GIAC
CERTIFICATIONS

Global Information Assurance Certification Paper

Copyright SANS Institute
Author Retains Full Rights

This paper is taken from the GIAC directory of certified professionals. Reposting is not permited without express written permission.

Interested in learning more?

Check out the list of upcoming events offering
"Network Monitoring and Threat Detection In-Depth (Security 503)"
at http://www.giac.org/registration/gcia

Benefits and Adoption Rate of TLS 1.3

GIAC (GCIA) Gold Certification

Author: Ben Weber, ben.weber@student.sans.edu
Advisor: Johannes Ullrich

Accepted: July 8th, 2020

Abstract

The cybersecurity industry is often reluctant to adopt new technologies due to perceived complications, assumed dependencies, and unclear information about the benefits. Digital communication protections are not exempt from this phenomenon and are often overlooked when maintaining a secure environment. Adopting new technologies is essential to utilize recent advancements in speed, security, and other newly available features. RFC 8446, better known as TLS 1.3, was released in August of 2018 and included enhancements to the speed and security of a TLS session. Older versions of TLS that still exist, however, fall short when compared to TLS 1.3. This paper provides data testing the speed and security of TLS 1.3 compared to TLS 1.2 across major TLS libraries and a point-in-time measurement of TLS 1.3 adoption across the top 500 websites in the business, retail, technology, and news sectors.

© 2020 The SANS Institute Author Retains Full Rights

© 2020 The SANS Institute Author retains full rights.

1. Introduction

Information Technology practitioners are often reluctant to make changes to an environment or technology without a driving force supporting the migration. Sometimes, that driving force is performance-related: for example, an organization may make a change because the organization expects a 10% increase in performance. Other times, the driving force is security related: for example, an organization may make a change because the organization must resolve a vulnerability. Transport Layer Security version 1.3 (TLSv1.3) is described as a solution that brings both performance and security improvements with minimal risk of negative impact. This research will investigate the performance impact in enabling TLS 1.3 when compared to TLS 1.2 across commonly used TLS libraries. Additionally, this research will measure the current adoption rate among various industry sectors. The results of this research and related experiments will provide evidence related to implementing TLS 1.3 in an environment.

1.1. An overview of TLS

Transport Layer Security (TLS) is a widely adopted security protocol designed to facilitate privacy and data security for communications over the internet ("Transport Layer Security TLS", n.d.). TLS is the successor to SSL; SSL Version 1 was first developed by Netscape in 1995 but was never released because it was riddled with serious security flaws (Onelski, 2020). SSL Version 2 was the first official version of SSL released in late 1995, and SSL Version 3 was released in 1996 (later documented under RFC6101). TLS was first released as TLS 1.0 in January 1999 under RFC2246 (IETF) – TLS 1.0 was an upgrade from SSL Version 3 and the differences were not dramatic (wolfSSL, "Differences between SSL and TLS Protocol Versions (#TLS13)", 2018). New versions have been released since then: TLS 1.1 released in April 2006 under RFC2246, TLS 1.2 released in August 2008 under RFC5246, and finally, TLS 1.3 released in August 2018 under RFC8446. TLS protects data between two endpoints by providing a method to set up an encrypted, authenticated, and integrity-checked communication channel.

© 2020 The SANS Institute Author retains full rights.

1.2. TLS Cipher Suites

All versions of TLS leverage cipher suites, which describe how the encrypted channel is initiated. The cipher suite is split into four main sections: the algorithm used for key exchange, the algorithm used for authentication, the algorithm used for bulk encryption, and the algorithm used for hashing. In the example 'ECDHE_ECDSA_WITH_AES_128_GCM_SHA256', ECDHE describes the key exchange, ECDSA describes the authentication, AES_128_GCM describes the bulk authentication and SHA256 for hashing. Various cipher suites are considered depreciated due to weaknesses in the cipher – for example by using weak encryption or hashing. The TLS ciphers used can directly impact the confidentiality and integrity of an encrypted communication.

1.3. Perfect Forward Secrecy

Perfect Forward Secrecy (PFS) describes a configuration of TLS, which prevents previous TLS sessions from being decrypted should the server's private key ever be compromised (Enabling Perfect Forward Secrecy, n.d.). If RSA is the key exchange algorithm, during the session negotiation, a link is created between the servers' key pair and the session key generated for each unique session (Enabling Perfect Forward Secrecy, n.d.). Thus, if an attacker is ever able to get hold of the server's private key, they can decrypt your TLS session and any saved TLS sessions (Enabling Perfect Forward Secrecy, n.d.). In contrast, if PFS is enabled, the link between the servers' private key and the session key is broken, making it impossible to decrypt prior TLS sessions (Enabling Perfect Forward Secrecy, n.d.). To enable Perfect Forward Secrecy, you must do the following: Reorder your cipher suites to place the ECDHE (Elliptic Curve Diffie-Hellman) suites at the top of the list, followed by the DHE (Diffie-Hellman) suites (Enabling Perfect Forward Secrecy, n.d.). The downside to PFS is that traditional intrusion detection solutions will not be able to decrypt traffic with the private key of the server. Instead, the protection will need to terminate the TLS connection, inspect the traffic, and re-encrypt the traffic.

© 2020 The SANS Institute Author retains full rights.

1.4. TLS version negotiation and its significance

TLS version negotiation describes a step within the TLS session setup process which compares supported TLS versions and ciphers on both client and server to determine what versions are supported by both. For example, if a web browser supports TLS 1.1 and TLS 1.2 and the webserver supports TLS 1.3 and TLS 1.2, the protocol will 'negotiate' and use TLS 1.2 (that is, the highest supported version that both web servers have in common). The same process happens with TLS Ciphers. This process can be seen below in Figure 1.4.1 in the first two communications between client and server (called the handshake).

© 2020 The SANS Institute, Author Retains Full Rights

© 2020 The SANS Institute Author retains full rights.



Figure 1.4.1: The TLS Handshake Process (Kemmerer, 2015)

TLS negotiation is crucial because it allows web servers to support the "Latest and Greatest" TLS version and ciphers even if all clients do not support them yet. Clients will negotiate down to the best supported TLS version and cipher until they can support a better combination.

Ben Weber, ben.weber@student.sans.edu

© 2020 The SANS Institute Author retains full rights.

2. Comparison of TLS 1.2 and TLS 1.3

2.1. TLS 1.2 - Session Setup Process

TLS 1.2 leverages two round trips to set up the TLS session. The first round trip (Steps 1 and 2 from Figure 2.1.1) is responsible for negotiating a TLS version and cipher, transferring the server certificate to the client, and transferring the "Server Random" used during key derivation ("What Happens in a TLS Handshake?," n.d.). In the second round trip (Steps 3 and 4 from Figure 2.1.1), the client uses the cipher suite to generate the pre-master secret and sends the pre-master secret back to the server. The server then acknowledges the key back to the client. Now the TLS tunnel is completed, and application traffic can flow (in this example, HTTP).

© 2020 The SANS Institute, Author Retains Full Rights

© 2020 The SANS Institute Author retains full rights.

