The Case for Prefetching and Prevalidating TLS Server Certificates

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ABSTRACT

A key bottleneck in a full TLS handshake is the need to fetch and validate the server certificate before a secure connection can be established. We propose a mechanism by which a browser can prefetch and prevalidate server certificates so that by the time the user clicks on an HTTPS link the server's certificate is immediately ready to be used to setup a TLS session. Combining this with a recent proposal called Snap Start reduces the TLS handshake to zero round trips so that an HTTP request can be sent over HTTPS immediately upon request. Prefetching and prevalidating certificates improves web security by making it less costly for websites to enable TLS and by removing time pressure from the certificate validation process. We implemented prefetching and prevalidation in the open-source browser Chromium, and performed extensive experiments to study the effects of four different prefetching strategies on server performance. Along the way we conducted a study of a popular certificate validation mechanism called OCSP and report on the performance and characteristics of common OCSP responders in the wild. The OCSP data collected, which is of independent interest, enabled us to evaluate the effectiveness of prefetching and prevalidating in reducing TLS handshake latency. We show a factor of four speed-up over the standard TLS handshake.

1. INTRODUCTION

Web browsers and servers use the Transport Layer Security (TLS) protocol [11] to secure and authenticate sensitive data in transit, but TLS often presents difficulties for both clients and servers. TLS misconfigurations and certificate warnings are common and they can result in security vulnerabilities and usability problems [3] [35]. TLS-enabled servers face a heavier load [6] that discourages them from using TLS when possible, leading to session hijacking exploits [5]. Serving websites over TLS also increases client latency. In addition to negatively imapcting the user experience, even small additions to client latency can have an impact on website traffic, usage, and revenue [34]. In this paper we address the client latency imposed by TLS.

The standard TLS handshake requires two round trips before a client or server can send application data. The network latency imposed by the handshake impacts user experience and discourages websites from enabling TLS. The web browser must also validate the server's certificate using certificate revocation protocols such as the Online Certificate Status Protocol (OCSP) [30], adding more latency and leading clients to cache certificate validation results. Because high latency discourages websites from enabling TLS and forces browsers to compromise the freshness of certificate validation, there is a tradeoff between security and user experience. Decreasing TLS handshake latency can encourage wider use of TLS and improve web security.

Recent proposals have mitigated the TLS performance penalty by decreasing the number of round trips needed to perform a TLS handshake. A proposal called Fast-track removes one round trip from the handshake when the client has cached long-lived parameters from a previous handshake [33]. More recent proposals work only when the client sends data first, as is the case for HTTP. TLS False Start reduces the handshake to one round trip when whitelisted secure cipher suites are used [23]. TLS Snap Start reduces the handshake to zero round trips when the client has performed a full handshake with the server in the past and has cached static parameters [20]. Even when Snap Start is used, the client may not have the certificate's validation status in its cache, and the latency imposed by the certificate validation will still negatively impact user experience.

In this paper, we introduce server certificate prefetching and prevalidation, a method by which web browsers can perform zero round trip Snap Start handshakes with a server even if the browser has never seen the server before. In addition to enabling Snap Start handshakes, certificate prefetching allows the client to prevalidate the certificate, so that certificate validation does not lead to perceived latency for the user. By allowing browsers to use Snap Start more often and by removing certificate validation from the time-critical step of a page load, prefetching can encourage servers to enable TLS and allow browsers to verify certificate status more often and strictly.

The Chromium browser uses *DNS prefetching*, in which DNS resolutions are done long before they are needed. Our work applies prefetching to certificates, which has the additional benefit of enabling certificate validation before a user click.

1.1 Contributions

- We propose server certificate prefetching and prevalidation as a mechanism that significantly speeds up the full TLS handshake. We discuss four certificate prefetching strategies: (1) prefetch from DNS as part of a DNS domain-name resolution, (2) prefetch using an HTTP request to the server itself, (3) prefetch with an HTTP request to a content distribution network (CDN), and (4) prefetch using a truncated TLS handshake with the server. Once the server certificate is prefetched, the browser applies prevalidation to the certificate either by consulting a certificate revocation list (CRL) or by communicating with an online OCSP responder.

- We present detailed statistics from OCSP responders in the wild, including measurements of the validity durations and response times. We observe a noticeable penalty for TLS connection time due to OCSP. This data shows the strong benefits of certificate prevalidation, which eliminates the expensive OCSP check from the critical path. We also identify an interesting attack on private browsing modes that results from the implementation of OCSP in all major browsers other than Firefox.

- We implemented two prefetching methods (HTTP and DNS) in the open-source browser Chromium. Our implementation integrates with an experimental implementation of Snap Start in Chromium to obtain a highly optimized zero round trip TLS handshake protocol. We also implemented server-side Snap Start in OpenSSL to study the effects of prefetching and prevalidation on a TLS server's performance. We present results of experiments comparing multiple prefetching and prevalidation strategies and demonstrate their benefits.

2. BACKGROUND

In this section, we review the features of TLS, Snap Start, DNS, and OCSP that are relevant to certificate prefetching.

2.1 Transport Layer Security

TLS is a protocol for encrypting and authenticating traffic between a client and a server [11]. To set up a secure connection, the client and server perform a handshake in which each party can authenticate itself by providing a certificate signed by a certificate authority. Using a cipher suite negotiated in the handshake, the client and server agree on a key to secure the application data that is sent after the handshake.

On the web, TLS provides privacy and data integrity for HTTP traffic between a web browser and a website. Figure 1 shows a full TLS handshake using RSA key exchange and no client certificate, which is a common configuration on the web. The ClientHello and ServerHello establish an agreement between the client and the server on which version of TLS and which cipher suite to use. These initial messages also allow the client and server to exchange fresh random values used in deriving the session key, which prevents message replay. The client's random value includes the client's clock time. After the server has received the ClientKeyExchange message, both the client and the server can derive the master key with which the application data is encrypted. The ChangeCipherSpec messages indicate to the other party that subsequent messages will be encrypted with the negotiated cipher suite. Finished messages contain a hash of the entire handshake to ensure to both parties that handshake messages have not been altered by a network attacker. The client only sends the first application data, in this case an encrypted HTTP request, after two round trips between the client and server.

