Blocking-resistant communication through high-value web services

David Fifield, Chang Lan

May 13, 2014

Abstract

We describe meek, a blocking-resistant Internet communication system for censorship circumvention. meek uses HTTP as a mechanism for transporting data, but it is not a steganographic HTTP transport; rather, it relies on HTTPS to hide the contents of communications from a censor. Communications are proxied through a web service that may itself be blocked by the censor: "domain fronting"—in which the domain name used in the (censor-visible) DNS request and TLS server name extension doesn't match the name in the (censor-invisible) HTTP host header—enables communication that is apparently with an allowed host but actually with a forbidden host.

Though HTTPS frustrates blocking by hiding the underlying communication, differences in TLS implementations give rise to distinguishing features that may be used to block circumvention traffic. We describe how we use a web browser as a tool for making HTTPS requests, so that the TLS signature of circumvention traffic resembles that of ordinary web browsing. We present other, more subtle traffic characteristics that may enable blocking, and identify potential countermeasures to such blocking.

We describe our experience implementing meek as a pluggable transport for Tor, and the results of an initial experimental deployment.

1 Introduction

Censorship is a daily reality for many Internet users. Workplaces, schools, and governments use technical and social means to prevent access to certain information by the network users under their control. In response, those users use technical and social means to gain access to the forbidden information. What has emerged is an ongoing conflict between censor and censored, with advances on both sides, more subtle evasion being countered by more powerful detection.

In this paper we describe the design and deployment of meek, a censorship-resistant communication system that aims at defeating known technical means of censorship. meek tunnels traffic through HTTP, but does not attempt to look like plaintext HTTP; it uses HTTPS to hide the contents of communications while relaying them through a third-party web services that it itself hard to block. meek is implemented as a Tor pluggable transport [2]. We have done an initial deployment of the system and it is in use by a small number of users.

"Domain fronting" is the term we use for one of the key techniques used by meek. Domain fronting is the use of different domain names at different layers of the network stack. In the DNS query and TLS server name indication (SNI) [7, Section 3], which are visible to the censor, one domain name (the "front domain") appears; while in the HTTP Host header [8, Section 14.23], which is hidden from censor by HTTPS encryption, a different name (the actual destination) appears. Domain fronting works in systems that use the Host header in order to multiplex many domain names behind one HTTPS frontend; among these systems are Google's infrastructure and the CloudFlare content delivery network. Domain fronting can also work using only an IP address in place of a front domain. In this case there is no DNS query and no SNI in the TLS layer, but the actual destination still appears in the Host header. Domain fronting has been used successfully for years by GoAgent [1] (which uses a bare IP address without SNI) and by one of the rendezvous methods of flash proxy [9]. In the examples in this paper, the front domain is www.google.com and the actual hidden destination domain is meek-reflect.appspot.com, which is our custom web app that aids in circumvention.

meek may be regarded as a steganographic transport only in that it must blend in with other HTTPS traffic. Tunneling inside HTTPS greatly eases the steganography problem: It's not necessary to generate plausible HTTP, only plausible TLS, because TLS payloads are encrypted, and to a first approximation all encrypted payloads look alike. We need only make sure that the TLS handshake and other meta-attributes of the connection are not uniquely fingerprintable. Section 5 describes the use of a web browser extension as a instrument for making HTTPS requests, so things like the TLS handshake, DNS lookup, and TCP connection reuse match those of a browser as closely as possible. Of course, there are more subtle considerations that go into making a circumvention HTTPS stream look like an allowed HTTPS stream, things like packet size and timing, and duration of TCP connections. These additional considerations are the subject of Section 6.

For concreteness, and because it is what we have deployed so far, the examples in this paper will use Google and App Engine as the specific third-party web service used for circumvention. Other systems that support domain fronting may be substituted for Google, and other alternative deployments are discussed in Section 7.1.

2 Background and related work

Broadly speaking, there are two main challenges to proxy-based circumvention: blocking by content and blocking by endpoint. A content-blocking censor inspects packets and payloads, looking, for example, for forbidden protocols or keywords. Content-based blocking is countered by obfuscation: making circumvention traffic difficult to distinguish from traffic the censor wishes to allow. Blocking by endpoint is based on *whom you are speaking to*, and blocking by content is based on *what you are saying.* A skilled censor will do both, and effective circumvention requires meeting both challenges. An endpoint-blocking censor forbids all communication with certain addresses, for example IP addresses and domain names, whatever the contents may be. The challenge of endpoint blocking is met by making it difficult for the censor to learn proxy addresses; by having overwhelmingly many proxies; or by colocating proxies with high-value services so that both must be blocked or both allowed.

To the above challenges we may add the related challenge of active scanning for proxies. Though a circumvention protocol may be difficult to identify on the wire, it may nevertheless be easy to scan for servers that speak the protocol, and thereafter block the server by its address. Winter and Lindskog [28] confirmed an earlier discovery of Wilde [27] that China's Great Firewall identifies Tor bridges by actively scanning destination addresses to see if they speak the Tor protocol. The discovery of active probing was the motivation for probing resistance in ScrambleSuit [29] and in this work.

