TLS Proxies: Friend or Foe?

Mark O’Neill, Scott Ruoti, Kent Seamons, Daniel Zappala
Brigham Young University
Department of Computer Science
Provo, UT 84602
mto@byu.edu, ruoti@isrl.byu.edu, seamons@cs.byu.edu, zappala@cs.byu.edu

Abstract
The use of TLS proxies to intercept encrypted traffic is controversial since the same mechanism can be used for both benevolent purposes, such as protecting against malware, and for malicious purposes, such as identity theft or warrantless government surveillance. To understand the prevalence and uses of these proxies, we build a TLS proxy measurement tool and deploy it via a Google AdWords campaign. We generate 2.9 million certificate tests and find that 1 in 250 TLS connections are proxied. The majority of these proxies appear to be benevolent, however we identify over 1,000 cases where three malware products are using this technology nefariously. We also find numerous instances of negligent and duplicitous behavior, some of which degrade security for users without their knowledge. To better understand user attitudes toward proxies, we conduct a survey of 1,261 users. The conflicting purposes of TLS proxies are also demonstrated in these findings, with users simultaneously comfortable with benevolent proxies but wary of attackers and government intrusion. Distinguishing these types of practices is challenging in practice, indicating a need for transparency and user opt-in.

1. INTRODUCTION
Communicating securely over the Internet requires authenticating the identity of a website to establish trust. To pay a bill with your bank, make a purchase on Amazon, or login to Facebook, your web browser must verify the identity of the server you want to access. To validate the identity of a website such as Amazon, the web browser relies on certificate authorities (CAs), which digitally sign certificates vouching for the identity of the web servers with which we communicate. Web browsers authenticate a site by validating a chain of trust from the site’s certificate back to one of a set of trusted root certificates. These certificates comprise the root store and are typically bundled with the operating system or browser.

This validation system is currently being compromised by the use of TLS proxies, which can act as a man-in-the-middle (MitM) for TLS connections (e.g., [3][20][21][1][48]). A TLS proxy can issue a substitute certificate for any site the user visits, so that the user establishes an encrypted connection to the proxy rather than the desired web site. To avoid browser warnings that a substitute certificate would ordinarily trigger, an organization installs a new trusted root certificate on the user’s machine, via a custom system image, manual install, or an enterprise PKI system. For example, if the user wishes to create a secure connection to Google, the proxy intercepts the request, generates a certificate for Google, and masquerades as that site to the user. Companies typically employ TLS proxies for benevolent reasons, particularly to protect intellectual property and to protect their network from intruders. Personal firewalls use similar techniques to protect users from malware and phishing attempts.

Despite their benevolent uses, TLS proxies can also be used by a malicious entity to steal a user’s private information, such as a credit card number, or by a government to snoop on encrypted traffic. There are various ways attackers can bypass browser warnings of substitute certificates. Evidence suggests cases of compromised and negligent certificate authorities are not uncommon [13]. Some governments control their own root certificate authorities, and evidence suggests that some governments coerce authorities into granting them certificates for domains they do not own [34]. Malware may add new certificates to a client’s root certificate store when it is installed. In the private sector, nothing prevents a manufacturer from adding certificates in the root store of their devices; Nokia was recently found to be using TLS proxies on mobile devices and has experienced a public backlash against this being done without users’ knowledge [38].

The most dangerous aspect of TLS proxies is that the user is entirely unaware that encrypted traffic is being intercepted by an organization or attacker. Current browser software shows a reassuring lock icon during such sessions, which could lead most users to assume they are having a confidential conversation with the website. Essentially, in the name of providing increased security, TLS proxies have violated the authentication guarantees TLS was designed to create.

Although TLS proxies subvert the security of a TLS connection, little work has been done to characterize the prevalence and use of these proxies. A forthcoming paper from Huang et al. measures the prevalence of TLS proxies using measurements deployed at Facebook [25], finding 0.20% of TLS connections are proxied, mostly by corporate Internet filters and personal antivirus software. In addition, a small number of connections were found to be intercepted by malware. Prior to this publication, only a few isolated attacks had been observed in the wild, notably in Iran [1] and Syria [13]. Eckersley provides evidence that governments are coercing...
CAs to provide them with forged certificates [15].

Our focus in this paper is to better understand the current uses of TLS proxies through a large-scale measurement of TLS proxies found in the wild. Because proxies can have different uses, we supplement our measurement study with a user survey to report attitudes toward proxies.

The contributions of this paper include:

- A tool to automatically measure the presence of TLS proxies, using the Flash runtime. Other tools require individual, security-conscious users to install the tool in order to help detect fraudulent certificates or MitM attacks. Our method requires no user action and silently runs to determine whether a proxy is present whenever the user visits our web site.

- A measurement study of TLS proxies using a novel Google AdWords campaign. With this campaign, we automatically scan TLS connections when Google serves our ad, without any user involvement. Our study found 11,764 proxied connections out of 2.9 million total measurements (0.41% of all connections) spanning 142 countries. We found that most substitute certificates claim to be from benevolent TLS proxies, with 54.27% claiming to be generated by a personal firewall and 16.25% claiming to be generated by a corporate network.

- We found several instances of negligent and malicious behavior. Our analysis of one parental filter finds that it masks forged certificates from an attacker, allowing the attacker to easily perform a MitM attack against the firewall’s users. In addition, we found three malware products affecting over 1,000 systems that install a new root certificate and act as a TLS proxy to dynamically insert advertisements on secure sites. We also found evidence that spammers are using TLS proxies in their products and we found numerous other suspicious circumstances in substitute certificates, such as a null Issuer Organization, falsified DigiCert signatures, and downgraded public key sizes.

