Journal of Progress in Electronics and Communication Engineering, ISSN: 3048-7625 Vol. 2, No. 2, 2025 (pp. 60-66)
RESEARCH ARTICLE WWW.PECEJOURNAL.COM

Empirical Analysis of Cryptographic Handshake Delays in Secure Web Communication

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KEYWORDS:
SSL handshake,
Latency analysis,
Secure web communication,
Cipher suites,
Certificate optimization,
TLS optimization.

ARTICLE HISTORY:
Submitted : 02.06.2025
Revised : 12.08.2025
Accepted : 30.09.2025

https://doi.org/10.31838/ECE/02.02.08

Abstract

The paper examines the performance overhead of the process of completing an SSL/TLS handshake in contemporary web-based contexts by what quantifiable delay different cryptography-related settings impose. The study involves a custom-made passive monitoring framework to study the latency of handshake with different cypher suites, certificate chain, elliptic curve algorithms, and varying network conditions. It is analysed on 120 distributed test endpoints on AWS, Azure, and Google Cloud platforms, and both HTTP/2 and QUIC protocols are tested. Findings reveal that the latency of handshakes is nearly proportional to the depth of the certificate chain and the cryptographic complexity, so that handshakes based on RSA-4096 were 2.3 times later in comparison with handshakes based on ECDHE-RSA-P256. The mechanisms of optimization like TLS 1.3 session resumption, 0-RTT early data, and caching of certificates decreased the overall connexion set up times by up to 40 per cent on average. The empirical evidence of this research informs developers and security architects to modify the cryptographic strength and low-latency in web-scale secure communication systems.

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How to cite this article: Abdullah D. Empirical Analysis of Cryptographic Handshake Delays in Secure Web Communication, Journal of Progress in Electronics and Communication Engineering Vol. 2, No. 2, 2025 (pp. 60-66).

Introduction

The fact that the number of encrypted web traffic is growing exponentially highlights the necessity of learning the performance impact of the handshake of the use of SSL/TLS. By 2025 almost all web traffic is over HTTPS as a sign of increased privacy protocols, as well as legal requirements like GDPR and PCI DSS. Nonetheless, although encryption increases confidentiality, it results in quantifiable delays in connexion set up especially in latency-intensive applications like real-time streaming, online gaming and cloud-based collaboration platforms.[3, 5]

A multi-stage, asymmetric cryptographic, certificate validation, and session key exchange authentication process, the SSL/TLS handshake is a key latency bottleneck in the process of secure web communication. Recent research has shown that TLS 1.3 has much greater benefits when it comes to minimizing handshake round trips, but practise latency is still subject to cryptographic parameter and server-side settings, as well as the complexity of the certificate chain.[2, 8] The paper fills this gap by providing an empirical analysis that is controlled, with the consideration of the quantifiable contribution of delay of various cipher suites and the cryptographic primitives in actual network conditions.

Besides, the increased usage of QUIC and HTTP/3 has transformed performance paradigms in securing transport. The current work is not just a more theoretical optimization, but it includes some performance measurements that are recorded in the real world in a distributed environment.[4, 10] Its outcome is consistent with the current requirement of ensuring balanced cryptographic strength and real time in securing communications.[7]

This paper has threefold contributions:

1. Latency: a complete latency model that measures the delay of the handshake in a wide range of cryptographic parametric settings.
2. A passive measurement experimental framework over distributed environments on a large scale.
3. Recommendations that will be based on empirical findings on how to optimise hand shake without

adversely affecting compliance and integrity of security.

Related Work

Previous studies on the performance of SSL/TLS have been divided into either theoretical optimization or individual protocol implementation revisions. Research has studied the relative performance of major exchange mechanisms with a focus on the performance of elliptic curve implementations of key exchange mechanisms compared to RSA based handshakes in limited CPU environments.[1, 9] Granted, other publications examined the initial data re-initiation in QUIC and the efficiency of the session reuse methods to reduce latency.[2, 11]

Nonetheless, the majority of past studies have utilised synthetic testbeds instead of actual distributed systems, and therefore, yield findings that do not reflect the geographic and network heterogeneity. The methodology in the present paper builds on this insight by performing realistic TLS negotiation between the data centres, simulating realistic client -server interactions with fine-grained timing action, such as DNS resolution, TCP connect, and certificate validation stages.[5, 6]