Traffic obfuscation has been approached in many different ways, which may be classified into two general techniques. The first technique is to look unlike anything forbidden by the censor; that is, fail to match a blacklist. The second is to resemble a protocol that is explicitly allowed by the censor; that is, match a whitelist. Falling into the first category are "look-like-nothing" transports whose payloads are indistinguishable from a uniformly random byte stream. Classic example of look-like-nothing protocols are obfs2 [16] and its successor obfs3 [17], which have been Tor's go-to pluggable transports since early 2012 [4]. ScrambleSuit [29] is like obfs3 in the content of its payloads, but it takes additional steps to obscure its traffic signature (packet lengths and timing), and is designed to resist active scanning (the proxy server remains silent until the client proves knowledge of a shared secret).

The other category of obfuscation contains transports that take the steganographic approach: look like something the censor doesn't block. StegoTorus [26] encodes traffic to look like a cover protocol, such as unencrypted HTTP, using special-purpose encoders. Code Talker Tunnel (formerly called SkypeMorph) [20] mimics a Skype video call. FreeWave [14] encodes a digital stream into an acoustic signal and sends it over VoIP to a proxy which decodes and forwards it to the destination. fteproxy [6] uses format-transforming encryption to encode data into strings that match a given regular expression, in order to match a firewall's whitelist or avoid matching a blacklist.

Houmansadr et al. [12] evaluate "parrot" systems that imitate a particular implementation of a protocol and conclude that unobservability by imitation is a "fundamentally flawed approach." To fully mimic a complex and sometimes proprietary protocol like Skype is difficult in that the system must imitate not only the protocol's normal operation, but also its reaction to errors, its typical traffic patterns, and quirks of common implementations. Geddes et al. [11] demonstrate that even non-parrot systems may be vulnerable to attacks that disrupt covert communication while having little effect on legitimate traffic.

Their examination is specific to VoIP protocols, where packet loss and duplication are acceptable. The censor may deliberately drop or inject ACKs in order to disrupt the covert channel, without causing much collateral damage.

The other grand challenge of proxy-based circumvention is endpoint blocking, against which there have been a few approaches proposed. Tor has long faced the problem of its entry relays being blocked. The list of relays is public, so it easy to block all of them by IP address. Tor bridges [5] are relays that are not universally known, intended to serve as entry points for censored users. A database of bridges (BridgeDB) seeks to provide a few secret bridges to anyone who asks, while at the same time making it difficult to learn the entire list. The database is accessible over HTTPS and email. The HTTPS interface requires solving a captcha, and the email interface responds only to addresses from certain providers, like Gmail, that have defenses against bulk account creation. BridgeDB has the feature that repeated queries from the same address (IP subnet or email address) will receive the same small set of bridges. Its resistance to enumeration therefore depends both on having a large number of potential bridges, and on the censor not being able to control large numbers of IP and email addresses. BridgeDB is capable of distributing the addresses of obfsproxy and ScrambleSuit bridges. The combination of careful bridge address disbursement and obfuscated protocols gives Tor's system a realistic claim to addressing both challenges of proxy-based circumvention. Address distribution appears to be the weaker side of the defense, as evidenced by real-world censors' apparent preference for blocking bridge addresses over real-time deobfuscation [28].

Flash proxy [9] attempts to address endpoint blocking by conscripting web users as temporary proxies. Proxies last only as long as a web user stays on a page, so the pool of proxies is constantly changing; even if one of them is blocked, there will soon be another to replace it. Flash proxy's approach to endpoint blocking is in a sense the opposite of ours: where flash proxy uses cheap, disposable, individually blockable proxies, we use just one high-value proxy, which shares its fate with network infrastructure that is expensive to block. A quirk of the browser proxy model is that the proxy connects to the client rather than the other way around. The client must be able to receive a TCP connection; in particular it may not be behind network address translation (NAT), which limits flash proxy's usefulness. Flash proxy itself does nothing to defend against content blocking. Connections between censored clients and browser-based proxies use WebSocket, a meta-protocol running on TCP, but inside the WebSocket framing is the ordinary Tor protocol. There exists a prototype transport that attempts to get both content-based and endpoint-based blocking resistance by obfuscating traffic with obfsproxy before sending it through flash proxy [22]. However it is limited because it is not possible to obfuscate the outermost WebSocket layer; the censor could decide simply to block all WebSocket.

A technique known as OSS [10] (for "online scanning service") bounces data through third-party web services that are capable of making HTTP requests. For example, a censored client may ask a translation service to translate a web page at `http://proxy.example.com/...`, where "`...`" stands for the data payload that the client wishes to send—data are embedded in the URL. Simply by making the HTTP request, the service sends the client's message. The client cannot rely on being able to receive the response to its message in an HTTP response, because online scanning services do not in general return unmodified the contents of the page they are ordered to retrieve. The translation service, for example, returns the page in another language. For this reason, the server sends a response message by making another reflected HTTP request back to the client, through the same OSS or a different one. The need for the client to receive a connection means that OSS has the same problem with NAT that flash proxy does. The NAT aspect is the most important way in which our work improves on OSS. App Engine is effectively an unblockable OSS that we fully control. We can ensure that reflected HTTP bodies are unmodified, and therefore use them to carry traffic without having to connect to the client.