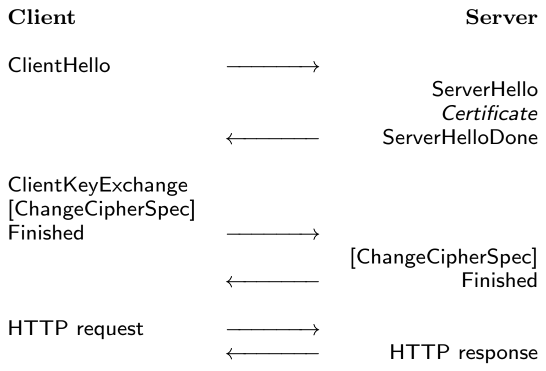


Figure 1: A standard TLS handshake, with RSA key exchange and no client certificate.

TLS allows connections to be established by resuming previous sessions. If a session is to be resumed in the future, the server provides a session ID in the ServerHelloDone message of the full handshake. To resume a session, the client begins a resume handshake by sending the saved session ID in its ClientHello. An extension called TLS SessionTicket allows session resumption without server-side state [32]. If the client and server both include empty SessionTicket extensions in their Hello messages, then the server sends a NewSessionTicket message after receiving the client's Finished message. The NewSessionTicket contains encrypted and authenticated state that the server needs to resume the session. To resume a session, the client sends its cached session ticket in the SessionTicket extension in its ClientHello. Session tickets are used to enable Snap Start handshakes that can be resumed.

TLS specifies an alert protocol for handling errors and connection closures. An alert may be sent at any point during the connection, and alerts specify a description (for example, `unexpected_message` or `bad_record_mac`) and an alert level of warning or fatal. Each party must send a `close_notify` alert before closing the connection. If either party sends a fatal alert at any point during the connection, then the server must invalidate the session identifier.

A proposal called TLS False Start, enabled by default in Google Chrome, removes one round trip from the TLS handshake [23]. In a False Start handshake, the client sends ap-

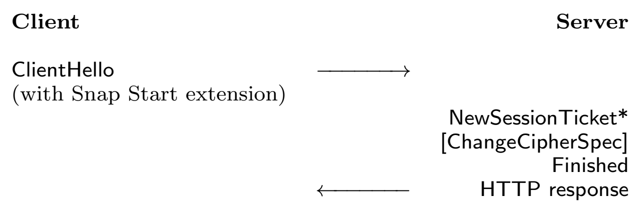


Figure 2: A TLS Snap Start handshake. The client's ClientKeyExchange, ChangeCipherSpec, and Finished messages, as well as the first HTTP request, are all sent in an extension in the ClientHello. Asterisk (*) indicates an optional message.

plication data immediately after sending its Finished message, without waiting for the server's Finished message. The server buffers the encrypted application data until after it has sent its Finished message, and then it processes the encrypted record. The False Start proposal argues that, as long as the client has negotiated a secure cipher suite, the encrypted data can only be decrypted by the expected peer. If an attacker has interfered with the handshake, neither the server nor the attacker will be able to decrypt the data that the client sent preemptively.

The hidden costs of TLS handshakes. A little-known but significant contributor to the cost of TLS is the modified browser caching behavior under HTTPS. We give two examples.

First, Internet Explorer will not use locally cached HTTPS content without first establishing a valid TLS connection to the source web site [24]. While web servers can use a `Cache-Control` header to tell the browser that certain content is static and can be used directly from cache, Internet Explorer ignores this header for HTTPS content and insists on an HTTPS handshake with the server before using the cached content (in IE9 this session is used to send an unnecessary `If-Modified-Since` query). This behavior is especially damaging for sites who use a content distribution network (CDN) since IE will insist on an HTTPS handshake with the CDN before using the cached content. These redundant handshakes, which include a certificate validation check, discourage web sites from using HTTPS. Our approach to prevalidating certificates greatly reduces the cost of these handshakes.

Second, some browsers such as Firefox are reluctant to cache HTTPS content unless explicitly told to do so using a

```
Cache-Control: public
```

header [4]. Websites that simply turn on TLS without also specifying this header see vastly more HTTPS requests for static content. This issue has been fixed in Firefox 4.

2.2 TLS Snap Start

Figure 2 shows the message flow of a TLS Snap Start handshake [20]. The client must have performed a full TLS handshake in the past. In this full handshake, the client sends an empty Snap Start extension, and the server echoes a Snap Start extension that includes a selected cipher suite and a value called an orbit. The orbit is made up of eight bytes chosen by the server, and the orbit helps the server synchronize the rejection of replayed messages across multiple geographically separated locations. Since the server does not provide its own random value in a Snap Start handshake, it must keep track of client randoms that it has seen within a certain time interval, and it rejects handshakes that include an orbit different than its own or a client time older than its chosen allowable interval. By assigning a different orbit to each of its geographically separate server locations, a website can ensure that a handshake with one of its server locations cannot be replayed to a server in another location, since the latter server will reject the incorrect orbit.

By caching the server certificate, selected cipher suite, and orbit, the client can later perform a Snap Start handshake. In a Snap Start handshake, the client sends a Snap Start extension in its ClientHello. The extension includes the server's orbit value, twenty "suggested" random bytes, a hash of the server's handshake messages (which the client predicts using its cached information), and TLS ciphertext records, including ClientKeyExchange, ChangeCipherSpec, Finished, and the first HTTP request.