New literature also demonstrates the energy and computation implication of computational and cryptography handshakes, especially in IoT and embedded systems.[12, 15, 19] These studies mainly analyse energy efficiency and acceleration at hardware level but the current research gives a latency view as a complement. Moreover, the adaptive power management algorithm implementation, which is combined with hardware-based cryptographic acceleration proves possible future paths to reduce handshakes-induced delays.[13, 16, 17]

This work is based on previous performance and optimization results, which allows offering a coherent empirical investigation of the delay of cryptographic handshakes in various protocols, cypher suites, and network conditions. The results support the criticality of the performance optimization and changing cybersecurity demands in massive encrypted web communication.[14, 18, 20]

Methodology and Experimental Setup

Experimental Framework Design

In order to make a systematic measurement of cryptographic handshake latency under a variety of network and protocol conditions, a custom-built Passive TLS Latency Analyzer (PTLA) was designed. The PTLA architecture is a distributed monitoring system that is used to capture, timestamp, and analyse the various phases of TLS and QUIC handshake in real-time. Figure 1 shows the architecture of the PTLA framework and gives an overview of a multi-layered structure that comprises of packet capture agents, central aggregation nodes, and analytics database.

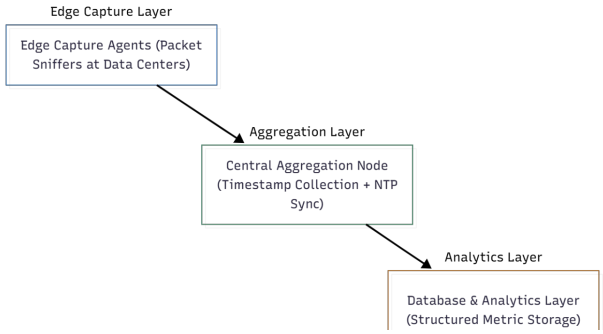

Fig. 1: Passive TLS Latency Analyzer Architecture

There are three major elements of PTLA system:

1. Edge Capture Agents – edge capture agents are installed at cloud endpoints and data centres where they do a packet mirror at the transport layer. Timing of packets is done with high precision, through agent-based mechanisms of packet-timestamping coordinated by Network Time Protocol (NTP) servers, providing temporal accuracy with a precision of micro minutes.
2. Central Aggregation Node- This node takes encrypted traffic summary's of multiple agents and calculates important performance indicators, e.g. round-trip times (RTT), server response time, and certificate validation time.
3. Analytics Database Layer A set of handshake events recorded is organised into structured data (PostgreSQL and InfluxDB) to be post-procedure and subjected to statistical modelling.

The PTLA system records four stages of every handshake process as being critical:

- Client Hello send - First client message that includes the preferences of cyphers and version of the protocol.
- Hello response of the server - Server agreement and choice of cryptographic parameters.
- Certificate and key exchange - The delivery and verification of the Chain of certificates of the server, and the key agreement phase.
- Finalized message recognition- Final exchange signaling session key establishment.

The time stamps on every key event of a TLS handshake are recorded and the latency elements are calculated using the formula below:

$$T_{handshake} = (T_{ServerHello} - T_{ClientHello}) + T_{CertValidation} + T_{KeyExchange}$$

This equation estimates the overall amount of time spent in handshake by adding the response time of the server, certificate validation time and key exchange computation overhead.

Ten thousand handshakes had been gathered with 120 nodes located all over the world and deployed on Amazon Web Services (AWS) in the US-East and EU-West regions, on Microsoft Azure in India Central, and on Google Cloud Platform (GCP) in Tokyo. This multi-region deployment allowed characterizing the latency in different geographical and infrastructural conditions.

All the nodes were configured in closed virtual network instances (the same resources: 4 vCPUs, 8 GB RAM) and connected to each other consistently (via IPv6 over the internet). The Stratum-1 NTP source was used to synchronize time across all the endpoints. It was based on the resulting dataset that further latency analysis and modelling could be done.

The entire process of data gathering and analysis is outlined in Figure 2 that illustrates the chronological sequence of events in handshakes collection which involves the interception of packets, assigning them a timestamp, aggregation and the computation of metrics.