Decoy routing [18] is a technique that puts proxies in the middle of network paths, rather than at the endpoints. Realizations of the decoy routing idea include Telex [30] and Cirripede [13]. Decoy routing asks friendly ISPs to deploy special software on routers that lie between censored users and uncensored Internet destinations. Circumvention traffic is "tagged" in a way that is detectable only by decoy routers, and not by the censor. On receiving a tagged communication, the decoy router shunts it away from its apparent destination and toward the censored destination requested by the client. Our work is conceptually similar to decoy routing, though the action happens at the application layer rather than the network layer. Both systems use a piece of network infrastructure as a decoy to redirect certain flows: in decoy routing it is an ISP router; for us it is the front domain. Both tag flows in a way that is visible only to the decoy router: in decoy routing a tag may be, for example, a hash embedded in the TLS client randomness; for us it is the HTTP Host header, encrypted within an HTTPS stream. Decoy routing generally requires the cooperation of large, centrally located router operators, whereas we only need to buy web application hosting.

CensorSpoofer [25] decouples the upstream and downstream channels. The client sends upstream data to the CensorSpoofer proxy over a low-bandwidth covert channel such as email. At the same time, the client pretends to have an innocuous communication (such as a VoIP call) with an unblocked dummy host. The CensorSpoofer proxy sends encrypted UDP data back downstream to the client, protecting its true IP address by spoofing the source of all its packets so that they appear to come from the dummy host. From the censor's point of view, the client is carrying on a conversation only with the dummy host. If the dummy is blocked, another can be used in its place, as the CensorSpoofer proxy's true IP address remains unknown.

A recent study [15] on AS topology suggests that defeating decoy routing is likely to be expensive for the censors, if the decoy routers are strategically deployed. Despite that decoy routing is a sound technical approach, it is not clear whether ISPs are willing to act against censors. However, the takeaway is that the censors are unwilling to completely block day-to-day Internet access, which we can take advantage of.

GoAgent [1] is a direct inspiration for our system in its use of App Engine and Host header–based domain fronting. As in our system, traffic is fronted by the Google frontend server and delivered to its destination by a specialized app running on App Engine. GoAgent requires users to upload a personal copy of the server code to App Engine, which harms usability but requires no central management and enables users to stay within bandwidth limits that exist for unpaid apps. GoAgent is an HTTP and HTTPS proxy only. It works by encapsulating a desired HTTP request, including URL and POST body, if any, and uploading the request to App Engine. The app unpacks the encapsulated request and directly requests the desired URL using App Engine's URL-fetching API. The design is simple but has disadvantages, stemming from the web app's need to know what URL to request. In order to proxy HTTPS, the local GoAgent proxy program does a benign man-in-the-middle attack on the browser, which must have previously trusted the GoAgent CA certificate. The local proxy program decrypts the HTTPS in order to read from it the HTTP request including the URL. When the response comes back, the local proxy re-encrypts it under its own key. End-to-end security is lost; an attacker positioned at the web app is able to observe and modify all traffic. In our system, such an attacker may only deny service or perform traffic analysis on ciphertext. Additionally, we allow proxying of any TCP-based traffic, not only HTTP. According to a May 2013 survey [24], GoAgent was the circumvention tool most used in China, with 35% of survey respondents having used it in the previous month. This figure is higher than that of paid (29%) and free VPNs (18%), and far above that of other special-purpose tools like Tor (2.9%) and Psiphon (2.5%). Users identified reliability, speed, and ease of installation as the most important features of a circumvention tool.

3 Threat model

The censor is able to inspect all traffic that passes through the censorship boundary and block or allow it at will. The censor is able to actively scan for proxies, and issue followup connections to hosts that clients connect to, in order to determine whether they are proxies. The censor may block the web host on which the reflector web app runs, but it must allow access to some domain that can front for it. In our deployment using App Engine, the censor may block appspot.com, but must allow www.google.com (or its IP address, or some other domain that goes through the frontend server).

The censor must operate at line rate; that is, it must not delay traffic unduly while deciding whether to allow it. This consideration is one facet of the censor's sensitivity to collateral damage caused by false positives: mistakenly blocking or degrading non-circumvention traffic causes the censor to incur some penalty, just as mistakenly allowing circumvention traffic does. The censor must allow TLS connections; meek does not try to look like plaintext.

The user's computer, the third-party infrastructure (e.g., Google), and the Tor bridge are all uncontrolled and uncompromised by the censor. The user has a way to get a copy of the necessary client programs.

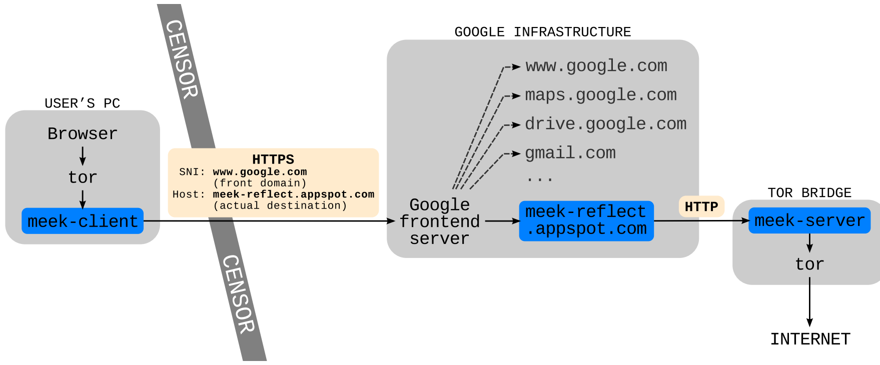


Figure 1: System architecture. The Google frontend server is the server that dispatches requests to different services depending on the Host header. Components that are new in our system are outlined in blue. The "Google infrastructure" block may be replaced by other infrastructure that supports domain fronting.