- A survey of 1,261 users on their attitudes toward TLS proxies, primarily from the US and India. The survey indicates that users have a complicated relationship with proxies. They accept the use of proxies for filtering and protecting against malware, but strongly favor being informed when a proxy actively intercepts their encrypted traffic. They overwhelmingly do not want law enforcement to use TLS proxies, and strongly favor legislation requiring user consent when proxies are used.

We developed our tool and conducted our measurement study independently and prior to the dissemination of Huang’s forthcoming publication [25]. The advantage of Huang’s methodology is that they find proxies specifically targeting Facebook, whereas the advantage of our methodology is that we can collect results without the cooperation of a major website and find proxies that may have whitelisted Facebook or other high-profile sites. As compared to Huang, we find that TLS proxies are twice as common, we find some additional malware, we find evidence of spammers using TLS proxies, and we find that one parental filter weakens security for its users by opening them up to a MitM attack. We discuss the detailed differences between our findings in section 5.

2. MEASUREMENT TOOL

We have developed a tool to measure the prevalence of TLS proxies using existing, widely-deployed technologies. The tool runs silently from the perspective of the user; no user action is required, either to install any software or to interact with the tool. This is a significant advantage as compared to other work that requires client-side software installation [51, 54, 9, 29, 9, 0], since it enables us to quickly deploy our measurement tool and obtain millions of measurements within a week. We do not need to encourage users to adopt our tool in order to obtain measurements. The primarily limiting factor regarding how fast we collect data is the amount of money we wish to spend on Google’s ad network.

2.1 Design

To meet our objective of using existing browser technologies without requiring further client installation, we take advantage of the widespread deployment and transparency afforded by the Adobe Flash runtime. By hosting a Flash application on a web page the server can upload it to a visiting client, which runs it without any user interaction. Our tool works by sending a ClientHello message to a TLS-enabled server and recording the ServerHello and Certificate messages received in response. The retrieved certificate(s) is then forwarded to the Web server for verification. This process is handled in three steps, illustrated in Figure 1.

1. Retrieve measurement tool. The client browser connects to the web server where the Flash application is hosted. The application need not be visible to the user and can merely be embedded in the background of an otherwise normal web page. The web page data, along with the embedded Flash application, is then downloaded by the client.

2. Record certificate. The Flash tool is run automatically by the browser. The tool sends a ClientHello message back to the server to initiate a TLS handshake. The tool then records the ServerHello and Certificate messages received in response and terminates the handshake.

3. Report results. The tool reports these results back to the server using an HTTP POST request. The server then compares the certificate received with the original sent and reports a mismatch as a TLS proxy.
To deploy our tool a website administrator need only do the following:

1. **Host the Flash application on the web server** and reference it within the HTML of desired pages. The tool can be deployed transparently within existing web pages with no visible changes.

2. **Host a simple “socket policy file” on the server.** For security reasons the Flash runtime requires that applications attempting to establish a TCP connection with a remote host first obtain permission from that host via a simple policy file. The request for this file is sent automatically by the Flash runtime. The software to host such a file is extremely simple, easily deployed, and included in our solution. This particular security feature of Flash prohibits the tool from testing client connections to arbitrary hosts; all hosts tested must first grant permission through their respective socket policy files.

### 2.2 Implementation

To implement our tool it was necessary to retrieve the certificate used during a TLS handshake. It would have been preferable to use JavaScript or HTML5 to retrieve the certificate used as part of a current TLS connection, but unfortunately there is no API available for this. Firefox enables a plugin to request the certificate, but developing a plugin would require client installation. This left us with the alternative of establishing a plain TCP connection with the target server and then initiating a TLS handshake. Unfortunately, the ability to use a plain TCP connection rules out the use of HTML5 WebSockets.

Due to these constraints, we opted to use the Adobe Flash platform. Beginning with version 11.0 of the Flash runtime, Adobe made available a `SecureSockets` API available that allows developers to access certificate data from a TLS connection. However, these versions of Flash were too recent to enjoy the reported 98.9% desktop market penetration of Flash 9.0 [2]. Thus we implemented our tool in ActionScript using only libraries supported by the Flash 9.0 runtime. Using the `Socket` API provided by Flash 9.0 we implemented functionality required to perform a partial TLS handshake. After receiving the full `Certificate` message from the desired host the handshake is aborted and the connection is closed. The Flash application records and parses all certificates received from the `Certificate` message (as some hosts offer certificate chains) and stores them locally until it parses the final one. All certificate data, in PEM format, is concatenated and then sent as an HTTP POST request back to the host for analysis.

### 2.3 Deployment

To collect measurements, we have deployed our tool as shown in Figure 2. In this setting the Flash application is hosted on an ad network, such as Google AdWords, with measurements then directed to our web server. This configuration decouples dissemination of the tool from its operation, enabling us to conduct measurements using advertisements. We serve our socket policy file on the same port used by our web server (80). This reduces the effect of captive portals, which often block traffic targeting ports other than those used by HTTP and HTTPS (e.g., airport public access WiFi). An additional deployment option is available for administrators who wish to send the certificate report back to a third server (other than the ad server or web server). Our data and code will be available for download at [http://tlsresearch.byu.edu](http://tlsresearch.byu.edu).

To accommodate placement in advertisements, our measurement tool contains a visible canvas on which we place a simplistic advertisement for our research lab. Figure 3 shows the advertisement as it appeared to web users during our measurement study. We also replace random numbers used by the TLS handshake code with static values, as some ad networks block Flash advertisements that use random number generators. With these adaptations, we widely distribute the application through a Google AdWords campaign, having the application itself be the advertisement. This is possible because AdWords (and various other advertisement networks) allow Flash applications to be served as advertisements. Visitors of AdWords-enabled websites automatically download the tool and run it on their computers as they browse the web. The Flash tool performs a partial TLS handshake with our web server and reports the retrieved certificate back to that server. Section 2.4 discusses the results from this study.