Upon receiving a full Snap Start extension in a ClientHello, the server forms its server random from the twenty suggested random bytes, the orbit, and the time included in the client random. Since the server does not choose its random value, it must prevent replay attacks by rejecting incorrect orbit values, requiring the time in the ClientHello to be within some interval of the server's current clock time, and keeping track of client-suggested random values that it has already seen within this interval. Since the server rejects client times that are older than its allowable interval, the client and server clocks must be synchronized to some degree for a Snap Start handshake to be successful. Since the client must be able to predict the contents of the server's handshake messages, the ServerHello cannot include a session ID. Instead, the connection can use session tickets, since NewSessionTicket is sent after the client's Finished message and the client only needs to predict up to the ServerHelloDone message.

If the client has sent a valid Snap Start extension, the server does not send its handshake messages. The server processes the records in the Snap Start extension to derive the master key and validate the handshake. It then sends its Finished message, processes the first HTTP request, and sends an encrypted HTTP response. Overall, no extra round trips are added to the interaction beyond what is needed to precess an unencrypted HTTP request.

Before starting a Snap Start session, the browser must validate the server's certificate by consulting a CRL or by issuing an OCSP query. Hence, while Snap Start reduces round trips with the web server, the browser must still communicate with a certificate validation authority before setting up the connection. Our OCSP study (Section 2.4.2) shows that this step is quite costly and happens often. Our approach to prevalidation removes this costly step from the critical path, thus enabling the full benefits of Snap Start.

2.3 DNS Prefetching

When establishing connections with web servers, the web browser relies on the Domain Name System (DNS) [28] to translate meaningful host names into numeric IP addresses. The IP addresses of recently resolved domain names are typically cached by the local DNS resolver, e.g. the web browser or operating system. If the resolution of a domain name is not locally cached, the DNS resolver sends requests over the network to DNS servers which answer the query by itself, or by querying other name servers recursively. Previous studies reveal that DNS resolution times cause significant user perceived latency in web surfing, more so than transmission time [8]. To increase responsiveness, modern browsers such as Google Chrome implement DNS prefetching (or pre-resolving), which resolves domain names before the user clicks on a link [13]. Once the domain names have been resolved, when the user navigates to that domain, there will be no effective user delay due to DNS resolutions.

Web browsers deploy various heuristics to determine when DNS prefetching should be performed. A basic approach is to scan the content of each rendered page, and resolve the domain name for each link. In Google Chrome, the browser pre-resolves domain names of auto-completed URLs while the user is typing in the omnibox. In addition, DNS prefetching may be triggered when the user's mouse hovers over a link, and during browser startup for the top 10 domains. Google's measurements show that the average DNS resolution time when a user first visits a domain is around 250 ms, which can be saved by DNS prefetching [31].

We extend the DNS prefetching architecture in modern browsers to also prefetch and prevalidate TLS server certificates. Our experiments show significant improvements in TLS handshake performance.

2.4 Certificate Validation

In the X.509 [10] public key infrastructure, a certificate issued by a certificate authority (CA) binds a public key with an individual, commonly a domain name. Web browsers determine the authenticity of a HTTPS website by validating the server certificate obtained via the TLS handshake. Fundamentally, a server certificate must be signed by a trusted source. Web browsers and operating systems come with a pre-installed list of trusted signers in their root CA store. More often, the root CAs will not directly sign certificates due to security risks, but delegate authority to intermediate CAs that actually sign the certificates. Therefore, the browser should verify that the leaf certificate is well-rooted, or bundled with a certificate chain leading to a trusted root CA.

To determine the validity period of a public key certificate, each certificate specifies the date it becomes valid, and the date it expires. In addition, X.509 defines mechanisms for the issuing CA to revoke certificates that haven't expired but should no longer be trusted, e.g. when the private key corresponding to the certificate has been compromised, or more often because the certificate was reissued. The common certificate revocation checking mechanisms are Certificate Revocation Lists (CRL) and the Online Certificate Status Protocol (OCSP).

2.4.1 CRL

A CRL [10] is a list that contains serial numbers of certificates that are revoked, signed by a CA. Web browsers may download CRLs published by CAs to verify the revocation status of a certificate. The location of where the CRL is periodically published for each certificate is indicated by the CRL distribution point extension. However, downloading a complete list of all unexpired certificates that have been revoked can be cumbersome, especially for large CAs. Alternatively, the CAs may issue delta CRLs which only list the certificates whose revocation statuses have changed since a previous complete CRL cached by the client. Delta CRL requires support on both CAs and clients and has not been widely deployed in practice.

2.4.2 OCSP

OCSP [30] was introduced as an alternative to CRL. Web browsers can check whether a specific certificate has been revoked by asking the OCSP responder of that certificate. The location of the OCSP responder for each certificate is indicated by the authority information access (AIA) extension. Since an OCSP response is typically smaller than a CRL, it is more feasible for a CA (or the delegated OCSP signing authority) to issue OCSP responses with shorter validity intervals (10 days maximum recommended by Mozilla [29], and 2 weeks recommended by Microsoft [26]), defined with the `thisUpdate` and `nextUpdate` fields.

In practice, we observe that the actual OCSP response caching behaviors may vary on different web browsers and operating systems. On Windows, Internet Explorer, Safari, and Google Chrome all use CryptoAPI to perform certificate validation, which shares OCSP response caches maintained by the operating system and cleared on expiration. Similarly on Mac OS X, Safari and Google Chrome both use Security Framework API and share OCSP response caches maintained by the operating system and cleared on expiration. For Opera on all platforms, OCSP responses are cached by the browser, which are cleared on expiration and also when the user clears private data. For Firefox on all platforms, OCSP responses are cached by the browser using NSS, independent of operating system caches. In particular, the OCSP cache is stored in memory and cleared when the program closes, or on expiration. In addition, Firefox forces a maximum OCSP response lifetime of 24 hours regardless of longer expiration times. On Linux, Google Chrome also uses NSS and stores OCSP caches in memory. Note that shorter OCSP lifetimes may provide better freshness, but induce more frequent OCSP lookups. Furthermore, we discovered that when OCSP checking is performed for the whole certificate chain, multiple OCSP requests are not performed in parallel, which may result in longer delays [17].