4 Architecture

The components of the system are shown in Figure 1. The three parts that are new in our system are:

1. The client program meek-client. Using the pluggable transports protocol, Tor treats meek-client as a SOCKS proxy. When meek-client receives data from Tor, it bundles it up in an HTTP POST request and sends it to the web app, using HTTPS to hide the contents and the domain fronting trick to hide the true destination. Downstream data are returned in HTTP responses, which meek-client decodes and sends back to Tor.

2. The "reflector" web app, running on App Engine. Its domain name meek-reflect.appspot.com is protected by domain fronting. It is called a reflector because it doesn't do anything intelligent: it merely copies the HTTP requests it receives and forwards them to meek-server running on the Tor bridge.

3. The server program meek-server, which acts as an HTTP server. It receives reflected requests from the web app, decodes their bodies, and forwards the contents to an instance of Tor running on the same host. If there is anything pending to be sent back to the client, meek-server sends it along with its HTTP response. meek-server also takes care of stringing together multiple HTTP requests into one logical stream and multiplexing multiple concurrent connections, both using the technique of session IDs described in this section.

The main technical challenge in making this system work is in encoding a TCP stream as a sequence of HTTP requests and responses. meek-server handles many clients at once, and their data streams are split across multiple HTTP transactions. In TCP, different streams are distinguished by their (source IP, source port, dest IP, dest port) tuple, but we cannot do that because streams are split across multiple TCP sessions. Rather, each instance of meek-client generates at startup a random 32-byte session ID, which is sent along with its requests in a special X-Session-ID HTTP header. meek-server, when it sees a particular session ID for the first time, opens up a new connection to the local Tor process, and stores the session ID in a cache. Subsequent requests with the same session ID will reuse the same Tor connection. Entries are removed from the cache after a period of inactivity.

HTTP is fundamentally a pull-based protocol. There is no way for the server to send data to the client without the client first making a request. The same applies to meek: when meek-server has data to send back to a client with a particular session ID, it cannot do so until it receives a request from that client. For this reason, meek-client polls the server, sending an empty request if necessary, every so often. The polling interval starts short (100 ms) and grows exponentially up to a maximum of 5 s. Alternative techniques for push-like behavior, such as HTTP long polling, don't work well with App Engine, because App Engine requires requests to finish within 60 seconds.

We implemented meek as a pluggable transport [2] for Tor. Although it is possible to use the system with proxies other than Tor, using Tor has some attractive features. The pluggable transports infrastructure makes it relatively easy to prototype a circumvention technique and connect it to a global proxy network. We can treat confidentiality and integrity of tunneled communication as a problem solved by Tor, which we don't need to solve separately. Tor's extra proxy hops mean that the HTTP reflector (App Engine) and the entry bridge do not have to be trusted.

5 Making the TLS handshake indistinguishable

The practice of routing traffic through a web service with domain fronting defeats both endpoint-based blocking and active scanning. The endpoint (which appears to be the front domain; e.g. www.google.com) cannot be blocked because to block it would cause collateral damage. Active scanning is defeated because if the censor accesses the same endpoint as the client, all they see is a web page served by the front domain. Even though the censor knows some traffic is being fronted, by looking only at IP addresses and domain names, it cannot determine which.

However, a savvy censor may also use content-based blocking (deep packet inspection) as a basis for blocking. Anything that reliably distinguishes meek's traffic from that of normal allowed traffic (presumably web browsing) must be eliminated. In this section we demonstrate how the client part of the TLS handshake can be used to fingerprint different TLS implementations, and how we use a web browser to camouflage meek's TLS.

There are many parts of the TLS handshake, but the two that most dis-

```
TLS_ECDHE_RSA_WITH_AES_128_GCM_SHA256
TLS_ECDHE_ECDSA_WITH_AES_128_GCM_SHA256
TLS_ECDHE_RSA_WITH_RC4_128_SHA
TLS_ECDHE_ECDSA_WITH_RC4_128_SHA
TLS_ECDHE_RSA_WITH_AES_128_CBC_SHA
TLS_ECDHE_ECDSA_WITH_AES_128_CBC_SHA
TLS_ECDHE_RSA_WITH_AES_256_CBC_SHA
TLS_ECDHE_ECDSA_WITH_AES_256_CBC_SHA
TLS_RSA_WITH_RC4_128_SHA
TLS_RSA_WITH_AES_128_CBC_SHA
TLS_RSA_WITH_AES_256_CBC_SHA
TLS_ECDHE_RSA_WITH_3DES_EDE_CBC_SHA
TLS_RSA_WITH_3DES_EDE_CBC_SHA
```