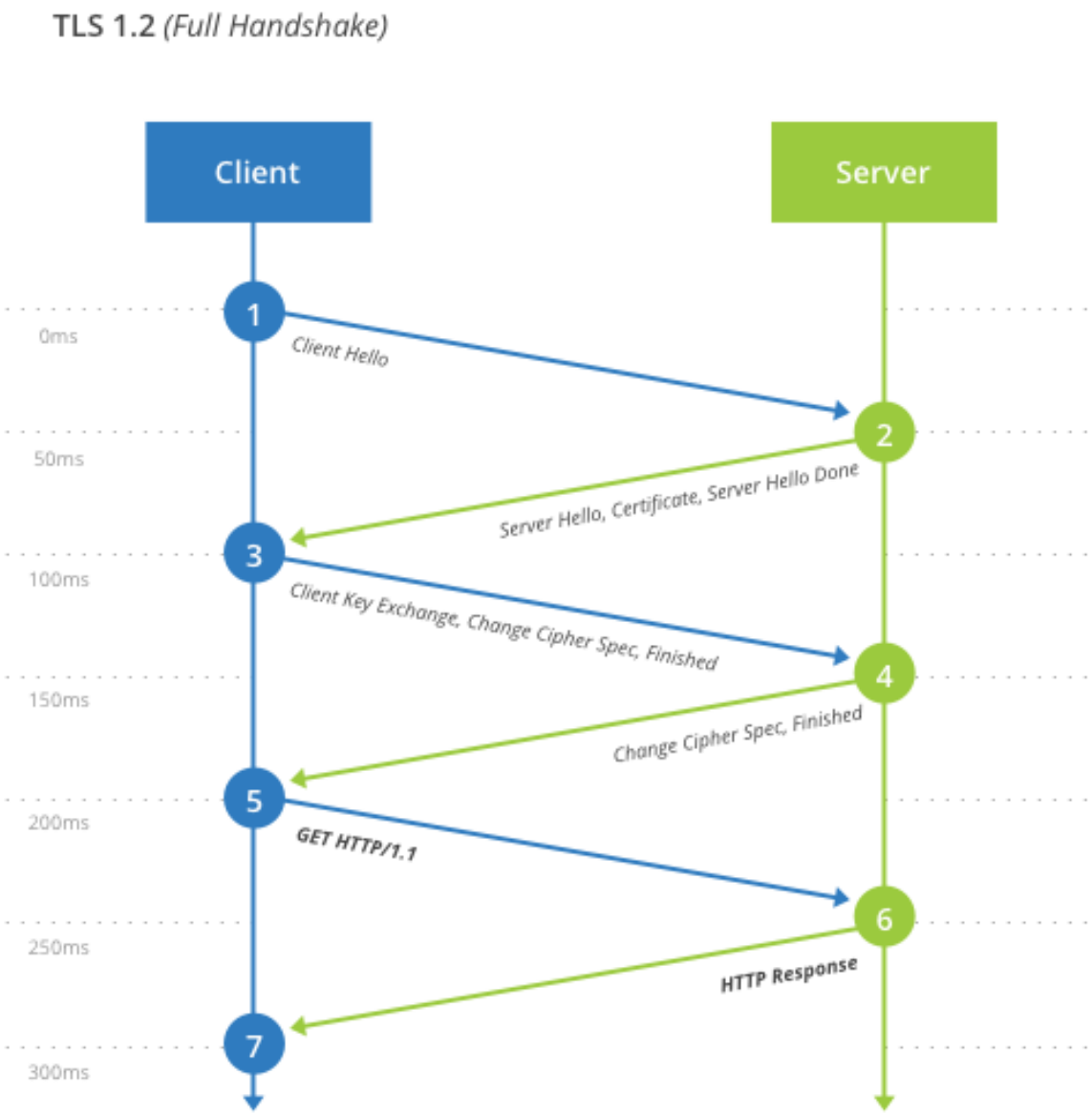


Figure 2.1.1 ("What's new in TLS 1.3?," n.d.)

2.2. TLS 1.3 – Session Setup Process

TLS 1.3 differs from TLS 1.2 in that TLS 1.3 requires only one round trip to set up the TLS tunnel (as seen in Steps 1 and 2 of Figure 3). The version negotiation, cipher negotiation, and key sharing are completed in a single round trip meaning the setup time is reduced by a full round trip (2 trips for TLS 1.2, 1 trip for TLS 1.3). This is a primary use case for enabling TLS 1.3 as it should be more performant. Test 1 below will test this claim.

© 2020 The SANS Institute Author retains full rights.

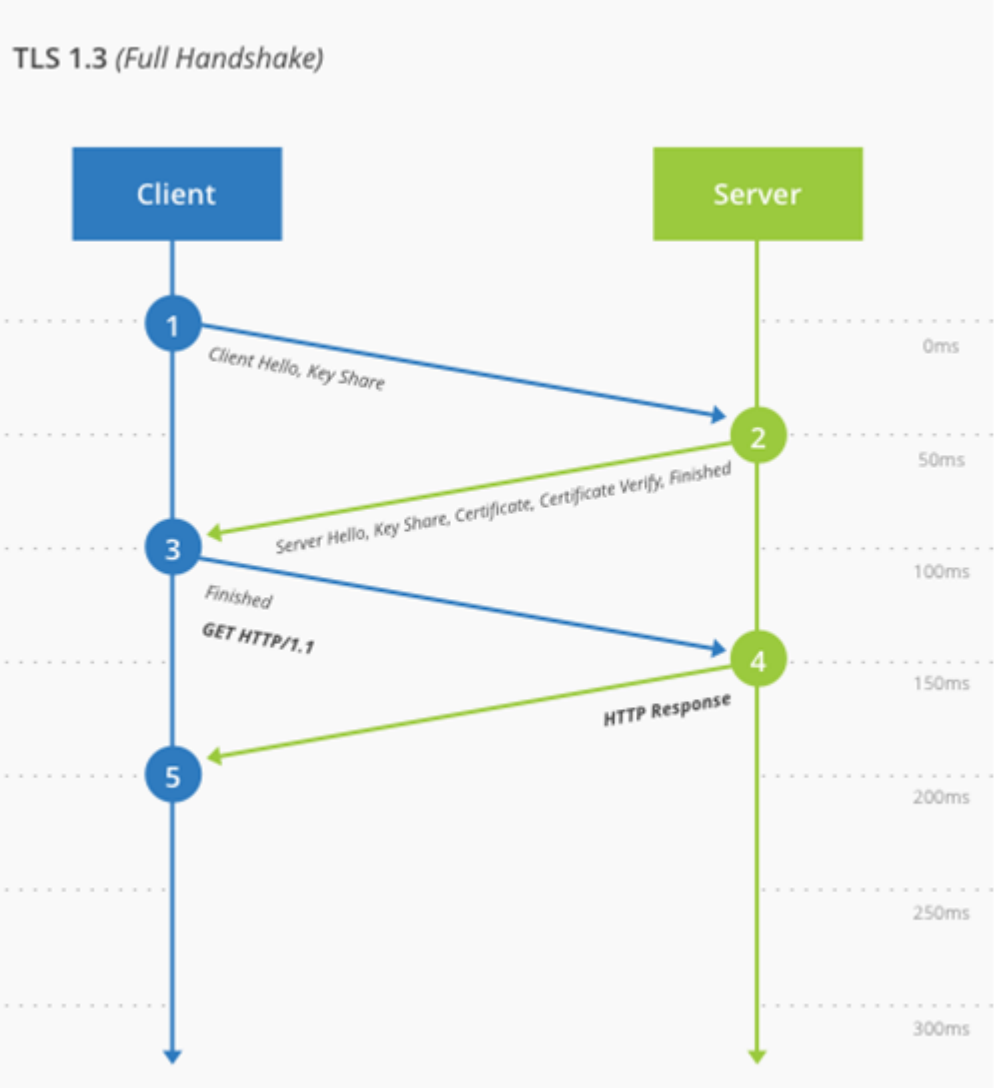


Figure 3 ("What's new in TLS 1.3?," n.d.)

2.3. Cipher Support

An important difference between TLS 1.2 and TLS 1.3 is the volume of supported cipher suites. In almost 12 years of support, TLS 1.2 has varying types of key exchange, authentication, and hashing algorithms; some are deprecated due to vulnerabilities and some are deprecated due to weak algorithms in today's standards. In contrast, TLS 1.3 supports only five ciphers all of which enable PFS and strong protections.

© 2020 The SANS Institute Author retains full rights.

2.4. Browser Support

Below is a table of common web browsers and if/when TLS 1.2 and TLS 1.3 are supported.

	Google Chrome	Internet Explorer	Firefox	Safari
TLS 1.2	v29	v11	v27+	v7+
TLS 1.3	v70	Not supported as of publication.	v63	v12.1+ on OSX 10.14 +and above[1]

1 TLS 1.3 support is disabled by default and must be manually enabled.

2.5. Common Webserver Support

Below is a table of common webservers and if/when TLS 1.2 and TLS 1.3 are supported.

	NGINX	Apache	IIS
TLS 1.2	Release 13+	V2.2+	V7.5+
TLS 1.3	Release 17+	V2.4+	Not supported as of publication.

It is important to note the versions listed above represent out-of-the-box support for TLS 1.2 and TLS 1.3. It is possible to manually recompile NGINX and Apache to support TLS 1.3 with possible mixed results.

2.6. Common TLS library support

Below is a table of common TLS libraries and if/when TLS 1.2 and TLS 1.3 are supported.

	OpenSSL	GnuTLS	NSS	LibreSSL	SCHANNEL
TLS 1.2	v1.0.1+	v1.7.0+	v3.15.1+	Supported at release	Windows 2008 SP2+
TLS 1.3	v1.1.1+	3.5.x+	vV3.29.0+	V3.1.1 (client only)	Not supported as of publication.

