Chasing Shadows: A security analysis of the ShadowTLS proxy

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Abstract

ShadowTLS is a new type of circumvention tool where the relay forwards traffic to a legitimate (unblocked) TLS server until the end of the handshake, and then connects the client to a hidden proxy server (e.g. Shadowsocks). In contrast to previous probe-resistant proxies, this design can evade SNI sniffing, since to the censor it appears as a legitimate TLS connection to an unblocked domain.

In this paper, we describe several attacks against ShadowTLS which would allow a censor to identify if a suspected IP is hosting a ShadowTLS relay or not (and block it accordingly), distinguishing it from the legitimate TLS servers it mimics. Our attacks require only a few TCP connections to the suspected IP, a capability that censors including China have already demonstrated in order to block previous proxies.

We evaluate these vulnerabilities by performing Internet-wide scans to discover potential ShadowTLS relays, and find over 15K of them. We also describe mitigations against this attack that ShadowTLS (and proxies like it) can implement, and work with the ShadowTLS developers to deploy these fixes.

1 Introduction

ShadowTLS [12, 13] is a TLS-based circumvention proxy gaining popularity in China that aims to circumvent *TLS Certificate allowlists* by relaying the TLS handshake to existing unblocked websites, and then switching to a ***proxy server*** for the proxy requests and responses. In a typical setup of ShadowTLS, as shown in Figure 1, during the initial handshake, the ***relay*** forwards messages from the client to a legitimate HTTPS server (***mask site***), so that the client is effectively performing a TLS handshake with the legitimate server. After the handshake completes, the relay forwards subsequent TCP stream to a proxy server, such as a Shadowsocks [5] or V2Ray [4] server. Since the initial handshake is with a legitimate (and unblocked) TLS website, the idea is that the censor will not be able to distinguish these proxies from the popular websites they mimic, making them harder to block.

In this paper, we identify and evaluate several attacks against ShadowTLS' mimicry technique. In particular, despite its design, we find ways a censor could employ to actively probe a ShadowTLS relay or passively analyze client traffic in order to distinguish ShadowTLS relays from legitimate TLS servers. To evaluate our attacks, we perform an Internet-wide scan of TLS servers behaving similar to ShadowTLS, and identify over 15K deployments of them.

We suggest changes to the ShadowTLS design that could mitigate these problems, and work with the developers to get them implemented and deployed. We also discuss other types of attacks that may pose a threat to ShadowTLS and similar TLS-based proxies. To our knowledge, our work is the first to investigate the emerging style of censorship circumvention demonstrated by ShadowTLS.

2 Background

2.1 Motivation

Prior to ShadowTLS, fully-encrypted proxies like Shadowsocks were popular in censoring countries like China [14]. Fully-encrypted proxies work by encrypting every byte, including headers, to avoid matching a specific protocol fingerprint. However, these protocols can still stand out and be blocked by censors due to specific patterns/behaviors. Recently, China has performed active probing attacks to discover and block Shadowsocks servers [1]. Although countermeasures have been researched and deployed [10], there are more recent reports showing that Shadowsocks and other fully-encrypted proxies being detected and blocked passively [2].

TLS-based proxies avoid many of the shortcommings of fully-encrypted ones. Since TLS traffic is ubiquitous online [8], censors are unlikely to block the protocol outright.

However, TLS-based circumvention tools face several challenges. One major challenge on the server side is that the proxy needs to appear to host a realistic TLS service or website without any identifiable features unique to the proxy. Otherwise, censors could actively probe suspected proxies

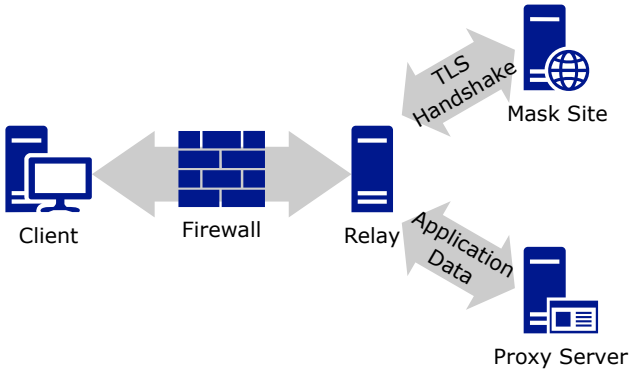

Figure 1: In a typical ShadowTLS setup, the ***client*** within a firewall will perform the TLS handshake with a ***relay*** across the firewall. The ***relay*** will forward these handshake packets to a *Mask Site* which is a legitimate (unblocked) HTTPS server. Once the handshake is done, all following packets are forwarded to a ***proxy server***.