(a) meek-client

```
TLS_ECDHE_ECDSA_WITH_AES_256_CBC_SHA
TLS_ECDHE_ECDSA_WITH_AES_128_CBC_SHA
TLS_ECDHE_RSA_WITH_AES_128_CBC_SHA
TLS_ECDHE_RSA_WITH_AES_256_CBC_SHA
TLS_ECDHE_ECDSA_WITH_3DES_EDE_CBC_SHA
TLS_ECDHE_RSA_WITH_3DES_EDE_CBC_SHA
TLS_ECDHE_ECDSA_WITH_RC4_128_SHA
TLS_ECDHE_RSA_WITH_RC4_128_SHA
TLS_DHE_RSA_WITH_AES_128_CBC_SHA
TLS_DHE_DSS_WITH_AES_128_CBC_SHA
TLS_DHE_RSA_WITH_CAMELLIA_128_CBC_SHA
TLS_DHE_DSS_WITH_CAMELLIA_128_CBC_SHA
TLS_DHE_RSA_WITH_AES_256_CBC_SHA
TLS_DHE_DSS_WITH_AES_256_CBC_SHA
TLS_DHE_RSA_WITH_CAMELLIA_256_CBC_SHA
TLS_DHE_DSS_WITH_CAMELLIA_256_CBC_SHA
TLS_DHE_RSA_WITH_3DES_EDE_CBC_SHA
TLS_DHE_DSS_WITH_3DES_EDE_CBC_SHA
TLS_ECDH_ECDSA_WITH_AES_128_CBC_SHA
TLS_ECDH_RSA_WITH_AES_128_CBC_SHA
TLS_ECDH_ECDSA_WITH_AES_256_CBC_SHA
TLS_ECDH_RSA_WITH_AES_256_CBC_SHA
TLS_ECDH_ECDSA_WITH_3DES_EDE_CBC_SHA
TLS_ECDH_RSA_WITH_3DES_EDE_CBC_SHA
TLS_ECDH_ECDSA_WITH_RC4_128_SHA
TLS_ECDH_RSA_WITH_RC4_128_SHA
TLS_RSA_WITH_AES_128_CBC_SHA
TLS_RSA_WITH_CAMELLIA_128_CBC_SHA
TLS_RSA_WITH_AES_256_CBC_SHA
TLS_RSA_WITH_CAMELLIA_256_CBC_SHA
TLS_RSA_WITH_SEED_CBC_SHA
SSL_RSA_FIPS_WITH_3DES_EDE_CBC_SHA
TLS_RSA_WITH_3DES_EDE_CBC_SHA
TLS_RSA_WITH_RC4_128_SHA
TLS_RSA_WITH_RC4_128_MD5
```

(b) Firefox 24

```
TLS_ECDHE_ECDSA_WITH_AES_128_GCM_SHA256
TLS_ECDHE_RSA_WITH_AES_128_GCM_SHA256
TLS_DHE_RSA_WITH_AES_128_GCM_SHA256
TLS_ECDHE_ECDSA_WITH_CHACHA20_POLY1305_SHA256
TLS_ECDHE_RSA_WITH_CHACHA20_POLY1305_SHA256
TLS_RSA_WITH_AES_128_GCM_SHA256
TLS_ECDHE_ECDSA_WITH_AES_256_CBC_SHA
TLS_ECDHE_RSA_WITH_AES_256_CBC_SHA
TLS_DHE_RSA_WITH_AES_256_CBC_SHA
TLS_RSA_WITH_AES_256_CBC_SHA
TLS_ECDHE_ECDSA_WITH_RC4_128_SHA
TLS_ECDHE_ECDSA_WITH_AES_128_CBC_SHA
TLS_ECDHE_RSA_WITH_RC4_128_SHA
TLS_ECDHE_RSA_WITH_AES_128_CBC_SHA
TLS_DHE_RSA_WITH_AES_128_CBC_SHA
TLS_DHE_DSS_WITH_AES_128_CBC_SHA
TLS_RSA_WITH_RC4_128_SHA
TLS_RSA_WITH_RC4_128_MD5
TLS_RSA_WITH_AES_128_CBC_SHA
TLS_RSA_WITH_3DES_EDE_CBC_SHA
```

(c) Chrome 33

Figure 2: Differences in ciphersuites offered by our meek-client program when it accesses the network directly, and by two web browsers. The distinctive ciphersuites offered by meek-client can be used as part of a blocking fingerprint. As a remedy we have meek-client proxy its TLS through a web browser extension.

tinguish the client are the list of ciphersuites and the list of TLS extensions in the Client Hello. Figure 2 shows how the list of ciphersuites differs in different client implementations. Figure 2a is how our first prototype of meek-client appeared on the wire, using the built-in crypto/tls library of the Go programming language. The list of ciphersuites is unlike that of a web browser, and could be used as a fingerprint for blocking. Tor itself was blocked by China in 2011 in exactly this way [21]. Similarly the list of TLS extensions (not shown) differed between meek-client and popular browsers.

In response to the threat of TLS fingerprinting, we modified meek-client to proxy its HTTP requests through a local web browser extension. meek-client tells the extension what URLs to fetch, and the extension fetches them. The TLS fingerprint looks like that of a browser, because it is that of a browser. We implemented two versions of the extension, one for Firefox and one for Chrome. They work similarly: they open a TCP port on localhost, await instructions from meek-client on what HTTP requests to make, issue the requests, and return the responses.

Figure 3 shows the interaction of components on the user's computer. Rather than starting meek-client as a pluggable transport directly, the tor process starts a helper process that starts both meek-client and a headless browser instance. The headless browser runs our extension in a separate process and separate

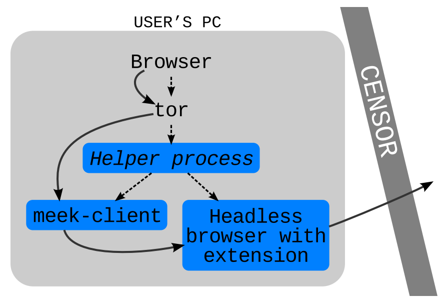


Figure 3: Client architecture including a browser extension for TLS camouflage. Dashed lines show the process hierarchy. Solid lines show the flow of outgoing communication. The headless instance of the browser runs in the background and is invisible to the user. This figure is a detailed view of the "User's PC" component of Figure 1.

