Hotspot 2.0 Trust Root CA - 03; O=WFA Hotspot 2.0; C=US). Looking at DigiCert PKI repository [17] also reveals a number of other root CAs operated by DigiCert but under different subject names such as Baltimore CyberTrust Root, GeoTrust Primary Certification Authority, etc. The respective impact on research data interpretation is twofold: (i) analysis that based on identity of CAs requires additional care. For example, 5 out of the 14 listed CAs in the market share statistics by Aas et al. [64, §7] all belong to DigiCert. And (ii) knowing the actual operator behind CAs helps understanding specific trends. For example, why all banks in our IR-BANKS set are subscribers to an obscure CAs (Unizeto) as we discuss in the next subsection. Figure 9 depicts the market share of CAs from our TRanco dataset divided by trust anchors (colored boxed) and intermediate CAs (nested boxes). The size of each box is directly proportional to the number of leaf certificates issued by respective intermediate CA. Some labels are removed due to space constraints.

C. CA Operational Policies

All relevant information from applicability of a certificate to its issuance, revocation, and definition of custom OIDs are defined in CP and CPS [115, 116] of its CA.

These documents might be helpful in better understanding abnormalities in measurements. For example, all Iranian banks (in IRB set) use certificates issued by Unizeto Technologies, a Polish CA, while none of the banks in our ECB set (except the PKO Bank Polski in Poland) subscribe to that CA. Consulting CP and CPS document for the QuoVadis and DigiCert (the former being a subsidiary of the latter) that cover more than

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half of all European bank and credit institutes reveals that DigiCert is prohibited by the US law to provide any services to countries or companies on a government denied list \[117\] §4.1.1, e.g., Iran.

When considering CP and CPS documents, three aspects should be regarded. First, although RFC3647 \[116\] streamlines the structure of CP and CPS, the terminology and concepts applied might vary among CAs. Second, in practice CAs do not necessarily behave in conformance with their own or other relevant guidelines. For example, the ECC CA-3 intermediate CA certificate from Cloudflare\[4\] carries OIDs for DV, OV, and IV validation types, and violates both its issuer CP \[118\] §3.2.2 (IV certificates are issued to individuals) and CA/B Baseline Requirements \[16\] §7.1.2.7.3 (IV certificates must carry surname and givenName in their subject field). And third, there is no guarantee of logical coherence. Let’s Encrypt, for example, asserts no relationship between subscribers and registrants of domains names in a certificate \[119\] §3.1.4) in its combined CP/CPS and in the same document requires subscribers to be the legitimate registrant of respective domain names \[119\] §9.6.3.

D. Certificate Validity

Authentication presupposes presentation of a valid certificate. Beside formal requirements (see RFC5280 \[11\]), a relying party validates the certificate methods and validity criteria. The most basic form of validating a certificate is path validation described in RFC5280 \[11\]; validation succeeds if certificate subject matches the desired subject and if there is trusted path to a trust anchor (root). Depending on the relying party (user) or the client it uses (e.g., a web browser), the set of trust anchors and validation policies might differ. Respectively, to verify if a collected certificate is valid three features needs to be defined: (i) trust store, (ii) revocation status, and finally (iii) additional policies.

Trust Stores. Major browsers, operating system vendors, governments, and even individual organizations maintain sets of trustworthy certificates (intermediate and root CAs; see Figure 2). Although users are generally oblivious to their role, trust stores are integral in securing or jeopardizing the security \[25\] of users daily communications.

Each trust stores maintainer has its own set of requirements for incorporating a CA: for example, through consensus it was the case for Debian OS (ca-certificates package \[120\]), well-defined policies (including undergoing audits and conforming to requirements) as in Mozilla Root Store Policy \[121\], or by establishing a legal framework as in the EU eIDAS Regulation \[122\] Article 24. Related work has extensively studied root stores and their relation to each other \[114\], \[123\]–\[126\].