3. Lab Setup

3.1. Setup for Test 1 – TLS 1.2 vs. TLS 1.3 session speed

A major difference in TLS 1.2 vs. TLS 1.3 is the difference in the session setup process – As Section 2.1 and 2.2 explained, TLS 1.3 has an advantage due to the one

© 2020 The SANS Institute Author retains full rights.

© 2020 The SANS Institute, Author Retains Full Rights

less round trip needed. In Test 1, TLS 1.2 and TLS 1.3 will be compared to measure how many TLS Sessions can be set up per second. To do this, three machines were used:

- Machine 1: The client
  - 4 CPU, 8GB Ram
  - CentOS v8.1.1911. Kernel 4.18.0-147.8.1.el8_1.x86_64
  - Openssl version 1.1.1c FIPS
  - LibreSSL 3.1.2
- Machine 2: TLS Library Host
  - 4 CPU, 8GB Ram
  - CentOS v8.1.1911. Kernel 4.18.0-147.8.1.el8_1.x86_64
  - OpenSSL 1.1.1c FIPS
  - GNUTls v3.6.8

The host for these 3 virtual machines is a Dell R620. For capturing the speed, we will use the 's_time' function of openssl and LibreSSL: "openssl s_time -connect $ip-address$:443 -new". There will be eight datasets captured in total:

1.) Openssl connecting to openssl over TLS1.3 using TLS_AES_256_GCM_SHA384
2.) Openssl connecting to openssl over TLS1.2 using ECDHE-RSA-AES256-GCM-SHA384
3.) Openssl connecting to GnuTLS over TLS1.3 using TLS_AES_256_GCM_SHA384
4.) Openssl connecting to GnuTLS over TLS1.2 using ECDHE-RSA-AES256-GCM-SHA384
5.) LibreSSL connecting to openssl over TLS1.3 using TLS_AES_256_GCM_SHA384
6.) LibreSSL connecting to openssl over TLS1.2 using ECDHE-RSA-AES256-GCM-SHA384
7.) LibreSSL connecting to GnuTLS over TLS1.3 using TLS_AES_256_GCM_SHA384

© 2020 The SANS Institute Author retains full rights.

8.) LibreSSL connecting to GnuTls over TLS1.2 using ECDHE-RSA-AES256-GCM-SHA384

Each dataset consists of 500 datapoints on the average number of TLS sessions setup in a 30-second period. At the time of testing, LibreSSL did not have a method to stand up a simple testing server like Openssl and GnuTls so LibreSSL was excluded from server-side testing.

3.2. Setup for Test 2 – Simulating a stolen private key and testing PFS configuration

Test 2 will simulate a stolen private key to test PFS in both a weak TLS 1.2 configuration and a default TLS 1.3 configuration. For this test, we used Machine 2 from Test 1 and configured NGINX to use a cipher that does not leverage PFS (TLS_RSA_WITH_AES_256_GCM_SHA384) with TLS 1.2. Using the attack machine, HTTP over TLS traffic was generated and captured using Wireshark. After loading the private key into Wireshark, we checked to see if only the private key could be used to decrypt the traffic. A second sample was performed using a default configuration with Nginx and TLS 1.3 and results are compared.

3.3. Setup for Test 3 – Scanning sites for TLS support

During Test 3 information will be captured to document the current adoption rate of TLS 1.3 in various business sectors. This will be accomplished using the top 500 websites from Amazon's Alexa service in the Business, Retail, Technology, News, and "Kids and Teens" sections. With the lists, Qualys' SSL Labs API was used to scan each site for supported TLS protocols and exported the findings. The script ran on a Dell XPS15 laptop.

4. Analysis

4.1. Test 1 Analysis, Graphs, and key takeaways

This test will measure the speed with which a TLS session can be set up in TLS 1.2 and TLS 1.3 using three major TLS libraries. Looking back at the comparison

© 2020 The SANS Institute Author retains full rights.

between session setup in TLS 1.2 and TLS 1.3 above (2.1 and 2.2 respectively), the expected outcome is that TLS 1.3 is faster than TLS 1.2 by a factor of the latency between client and server because of the reduced round trips needed.

4.1.1. Libressl connecting to GnuTLS

During Test 1, Libressl is used to connect to GnuTls. Using TLS1.2 shown in Figure 4.1.1.1, the average number of connections per second is 39.5, with a standard deviation of 2.09. Figure 4.1.1.2 shows when TLS1.3 is used, the average increases to 43.3, and the standard deviation is reduced to 1.69. Comparing the two, the average number of sessions per second increased by 9.62%, and the standard deviation reduced by 19.14%. In other words, **TLS1.3 is 9.62% faster on average than TLS1.2 and 19.14% more consistent using Libressl and GnuTls.**

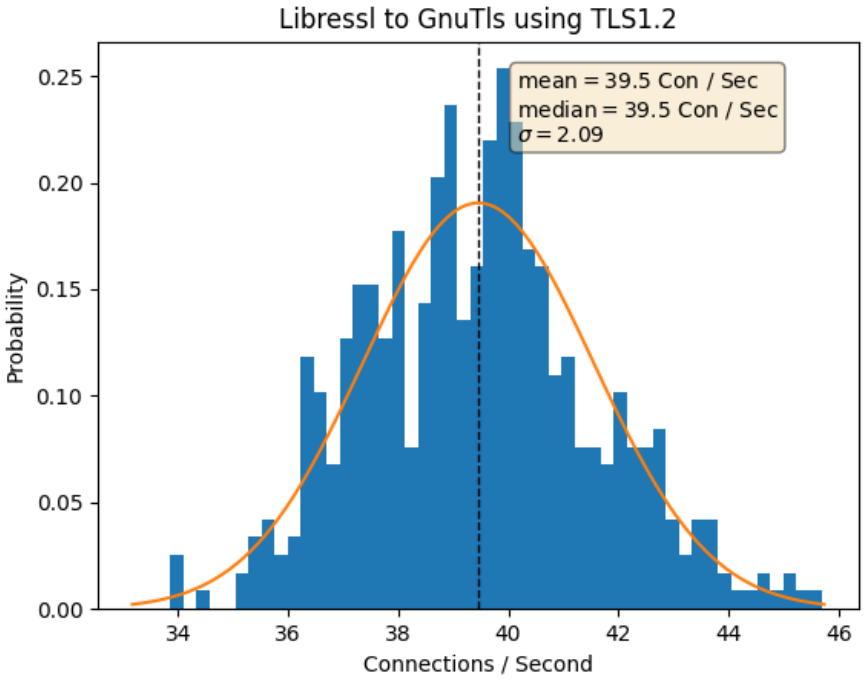


Figure 4.1.1.1

© 2020 The SANS Institute Author retains full rights.

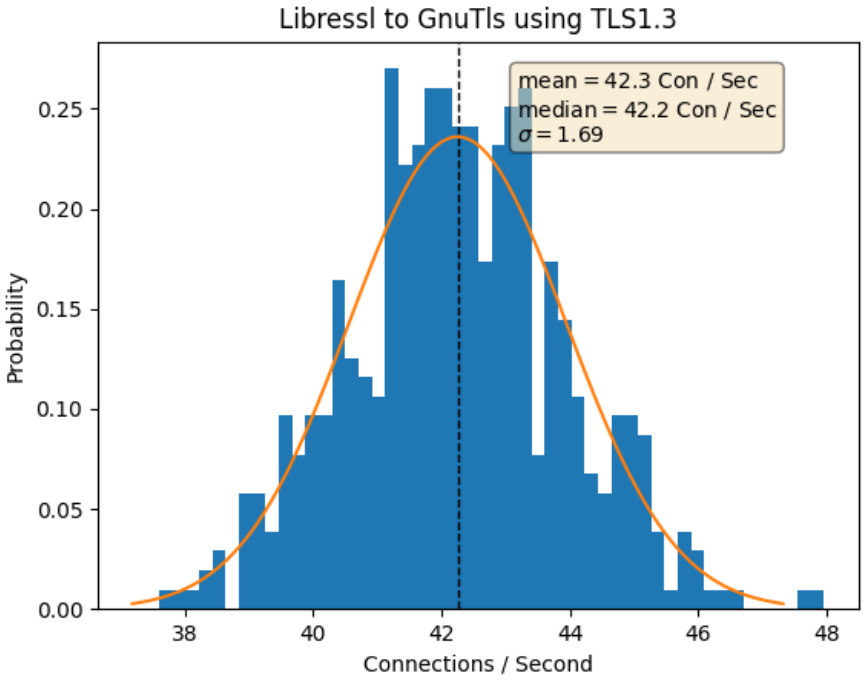


Figure 4.1.1.2

4.1.2. Libressl connecting to Openssl

In the second set of Test 1, Libressl is used to connect to GnuTls. Using TLS1.2, the average number of connections per second is 72.8, with a standard deviation of 2.59. These results are shown in Figure 4.1.2.1. Figure 4.1.2.2 represents when TLS1.3 is used, the average increases to 76.6, with a standard deviation of 1.59. This results in a 5.22% increase in speed and a 38.61% decrease in standard deviation. **Using LibreSSL and Openssl, TLS1.3 is 5.22% faster and 38.61% more consistent than TLS1.2.**

© 2020 The SANS Institute Author retains full rights.