### 2.4 Limitations

Our tool is unable to measure TLS proxies being used against most mobile devices. An overwhelming majority of mobile platforms do not support Flash and Adobe has discontinued their development of Flash for mobile devices.

It is possible that TLS proxies could be engineered to cir-
cumvent our measurements. At the time of our study, our measurement methodology was not well known, so there is no reason to believe that any attacker was evading detection or tampering with our reports. However, in the case that this methodology becomes well-known, it would be difficult to prevent dedicated attackers from modifying their TLS proxies to avoid our measurements. We discuss several ideas for increasing the difficulty of circumventing our measurements in Section 5.

3. MEASUREMENT STUDY
To determine the prevalence and uses of TLS proxies, we conducted an advertising campaign using Google AdWords. We uploaded our tool as a Flash advertisement. When users visit a page with the ad, the tool automatically runs, retrieves the certificate attached to our website, and reports the results back to us. This strategy for using an advertising campaign to conduct an end-user measurement study has previously been used to study CSRF attacks [7], DNS rebinding attacks [28], and DNSSEC deployment [26, 27, 32]. Our study is the first to use this same method to measure the deployment of TLS proxies. The results from this study shed light on the legitimate demand for TLS proxies as well as several suspicious or duplicitous practices.

3.1 Data Collection
Our advertising campaign ran from January 6, 2014 to January 30, 2014. We used the CPM (cost-per-impression) bidding model for our campaign, which maximizes the number of unique clients that were served our ad. To help us reach a global audience we indicated that our ad should be served to all locations and languages. Additionally, since ads are shown only on websites that match a set of designated keywords we selected our keywords based on the those that were currently trending globally on Google Trends [20]. Finally, we set our ad to display evenly throughout the day so as to avoid biasing it to a certain set of time zones.

During the duration of our ad campaign, we served 4.6 million ads and successfully completed 2.9 million measurements. In total we spent $5,101.88. Along with the certificate, we also recorded the IP address of the client tested. This IP address was then used to query the MaxMind GeoLite [36] database to gather geolocation information. Of those tests, 11,764 returned a different X.509 certificate than was served by our certificate. It is certainly possible that malicious proxies have hidden their tracks by masquerading as a legitimate enterprise, however they produce software that disguises itself as a legitimate enterprise, and we cannot detect this.

Table 2 shows the values for the Issuer Organization field of the substitute certificates. Table 3 provides a breakdown of values present in the Issuer Organization field of the substitute certificates. The majority of certificates from proxied connections have an Issuer Organization field matching the name of a personal or enterprise firewall (71.2%). Another 12.3% have the name of an organization set as the Issuer Organization (e.g., Lawrence Livermore National Laboratory, Lincoln Financial Group). Additionally, 7% (829) of the substitute certificates we collected have hidden their tracks by masquerading as a legitimate organization in the Issuer Organization field, and we cannot detect this.

Table 1 shows the values for the Issuer Organization field of the substitute certificates. Table 2 provides a breakdown of values present in the Issuer Organization field of the substitute certificates. The majority of certificates from proxied connections have an Issuer Organization field matching the name of a personal or enterprise firewall (71.2%). Another 12.3% have the name of an organization set as the Issuer Organization (e.g., Lawrence Livermore National Laboratory, Lincoln Financial Group). Additionally, 7% (829) of the substitute certificates we collected have hidden their tracks by masquerading as a legitimate organization in the Issuer Organization field, and we cannot detect this.

Table 3 shows the countries with the most proxied connections in our study. For each country, the table lists the total number of proxied connections, the total number of connections, and the percentage of total connections to that country that were proxied. Some countries have significantly higher percentages of proxied connections than the average, including France (1.09%), Canada (0.87%), Belgium (0.81%), the United States (0.79%), and Romania (0.74%). Together, connections from the United States and Brazil account for 36% of all proxied connections.

3.2 Analysis of Issuer Organization
We first analyze the contents of the Issuer Organization in the substitute certificates we collected. We use OpenSSL to decode the certificates and store them in a database, where we can run queries. We also manually inspect the contents of the relevant fields to identify the issuing organization and their software products, using web searches to determine their identity. We emphasize that our results in this section are based on the intercepting proxy self-identifying themselves in the certificate. It is certainly possible that malicious proxies have hidden their tracks by masquerading as a legitimate organization in the Issuer Organization field, and we cannot detect this.

The most suspicious activities discovered were revealed by certificates with an Issuer Organization that matched the names of malware. “Sendori, Inc.”, “WebMakerPlus Ltd”, and “IoPFailZeroAccessCreate” appeared in 966, 95, and 21 Issuer Organization fields, respectively. Sendori poses as a legitimate enterprise, however they produce software that
Table 2: Issuer Organization field values

<table>
<thead>
<tr>
<th>Proxy Type</th>
<th>Connections</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personal Firewall</td>
<td>6,384</td>
<td>54.27%</td>
</tr>
<tr>
<td>Enterprise Firewall</td>
<td>463</td>
<td>3.94%</td>
</tr>
<tr>
<td>Personal/Enterprise Firewall</td>
<td>1,528</td>
<td>12.99%</td>
</tr>
<tr>
<td>Organization</td>
<td>1,448</td>
<td>12.31%</td>
</tr>
<tr>
<td>Malware/Spam</td>
<td>1,141</td>
<td>9.70%</td>
</tr>
<tr>
<td>Unknown</td>
<td>800</td>
<td>6.80%</td>
</tr>
</tbody>
</table>

The WebMakerPlus malware is primarily associated with inserting advertisements into Web pages. Since modern browsers issue warnings when insecure content is queried from secure connections, we hypothesize that WebMakerPlus uses a TLS proxy to simulate that their advertisements are served from a secure connection. Substitute certificates containing markings for WebMakerPlus originated from 16 distinct countries.