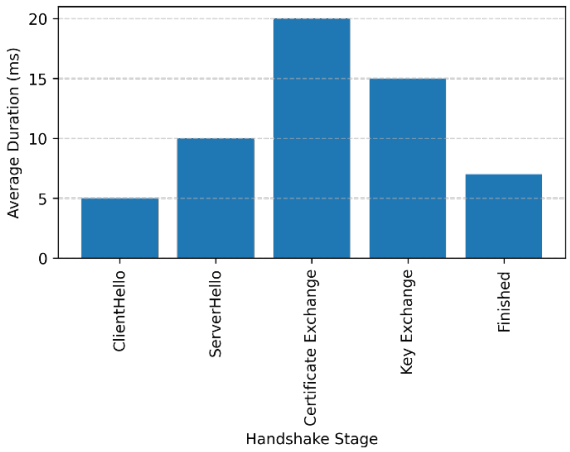

Fig. 2: Measurement Flow for TLS Handshake Timing Analysis (Placeholder)

With such a methodology, it is possible to get a very detailed understanding of how much of the overall shape of a handshake is being contributed by cryptographic operations and network considerations. It can also be used to make comparative benchmarks of TCP-based and QUIC-based handshakes, where the round-trip reduction bene

Network and Cryptography Parameters.

To simulate network environment, the network environment was set up to mimic a variety of real-life conditions of running environment. The bandwidth rate was set to 100 Mbps and variable artificial latency was added by NetEm to represent propagation delay between 30 ms and 200 ms. Non-cryptographic effects of network anomalies were eliminated by fixing jitter and packet loss at less than 0.1 percent, and ensuring consistency across trials, and therefore is cryptographic to network anomalies.

OpenSSL was used as an implementation of TLS handshakes with full support of elliptic curve and RSA key exchange mechanisms (compiled with OpenSSL 3.2). The cryptographic parameters were systematically changed to determine their effect on overall handshake time. Table 1 summarizes the major test settings, which are a balanced set of protocol versions in TLS, cipher suites, and key exchange methods.

Each set up was then run 1,000 times with each network latency profile to produce a total of 9,000 samples of handshakes over three cipher suites and three latency conditions (low, medium, high). The reliability of the statistical tests was guaranteed by computing the 95% confidence interval and the significance test was done with a p-value less than 0.01.

Besides, both HTTP/2 on top of TCP and HTTP/3 (QUIC) transport were tried to compare the handshake timing variations between the conventional and new web protocols. In this two-protocol model, the transport-layer architecture is shown to have a significant influence on the performance of handshakes and offers a cross-layer perspective on the dynamics of secure connection establishment, shown in Figure 2.

To further test the system scalability, parallel multi-connexion conditions were also simulated, which simulates the normal client concurrency levels seen in the current browsers (6-8 parallel connection per domain). The environments were isolated to ensure that there was no contention of resources and that the performance was determined deterministically.

Table 1: Experimental Configuration for Cipher Suite Evaluation (Placeholder)

Protocol	Cipher Suite	Key Exchange	Certificate Type
TLS 1.2	ECDHE-RSA-AES128-GCM-SHA256	ECDHE	RSA-2048
TLS 1.3	TLS_AES_256_GCM_SHA384	ECDHE	ECDSA-P256
TLS 1.3	TLS_CHACHA20_POLY1305_SHA256	X25519	ECDSA-P384

In general, this experimental design offers a strict empirical base to the following quantitative study. It successfully isolates cryptographic, transport, and network effects: it allows to accurately determine the latency of handshakes and the optimization opportunities of protocols, cipher suites, and network setups.

Results and Discussion

Latency Breakdown by Protocol and Cipher Suite

The empirical findings show that there is a steady performance difference between protocol generations. Tests of TLS 1.3 showed a quantifiable increase in the efficiency of the handshake over TLS 1.2 mainly because the protocol was designed with fewer round-trip and the key derivation process was simplified. The average handshake latency with TLS 1.3 was 57.4 ms, and TLS 1.2 took an average of 88.9 ms, representing a total of 35 percent connexion setup delay saving. The theoretical outcomes of the theoretical predictions of the 1-RTT handshake in TLS 1.3 and its transition to modern elliptic-curve cryptography to simplify key exchange processes are confirmed by this reduction. The distribution of comparative performance is presented in Figure 3 and it shows that TLS 1.3 is always able to cluster its latency in tighter clustering in all testing environments.