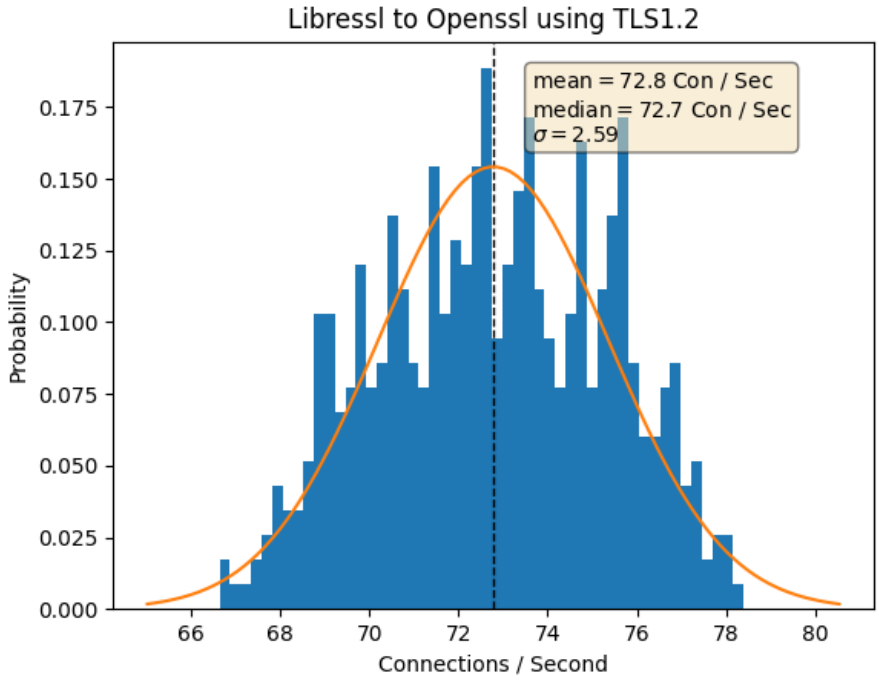


Figure 4.1.2.1

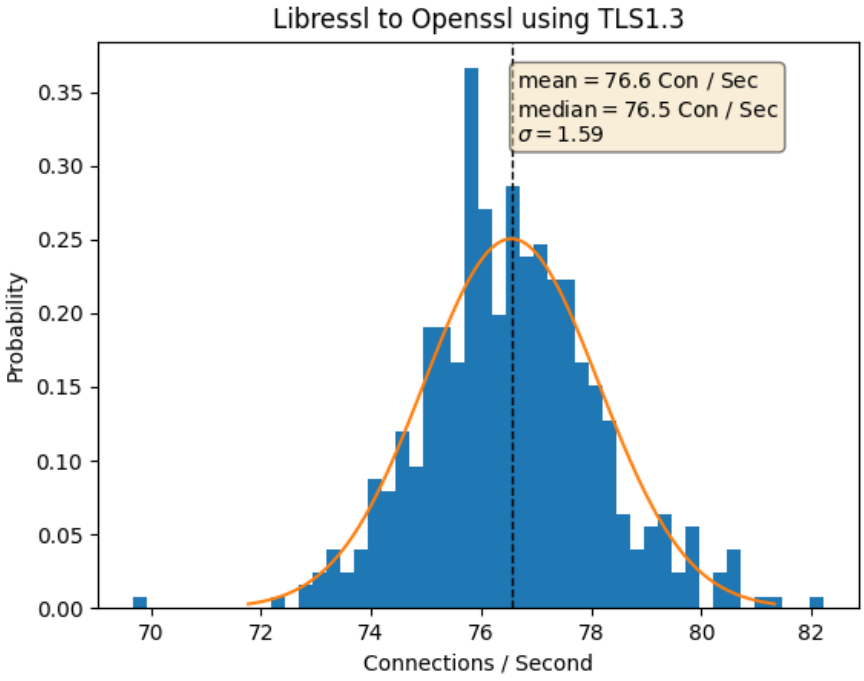


Figure 4.1.2.2

© 2020 The SANS Institute Author retains full rights.

4.1.3. Openssl connecting to GnuTLS

When using Openssl to connect to GnuTLS, TLS1.2 has an average of 41.9 and a standard deviation of 2.71 (Figure 4.1.3.1) compared to an average of 45.3 and a standard deviation of 2.02 in TLS1.3 (Figure 4.1.3.2). **In this dataset, TLS1.3 is 8.11% faster and 25.46% more consistent than TLS1.2.**

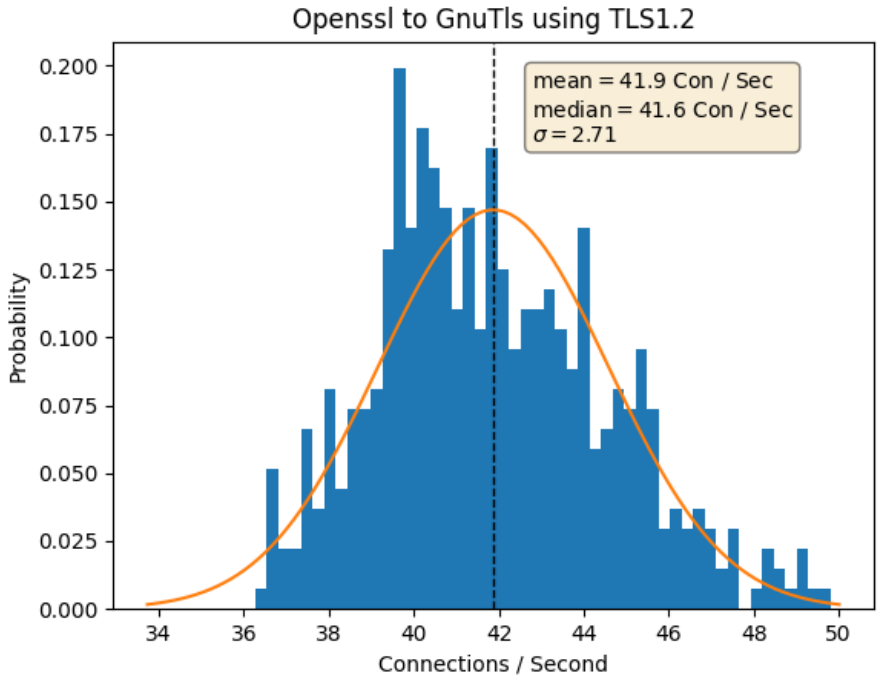


Figure 4.1.3.1

© 2020 The SANS Institute Author retains full rights.