Manual Internet queries revealed that malware was responsible for an Issuer Common Name field value of “IopFailZeroAccessCreate”. The certificates containing this value originated from 14 distinct countries. Disturbingly, each certificate contained the same 512-bit public key. This malware was also reported by [25].

It is somewhat surprising that these malware programs self-identify in the substitute certificates they generate, as an attacker can arbitrarily select values for the fields in a substitute certificate.

In addition to malware discoveries, we found that the names of two companies highly associated with spam were also present in numerous Issuer Organization fields. The names “Sweesh LTD”, and “AtomPark Software Inc” were found in 39 and 20 substitute certificates, respectively. AtomPark offers tools for spammers including “email extractors” and “bulk mailers”. Sweesh offers services to spammers to overcome “hurdles” faced by advertisers and publishers. Internet searches reveal that Sweesh may be responsible for the development of WebMakerPlus.

3.3 Negligent Behavior

Where possible, we installed and characterized personal firewall software from many of the most common companies whose names were provided in the Issuer Organization, Issuer Organizational Unit, and Issuer Common Name fields of our collected certificates. We characterized the behavior of these solutions when running behind our own TLS proxy which issued certificates signed by an untrusted CA. While most solutions properly rejected our forged certificates, Kurupira, a parental filter that is responsible for 267 proxied connections in our dataset, did not. When visiting google.com and gmail.com, Kurupira replaced our untrusted certificate with a signed trusted one, thus allowing attackers to perform a transparent man-in-the-middle attack against Kurupira users without having to compromise root stores. In contrast, BitDefender not only blocked this forged certificate, but also blocked a forged certificate that resolved to a new root we installed in the victim machine’s root store.

Among the negligent behavior we found are TLS proxies that generate substitute certificates with weak cryptographic strength. Our original certificate has a public key size of 2048 bits. However, we find that 5,951 (50.59%) substitute certificates have public key sizes of 1024 bits and 21 certificates have public key sizes of 512 bits. 23 (0.20%) TLS proxies generated substitute certificates that used MD5 for signing, 21 (0.18%) which were also 512 bit keys. Interestingly, some TLS proxies generated certificates that have better cryptographic strength than our certificate. Seven (0.06%) used certificates with a key size of 2432 and five (0.04%) used SHA-256 for signing.

In addition to problems with cryptographic strength, we discovered that 49 (0.42%) substitute certificates claim to be signed by DigiCert, though none of them actually are. The original certificate from our secure web server is issued by DigiCert High Assurance CA-3, indicating the TLS proxy likely copied this field when creating the substitute.

Finally, we note that 110 substitute certificates have modifications to the subject field. For 51 (0.43%) certificates, the subject did not match our website’s domain. In many cases
a wildcarded IP address was used that only designated the subnet of our website. In two cases the substitute certificate is issued to the wrong domain entirely: mail.google.com and urs.microsoft.com. These certificates appear to be legitimate for those domains and properly validate back to GeoTrust and Cybertrusts' roots, respectively.

4. USER ATTITUDES

Our measurement results indicate that most proxies we detected are likely deployed in enterprise settings or via personal firewalls. Yet, research in this area has often treated all proxies as malicious because they do in fact act as a MitM attack. Any enhancement or replacement of the existing TLS ecosystem to address the complicated nature of proxies will require widespread and willing adoption by users. Thus, to ascertain user attitudes toward TLS proxies, we conducted an online survey using the Amazon Mechanical Turk crowdsourcing service (MTurk). Traditionally MTurk has been used to aid data mining and machine learning by gathering human annotation and classification of data sets, but more recently MTurk has been shown to be an effective tool for gathering information about users’ attitudes and habits related to security and usability [50, 29, 8].

4.1 Methodology

Two versions of an online survey were used in this work. The first survey was distributed to 87 participants and used to calibrate our questions for the second survey. In this preliminary phase, participants were paid between $0.75 and $1.15 USD for survey completion. Responses from participants were analyzed to determine which questions provided interesting results. The second version of the survey reduced the number of questions with the intent of reducing the time required to complete the survey to between five and ten minutes. Since the first survey was used for calibration, we report only the results of the second survey here.

The second survey was published with the title “Take a 5-minute survey about the Internet and security”, but did not indicate that it concerned TLS proxies. Data was collected from 11 AM – 4:30 PM (Eastern Standard Time) on Wednesday, February 17, 2014. Participants were paid $1 USD for completing the survey and could only take the survey once. In total, 1,261 participants completed the second survey.

Both surveys were published after review by the IRB. No personally identifying information was collected from users. Additionally, at the beginning of the survey participants were informed that if they had any questions or concerns about the study they could contact us and have their responses removed. Finally, if users did not complete the survey we automatically deleted their responses.

The results for both surveys will be available at [http://tlsresearch.byu.edu](http://tlsresearch.byu.edu) To ensure users’ privacy, IP addresses and geolocation have been removed from the data sets. All other data recorded as part of the surveys has been included.

4.2 Demographics

The survey begins with a collection of demographic information. Participants in the survey were skewed towards male participants: male (60.9%), female (38.8%), preferred not to answer (0.3%). Ages were mostly uniform and centered around ages 25-32: ages 18–24 (20.0%), 25–34 (47.9%), 35–44 (18.2%), 45–54 (8.2%), 55 and older (5.5%), preferred not to answer (0.2%). Nearly all participants had completed high school, with the majority having completed some level of higher education: no diploma (1.0%), high school (11.2%), some college or university credit (26.6%), college or university degree (51.7%), post-secondary education (9.3%), prefer not to answer (0.2%).