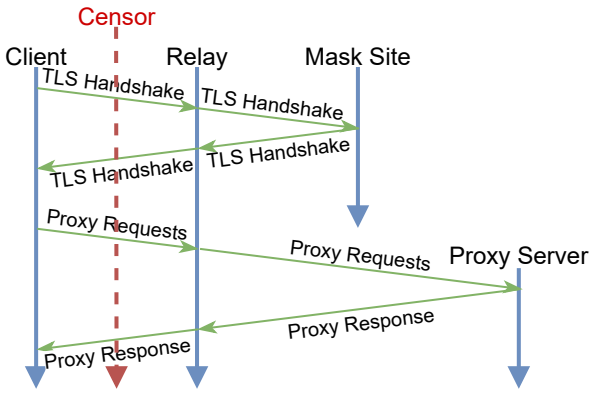

Figure 2: Data flow diagram of ShadowTLS

and block them based on the presence of such unique features, such as discrepancies in content or TLS protocol fingerprints.

In addition, proxies must commit to a real domain name, since the domain name used is visible to the censor in the Client Hello SNI extension and the censor can actively probe the server to obtain its certificate. The domain that the proxy uses must be real and popular, otherwise censors could easily block proxies by maintaining an domains allowlist for connection targets, and blocking TLS connections to domains not on that list. This technique has already been observed in Quanzhou, China [3].

2.2 ShadowTLS

ShadowTLS attempts to solve the previous issues of how to mimic a server by "putting on a play" in front of the censor. ShadowTLS operates using four components, as shown in Figure 1:

- A ***client*** starts a TCP connection with the ***relay***, and performs a TLS handshake with the relay.
- The ***relay*** forwards the client's TLS handshake messages to a relay-chosen ***mask site***, which is a popular website not blocked by the censor. Effectively, the ***client*** is performing a TLS handshake with the ***mask site***, with the ***relay*** acting as an intermediary. The ***relay*** does not learn the negotiated secret, due to the security of TLS.
- After the TLS handshake between the ***client*** and ***mask site*** is complete, the ***client*** begins to send data intended for the ***proxy server*** (e.g. Shadowsocks traffic) through the same TCP connection.
- Following the handshake, the ***relay*** forwards data to the ***proxy server***.

In this way, as shown in Figure 2, the client performs a TLS handshake with the mask site (via the relay's IP), which circumvents the censor's TLS certificate or domain allowlist. Once this handshake is complete, the same connection is reused to communicate with the proxy server (e.g. Shadowsocks).

For ShadowTLS to work, the relay needs to know when the TLS handshake has completed before being able to relay subsequent data to the proxy server. In ShadowTLS, the relay uses the `ChangeCipherSpec` message followed by an encrypted `Handshake` message (the `Finished` message) as a signal that the TLS handshake is finished. However, in TLS 1.3, these messages are encrypted and sent as Application Data records, making it difficult for the relay to know when the handshake has completed. For this reason, ShadowTLS only supports TLS 1.2 and earlier, where these handshake messages are not encrypted.

3 Security Analysis of ShadowTLS

In this section, we define the threat model and capabilities of the censor (e.g. the Great Firewall of China), and detail our attacks against ShadowTLS v0.1.4.

3.1 Threat Model

We assume a censor with similar demonstrated capabilities to that of the Great Firewall of China. In particular, the censor is able to passively observe traffic between the client and relay. And it can block, inject, or spoof fake requests or responses. The censor can also actively probe suspected proxies and observe responses. We assume the censor is unwilling to block all TLS traffic, but may maintain an list of allowed domains that can appear in a TLS certificate or Client Hello Server Name Indication field, and block any other connections , as done in Quanzhou [3]. We assume the client and relay

have a shared secret that the censor is not privy to, such as the secret used in Shadowsocks.

3.2 Attacks

In this section, we present attacks we have identified based on code analysis and experiments with our own ShadowTLS instances. These attacks exploit behavioral discrepancies between a ShadowTLS ***relay*** and other well-known TLS server implementations, even the ones used by ShadowTLS as mask sites.

TLS fingerprinting Prior work has shown that the TLS fingerprint of the Client Hello message can be used to distinguish TLS implementations [11], and this attack has been used by censors previously to block circumvention tools [9].

We measured the TLS fingerprint of the ShadowTLS client against the tlsfingerprint.io database, which collects TLS fingerprints from a university network tap. We found that the fingerprint produced by ShadowTLS (`ebaa863800590426`) was not observed in the tap dataset collected by tlsfingerprint.io, meaning the client fingerprint is likely unique to the ShadowTLS tool and could be used by censors to block it. To address this issue, we recommend that ShadowTLS use a library like uTLS [15] to mimic more popular TLS fingerprints and avoid this attack.

Alternative protocols TLS servers often return errors if they received a malformed request. For instance, sending a non-TLS record to a TLS server could result in a TLS Alert response, indicating the request was not understood. Alternatively, some TLS server implementations will respond to other protocols they can parse, such as HTTP, to help out users that have mistakenly connected using the wrong protocol.