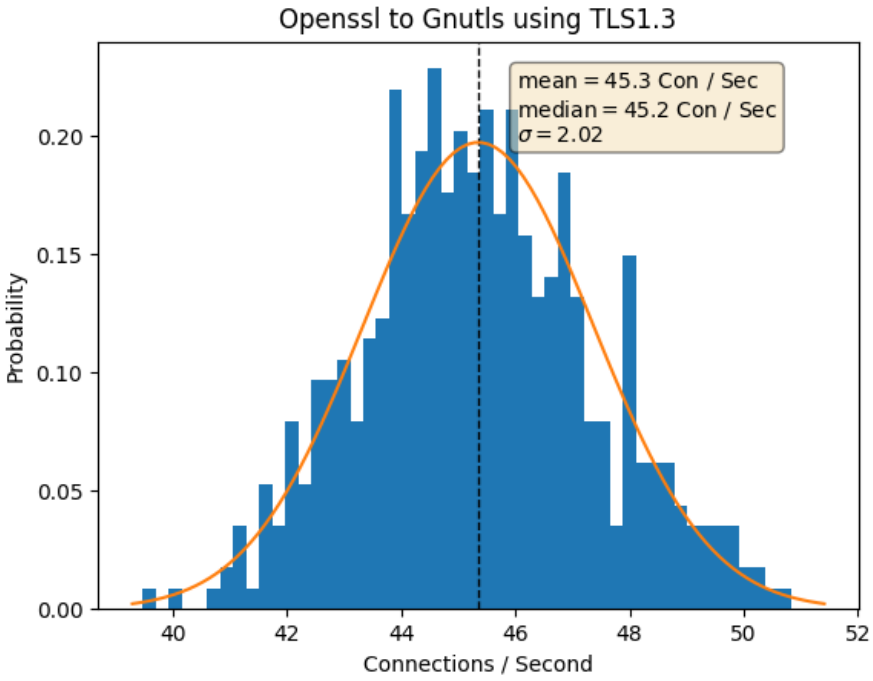


Figure 4.1.3.2

4.1.4. Openssl connecting to Openssl

Using Openssl to connect to Openssl, TLS1.2 has an average of 76.4 and a standard deviation of 2.64 (Figure 4.1.4.1) compared to 80.8 and 2.35, respectively in TLS1.3 (Figure 4.1.4.2). **TLS1.3 is 5.76% faster and 10.98% more consistent in this case.**

© 2020 The SANS Institute Author retains full rights.

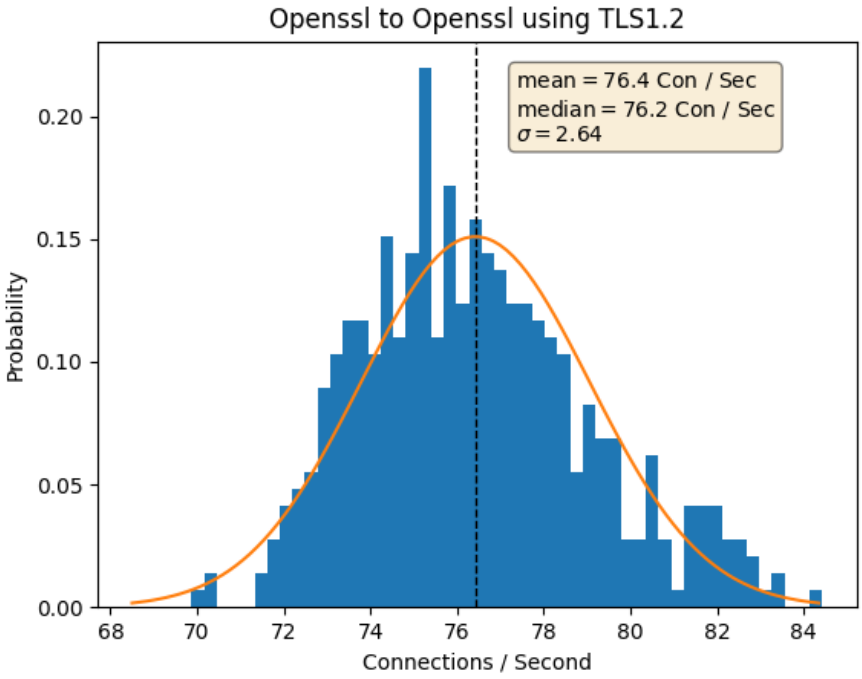


Figure 4.1.4.1

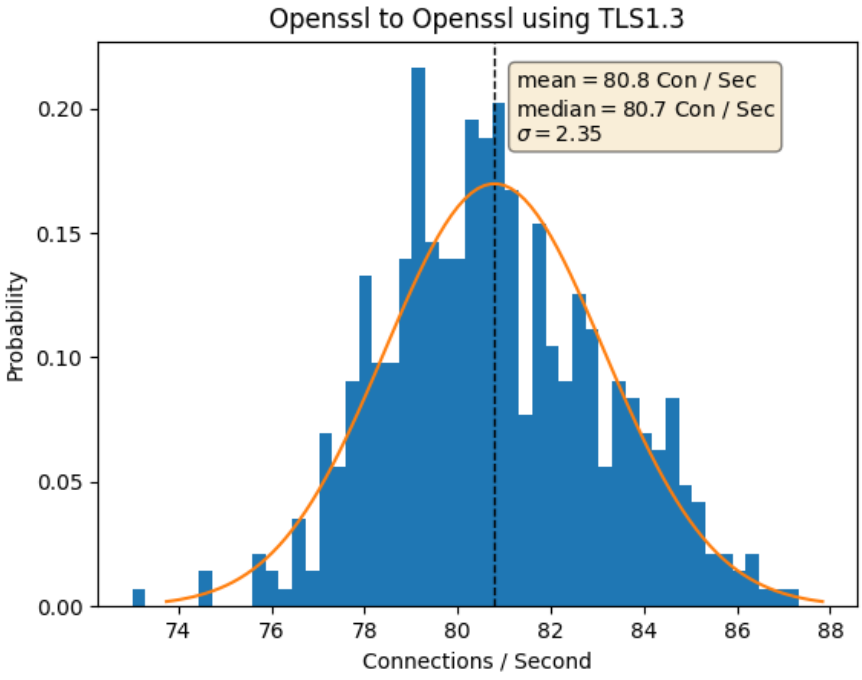


Figure 4.1.4.2

© 2020 The SANS Institute Author retains full rights.

4.2. Test 2 Analysis, Graphs, and key takeaways

Test 2 simulates a compromised private key in both a PFS and non-PFS configuration. In Figure 4.2.1 below represents a compromised private key, and a server configured with TLS1.2 without PFS ciphers enabled. In this example, an adversary was able to capture network traffic between a client and a webserver. The image shows Wireshark loaded with the private key of the server. Once loaded, the traffic is decrypted and the HTTP verbs and resources requested are seen in plaintext.

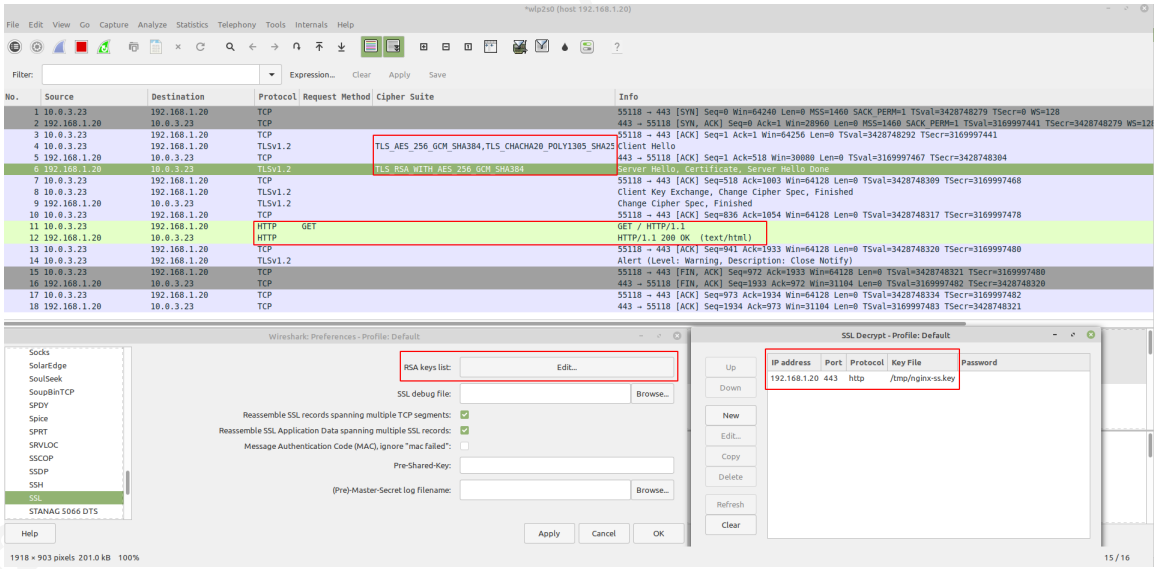


Figure 4.2.1

When a similar simulation is performed with TLS1.3 instead of TLS1.2 in Figure 4.2.2, Wireshark is unable to decrypt the traffic. This is because all ciphers supported in TLS 1.3 enable PFS by default.

© 2020 The SANS Institute Author retains full rights.