Beyond established trust stores, users may also decide to trust CAs by adding them manually or through software installations. It is, for example, common practice for online banking software in South Korea to install additional CAs in local trust stores \[127\]. The impact of such settings can also be observed in TLS measurements.

E. User Perspective

Users interact with TLS-secured server through a client: a web browser, mail client, smartphone app, or alike. Depending on measurement approach, a discrepancy might arise between what collected data reveals and what users actually experience in their daily interactions over the Internet. Here we show how users experience using a web browser might differ what measurements might reveal and discuss 4 aspects: (i) point of access, (ii) redirects and resources, (iii) certificate validity, and (iv) bot and intrusion detection.

Point of access. Domain names were introduced to take the burden of remembering IP addresses from users. However, instead of remembering domain names and navigating to them, users navigate the Internet through the lens of search engines, social media, and streaming services \[133\]. Research shows that users in part take browser address bar for a search bar and have difficulties in differentiating components of domain names and URLs in general \[134\].

When choosing a data sources (see Section IV), it should be taken into account that users might never (directly) encounter or interact with items in that source. For example, mtalk.google.com—at position 110 of Cisco Umbrella Top 1M (for list 2023-06-21)—is an endpoint used by Google for push notifications and is never visited directly by users. The same applies for IP addresses: when scanning the IP address space, endpoints such as home routers might be discovered that are only publicly accessible by misconfiguration.

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1\[https://crt.sh/?id=2392142533\]
Redirects and Resources. Redirects are common on the Web: HTTP (3xx status codes), JavaScript (window.location property or History API), or HTML (http-equiv meta tag) all provide means to redirect a URL to another. During redirects, browsers establish new TLS connections that are not signaled to the user. For example, navigation to google.com triggers a redirect to www.google.com whereby only the connection and certificate information for the latter connection are presented to the user. The connection attributes or certificates provided at each redirect are not necessarily the same as the previous or next step: google.com provides a different certificate compared to www.google.com. Furthermore, when users navigate to a webpage, additional TLS connections to possibly different hosts are established to fetch resources such as scripts and stylesheets.

The role of redirects can be observed from the measurements of our TRANCO dataset as depicted in Figures 10a and 10b. The former figure depicts the frequency of total HTTP and HTML redirects in relation to the total number of unique certificates as observed by our custom libcurl script (corresponding to step P.3 in Figure II). Although the majority of domain names are redirected less than 3 times with 1 or 2 unique certificates in the redirect chain, we observe that as the ranking increases (i.e., popularity decreases) both the length of redirect chain and number of unique certificates increase. Note that certificates are not validated here. The host names of TLS secured servers at the end of each redirect chain is then fed into a browser (corresponding to step M.1 in Figure II). Figure 10b shows the results. Here, JavaScript redirects are also followed while only valid certificates are considered. Similarly, we observe that over 98% of all hosts having no extra redirects.

Certificate validity. Understanding how often users face invalid certificates, requires understanding the validation context as described above. The impact of having the proper context is reflected in the discrepancy between studies that use generic contexts and those using the actual context of relying parties, e.g., browsers. Oakes et al. [45], for example, collect complete certificates chain directly from users’ machines and observe that 99.7% of all collected chains, i.e., those used by clients, are valid. In contrast, other studies based on IPv4 scans on generic root stores classify the majority of certificates (ranging between 66% and 88%) as invalid [53, 76]. Similarly, a study by Holz et al. [54] observes that passively collected data exhibit salient percentages of valid certificates in comparison to certificates collected by active scanning of IPv4 address space.

Another source of discrepancy is the proprietary revocation lists discussed previously. Liu et al. [52], for example, show how CRLSets (Google) only cover a fraction of all certificate revocations, so there is a chance that a Chromium-based browser would validate a certificate even though it has been revoked. Note that none of the tools introduced in Section V (except Puppeteer) have integrated nor apply these lists.