Although all major browsers support OCSP checking, recent studies have revealed that the implementations of OCSP checking are inconsistent, in particular the warning prompts and fallback mechanisms on status check failures [12]. Some browsers ignore bogus OCSP responses, while all avoid treating such errors as fatal; otherwise, websites would have to rely on the availability of OCSP responders. Researchers have suggested that current implementations of certificate revocation mechanisms in browsers are flawed due to lenient checking [21], as evidenced during the Comodo security breach [9] causing browser vendors to patch their browsers instead of relying on revocation. One possible solution would be OCSP stapling, in which the TLS server provides the OCSP response during the TLS handshake. This would effectively provide fresh OCSP responses and avoid additional OCSP lookups on the client. However, current implementations of OCSP stapling do not support multi-stapling, needed for intermediate CAs. Even if allowed, the responses might be too large to fit in the server's initial congestion window and result in additional round trips [22].

OCSP is mandatory for extended validation (EV) certificates [?] and EV certificates use dedicated OCSP responders. If both CRL and OCSP extensions are present in the certificates, web browsers will generally prefer to use OCSP rather than download a large CRL.

Regardless of using CRL, OCSP, or OCSP stapling, we propose to perform certificate validation during the prefetching phase, such that more strict and frequent validation checking can be obtained without impacting user experience. We note that some browsers do implement prevalidation, either by periodically validating certificates in the disk cache in CryptoAPI [27], or by concurrently validating certificates during DNS lookup phase for previously visited HTTPS websites in Google Chrome. However, existing prevalidation mechanisms are not effective for unvisited websites, therefore we propose to prefetch server certificates in advance. In the case that OCSP checking may be removed in the future due to wider use of short-lived certificates, certificate prefetching would still be beneficial, simply because certificates would expire more frequently and full TLS handshakes will more often be required.

3. OCSP MEASUREMENTS

3.1 Experimental Setup

To collect statistics of OCSP responses in the wild, we ran experiments on the Perspectives system [39]. Perspectives has a collection of network notary servers that periodically probe HTTPS servers and collect public key certificates, which allows clients (using our browser extensions) to compare public keys from multiple network vantage points. In this work, we extended the Perspectives system to probe OCSP responders for certificate revocation statuses if the queried certificate was configured with an OCSP responder URL. The data collected on the notary servers include the revocation status of the certificate, the validity lifetime of the OCSP response, and the latency of the OCSP lookup.

In addition to probing OCSP responders from the notary servers, we performed latency measurements for OCSP lookups on clients that have installed our Perspectives extension for Google Chrome. For each certificate that was fetched from an HTTPS website, we performed an OCSP request and measured the elapsed time to complete the lookup. As of May 2011, there were 242 active clients contributing data for this measurement. The notary servers receive data from clients with our Google Chrome extension as well as the previously deployed Firefox extension.

3.2 Results

3.2.1 OCSP response validity lifetime

Table 1 gives the OCSP response validity lifetime for certificates from OCSP responders for which the notary servers have performed more than 1000 OCSP lookups. We observe that 87.14% of the OCSP responses are valid for a period of equal to or less than 7 days. The minimum observed lifetime was 15 minutes. Analyzing the lifetime of OCSP responses helps us determine how often a prefetched OCSP response would expire before the certificate is actually used. Shorter OCSP response validity lifetimes reduce the effectiveness of OCSP response caching.

3.2.2 OCSP lookup response time

Figure 3 shows the distribution of the OCSP lookup response times that we recorded. The data shows that although 8.27% of the probes took less than 100 ms to complete, a majority of the OCSP probes (74.8%) took between 100 ms and 600 ms. In our measurements, the median OCSP lookup time is 291 ms and the mean is 497.55 ms. Table 2 gives the response time statistics breakdown of OCSP responders for which at least 500 OCSP probes were performed. Our data for OCSP responder response times only include measurements performed at the client side (using the Perspectives extension for Google Chrome) and not on the notary servers. We believe the measurements from real web clients more accurately reflect the latency experienced by a user. We observe that 95.3% of the OCSP responses are cached by the OCSP responders and are not generated at the time of request. These OCSP responders therefore do not support the optional OCSP nonce specified in the RFC 2560. If OCSP responders are required to support nonces and generate responses at the time of request, we expect an increase in response time for the OCSP responder to generate a response.

The actual response time of a user navigating to an unvisited HTTPS website typically consists of several round trip times for performing the DNS lookup, the TCP three-way handshake, the TLS handshake, the OCSP lookup (usually blocking the completion of the TLS handshake), and finally the HTTP request-response protocol. As previously introduced, DNS prefetching removes round trips for DNS lookups at the time of user navigation, while TLS False Start removes a round trip for the first HTTP request. In this paper, we propose certificate prefetching along with prevalidating to effectively remove the round trips for the TLS handshake and the OCSP lookup, which may reduce hundreds of milliseconds of the perceived latency on average.

3.3 OCSP and Private Browsing Modes

Most modern browsers implement a private browsing mode, designed to let users visit websites without leaving traces of their visits to these sites on their computer [2]. An attacker who takes control of the user's machine after the user exits private browsing should not be able to determine what the user did while in private mode.