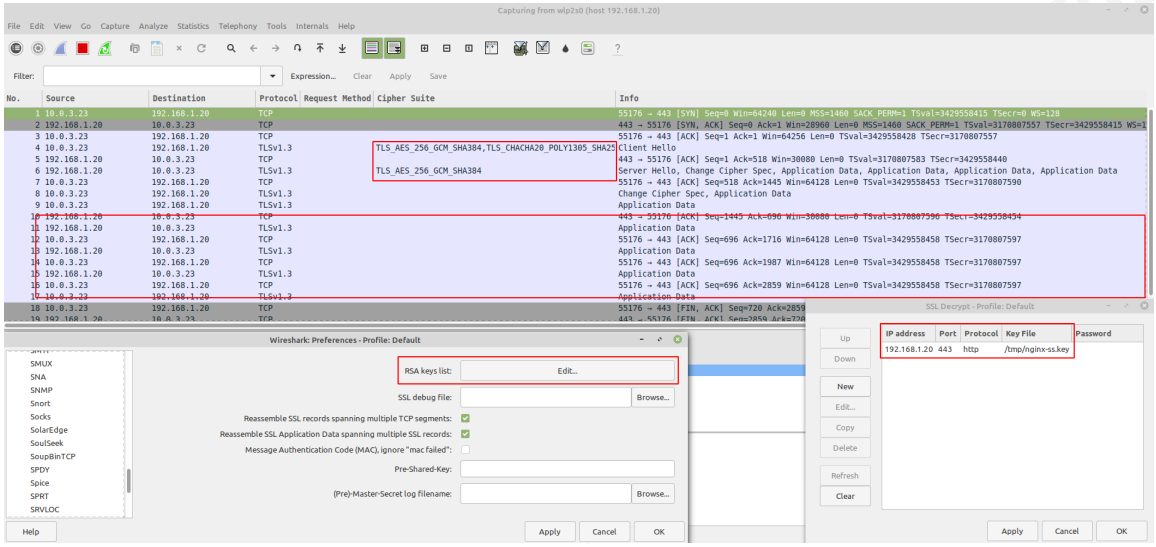


Figure 4.2.2

It is important to note that TLS 1.2 can be configured to only support PFS-enabled ciphers. However, this leads to the possibility of human error or configuration drift, allowing non-PFS ciphers to be enabled. If PFS is a requirement for an environment and strong configuration management is not in place, TLS 1.3 would be beneficial.

4.3. Test 3 Analysis, Graphs, and key takeaways

After determining that TLS 1.3 provides the benefit of speed of TLS 1.2 in Test 1, and the benefit of security in Test 2, the purpose of Test 3 is to measure the adoption rate of TLS 1.3.

4.3.1. Highest version of TLS Support

Figures 4.3.1.1 through 4.3.1.5 below represent the population of 500 websites in each category and what the highest TLS version enabled on the webserver.

© 2020 The SANS Institute Author retains full rights.

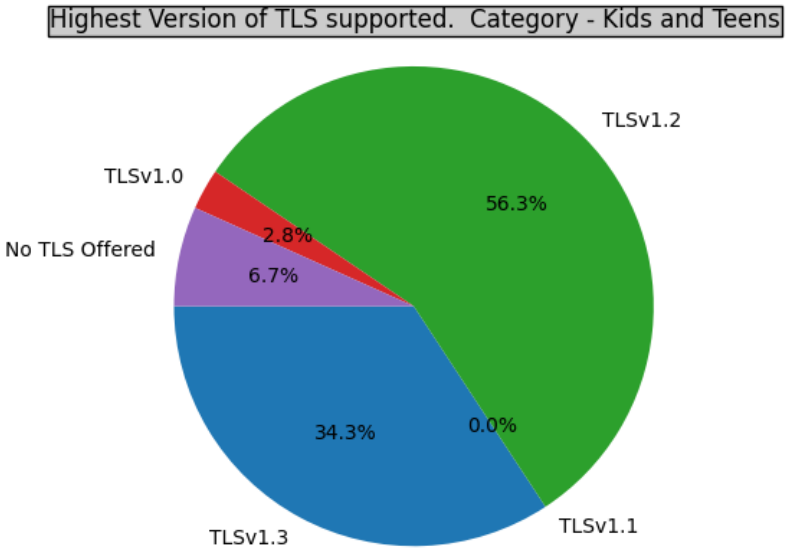


Figure 4.3.1.1

In Figure 4.3.1.1, the Kids and Teens category has 6.7% without any TLS enabled and almost 3% with TLS 1.0. TLS 1.2 is strongly represented, which is no surprise TLS 1.2 the highest adoption rate of any TLS version according to SSLLabs ("SSL Pulse", n.d.). TLS 1.3 has a surprisingly high adoption rate in this category at 34.3%.

© 2020 The SANS Institute Author retains full rights.

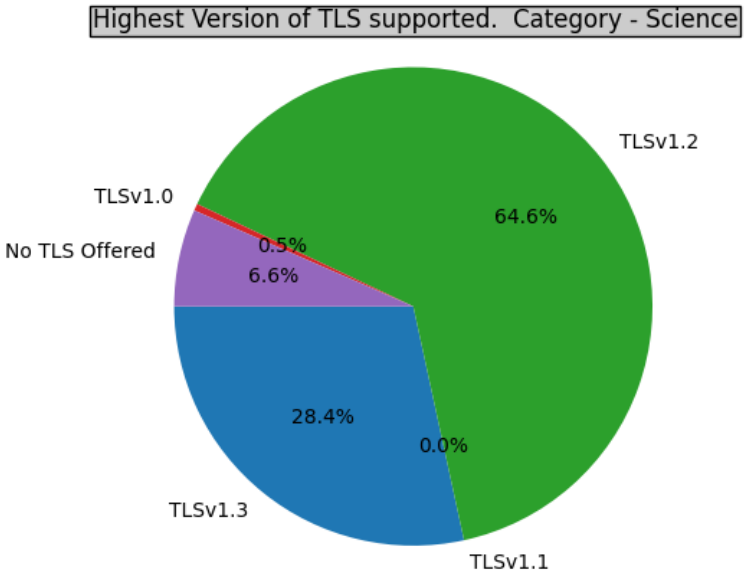


Figure 4.3.1.2

The Science category results in Figure 4.3.1.2 have the second lowest number of websites supporting no TLS or weak TLS (TLS 1.0) configurations at 7.1%. It is also noteworthy that 0% of the websites tested offer TLS 1.1 as the highest version. TLS 1.2 with 64.6% and TLS 1.3 with 28.4% show strong adoption rates for modern TLS libraries.

© 2020 The SANS Institute Author retains full rights.

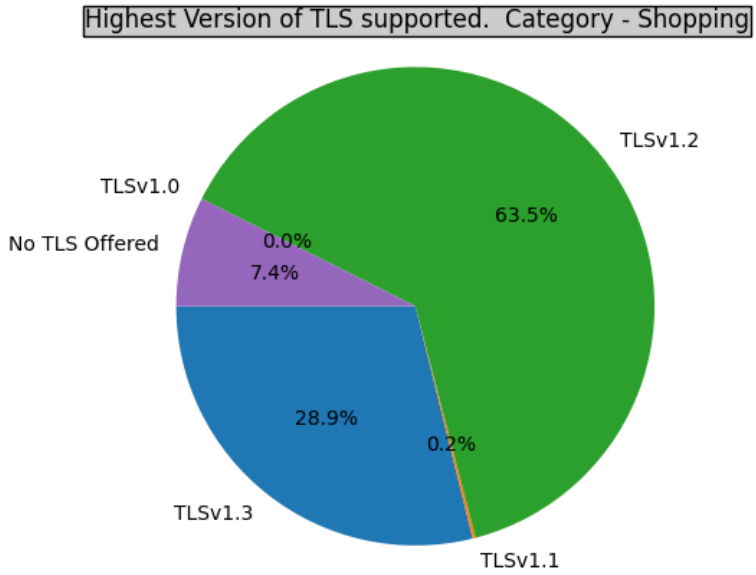


Figure 4.3.1.3

The Shopping category has positive results with low numbers in TLS 1.0 and TLS 1.1 – 92.4% of websites tested in this category support either TLS 1.2 or TLS 1.3 as the highest version.