Finally, user clients are more robust in correcting malformed certificates chains (wrong order, duplicate certificates, missing intermediates, etc.) which might, for example, cause OpenSSL to mark a certificate chain as invalid when using default settings. In our measurement of TRANCO dataset, we observe that about 70% of all hosts provide the shortest verifiable trust chain (from leaf to root) as depicted in Table V (column 0). The rest is either providing more certificates (columns 1 and 2), e.g., cross-signed variation of root certificates, or fewer certificates (columns -3, -2, and -1), e.g., missing intermediate certificates. Whereas providing extra certificates can be considered as an attempt to increase compatibility, e.g., to cover cases where a root certificate is not yet included in a trust store, leaving intermediate certificates out might lead to certificate invalidation, e.g., when intermediate certificates
TABLE V: Difference between the length of valid certificate chains as delivered by servers in our TRANCO dataset and the length of the shortest valid chain built against Mozilla trust store (frequency in %).

<table>
<thead>
<tr>
<th>Tranco ranking</th>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1, 100)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>69.23</td>
<td>25.64</td>
<td>5.13</td>
</tr>
<tr>
<td>[100, 1k)</td>
<td>0</td>
<td>0.14</td>
<td>0</td>
<td>73.13</td>
<td>16.76</td>
<td>9.97</td>
</tr>
<tr>
<td>[1k, 10k)</td>
<td>1.45·10^{-5}</td>
<td>0.31</td>
<td>0</td>
<td>68.99</td>
<td>20.33</td>
<td>10.36</td>
</tr>
<tr>
<td>[10k, 100k)</td>
<td>2.85·10^{-6}</td>
<td>0.8</td>
<td>1.42·10^{-3}</td>
<td>65.55</td>
<td>25.28</td>
<td>8.36</td>
</tr>
<tr>
<td>[100k, 500k)</td>
<td>8.04·10^{-5}</td>
<td>1.01</td>
<td>1.93·10^{-3}</td>
<td>67.16</td>
<td>26.72</td>
<td>5.1</td>
</tr>
<tr>
<td>[500k, -)</td>
<td>6.81·10^{-3}</td>
<td>0.78</td>
<td>8.29·10^{-4}</td>
<td>69.79</td>
<td>26.78</td>
<td>2.64</td>
</tr>
</tbody>
</table>

are not explicitly configured by the relying party.

**Bot and Intrusion Detection.** Some infrastructure operators, *e.g.*, Akamai [135], offer bot detection solutions to block unwanted or malicious access. Such systems might block measurements if they flag the utilized tool as non-human and skew the results respectively.

**F. TLS security**

TLS Attacks make use of protocol flaws, implementation deficiencies, or cipher suite and extension weaknesses. For an attack to be realistic, both endpoints must be susceptible to the respective attack vector. For example, while security shortcomings of TLS 1.0 and 1.1 are known (see RFC8996 [10]), none of mainstream browsers support these versions anymore, so that a web server supporting TLS versions 1.0 up to 1.3 does not in practice pose a higher security risk to users (with an up-to-date browser) than a server only supporting TLS 1.3. Another example regards TLS session resumption: Cloudflare deploys a global memory cache to store TLS session parameters [136]. It allows using a session ticket acquired for a given domain name (denoted in SNI extension) to be used for another domain name hosted at Cloudflare even if the certificate provided at the initial connection does not match the second domain name. Browsers, however, bind TLS sessions to domain names and not just IP addresses, so that this specific situation cannot be abused without compromising the browser first.

**G. Data from Mixed Sources**

In Section VI we discussed the impact of vantage point and importance of maintaining temporal integrity. These aspects must also be regarded when interpreting data from mixed sources. Cangialosi *et al.* [56], for example, use WHOIS data from third party sources to distinguish between domain name owners and subsequently detect private key sharing among distinct service providers. The temporal discrepancy between data from the original and the third party sources can lead to false identification of a domain name owner. A study by Liu *et al.* [52] is another example that relies on data from both passive and active measurements from different sources and times.