While not being defined in any standard/specification, we find many TLS implementations will respond when they receive a plaintext HTTP request instead of a TLS Client Hello as the first message in a connection. We performed an Internet wide scan of servers running on TCP port 443, and found that over 75% of them responded with either a non-TLS response (e.g. an HTTP error response), or reset the TCP connection. Only 17% of them behaved like ShadowTLS does, and closed the connection with a `FIN-ACK`. This means that over 80% of servers running on TLS port 443 can be trivially distinguished from ShadowTLS by seeing how they respond to a plaintext HTTP request.

TLS Application Data records Normal TLS connections encapsulate all data in TLS records, which contain a short header specifying record type, TLS version, and length of the data, followed by the data itself. Sending data without this header is an undefined behavior, and could trigger a response that distinguishes TLS servers from ShadowTLS relays.

By analyzing the source code of ShadowTLS and our own network traces while using it, we observe that after the handshake, ShadowTLS does not encapsulate data in TLS records. This presents two potential attacks: first, a censor could passively observe that data to a ShadowTLS server is not encapsulated in TLS records after the TLS handshake. Second, the censor could actively probe the ShadowTLS server, complete the TLS handshake to the mask site, and then check to see how the server responds to being sent random data.

A normal TLS server should error or close the connection, since it has received an invalid TLS record. However, ShadowTLS will forward the data to the proxy (e.g. Shadowsocks), which would ignore it (since the probing censor does not have the shared secret required to use the proxy). Thus, a real TLS server would close the connection, while ShadowTLS would silently ignore the invalid TLS record.

Response	Non-record	Ratio	Bad MAC	Ratio
Fatal Alert	26.9 M	87.3%	28.4 M	88.9%
Reset	2.5 M	8.2%	2.4 M	7.5%
Closed	1.2 M	3.8%	821 K	2.6%
Alert	167 K	0.5%	288 K	0.9%
No Response	**44 K**	**0.14%**	**40 K**	**0.12%**
Non-TLS	2 K	0.01%	5 K	0.02%
Total	*30.8 M*		*31.9 M*	

Table 1: Response from TLS Servers after we send Non-TLS Record Data (Non-record) or a well-formed TLS record but with an incorrect MAC tag (Bad MAC) following a successful TLS handshake. ShadowTLS' relay behavior is in **Bold**.

We performed an Internet-wide scan to determine what fraction of tcp/443 servers would complete a TLS handshake, but then silently ignore non-record data. We used ZMap [17] to scan the Internet on tcp/443, and our own custom TLS tool written in Go to test how servers would respond. To each server, we sent 35 bytes of ASCII, with an invalid record type, TLS version, but an accurate length field to avoid potentially triggering buggy implementations. We found that over 99% of the 30 million TLS hosts we completed handshakes with responded to our invalid record, most frequently with a fatal TLS alert. Only 0.14% of hosts behaved like ShadowTLS by not responding and keeping the connection open.

Corrupted TLS Application Data TLS protects against tampering by using a MAC or authenticated cipher on Application Data records. If a TLS host receives an Application Data record that does not properly decrypt or has an invalid MAC, the TLS RFCs [6, 7, 16] specifies that a fatal TLS alert (`bad_record_mac`) must be sent, and the connection closed.

In ShadowTLS, the relay does not have the shared secret negotiated between the client and mask site, meaning the relay cannot validate Application Data records to determine if the MAC is valid or it decrypts properly. Instead, after the

Technique	Ratio
Plain HTTP Request	17.0%
Non-TLS Record Data	0.14%
Corrupted TLS Application Data	0.12%
Combined	**0.05%**

Table 2: The ratio of TLS servers on the Internet that respond like a ShadowTLS relay to each active probing technique. When the results of these attacks are combined, only a very small fraction of hosts (0.05%) behave like ShadowTLS.

handshake ShadowTLS indifferently redirects data received to the proxy server.

Therefore, a censor could actively probe a suspected ShadowTLS relay, first by completing the handshake, and then sending a TLS Application Data record with correct version and length but a random (and therefore invalid) encrypted data in its payload. According to the TLS specifications, a normal TLS server should close the connection with a fatal TLS alert, but ShadowTLS might not send a response, since the payload will not have the correct proxy (e.g. Shadowsocks) secret and many proxy servers would not respond to an invalid payload.

We again performed an Internet-wide scan to see what fraction of hosts behave like ShadowTLS and silently ignore corrupt TLS Application Data records. We found only 0.12% of hosts behaved like ShadowTLS, making it possible for censors to distinguish it from other benign TLS servers.

Fixing this issue will require a design change to how ShadowTLS relays operate, which we discuss in Section 4.