OCSP permits a powerful attack on private browsing modes in all major browsers, except Firefox, on both Windows and Mac OSX. As mentioned before, IE, Chrome, and Safari use the Windows CryptoAPI for certificate validation. When Windows issues an OCSP query, it caches the result as specified by the nextUpdate field. Unfortunately, CryptoAPI provides no interface for removing specific entries from the

Table 1: Validity lifetime of OCSP responses

OCSP responder	Number of OCSP lookups	Number of distinct certificates	Validity lifetime (rounded to the closest hour)		
			Avg	Min	Max
http://EVSSL-ocsp.geotrust.com	2035	198	6 days 23 hours	12 hours	7 days 11 hours
http://ocsp.cs.auscert.org.au	1060	97	4 days	4 days	4 days
http://ocsp.cacert.org/	2381	76	3 hours	15 minutes	23 hours
http://ocsp.usertrust.com	3846	315	4 days	4 days	4 days
http://ocsp.godaddy.com	90925	4139	7 hours	6 hours	11 hours
http://ocsp.comodoca.com	56928	4581	4 days	4 days	4 days
http://ocsp-ext.pki.wellsfargo.com/	2612	53	20 hours	13 minutes	1 day
http://ocsp.entrust.net	18691	1474	7 days 14 hours	7 days	8 days 4 hours
http://ocsp.netsolssl.com	4117	570	4 days	4 days	4 days
http://EVIntl-ocsp.verisign.com	64403	1566	7 days	7 days	86 days 7 hours
http://ocsp.digicert.com	92093	1672	7 days	7 days	7 days
http://ocsp.starfieldtech.com/	9016	480	11 hours	6 hours	1 day 5 hours
http://ocsp.webspace-forum.de	2228	29	4 days	4 days	4 days
http://ocsp.startssl.com/sub/class1/server/ca	4963	348	5 hours	1 hour	1 day 4 hours
http://ocsp.startssl.com/sub/class2/server/ca	4597	160	6 hours	1 hour	1 day 4 hours
http://ocsp.serverpass.telesec.de/ocspr	2212	248	1 hour	1 hour	1 hour
http://ocsp.gandi.net	1060	78	4 days	4 days	4 days
http://EVSecure-ocsp.verisign.com	108993	465	7 days	7 days	7 days
http://ocsp.globalsign.com/ExtendedSSL	2441	115	7 days	7 days	7 days
http://ocsp.verisign.com	247251	12433	7 days	7 days	20 days 21 hours
http://ocsp.thawte.com	134321	3811	7 days	7 days	7 days
http://ocsp.tcs.terena.org	7823	675	4 days	4 days	4 days

Figure 3: Cumulative distribution of OCSP lookup response times

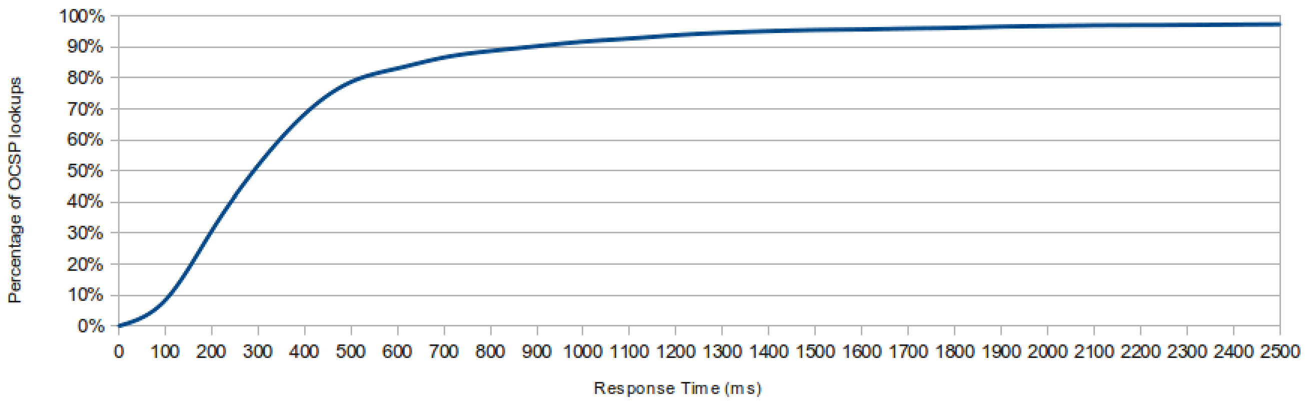


Table 2: Response times of OCSP responders

OCSP responder	Number of lookups	Response time			
		Median (ms)	Min (ms)	Max (ms)	Standard deviation
http://EVSecure-ocsp.verisign.com	938	167	25	7235	610.76
http://ocsp.digicert.com	1372	252	12	12303	759.64
http://ocsp.godaddy.com/	741	101	20	4832	515.53
http://ocsp.thawte.com	4209	564	10	12376	976.09
http://ocsp.verisign.com	1389	279	21	10209	743.53

cache. As a result, when the browser exits private browsing mode it does not remove the newly acquired OCSP responses from the cache. An attacker who wishes to learn what the user did while in private browsing mode need only dump the Windows OCSP cache. The contents of the cache divulge the identity of HTTPS websites visited. A similar attack applies to browsers on Mac OSX who use Apple's Security Framework API.

To give an example we use the Windows certutil tool [25] that can be used to manipulate the OCSP cache. To view the cache, the attacker issues the command

```
certutil -URLcache ocsp
```

on the browser's machine. A truncated sample output is

```
http://ocsp.thawte.com/MFEwTzBNMEswSTAJBgUrDgMCG...
http://ocsp.thawte.com/MEUwQzBBMD8wPTAJBgUrDgMCG...
```

In this example Thawte's OCSP responder was queried twice and the query path contains the certificates' serial numbers. The attacker can search for a web site whose certificate's serial number matches the query and learn what web sites were visited while the user was in private mode. Fixing this problem may be difficult since it requires changes to CryptoAPI.