Our participants were predominantly from the United States of America (77.5%) and India (20.9%). All other countries were represented by four or less participants: Romania, the former Yugoslav Republic of Macedonia, Bulgaria, Canada, Serbia, Barbados, Belgium, Sweden, United Arab Emirates, Lithuania, Germany, Argentina, and Mexico.

Participants were asked to self report their level of knowledge of Internet security: expert (3.6%), highly knowledgeable (16.6%), mildly knowledgeable (42.1%), somewhat knowledgeable (33.0%), no knowledge (4.2%), prefer not to answer (0.5%).

4.3 Awareness

After collecting demographic information we give participants instruction on TLS proxies. This includes a description explaining how TLS is intended to function in the context of HTTPS. Participants are then told how TLS proxies could be used to allow another party to decrypt the traffic between them and secure websites. Finally, participants are given a list of reasons for the use of TLS proxies. This list includes both protective uses (e.g., blocking malware and viruses, content filtering) and malicious uses (e.g., stealing passwords, spying, censorship). The writing is designed to be informative and neutral in tone, allowing participants to form their own opinions about TLS proxies. This instruction has been reproduced in Appendix A.

After reading this material, participants were asked how well our descriptions helped them to understand TLS proxies and whether they were aware of TLS proxies before this survey. Most participants agreed that our descriptions helped them clearly understand TLS proxies: clearly understood (90.6%), unsure (6.9%), did not clearly understand (2.5%). Most users were not aware of TLS proxies before the survey: unaware (59.0%), unsure (10.2%), aware (30.0%).

We speculate that, due to the effects of illusory superiority, the number of participants that were unaware of TLS proxies before the survey was even higher than reported [19, 24]. Additionally, participants may have conflated knowledge of traditional web proxies with knowledge of TLS proxies. This is important, as it indicates that a large portion of participants do not bring pre-existing biases for or against TLS proxies into the survey.

4.4 Acceptability of TLS proxies

Participants are next asked about their attitudes relating to TLS proxies. This includes asking them whether they feel TLS proxies are an invasion of privacy and whether there are acceptable uses for TLS proxies. Answers to selected questions are shown in Table A.
Nearly half of participants indicated that TLS proxies are an invasion of privacy, but a third also reported that they were unsure: invasion of privacy (49.5%), unsure (33.4%), not an invasion of privacy (17.1%). When asked whether there are acceptable uses for TLS proxies nearly three-fourths of participants responded positively: acceptable (72.5%), unsure (15.5%), unacceptable (12.0%). Perhaps even more interesting, of the users that indicated that TLS proxies are an invasion of privacy, nearly two-thirds still indicated that there are acceptable uses for TLS proxies: acceptable (60.9%), unsure (18.4%), unacceptable (20.7%).

Participants that indicated there are acceptable uses for proxies were also asked what organizations are justified in using proxies and for which uses. Unlike the other questions reported on in this survey, this question allowed free form textual entry. We group participant responses based on the following classes of TLS proxies:

1. **Institutional.** This includes the use of TLS proxies by businesses, government agencies (internal use), schools, and libraries. Many participants indicated that because these institutions provided the Internet for their employees or constituents they were permitted to use TLS proxies on their own networks. The use of TLS proxies in this case is centered around protecting the interests of the business and any benefit to users is considered incidental. Acceptable uses for TLS proxies included protecting company infrastructure against viruses and other external attacks, filtering inappropriate websites, and preventing the leak of sensitive information.

2. **Services.** This includes the use of TLS proxies by ISPs and firewalls. Specifically, users believe these services should be allowed to use TLS proxies to protect customers. Acceptable uses for TLS proxies included detecting and preventing phishing attacks, filtering inappropriate websites, and stopping the spread of malware.

### Table 4: Likert questions from the TLS proxy user survey (n=1,261)

<table>
<thead>
<tr>
<th>Question</th>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neither Agree nor disagree</th>
<th>Agree</th>
<th>Strongly agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>The above description (Appendix A) helped me to clearly understand what TLS proxies are and how they are used</td>
<td>0.24%</td>
<td>2.30%</td>
<td>6.90%</td>
<td>69.71%</td>
<td>20.86%</td>
</tr>
<tr>
<td>Prior to taking this survey, I was aware that organizations were using TLS proxies</td>
<td>16.49%</td>
<td>43.14%</td>
<td>10.23%</td>
<td>25.85%</td>
<td>4.28%</td>
</tr>
<tr>
<td>TLS proxies are an invasion of privacy</td>
<td>2.62%</td>
<td>14.59%</td>
<td>33.39%</td>
<td>37.91%</td>
<td>11.50%</td>
</tr>
<tr>
<td>There are acceptable uses for TLS proxies</td>
<td>3.33%</td>
<td>8.56%</td>
<td>15.54%</td>
<td>59.00%</td>
<td>13.56%</td>
</tr>
<tr>
<td>I am concerned that TLS proxies could be used by hackers to compromise my Internet security</td>
<td>1.43%</td>
<td>12.29%</td>
<td>13.88%</td>
<td>54.48%</td>
<td>17.92%</td>
</tr>
<tr>
<td>I am concerned that TLS proxies could be used by the government to collect my personal information</td>
<td>2.30%</td>
<td>11.97%</td>
<td>16.97%</td>
<td>42.51%</td>
<td>26.25%</td>
</tr>
<tr>
<td>Browsers should notify users if there is a TLS proxy intercepting and decrypting their Internet traffic</td>
<td>0.40%</td>
<td>2.62%</td>
<td>8.96%</td>
<td>43.46%</td>
<td>44.57%</td>
</tr>
<tr>
<td>There should be legislation that addresses TLS proxies</td>
<td>1.67%</td>
<td>6.26%</td>
<td>20.14%</td>
<td>47.18%</td>
<td>24.74%</td>
</tr>
</tbody>
</table>

3. **Law enforcement.** A small minority of participants (<3%) indicated that law enforcement agencies should also be allowed to use TLS proxies. This includes both local (e.g., city police) and federal agencies (e.g., FBI, NSA). These TLS proxies could be used to track the activities of individuals under investigation. Participants that indicated this use for TLS proxies also indicated that this case required a valid warrant or threat to national security.