Combining active attacks While each of the active probing attacks can distinguish ShadowTLS relays from a large majority of TLS servers, we find that these attacks work even better in concert. Table 2 shows that by combining these three attacks, our Internet-wide scan reveals approximately 15K servers (0.05%) on the Internet that behave similarly to ShadowTLS. Of these, only 6K of them provided TLS certificates for domains of the Alexa Top 1000 domains, with the most frequent being subdomains of *webex.com* (5969 servers) and *zoom.us* (149 servers). While many of these servers may be non-ShadowTLS, and we cannot confirm what fraction of them truly are, this low number suggests these attacks could be feasible and effective in practice.

While we cannot determine our actual false negative rate, we can get a sense of our true positive rate. We set up four public ShadowTLS relays prior to our scans, and confirmed that our scans discovered all four of our relays, and labelled them as ShadowTLS based on their responses.

Less Efficient: Redirect Connections A strong censor could also try to *prevent* use of ShadowTLS by redirecting connections to their alternative "true" destination resolved from the SNI in the *ClientHello* message. However, our experiment results in Appendix A.1 indicate that this attack is neither efficient nor accurate enough.

4 Defenses

An underlying issue in all of the attacks we discovered is that a censor is able to observe a difference between the ShadowTLS relay and the mask site it is mimicking. We note that if the ShadowTLS relay forwarded *all* packets to the mask site (and relayed responses), our attacks would not work. Of course, we need some way for packets to still reach the proxy server, otherwise ShadowTLS would only function as a transparent TCP relay.

To defend against these attacks, we suggest a subtle change to the ShadowTLS design. Rather than having the relay switch over to forwarding to the proxy after the TLS handshake, we instead have the ShadowTLS relay only forward TLS Application Data records that are encrypted and authenticated under a secret known only to the client and relay. The client will complete the TLS handshake as it currently does, and then will change the secret that it uses to encrypt/authenticate the TLS Application Data records that follow to one derived from the server random and client-relay shared secret. When the relay receives an Application Data record, it validates it using the same information. If validation fails, the record is forwarded to the mask site. Otherwise, the relay removes the TLS record and forwards the payload to the proxy.

This prevents our attacks, since the censor will not have the client-relay shared secret. Therefore, any packets that they attempt to send will end up being forwarded to the mask site, and the ShadowTLS relay will not have any application-layer distinguishing features: all of its responses to the censor will come from the true mask site that it is mimicking.

Responsible disclosure We disclosed our attacks to the ShadowTLS developers, and they incorporated our suggested defense. As of *ShadowTLS v0.2.3*, relays are no longer vulnerable to the active probing attacks we identified.

5 Conclusion

We presented several techniques to identify ShadowTLS *relays* on the Internet that would be trivial for a censor to implement and deploy. We evaluate our attacks, and find that after an Internet-wide scan, only 15K servers behave like a ShadowTLS relay among over 30 million HTTPS servers on the Internet. This is concerning, as it suggests censors could use these attacks to actively probe and block ShadowTLS relays. To address this, we identify a small-but-effective design change to ShadowTLS that defends against these attacks generally, and we worked with the ShadowTLS developers to implement and deploy this fix, protecting future ShadowTLS users from the active probing attacks we discovered.

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A Less Efficient Attacks

A.1 Redirecting connections

A censor could also try to *prevent* use of ShadowTLS altogether, by redirection connections to their "true" destination. For instance, when a client sends a Client Hello with a server name indication (SNI), the censor could perform a DNS lookup for the domain, and if the IP returned is different from the one the client is connected to, the censor could start a new TCP connection to the correct IP, and relay packets from the client to that IP. If the client were communicating to a ShadowTLS relay before, the censor would effectively redirect them to the mask site's actual IP address, bypassing the ShadowTLS relay.

However, such an attack might break legitimate TLS connections. For instance, if the censor used a different DNS resolver than the client, or the client is connecting to a private network address not reflected in public DNS. To evaluate this, we looked at TLS connections from our university's network, and collected the Client Hello SNI and destination server IP. We collected 27M `<SNI, IP>` pairs over 24 hours , and identified 472K unique pairs. We then queried DNS for each SNI domain to obtain the lookup IP(s), and compared it to the IP in the connection (the original IP). We found 6K SNIs that did not resolve, and 141K SNIs where the original IP was found in the A record. In other words, SNIs of about 325K pairs resolve to different IP addresses.

We perform a TLS connection using Zgrab2, to see if the first resolved IP of these 325K pairs will complete a TLS connection for the desired domain. If it does not, then we label the original `<SNI, IP>` pair as potentially being disrupted by this attack. Only 9K successfully completed a TLS handshake and 316K failed.

Therefore, 4.8% of connections we observed on our tap could be "disrupted" if a censor implemented this attack. We find Amazon Web Services, Apple iCloud and Hulu SNIs

among the connections we expect to fail. This likely makes this attack too costly for a censor to deploy to all traffic.