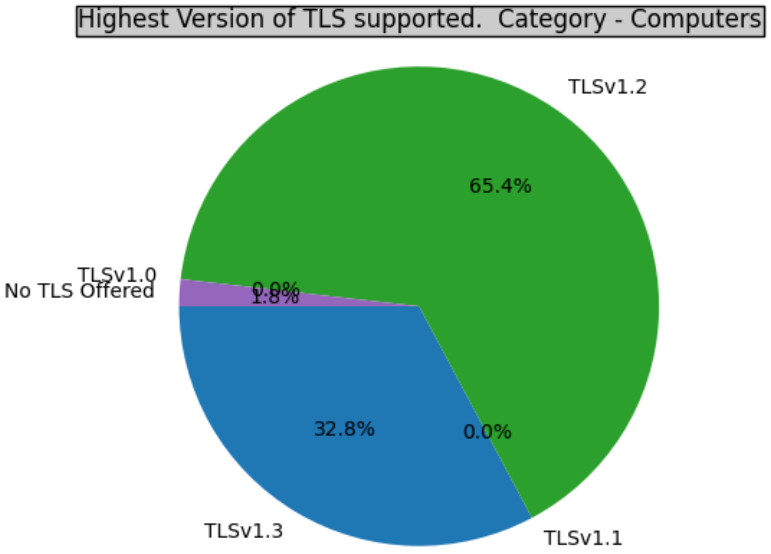


Figure 4.3.1.4

© 2020 The SANS Institute Author retains full rights.

The Computers category has the best overall score, with 0% of the websites tested supporting TLS 1.0 or TLS 1.1 as the highest version. 98.2% support either TLS 1.2 or TLS 1.3 as the highest version.

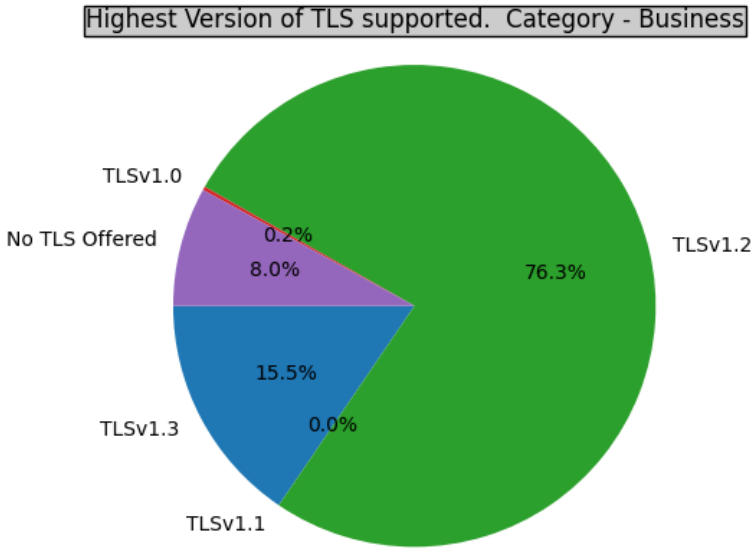


Figure 4.3.1.5

The Business category has the lowest adoption rate of TLS 1.3 across the five categories of sites tested. However, it also has the largest population of websites supporting TLS 1.2 as the highest version and low numbers for both TLS 1.0 and TLS 1.1.

Further testing in this area could include adding datapoints for the websites tested which have various audit requirements. For example, do companies with PCI environments have better adoption of modern TLS protocols and less support for older protocols? Additionally, it would be significant to measure the population of websites tested which use a hosting provider like Cloudflare. Is there a trend of websites with good TLS 1.3 adoption rates and usage of hosting providers? Do 'self-managed' websites have the same adoption rate as 'Third-Party Managed' sites? Answering these questions would help understand if the adoption rates are the result of many different companies following TLS best practices, or if the adoption

© 2020 The SANS Institute Author retains full rights.

rates are the result of many different companies using a third-party who follows TLS best practices.

4.3.2. Lowest Version of TLS Support

The second part Test 3 analyzes the same data used in the first part of Test 3 and extrapolates the lowest version of TLS offered by the domain. In this part of the test, very low numbers are expected for TLS 1.3 due to the unlikeliness that it is the only TLS version offered by a domain. However, it is interesting to compare the deprecation rate of TLS 1.0 and TLS 1.1 across sectors.

There are many reasons to disable deprecated TLS versions – many of which include confidentiality vulnerabilities. The IETF made very clear recommendations in March of 2019: “TLSv1.0 MUST NOT be used. Negotiation of TLSv1.0 from any version of TLS MUST NOT be permitted” ("Deprecating TLSv1.0 and TLSv1.1", 2019) and “TLSv1.1 MUST NOT be used. Negotiation of TLSv1.1 from any version of TLS MUST NOT be permitted.” ("Deprecating TLSv1.0 and TLSv1.1", 2019). NIST took a similar stance in its SP 800-52 Rev 2: “Guidelines for TLS Implementations”: “Servers that support citizen or business-facing applications … shall be configured to negotiate TLSv1.2 and should be configured to negotiate TLS 1.3. The use of TLS version 1.1 and 1.0 is generally discouraged” (McKay & Cooper, "Guidelines for the Selection, Configuration, and Use of Transport Layer Security (TLS) Implementations").

© 2020 The SANS Institute, Author Retains Full Rights

© 2020 The SANS Institute Author retains full rights.

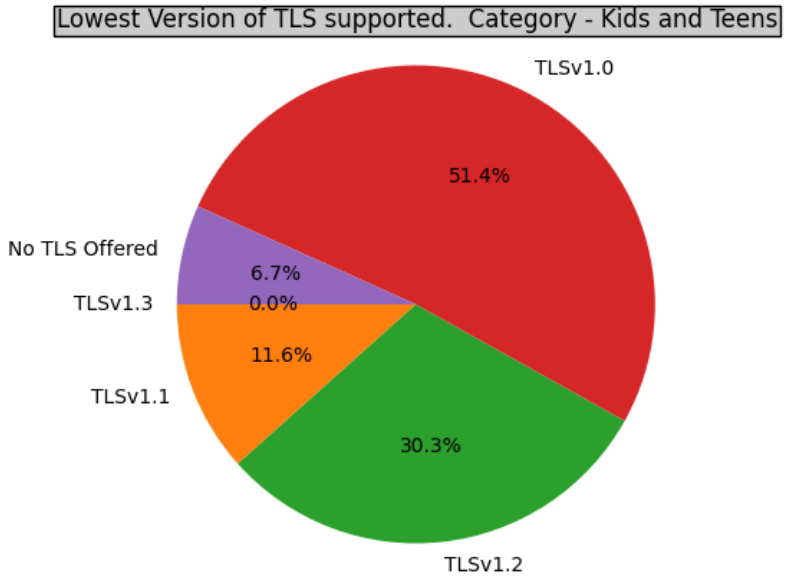


Figure 4.3.2.1

In Figure 4.3.2.1, 51.4% of domains tested in the Kids and Teens category still support TLS 1.0. 11% of the population have removed support for TLS 1.0 but support TLS 1.1.

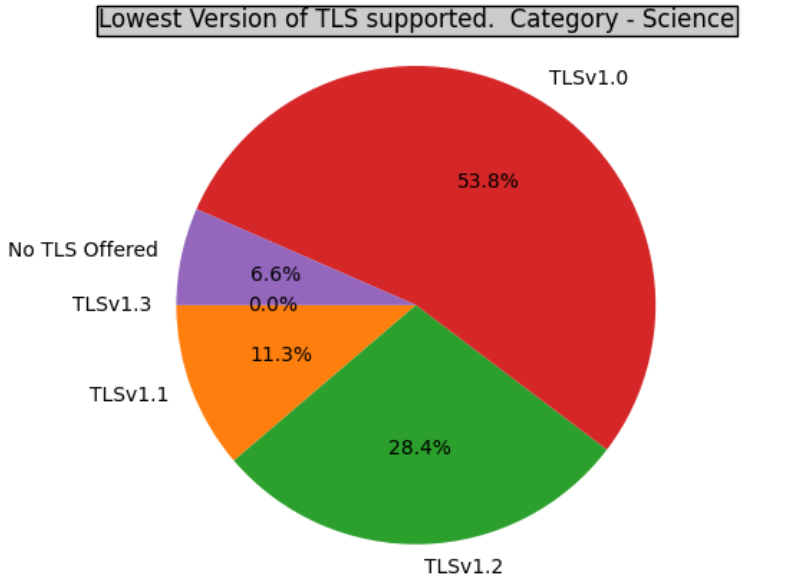


Figure 4.3.2.2

© 2020 The SANS Institute Author retains full rights.

In the Science category, almost 54% still support TLS 1.0, with an additional 11.3% still supporting TLS 1.1.