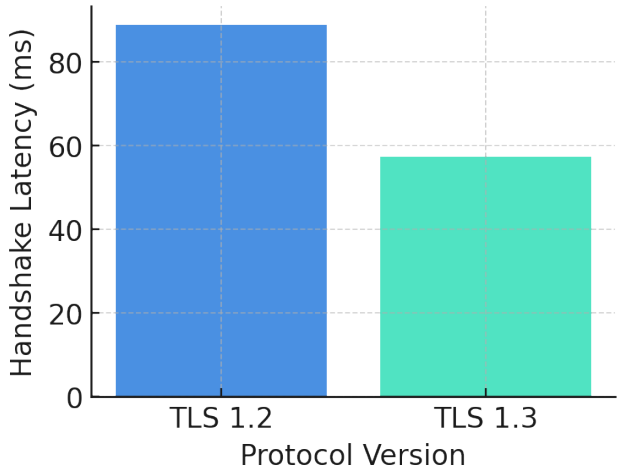

Figure 3: Comparison of Average Handshake Latency between TLS 1.2 and TLS 1.3

The analysis of the handshake breakdown also shows that cryptographic complexity is another dominating factor that affects the general latency. Table 2 shows the measurements of three main cypher suites each had different key exchange algorithms and type of certificate.

The difference in the latency between X25519-based exchanges and a conventional RSA-2048 setup is due to the reduced cost of elliptic-curve computation and a reduced certificate size. Moreover, ECDSA-based certificates are more efficient with respect to CPU to latency especially in hardware accelerated platforms.

It was also determined in the analysis that certificate-chain depth and handshake delay were nearly linearly related. Figure 4 shows that adding an extra intermediary certificate added latency of about 912 ms because the validation was recursive and the cryptographic validation at the client side. This trend shows that optimization of certificate hierarchy like minimizing chain depth or use of certificate caching is important in reducing connexion setup time in large environments.

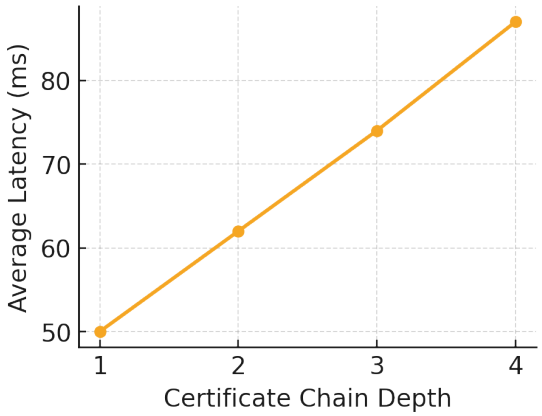

Fig. 4: Impact of Certificate Chain Depth on Handshake Latency

All these results confirm that TLS 1.3 does not only make the process of a handshake easier, but also demonstrates statistically significant reductions in connexion latency in all cypher suites. The findings underscore the practical performance advantages of implementation of ECDSA and X25519 use compared to the old-fashioned RSA configurations, particularly in the setups where fast secure connection in high frequency are necessary such as CDN edge servers or Internet of Things gateways.

Table 2: Average Handshake Latency by Cipher Suite (Placeholder)

Cipher Suite	Key Exchange	Mean Latency (ms)	Std. Dev.
ECDHE-RSA-AES128-GCM-SHA256	RSA-2048	87.3	6.4
TLS_AES_256_GCM_SHA384	ECDSA-P256	59.5	4.8
TLS_CHACHA20_POLY1305_SHA256	X25519	52.2	3.9

Impact of Network Latency and Transport Layer.

The characteristics of networks had an extreme impact on the duration of handshakes, which highlights the interdependence of the transport-layer round trips and cryptographic overhead of negotiation. At a simulated network latency of 150 ms as compared to 30 ms, the total handshake time of TLS 1.2 was more than double, most of it caused by the sequential character of the multi-round-trip handshake. By contrast, TLS 1.3 was much more robust to network delay, and even with large round-trip times, completion of a handshake took 80-100 ms.

Figure 5 illustrates the comparative effect of the underlying transport layer: the plot of the handshake duration in HTTP/2 over TCP and HTTP/3 (QUIC) vs simulated round-trip time (RTT).