4. SERVER CERTIFICATE PREFETCHING AND PREVALIDATION

To allow clients to prefetch its handshake information, a server publishes the concatenation of its certificate, cipher suite choice, and orbit. (For simplicity, we refer to the prefetching of this information and the prevalidation of the certificate as "certificate prefetching.") The client obtains this information when it is likely that the user might navigate to the website. The browser can use the same triggers that it uses to pre-resolve hostnames to determine when certificate prefetching is useful: for example, when the user is typing in the omnibox or when a user is viewing a page with links to HTTPS websites. In this section, we discuss two major benefits of certificate prefetching, and describe various methods for clients to download server information.

4.1 Benefits of Prefetching

4.1.1 Enable abbreviated handshakes

After prefetching a server's certificate, a web browser can use Snap Start without having performed a full handshake with the server in the past. Studies of user browsing behavior suggest that at least 20% of websites that a user visits in a browsing session are sites that the user has never visited before [1, 14, 7, 36]. These studies may underestimate how often certificate prefetching will be useful, since Snap Start without prefetching cannot be used when the browser cache has been cleared since the browser's last full handshake with a server.

4.1.2 Enable prevalidation of server certificate

Prefetching the server certificate allows the browser to validate the certificate in the background before the user navigates to the website. As discussed in Section 2.4.2, certificate validation performed during the TLS handshake introduces significant latency. Provided that the certificate status is not in the client's cache, a Snap Start handshake with a prefetched and prevalidated certificate is significantly faster than a Snap Start handshake without prefetching.

As discussed in Section 3.3, modern browsers commonly cache OCSP responses across public and private browsing modes. Further, Opera is the only one of the five browsers that clears the OCSP cache when the user opts to clear all private data. The persistence of OCSP responses is a privacy leak, and we note that, once fixed, certificate prevalidation will become more important because OCSP responses will be cached less frequently.

4.2 Prefetching Methods

A naïve prefetching method is to open a TLS connection to the server and cache the necessary information needed to perform a Snap Start handshake. These dummy connections basically perform a standard TLS handshake with the server, and would eventually disconnect on timeout. However, many clients performing TLS dummy handshakes may negatively impact server performance and also flood the server's session cache. We discuss four options for certificate prefetching that add little or no server load.

4.2.1 Prefetching with a truncated handshake

To perform a Snap Start handshake, a web browser requires the server's certificate, cipher suite choice, and orbit. In a standard TLS handshake, the browser has obtained all this information by the time it receives the ServerHelloDone message. Thus the browser can prefetch a server's certificate information by sending a ClientHello message with an empty Snap Start extension and sending a fatal alert after receiving the ServerHelloDone message. The alert ensures that the server closes the session, so that prefetching does not flood the server's session cache. After caching the appropriate information and validating the certificate, the browser can perform a Snap Start handshake if the user actually navigates to the website.

4.2.2 Prefetching directly from the server

For a web browser to prefetch a certificate via a HTTP GET request to the server, the server must place the concatenation of its certificate, supported cipher suites, and orbit in a file at a standardized location. (In our implementation, we prefetched from `http://www.domain.com/cert.txt`.) The web browser retrieves the file, parses and validates the certificate, and caches all the information for use in a Snap Start handshake later.

4.2.3 Prefetching from a CDN

To avoid placing any extra load on the server, a client can attempt to prefetch certificate information from a CDN, for example by sending a request to `http://www.cdn.com/domain.com.crt`. The browser cannot know in advance which CDN a particular website uses to host its certificate information, so it can send requests to multiple CDNs to have a high probability of successfully prefetching a server's certificate. Previous research suggests that sending requests to a small number of CDNs will cover a large percentage of the CDN market share [16]. Alternately, a DNS TXT record can hold the location where a browser should prefetch a server's certificate. Once the web browser has successfully obtained certificate information from a CDN, it proceeds to parse the certificate and cache the information.

4.2.4 Prefetching via DNS

Alternatively, the server may place its certificate information in a DNS record to offload the prefetching traffic. There has been previous work to store certificates or CRLs in DNS using CERT resource records [18], although not widely supported in practice. For the convenience of our prototype implementation, we stored the server's certificate information in a standard DNS TXT resource record, which allow servers to associate arbitrary text with the host name. Web browsers can prefetch certificates by querying for the domain's TXT record, in parallel with A records, during the DNS prefetching phase. Although TXT records were originally provisioned to hold descriptive text, in practice it has been freely used for various other purposes. For example, the Sender Policy Framework (SPF) [40] uses TXT records to specify which IP addresses are authorized to send mail from that domain. We also consider recent proposals in the IETF DNS-based Authentication of Named Entities (DANE) working group that suggest using DNSSEC to associate public keys with domain names, which introduce a new TLSA resource record type that allows storing a cryptographic hash of a certificate or the certificate itself in DNS [15].

5. PREFETCHING EXPERIMENTS

Our experiments studied the effects of different prefetching methods on a TLS server's performance, including:

- If many clients are prefetching certificates using one of the methods that affect the server (HTTP request to the server, truncated handshake), what is the impact on the server's performance?
- How do the methods that affect the server compare to each other, to methods that don't affect the server, and to the naïve method of doing a full dummy handshake in terms of server impact?
- How does latency experienced by the user compare for a Snap Start handshake with prevalidated certificate, a Snap Start handshake with a cached but not validated certificate, and a normal TLS handshake?

5.1 Experimental Setup

We used the hosting company Slicehost to acquire machines for running our experiments. Our server machine ran Apache 2.2.17 and OpenSSL 0.9.8p with our Snap Start implementation (on Ubuntu10.04 with 256MB of RAM and uncapped outgoing bandwidth). We ran clients on separate machines that generated Snap Start handshakes that didn't verify certificates, Snap Start handshakes that did verify certificates, normal TLS handshakes, truncated TLS handshakes, and HTTP requests. To generate traffic, we used Chromium, revision 61348 with our modifications to support truncated handshakes and Snap Start with a prevalidated certificate, and the command-line tool `httping` [38]. To measure latency, we generated 500 requests one after the other from a single client, which had 1GB of RAM and ran Ubuntu 10.04. To measure throughput, we set up eight clients (each with 256MB of RAM, running Ubuntu 10.04, and capped at 10Mbps outgoing bandwidth) making continuous requests, and we logged each request on the server.