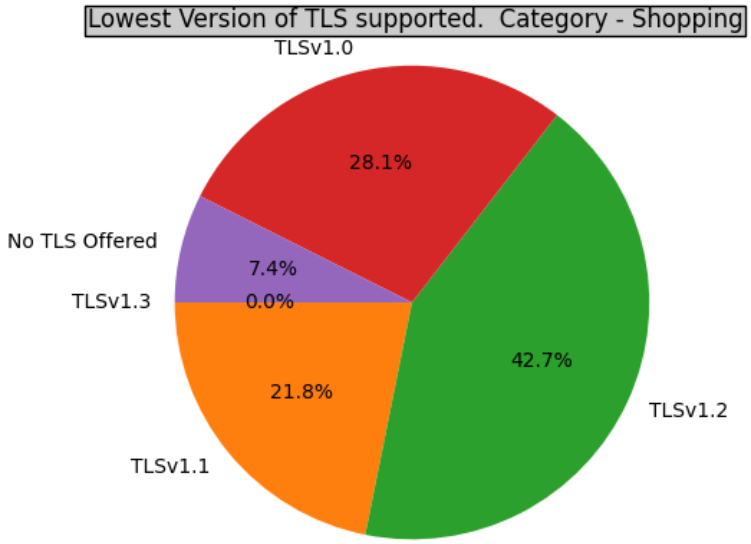


Figure 4.3.2.3

The Shopping category has the best results of all five categories in this test, with only 28.1% supporting TLS 1.0 and 21.8% supporting TLS 1.1. 42.7% of the domains tested have taken the guidance from IETF and NIST to disable TLS 1.0 and TLS 1.1.

© 2020 The SANS Institute Author retains full rights.

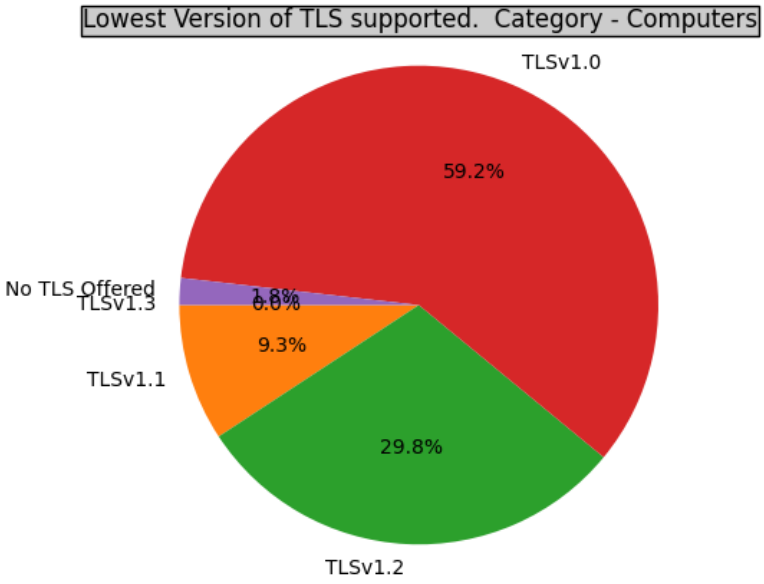


Figure 4.3.2.4

The Computers category has the worst results in this test, with 58.5% still supporting TLS 1.0 or TLS 1.1. The computer category has the lowest population of domains without TLS enabled, but the largest population of poor TLS configuration, which was an unexpected result.

© 2020 The SANS Institute Author retains full rights.

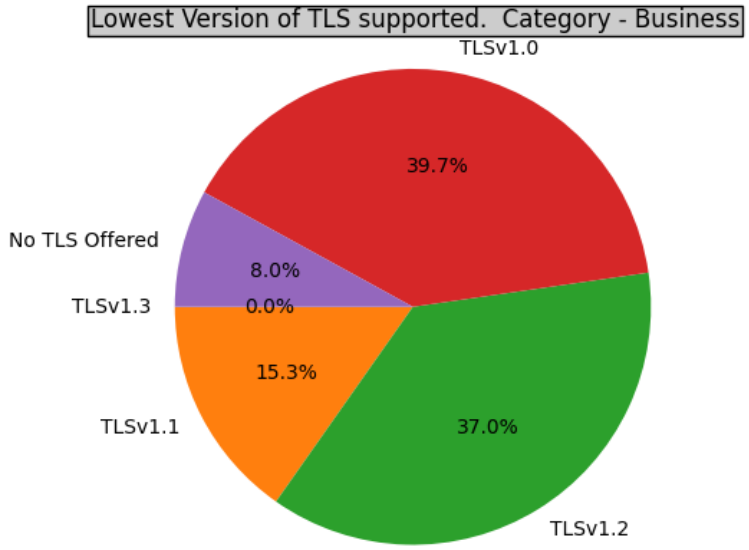


Figure 4.3.2.5

Finally, the Business category has approximately 54% of domains supporting deprecated protocols and only 37% of the population following IETF and NIST recommendations.

5. Conclusion

The purpose of this research is to provide evidence supporting or refuting the benefits of enabling TLS 1.3. In Test 1, TLS 1.3 was proven to be between 5%-9% faster on TLS session setup time and between 11%-38% more consistent in session setup time when compared to TLS 1.2. These speed-related benefits may not convince low-volume services to enable TLS 1.3 support, however large-volume services and CDNs would likely benefit by adopting TLS 1.3. Additionally, we found the fastest results when openssl is used as the server-side TLS library. Test 2 showed the benefits of TLS 1.3 when PFS is considered valuable to an organization without strong configuration drift management. Finally, Test 3 showed the number of popular high-volume websites that have seen the benefits of enabling TLS 1.3 and

© 2020 The SANS Institute Author retains full rights.

those who have not. Due to the low risk of enabling TLS 1.3 and the benefits illustrated, the recommendation is to configure TLS 1.3 to garner the speed and security benefits but to keep TLS 1.2 enabled for backward compatibility. Security practitioners who enable TLS 1.3 will gain the above benefits, take steps towards removing support for legacy protocols, and highlight the use of newer, better protocols across the industry.

© 2020 The SANS Institute, Author Retains Full Rights

© 2020 The SANS Institute Author retains full rights.

Appendix and References

CloudFlare.net. (n.d.). Transport Layer Security TLS. Retrieved May 14, 2020, from https://www.cloudflare.com/learning/ssl/transport-layer-security-tls/

Dierks, T., & Allen, C. (1999, January). The TLS Protocol Version 1.0. Retrieved May 14, 2020, from https://tools.ietf.org/html/rfc2246

Enabling Perfect Forward Secrecy. (n.d.). Retrieved May 15, 2020, from https://www.digicert.com/kb/ssl-support/ssl-enabling-perfect-forward-secrecy.htm

Kemmerer, C. (2015, March 3). The SSL/TLS Handshake: an Overview. Retrieved May 16, 2020, from https://www.ssl.com/article/ssl-tls-handshake-overview/

(n.d.). Retrieved May 16, 2020, from https://knowledge.digicert.com/generalinformation/INFO3299.html#Chrome

What's new in TLS 1.3? (n.d.). Retrieved May 16, 2020, from https://www.cloudflare.com/learning-resources/tls-1-3/

What Happens in a TLS Handshake? (n.d.). Retrieved May 16, 2020, from https://www.cloudflare.com/learning/ssl/what-happens-in-a-tls-handshake/

SSL Pulse. (n.d.). Retrieved May 26, 2020, from https://www.ssllabs.com/ssl-pulse/

Deprecating TLSv1.0 and TLSv1.1. (n.d.). Retrieved May 29, 2020, from https://tools.ietf.org/id/draft-ietf-tls-oldversions-deprecate-02.html#rfc.section.4

McKay, K. A., & Cooper, D. A. (n.d.). Guidelines for the Selection, Configuration, and Use of Transport Layer Security (TLS) Implementations. Retrieved May 29, 2020, from Guidelines for the Selection, Configuration, and Use of Transport Layer Security (TLS) Implementations

Onelski, J. (2020, February 13). SSL vs TLS - What's the Difference? Retrieved May 31, 2020, from https://www.globalsign.com/en/blog/ssl-vs-tls-difference

wolfSSL. (2018, September 13). Differences between SSL and TLS Protocol Versions (#TLS13). Retrieved June 15, 2020, from https://www.wolfssl.com/differences-between-ssl-and-tls-protocol-versions-3/

Ben Weber, ben.weber@student.sans.edu

© 2020 The SANS Institute Author retains full rights.