### 4.5 Mitigation of TLS proxies

While most participants were accepting of the uses of TLS proxies in certain situations, they were not without their reservations. Nearly three-fourths of participants were concerned that TLS proxies could be used by hackers to compromise their Internet security: concerned (72.4%), unsure (13.9%), unconcerned (13.7%). Similarly, two-thirds of participants were concerned that TLS proxies could be used by the government to collect their personal information: concerned (68.8%), unsure (17.0%), unconcerned (14.3%).

Participants were then asked what steps browsers and governments should take in relation to TLS proxies. Nine-tenths of users indicated that their browser should notify them when a TLS proxy is being used on their current Internet connection: should notify: (88.1%), unsure (9.0%), should not notify (2.0%).

Most participants felt that there should be legislation that addresses the use of TLS proxies: legislation needed (71.9%), unsure (20.1%), legislation not needed (8.0%). Participants who indicate they wanted to see legislation enacted were also asked what types of legislation they thought would be helpful (the following are not mutually exclusive): prevent their use
require organizations to obtain user consent (72.4%), require organizations to inform users (78.7%), other (2.2%) (e.g., require security audits of companies using TLS proxies, limit the organizations allowed to use TLS proxies).

4.6 Limitations
The online survey has limitations in regard to the population used. MTurk has known biases, but is still a mostly reliable platform for rapidly obtaining results related to user sentiment \[60, 29\]. MTurk limits workers to those over 18 years of age, and in this survey participant demographics were slightly skewed towards a younger male population. Additionally, nearly all participants were from the US and India. Future work should validate the results of this survey by attempting to ascertain opinions in various countries and determine if there are significant differences in this regard.

All of our data is self-reported, and as such carries with it inherent participant bias. For example, participants may have altered responses to appear more aware of issues raised in the survey. This bias may have also affected responses to questions about attitude surrounding TLS proxies. Lastly, the continuing news coverage of leaked NSA documents may have influenced user answers.

5. DISCUSSION
A paper by Huang et al., in the process of publication, independently develops a measurement tool that is very similar to ours and conducts a measurement study of substitute certificates from TLS proxies \[25\]. Whereas Huang conducted measurements by deploying their tool on Facebook’s server, we use a Google AdWords campaign to collect data. The advantage of Huang’s methodology is that they find proxies specifically targeting Facebook, whereas the advantage of our methodology is that we can collect results without the cooperation of a major website and find proxies that may have whitelisted Facebook or other high-profile sites.

In comparing our results to Huang, we both measure a similar number of connections (2.9 million in this paper vs 3.4 million in Huang), and find a similar distribution of proxies among personal firewalls, corporate filters, and malware. The prevalence of proxies in our study is roughly twice what was measured by Huang (0.41% versus 0.20%). This may be due to the increasing use of proxies (our measurements took place roughly a year after theirs). Another factor may be that our measurements tested the certificate on our lab’s server; some proxies may whitelist Facebook and focus on other traffic. We also find one very common Issuer Organization, Psafe Tecnologia S.A., that is not listed in Huang, possibly because our methodology resulted in finding a significant number of proxies in Brazil.

The measurements from Huang find the same Senderi and IopFailZeroAccessCreate malware, however we also find WebMakerPlus malware, as well as Swesses and AtomPark Software, which offer tools for spammers. This indicates that the number of companies creating ad-based malware is somewhat larger than Huang measured. Given that results in both papers are based on examining the Issuer Organization, which can easily be modified by the proxy, it is possible there are more products and more nefarious behavior than we have measured. Huang does not report a percentage of connections that were malware, but we find 8% of the proxies are from Senderi, whereas in Huang Senderi accounts for 5% of proxies. Both papers find a small number of certificates falsely claiming to be signed by a CA, though we also find some certificates use MD5 for signing and some use key sizes longer than 2048 bits.

One unique contribution of our paper is that we installed and examined numerous personal firewalls that act as TLS proxies. We found a significant weakness with the Kurupira parent filter; it masks a forged certificate, allowing attackers to perform a MitM attack against Kurupira users without compromising the root store.

Another unique contribution of our paper is the survey we conducted using Mechanical Turk. These results indicate that users have a complicated relationship with proxies. Most users believe there are legitimate uses for TLS proxies, though some in the technology and public policy arenas feel strongly that allowing anyone to violate end-to-end encryption is unacceptable. Of those users who believe there are acceptable uses for TLS proxies, 89% indicate that browsers should notify the user if a TLS proxy is present. However, survey participants also express concern over the capabilities of TLS proxies, and worry they could be used by hackers or for government surveillance. This controversy highlights that, if benevolent TLS proxies are considered acceptable, then we need mechanisms that enforce notification and acceptance of proxy presence, while prohibiting unauthorized proxies.

A benefit of our tool is that websites can deploy it to detect TLS proxies, similar to Huang’s use at Facebook, and unilaterally make decisions regarding whether to allow a secure connection to continue if a proxy is detected. For example, a news website may merely issue a proxy warning via an HTML element, whereas a banking or shopping website may choose to block proxied connections entirely. This enables the website to protect apathetic or unaware users from attack, whereas client-side tools are typically used only by security-minded users.