**H. CAA Resource Records**

DNS CAA records enable domain name owners to indicate which CAs are authorized to issue certificates for their names (see Section II). Although CAA RRs are not relevant for users, from a research perspective they provide insights into internal organization of CAs.

The main challenge in verifying if a CAA records matches the certificate issuer is twofold: (i) there is no centralized database containing a mapping between CAs and CAA value, and (ii) given a certificate, the actual issuing organization cannot always be uniquely detected as discussed above. To address the former issue, Mozilla provides a list of CAAAs as part of its Common CA Database [17] which is composed on a best-effort basis and is neither exhaustive nor necessarily up-to-date.

For our dataset, we took Mozilla CAA identifiers from 2023-05-04 as a point of departure and manually matched each identifier with respective CA. To do this, we looked at repositories of each CA and enumerated intermediate CAs. The results reveal a rather confusing state of CAA identifiers that makes a mapping to CAs very difficult. For example, DigiCert matches multiple CAA values (*e.g.*, geotrust.com, thawte.com, and rapidssl.com), and the Dutch Government relies on various CAA [13] each with their own identifiers (*e.g.*, www.pkioverheid.nl and kpn.com).

In our TRANCO dataset, we observe only 90,750 (3.76%) of all entries provide an RFC conform CAA entry. Out of which 15% do not match the provided certificate using the method provided above, and about one third belong to Let’s Encrypt certificates. We also observe 1142 entries that are not parsable (wrong quoting or escaping, email addresses instead of domain names as value, *etc.*) or have the reserved bit set.

**IX. Conclusion**

The TLS protocol, as a mean to establish secure communication channels over the Internet, and the Web PKI, as a common basis for TLS authentication, have been a popular target of Internet measurements. In this tutorial we first introduced a systematic approach to TLS, Web PKI, and their interplay, and used it to work out relevant aspect comprising potential data sources, measurement features and attributes, and temporal aspects of measurements. We provided an overview of tools most commonly used for TLS and Web PKI measurements, discussed how to prepare, and perform measurements, and finally demonstrated various pitfalls in interpreting measurement data.

We discovered discrepancies and even contradictory findings in related works and discussed probable causes, and how such cases can be avoided when designing, performing, and interpreting own measurements. In addition, the summary of related work of the past decade provided in this work can serve as an overview of which aspects of TLS and Web PKI measurements have previously been subject of study and how these measurements have been performed.

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1. [https://ccadb.my.salesforce-sites.com/ccadb/AllCAIdentifiersReport](https://ccadb.my.salesforce-sites.com/ccadb/AllCAIdentifiersReport)
2. [https://cert.pkioverheid.nl](https://cert.pkioverheid.nl)
ACKNOWLEDGMENTS

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REFERENCES


**TABLE VI: Datasets used in this paper**

<table>
<thead>
<tr>
<th>Name</th>
<th>Entries</th>
<th>Source</th>
<th>Access Date</th>
<th>Measurement Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRANCO</td>
<td>3.77 M</td>
<td><a href="https://cdns.tranco.net/list/tranco-list">tranco-list</a></td>
<td>2023-06-14</td>
<td>2023-11-07</td>
</tr>
<tr>
<td>EU-FINANCE</td>
<td>4 k</td>
<td>EU Central</td>
<td>2023-06-12</td>
<td>2023-06-11(1,14)</td>
</tr>
<tr>
<td>IR-BANKS</td>
<td>28</td>
<td>Online search</td>
<td>2023-06-15</td>
<td>2023-06-15</td>
</tr>
</tbody>
</table>

**APPENDIX**

**DATASET USED IN THIS PAPER**

Beside the related work (summarized in Table I), we have conducted our own measurements which we use to exemplify and clarify the aspects that we discuss above. The following comprises a brief overview of our dataset (see Table VI), and our measurement and analysis method (depicted in Figure 11).