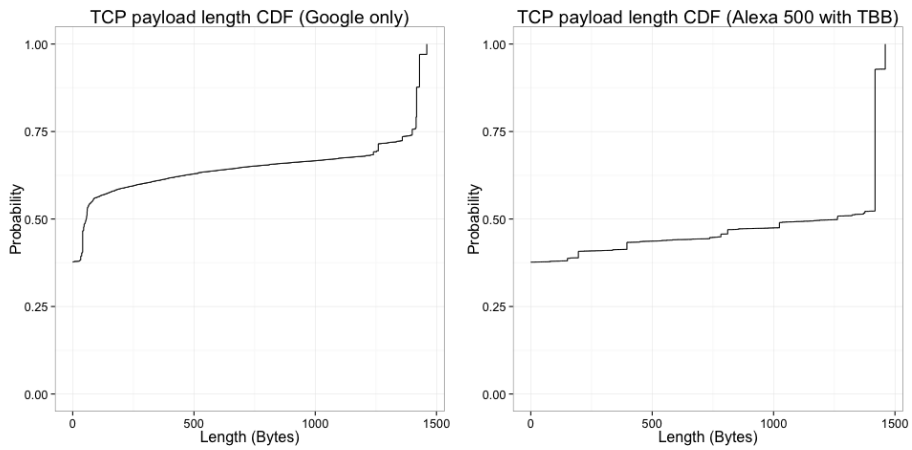
browser profile from the browser the user interacts with; the two browser instances share no state. meek-client is configured to issue its requests through the browser extension; in this configuration, the headless browser is the only thing that ever touches the network. When run with a browser extension, meek has the same TLS signature as Firefox (Figure 2b) or Chrome (Figure 2c).

The use of a browser extension offers benefits beyond its TLS signature. We inherit other characteristics of the browser: how often it resolves DNS names, its connection reuse, and HTTP keepalive behavior. The Firefox extension has special usability advantages because the Tor Browser Bundle uses a modified Firefox. We can include a small extension in the browser bundle, reusing the existing Firefox executable, without increasing the download size of the bundle much, and without requiring users to separately configure a browser to run the extension.

The development of the browser extensions posed some unexpected challenges. Tor Browser disables TLS session tickets because they can be used as linking identifiers, but the lack of session tickets shows up as a missing TLS extension, so we had to reenable them in the headless browser. (Doing so doesn't harm Tor Browser's anonymity: if session tickets are used, they are used only on the circumvention layer between the user and the frontend server. Tor Browser's own TLS is tunneled within the circumvention layer, and session tickets are still disabled at that level.) The Chrome extension needed to be split into two pieces, an extension and an app, because an extension cannot open a listening socket and an app cannot make HTTP requests.

6 Camouflage of traffic characteristics

The censor cannot sniff the content of communications or infer the usage of meek from packet *data*, since the communication is encrypted inside the TLS



(a) Normal Google Traffic

(b) Traffic Using meek

Figure 4: TCP packet payload size distribution

session, and we have devoted large efforts in hiding TLS handshake fingerprints. However, it is still possible that the censor can detect the existence of meek according to the *meta-data*, i.e. traffic characteristics. In this section we study a collection of traffic characteristics and evaluate their possibilities of becoming the censor's interest. Specifically, we consider three characteristics: 1) payload length of TCP packets, 2) number of concurrent HTTPS connections, 3) HTTPS connection lifetime.

To collect the traffic trace of meek, we browses the Alexa top 500 websites sequentially using the Tor Browser Bundle and dump the traffic trace from the network interface. We ensured only the browser can successfully access the network by setting up the `iptables` firewall so that packets from other processes will be dropped. We also obtain a 10-minute sample of normal HTTPS traffic trace from LBL. The trace is 983 MB in total. We also specifically extracted the traffic between LBL and Google from the trace. Since the trace only has packet headers, we cannot extract the domain information. However, the `TXT` DNS records of the domain `_netblocks.google.com` shows the IP address blocks that belongs to Google. Therefore, we determine whether a flow is from or to Google by examining the address in the IP header. We only interested in the Google traffic only, because the censor who wants to defeat meek will be mostly likely to compare suspicious traffic with normal Google traffic. The size of the Google trace is 312 MB.

TCP payload length Figure 4 shows the payload size distribution of normal traffic and meek's traffic. Both figures exhibit a significant amount of packets with no payload. These packets are mostly TCP SYN and ACK packets. Figure 4a shows the distribution of normal traffic, which indicates a large portion of small-sized packets. However, in the meek's traffic shown in Figure 4b, most packets are large packets ranging from 1400 bytes to 1500 bytes. This result is unexpected, because the underlying packets in the TLS session are sent from Tor. By default, each Tor cell is 512 bytes, but meek changes the packet size distribution. Therefore, meek provides traffic shaping without additional efforts.

To explain the phenomenon, recall that we use browsers to handle HTTPS connections for meek in order to hide TLS handshake characteristics. Browsers also apply techniques like HTTP pipelining to improve performance. Since meek is always communicating with the same Google frontend server, the browser will keep the persistent TLS connection. In addition, small requests can be batched into a large chunk before being sent. This explains why large packets are mostly seen from the trace that records meek's traffic. In contract, normal users may not have persistent connections to Google. For example, a user may search a keyword on Google, click a result, and then close the tab that displays search results. The browser may close the connection immediately after the user leaves the Google web page. Next time the user browses Google search, the browser opens a new connection. In this case, small requests do not have such opportunity for batching.