Toward this end, there are several improvements to the measurement tool to enable it to provide robust detection of proxies in the face of adversaries who may wish to circumvent detection. These include:

**Require measurement.** Servers could require successful execution of the measurement before continuing operation. This would prevent proxies from dropping the transmission of the measurement report or tool.

**Obfuscate the measurement.** Existing techniques to obfuscate web code \[47, 4\] could be used to make the measurement tool and report resemble ordinary web traffic, limiting the ability of proxies to specifically target the measurement.

**Sign the measurement report.** Before delivering the measurement tool servers could dynamically insert a random signing key into the measurement tool. This key would be randomly generated for each download of the tool and servers would require that measurement reports be signed by the

\[1\]See for example http://lauren.vortex.com/archive/001076.html
correct key. This could be further enhanced by:

- Obfuscating the key within the flash app making it more difficult for proxies to extract the signing key.
- Adding arbitrary, computationally expensive calculations to the signing process. While proxies could still emulate the signing process, this would make it more difficult for them to maintain line-level speeds for a large number of connections.
- Including client state (e.g., cookies, localstorage) with the measurement report being signed. This would require proxies to maintain state for each TLS connection they proxy, which becomes costly at large scale.
- Detecting in-flight modification to the web page or measurement tool to detect tampering. This would limit the proxy’s ability to push work off to the client, requiring that they address the above mitigations directly on the proxy.

We note that if it becomes standard practice for TLS proxies to include user notification and opt-in, then a detection tool could justifiably label all unannounced proxies as malicious. In addition, it is possible that a connection has more than one proxy, and this detection method can only identify the TLS proxy closest to the client. It is not clear yet how user notification and opt-in will interact with the presence of multiple proxies.

We also note that much of the overhead of our tool is due to the requirement that a separate TLS client be constructed and establish a connection with the target host. This requirement could be eliminated if standard web technologies provided a method to access the X.509 certificate of the current secure session. We recommend browser support for a JavaScript method to retrieve certificate data, removing the need for additional TLS connections.

6. RELATED WORK

There has been significant prior work to detect TLS MitM attacks. Clark and van Oorschot [10] provide an extensive survey of this area and provide one of the few research papers that acknowledges the existence of benevolent TLS proxies. Much of the previous work has focused on providing improvements or alternatives to the CA system. A primary goal has been to protect against impostors who may obtain a certificate fraudulently and conduct a MitM attack, since only one CA has to be compromised or mismanaged to allow this vulnerability to be exploited.

Multi-path Probing. Several proposed systems rely on multi-path probing to detect when a client receives a different server certificate than most other clients. Perspectives [37] was designed to address the problem of trust-on-first-use (TOFU) authentication in SSH and TLS. Convergence [34] was proposed as a replacement to the CA system. It overlaps significantly with Perspectives, but it adds one level of indirection similar to onion routing among the notary servers to better preserve client privacy. DoubleCheck [3] uses the Tor anonymization network as an alternate channel to verify a server certificate not signed by a CA the client trusts (e.g., self-signed certificate). The Mutually Endorsing CA Infrastructure (MECAI) [17] is a proposal to have existing Certificate Authorities serve as additional notaries to vouch for the authenticity of a server’s certificate. Crossbear [23] is a research system designed for volunteer hunters to work together to detect and localize real-world TLS MitM attacks. Clients send certificate chains to a central Crossbear server that utilizes its own data and Convergence to determine if the certificate chain is valid. When an attack is detected, Crossbear clients use traceroute to localize the origin of the attack. The ICSI SSL Notary [3, 8] was developed to detect malicious certificates by passively scanning certificates from live Internet traffic at seven different sites and storing data at a central notary server. Clients can query the notary server using a DNS API to determine if the certificate they receive matches what others have received in their connections to the website. In follow-on work, Amann et al. [4] illustrate how benign changes to the certificate ecosystem make it difficult for client-side detection tools to reliably identify active MitM attacks because common heuristics that would appear to identify an attacker overlap with the actual behavior of real servers.

Shared secrets. There are several proposals to leverage the shared password between the client and server to prevent a MitM attack. Direct Validation of Certificates (DVCert) [12] is an efficient modified PAKE protocol that permits the server to attest to the authenticity of all the certificates used in a session with the web application, including certificates from other domains. SSL/TLS Session-Aware User Authentication [11, 42] thwarts TLS MitM attacks through user authentication tokens based on client credentials and TLS session information. The proposed TLS-SRP protocol [19] would extend the TLS handshake to support mutual authentication based on a shared password. These approaches only apply to websites where the user has a password.

DNS. Several proposals leverage DNS to prevent MitM attacks. ConfiDNS [43] utilizes the temporal and spatial redundancy of the existing DNS system to assess agreement for IP resolution. The DNS-Based Authentication of Named Entities (DANE) [22] protocol enables administrators to bind hostnames to their certificates. This permits public keys to be transmitted via DNSSEC without involving a CA. DNSSEC has not yet been deployed in any modern browser and has been criticized for its trust for Certificate Authorities [34].

Pinning. Trust Assertions for Certificate Keys (TACK) [35] is a TLS extension for the server to pin a signing key that must sign all other keys in the domain. Certificate pinning [18] is a Google proposal for the web server to limit all future HTTPS connections to a limited set of server certificates. Pinning is a trust-on-first-use technology. The Google Chrome browser comes pre-configured with some Google certificates already pinned in advance so the user does not have to configure any local installed trusted roots, so benevolent proxies and malware can circumvent the pinning process.