We measured latency and throughput for four types of requests: Snap Start with a prevalidated certificate, Snap Start without a prevalidated certificate, a normal TLS handshake, and a HTTP HEAD request. Then we measured these types of requests with three different kinds of cover traffic: HTTP cover traffic generated with `httping` to simulate many clients prefetching via a HTTP request directly to the server, truncated handshake cover traffic generated with our modified Chromium client to simulate many clients prefetching via truncated handshakes, and HTTPS cover traffic generated with `httping` to simulate many clients prefetching via the naïve full dummy handshake method. For each type of cover traffic and each type of request, we measured latency and throughput with ten clients generating cover traffic.

5.2 Results

Table 3 shows the median and mean latency for each type of request. Snap Start with a prevalidated certificate corresponds to the situation when the client has prefetched and prevalidated the certificate and then performs a Snap Start handshake without needing to validate the certificate. The row labelled Snap Start corresponds to the situation when the client has cached the information necessary to perform a Snap Start handshake but must validate the certificate. **The data shows that the median latency for a Snap Start handshake with a prevalidated certificate is four times faster than a normal TLS handshake.** Prevalidation speeds up Snap Start by close to a factor of three.

Figure 4 shows how different prefetching methods affect the server's latency and throughput for different types of TLS handshakes. No cover traffic gives a baseline for how the server performs with prefetching disabled or when clients prefetch from DNS or a CDN. HTTP cover traffic simulates many clients prefetching via a HTTP request directly to the server. Truncated handshake cover traffic simulates many clients prefetching by performing truncated dummy handshakes (sending a fatal alert after receiving ServerHelloDone). HTTPS cover traffic simulates many clients prefetching by the naïve method of performing fully dummy handshakes.

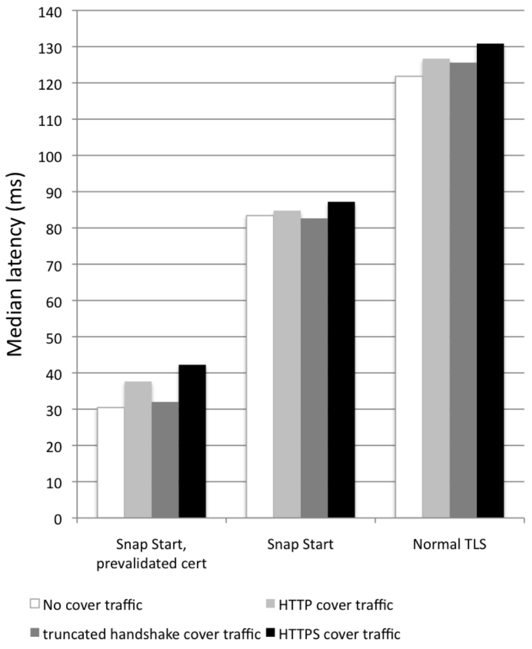
Full data for these experiments can be found in Appendix A.

6. ANALYSIS

Our experiments show that prefetching certificates allows for much faster handshakes than Snap Start without prefetching. We measured median latency for a Snap Start handshake with a prevalidated certificate to be 64% faster than a Snap Start handshake with an unvalidated certificate. However, this figure is probably a conservative estimate of the benefits of prevalidating, due to the unusually high speed of Slicehost's network connection. Our measurements of OCSP response times in the wild, shown in Figure 3, show that prevalidating certificates will reduce latency even more in a real-world setting. In addition to enabling Snap Start hand-

Table 3: Latency measurements for a Snap Start handshake with prevalidated server certificate (no verification during the handshake), a Snap Start handshake with online certificate verification, and a normal (unabbreviated) TLS handshake

	Median latency (ms)	Mean latency (ms)
Snap Start, prevalidated certificate	30.45	35.58
Snap Start, no prevalidation	83.40	99.86
Normal TLS	121.82	124.11



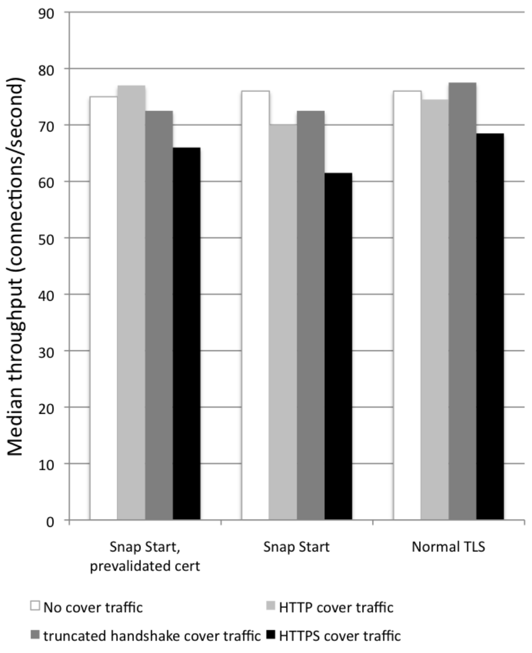


Figure 4: Median latency and throughput for TLS handshakes with different types of cover traffic.

shakes when the browser has never seen a website before, certificate prevalidation is useful when the browser has certificate information from a previous handshake but does not have its OCSP status cached. The frequency of this situation varies depending on the browser and the OCSP responder. As discussed in Section 2.4.2, Firefox on all platforms and Google Chrome on Linux clear the OCSP cache upon program exit; in this situation, prevalidating will often be useful even when the browser has visited a website recently enough to perform a Snap Start handshake without prefetching.