These browser techniques improve performance, but also pose unexpected consequences. Although meek alters the packet size distribution of underlying Tor traffic, the censor may be aware of the distribution of meek itself. Additionally, the persistent connection itself can be an issue. We thus investigated other related characteristics.

Concurrent connections Figure 5 shows how many HTTPS connections to Google did a user make during the 10-minute measurement window. There are 34,732 connections in total from 2,745 unique IPs. We observe that the majority of users have less than 50 connections to the Google frontend server, and most of the numbers concentrate on 1 10. This is not unexpected because a typical pattern of using Google is using the Google search as a stepping stone for other websites.

We measure the number of concurrent HTTPS connections during the automated browsing of Alexa top 500 sites using three platforms: Tor Browser Bundle, Safari + Firefox extension, and Safari + Chrome extension. Figure 6 shows the number over time. We can see that most of the time the browser has one HTTPS connection to Google. Sometimes the browser may have more than one connection due to background activities such as statistics reporting. In all cases the number of connections is always less than 5. We can conclude that the number of concurrent connections does not show distinct characteristics, as a small number of connections can be considered as a normal behavior.

Connection lifetime We consider the connection lifetime as a potential weakness. Figure 7a shows the connection lifetime distribution of normal traffic. Interestingly we can see the concentration on several discrete values: 60s, 120s, 180s, 240s. We hypothesize that it is due to the HTTP Keep-Alive timeout

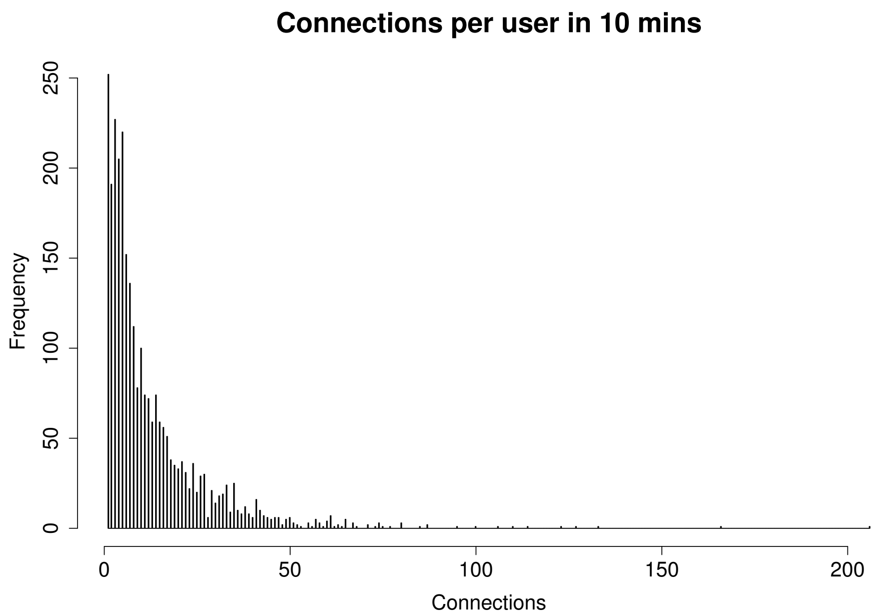


Figure 5: Histogram of each user's connections in the 10-minute window

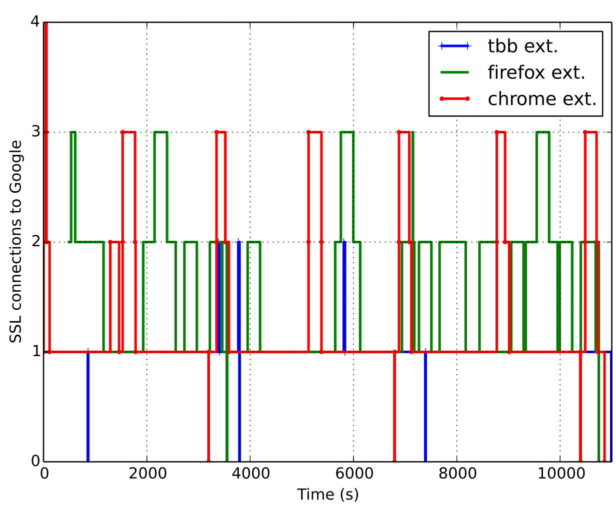
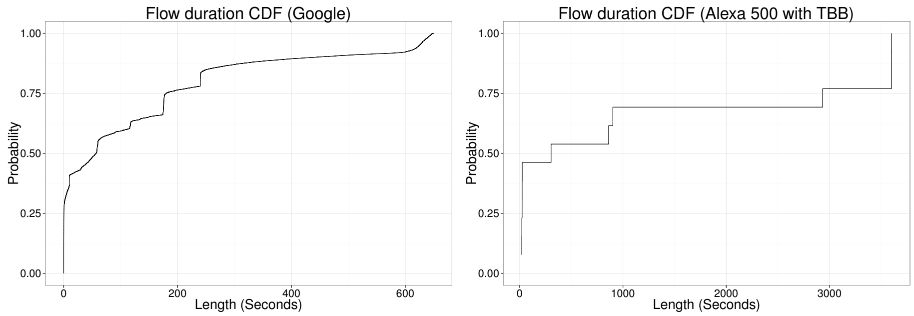


Figure 6: Concurrent HTTPS connections over time. We measure the trace for the Tor Browser Bundle and Firefox/Chrome extensions.