Public Log Files. Certificate transparency (CT) [31] is a centralized audit log of all the certificates issued by certificate authorities. The log is append-only so that any misbehavior by a CA will be detected. The log serves as a deterrent for an
untrustworthy CA to issue a certificate without the subject’s knowledge. Ryan [20] recently proposed an extension to certificate transparency that supports revocation. The EFF sovereign keys (SK) project [16] is an experiment to have web servers publish a sovereign key for their domain into an append-only log file. All certificates for the domain should be cross-certified using the sovereign key. Accountable Key Infrastructure (AKI) [30] is a proposal for new infrastructure to validate public keys and reduce the reliance on CAs. The system includes public log servers that support public validation of certificate integrity.

**Transparency.** A number of industry products support TLS inspection (e.g., [9] [20] [21] [11] [23]). Users are largely unaware that these inspection proxies are present. Several proposals to the IETF from industry introduce mechanisms that would make proxies visible to the other participants in a chain of TLS connections and could include user notification and consent. McGrew et al. [37] propose an extension to TLS wherein a proxy completing a TLS handshake with a server (or the next proxy in the chain) returns a digitally signed set of information to disclose all the other certificates present along the chain of TLS connections. Loreto et al. [33] propose that explicit trusted proxies be supported in HTTP/2.0 through the use of proxy certificates that would replace the substitute certificates generated today that are intended to impersonate the target server.

Nir [40] proposes an extension to TLS that enables a client to share decryption keys with a TLS proxy. This approach lets the client establish a TLS connection with the target server without a transparent benevolent proxy impersonating the server in the middle. This solution would not conflict with many of the proposals discussed in this section for detecting MitM attacks. It would cleanly separate benevolent proxies into using a separate mechanism for TLS inspection. A potential drawback is that the key sharing mechanism represents a new attack surface that hackers could attempt to exploit to acquire the decryption keys for a TLS session.

**Summary.** The approaches using multipath probing, DNS, and public log files treat benevolent TLS proxies as malicious. Certificate pinning does not distinguish between locally trusted benevolent proxies and malware. All of the prior work in this area requires that new software be deployed on the client. We differ from this earlier work by being one of the first to measure the presence of TLS proxies in the wild without requiring new client software.

### 7. CONCLUSION AND FUTURE WORK

Using an automatic measurement tool and a Google AdWords campaign, we show that corporations and a surprising number of individuals are deploying proxies to protect against malware, phishing, and other undesirable practices. However, our study also shows that malware is using this same technique, comprising 9.70% of all proxied connections, and that spammers are using TLS proxies in their products. In some cases a personal firewall acting as a TLS proxy may weaken user security. Our analysis of the Kurupira parental filter finds that it masks forged certificates from an attacker, allowing the attacker to easily perform a MitM attack against the firewall’s users. We also find numerous other suspicious or negligent circumstances in substitute certificates, such as a null Issuer Organization, falsified DigiCert signatures, and downgraded public key sizes.

Our user study shows that the use of TLS proxies remains controversial and that users have a complicated relationship with this technology. When shown neutral material describing TLS proxies and their uses, users are supportive of benevolent proxies but wary of hackers and government spying. Users strongly favor being informed when a proxy actively intercepts their encrypted traffic, and want legislation imposing this requirement. They overwhelmingly do not want law enforcement to use TLS proxies.

Considering that most users were unaware of TLS proxies before our survey, it is likely that users of personal firewall products are unaware that the software is modifying their root store. Our measurements show that malware and spammers are already exploiting this ignorance. These problems, combined with corporate use of proxies, are a clear sign that the CA and TLS infrastructure does not meet current needs and is in need of significant changes. We recommend that, at a minimum, vendors strengthen protection of the root store to require user approval when adding certificates.

Our investigation points the way to a number of avenues for future work. First, we are investigating alternative non-Flash implementations of our tool that would run on mobile platforms. Second, we are investigating approaches to thwart active TLS proxies that wish to remain undetected by our tool, as discussed in Section 6. Finally, we plan to expand our user survey and our measurement study. In the next round of our survey we plan to target opinions from residents of additional countries, and in our measurements we plan to investigate whether stores and banks are targeted by malicious proxies. We also plan to repeat our proxy measurements in 6 months and in a year to measure any changes in the prevalence and uses of TLS proxies.

### 8. ACKNOWLEDGMENTS

The authors would like to thank Rich Shay of Carnegie Mellon University for his help with setting up the Mechanical Turk Survey described in this work.

### 9. REFERENCES


APPENDIX

A. MECHANICAL TURK SURVEY — TLS DESCRIPTION

When you connect to the Internet you do so through some organization’s network. For example, at home you connect to your Internet service provider’s (ISP) network, while at work you connect to your employer’s network. To protect your information from others on the network you can create secure connections to the websites you use (HTTPS). This is done automatically for you when you log into a website. The secure connection encrypts your Internet traffic so that no one else can view or modify your communication with the website (see Figure A).

The network you use to connect to the Internet can also be set up to use a system called a TLS proxy. TLS proxies sit in the middle of your secure connection to the websites you view (see Figure B). At the TLS proxy your Internet traffic is decrypted and the web proxy can view and modify it. Afterwards, the TLS proxy will then re-encrypt your traffic and forward it along. This is done silently and without the knowledge of you or the website you connect to.

TLS proxies can be set up by the organization that controls your Internet (for example, your ISP, school, or employer) and also by malicious attackers. TLS proxies have many different uses:

**Protective**
- Blocking malware and viruses
- Protecting company secrets
- Blocking harmful websites
- Catching malicious individuals

**Malicious**
- Stealing passwords
- Identity theft
- Tracking government dissidents
- Spying (for example the NSA)
- Censorship