Our experiments also show that prefetching via any of our proposed prefetching methods has a less dramatic impact on server performance than doing full dummy handshakes, especially for server throughput. We also observed that prefetching via a HTTP request to the server and via truncated handshakes have about the same effect on server performance, so clients and servers choosing between these two methods should consider other factors, such as client-side code complexity, that we discuss below. Since prefetching via full dummy handshakes places a heavier load on the server and is also more computation for the client, we conclude that full dummy handshakes are a poor choice for prefetching.

While Snap Start and prevalidating certificates reduce latency, throughput with no cover traffic is about the same for all three types of handshakes. This is because the server does about the same amount of computational work in each handshake, with the main difference being how long the socket stays open.

6.1 Pros and Cons of Prefetching Methods

Having observed the performance impact of each prefetching method, we consider the benefits and drawbacks of each method and discuss how browsers and servers might choose which method to implement.

Prefetching with a truncated handshake. Like full dummy handshakes, truncated handshakes allow a browser to prefetch certificate information even if the server has not taken any actions to enable prefetching. A truncated handshake requires both the client and the server to do much less work than a full dummy handshake, and as a result the impact on the server is less dramatic. A truncated handshake requires slightly more client-side code complexity than prefetching via a HTTP GET request directly to the server, since the TLS implementation must be modified to truncate the handshake when prefetching. (For example, in Chromium, we used a `URLFetcher` interface to prefetch a certificate via HTTP, but making a HTTPS request that truncates after receiving ServerHelloDone requires going below this abstraction to modify the TLS implementation.) Truncated handshakes will also dirty server logs; without adding a new TLS alert number, a browser performing a truncated handshake for prefetching will have to use an inaccurate alert such as `user_canceled` or `internal_error` to close the connection.

Prefetching via a HTTP GET *request to the server.* Prefetching via a HTTP request directly to the server is the simplest prefetching method to implement in a browser, but for clients to be able to prefetch via HTTP, the server must explicitly enable it by creating a file with its certificate, orbit, and supported cipher suites. The impact on the server from clients prefetching via HTTP requests is about equal to that of prefetching via truncated handshakes.

Prefetching from a CDN. Prefetching certificates from a CDN has no impact on server performance, and for a server that already uses a CDN to distribute static content, enabling prefetching via CDN will be as simple as enabling prefetching for other methods. However, the main drawback of prefetching from CDNs, as discussed in Section 4.2.3, is that the browser cannot know from which CDN to prefetch the certificate for a particular website, so the browser must send requests to multiple CDNs to increase its probability of a successful prefetch. These requests can be performed asynchronously, but still use more client bandwidth than the other methods. As a compromise, we suggest that a DNS TXT record can hold the location of a server's certificate (whether it is on a CDN or on the server itself), which allows web browsers to prefetch certificates from CDNs without making requests to multiple CDNs.

Prefetching from DNS. Like CDN prefetching, DNS certificate prefetching places no additional load on the server, but DNS also uses minimal client bandwidth and it is also a more accessible option for servers that don't already use a CDN. DNS certificate prefetching may be slightly limited by the fact that not all domain registrars and DNS providers support DNS TXT records [19] [37]. DNS prefetching also has the undesirable effects of swelling DNS records and overloading the meaning of TXT records.

7. CONCLUSION

Client latency from TLS handshakes costs websites in traffic and revenue, and discourages websites from using TLS. Server certificate prefetching and prevalidation can enable abbreviated TLS handshakes and remove certificate validation latency. In our tests, a Snap Start handshake with a prevalidated certificate was about four times faster than a normal TLS handshake. We also found that 74.8% of OCSP lookups took between 100 ms and 600 ms, so for many users in the wild, prefetching enables an even more dramatic speed-up over standard TLS.

Web browsers can prefetch server certificates either from the server itself (via a truncated TLS handshake or a HTTP GET request) or from a third party (a CDN or DNS). While each method of prefetching has benefits and drawbacks, we suggest that using a DNS record to notify the web browser of the server's certificate location may be a flexible and effective compromise.

Certificate prefetching, in addition to decreasing client latency, allows browsers to validate certificates more frequently, since prevalidation does not affect client latency. We hope that certificate prefetching encourages deployment of Snap Start in web browsers and servers, since prefetching makes Snap Start applicable more often, and motivates more websites to enable TLS.

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APPENDIX

A. FULL DATA FROM PREFETCHING EXPERIMENTS

Tables 4 and 5 give the data from the prefetching experiments discussed in Section 5. We measured mean and median latency (in milliseconds) and throughput (connections/second).

Table 4: Latencies, in milliseconds, for different types of requests with no cover traffic and with ten clients generating HTTP, truncated handshake, and HTTPS cover traffic.

	no cover traffic		HTTP		truncated handshake		HTTPS	
	Median	Mean	Median	Mean	Median	Mean	Median	Mean
Snap Start, prevalidated certificate	30.45	35.58	37.65	57.77	32.00	61.82	42.25	61.53
Snap Start	83.40	99.86	84.76	101.14	82.64	104.11	87.20	103.05
Normal TLS	121.82	124.11	126.69	137.00	125.60	213.94	130.84	273.96
HTTP HEAD request	15.59	15.76	15.75	16.85	15.67	18.19	16.02	17.70

Table 5: Throughput, in connections per second, for different types of requests with no cover traffic and with ten clients generating HTTP, truncated handshake, and HTTPS cover traffic.

	no cover traffic		HTTP		truncated handshake		HTTPS	
	Median	Mean	Median	Mean	Median	Mean	Median	Mean
Snap Start, prevalidated certificate	75.00	72.25	77.00	72.79	72.50	63.89	66.00	62.88
Snap Start	76.00	76.67	70.00	68.54	72.50	70.45	61.50	56.98
Normal TLS	76.00	76.50	74.50	76.81	77.50	77.05	68.50	74.89
HTTP HEAD request	503.00	500.13	456.00	423.65	429.00	413.35	184.50	175.03