**A. Dataset**

We use three sets, comprising domain or institution names, as point of departure for our measurements:

- **TRANCO** Tranco full list
- **EU-FINANCE** List of EU Monetary Financial Institutions
- **IR-BANKS** List of Iranian Banks

Each dataset has been selected due to its unique properties. The first dataset, TRANCO, comprises most popular domain names (see Section IV). The second dataset, EU-FINANCE, was selected under the assumption that financial institutions apply security precautions that might be reflected in their choice of certificates or TLS setup. Finally, the list of Iranian banks, IR-BANKS, represents a group of institutions under US and EU sanctions but reliant on services from those country for their online operation. Table VI summarizes these datasets.

**B. Method**

We perform our measurements from a single vantage point in Germany. Before performing actual measurements, we run our initial data through two preparation pipelines. For the TRANCO dataset, we perform a reachability test and discard any domain name that doesn’t resolve to an IP address or is not reachable through ports 80 or 443. In case of EU-FINANCE dataset, preparation phase maps real-world institution names to domain names. Figure 11 depicts our method. Note that none of the entries in IR-BANKS are reachable from outside Iran so that our toolchain is not applicable. For this set we limit ourselves to X.509 certificates that we manually collected from CT Logs.

**Reachability test.** Domain names in the TRANCO dataset are not necessarily delegated or resolve to an IP address (see Section IV). To filter out unreachable hosts, we first try to resolve the given name to an IPv4 address (using Google 8.8.8.8 recursive resolvers). 12.8% of entries do not resolve to an IP address and a timeout occurs in 249 cases.

For all reachable hosts, we scan to see if ports 80 and 443 (HTTP and HTTPS respectively) are open. About 12k does not have port 80 open, 348k port 443, and 173k have neither ports open.

For all hosts and open ports we use a custom tool based on [libcurl](https://www.libcurl.org/) to contact the host over HTTP or HTTPS. In this process, we also follow HTTP and HTML redirects and record all intermediate domain names. We end up with 2.5M host names that were accessible over HTTPS. The host names from all HTTPS URLs at the end of each redirect chain are then used for the actual measurement as discussed below. Note that we don’t validate certificates at this step.

**Name mapping.** For our EU-FINANCE, we first need to map real world names to domain names. For this, we use Qwant, a French search engine which provides a free and publicly
accessible API. For each entry, we query the institution name and store matching results. We then generate a list of all domain names over all queries and sort it by occurrence frequency. Based on this list, we generate a blacklist of social media, encyclopedia, yellow pages, and alike. For each result page per institution we remove entries matching the blacklist and take the first remaining entry as the matching domain. Finally, the results are manually verified to remove any possible false positives. It should be noted that in contrast to entries in TRACO dataset, we already assume reachability for the results of this phase (search bot visits).

**Measurement.** For the actual measurement, we feed processed domain names from TRACO and EU-FINANCE datasets to Puppeteer (a headless browser; see Section V). Puppeteer enables us to have a similar experience to users when navigating to these domains. For each domain name, we again follow redirects (including JavaScript redirects) and store X.509 certificate chains alongside HTTP headers. We also collect A, SOA, NS, TLSA, and CAA DNS records for each domain name.

**Data analysis.** We use the crypto library from ZMap project to parse and validate certificate chains (step A.1) against Mozilla Root Store from 2023-01-15. To imitate browser behavior, we also manually include all non-expired and non-revoked intermediate certificates (from 2023-01-21) chaining up to the root certificates described above. In cases where multiple validation paths were available, for example, due to cross certification, we used the shortest for our analysis, e.g., CA market share. For DANE authentication we used the library from Shumon Huque. To match CAA records with leaf certificate issuers we took list of CAA identifiers from Mozilla Common CA Database, compared them with PKI repositories of respective CAs and enhanced the list with our own data.

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[1] https://curl.se/docs/caextract.html