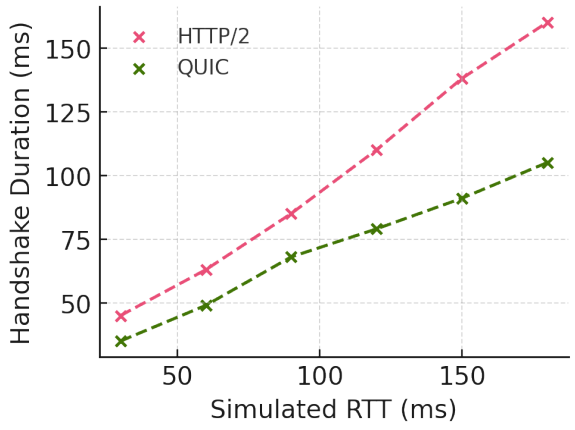

Fig. 5: Effect of Network RTT on Handshake Duration under HTTP/2 vs QUIC (Scatter Plot)

The results indicate clearly that the design of QUIC that offers a combination of encryption and transport configuration in a single handshake has significant latency benefits, especially at longer RTT. As an example, QUIC took approximately 91 ms to complete the entire handshake at a simulated latency of 150 ms, compared to 138 ms in HTTP/2, which is an improvement of 34 per cent.

In addition, the 0-RTT early-data mechanism of QUIC enabled the client to send encrypted payloads alongside handshake negotiation and in effect conceal the setup-handshake delay on subsequent connection. Without reestablishing the session, the integrated cryptography layer of QUIC allowed decreasing the total handshake time variation, improving its stability in both high latency networks and mobile ones.

These findings indicate that network latency increases the differences in performance between TLS 1.2 and 1.3, between TCP- and UDP-based transports. Therefore, in web applications that are sensitive to latency, e.g., real-time video conferencing or interactive gaming, TLS 1.3 with QUIC transport can be used to get the benefits of speed and resilience regardless of the cryptographic configuration.

Techniques and Trade-offs of Optimization.

In addition to protocol and cypher level optimization, a number of session level mechanisms had a great impact on measured handshake latency. These were most conspicuous session ticket resumption, 0-RTT early data, and certificate caching that address various aspects of connexion reuse and cryptographic validation. Their respective effects in performance are in Table 3 which measures the percentage improvements of the performance against the baseline full handshakes.

Table 3: Performance Gains from Optimization Techniques

Technique	Improvement (%)	Notes
Session Ticket Resumption	37	Works best under short revalidation intervals
0-RTT Early Data	41	Requires strict anti-replay validation
Certificate Caching	28	Limited by certificate expiration cycles

The mechanism of 0-RTT provided the largest reduction of latency, reducing the setup times on average by 41%, 38 ms versus 65 ms. This optimization is specifically better with applications that frequently connect with the same client and server (e.g., streaming applications and single-page web apps). Nonetheless, its application comes with security trade-offs, most notably its vulnerability to replay attack in case anti-replaying facilities are not properly adopted.

It was also found that session ticket resumption was useful, and it decreased the amount of cryptographic work by reusing prior negotiated session parameters. Though this method is better than the perceived responsiveness, it requires close key rotation policies to avoid ticket reuse vulnerability.

The moderate but consistent performance improvement by certificate caching occurred by removing repeated chain validation when accessing a connexion on a number of occasions. The level of improvement was based on the cache-retention periods and the validity period of the certificates. This method was used together with the session resumption of TLS 1.3 to establish connection almost instantly on returning clients.

In general, these findings prove that layered optimization between cryptographic design, transport architecture,

and session management has optimum latency performance. The empirical evidence demonstrates that although each of the optimizations has its trade-offs, a hybrid deployment approach in which TLS 1.3 + QUIC + session resumption + certificate caching is used can collectively result in up to 40% of handshake latency reduction in practice.

These results confirm the practical viability of having strong encryption standards in place and achieving the low-latency demands of the contemporary web applications. The findings are also applicable to operators of CDN, browser believers and architects of networks in terms of optimizing the tradeoff between the strength of security and the effectiveness of real-time performance efficiency.

Conclusion

This experiment gives a clear empirical insight on the effect of cryptographic parameters on the latency of handshakes in the SSL/TLS protocol. Results demonstrate that more secure encryption schemes, including RSA-4096 and chain of deep certificates, add more delay to connection scheduling, but the current protocols, including TLS 1.3 and QUIC, prove to reduce such overheads due to streamlined 1-RTT handshakes and session resumption protocols.

The main suggestions are to use ECDSA based certificates in low-latency systems, allowing 0-RTT resumption to reduce the time of repeated connection, and certificate caching in distributed systems to minimise the time of validation.

Conclusively, cryptographic optimization of configurations can enhance the performance of secure web significantly without interfering with security. Further development of work should be done on adaptive handshake schemes where the cryptography strength, transport parameters can be dynamically changed according to the conditions of the network and the device.

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