(a) Normal Google Traffic (b) Traffic Using meek (Notice the x-axis)

Figure 7: Connection lifetime distribution

of different browsers and web services. Another important observation is the concentration on durations that exceed 600 seconds. Note that our trace only contains 10 minutes' data, therefore the concentration on 600 seconds does not reflect that these connections' actual duration is 600 seconds. Rather, 600 seconds is the lower bound of their actual duration. Thus, we can conclude that only about 10% connections last longer than 600 seconds.

The distribution of meek's traffic, in contrast, is totally different. First, there are much fewer connections, which is consistent with the discussions above. Second, the durations are much longer if we notice the x-axis in Figure 7b. If there is not a case in which normal users also have such long connections when browsing Google, the censor can potentially block any long connections between users and Google. Even if this is the case, the censor has to wait until a time threshold is reached. The user might have already obtained the forbidden data she wants, or meek could simply restart a connection.

Conclusion So far we do not find any obvious traffic characteristics that can be useful for distinguishing meek's traffic. But admittedly there two potential weaknesses: long-lived connections with bulk data transfer, and deviated distribution of packet sizes. To fundamentally fix these weaknesses we need to transform to the traffic into the normal-looking traffic. The problem is inherently difficult, because we need to know *what* is normal traffic, i.e. what is the model of normal traffic, which is an open problem. However, the arm-race game is symmetric; since finding a right model is a difficult task for us, it is also difficult for the censor. Therefore, the censor can only find ad-hoc features to block forbidden traffic, which are relatively easy to defend against.

7 Deployment

We implemented meek as a Tor pluggable transport [2] and built experimental releases of the Tor Browser Bundle featuring meek. The browser bundle includes

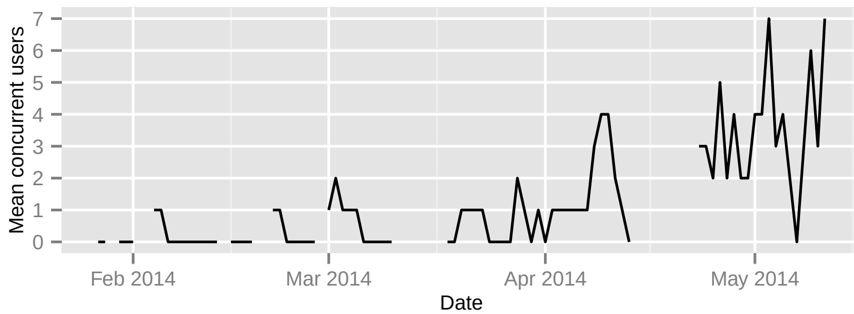


Figure 8: Number of concurrent users using the meek transport, as reported by the Tor Metrics Portal. The gap between April 14 and April 22 is when the Tor bridge authority was down because of the Heartbleed OpenSSL vulnerability [3], and wasn't collecting statistics.

Tor and a version of Firefox called Tor Browser that is patched to defend against application-layer identity leaks. Users need to download and run the bundle and select meek from the list of transports, and then a browser window appears, configured to use meek for circumvention and Tor for anonymity. We announced our prototype bundles on Tor development mailing lists, and from there they were picked up by Tor Weekly News on the Tor blog.

Figure 8 shows the number of concurrent users of meek between January and May 2014, as reported by the Tor Metrics Portal [23]. The number of concurrent users is estimated by counting directory requests made over the transport [19]. The drop to zero on May 8 coincides with the reinstallation of the Tor bridge used by meek.

We are running a paid instance of the web app on App Engine for use by the public. The cost for bandwidth on App Engine is \$0.12 per gigabyte, with one gigabyte free each day. The total cost has so far been \$1.11, with bills of \$0.09 in March, \$0.73 in April, and \$0.29 in the first half of May.

meek has a home page at `https://trac.torproject.org/projects/tor/wiki/doc/meek`. Our source code is in the Git repository at `https://git.torproject.org/pluggable-transports/meek.git`. As of version 0.5 (May 7, 2014), the source code consists of about 800 lines of Go for the client programs, 400 lines for meek-server, and 100 lines for the intermediary web app. Each of the browser extensions (one for Firefox, one for Chrome) is about 300 lines of JavaScript.

7.1 Other deployment scenarios

The deployment we envision and have started to implement uses a single paid App Engine instance, which is publicly known and usable by anyone. Client software is configured to use this public instance by default. A preconfigured public instance has great usability advantages because there is nothing for the user to upload and nothing to configure. The number of parties able to analyze users' traffic patterns is somewhat increased: the path from user to Tor bridge now includes App Engine and the web app operators, in addition to the ISP and intermediate routers that were there before. On the other hand, the Tor bridge no longer gets to see users' IP addresses: all it sees are many connections from the App Engine. In effect, App Engine and the web app become what Tor calls a "guard node," a privileged relay that takes the first hop in the chain of relays. Because Tor is encrypted and integrity-protected, neither App Engine nor the app operators are able to read or alter users' communications, but being on path enables them to do things like measure packet timing patterns.

Users are also free to upload their own personal copy of the App Engine code, as is done with GoAgent. App Engine imposes bandwidth quotas on unpaid apps, but they are high enough to allow daily web browsing. In this scenario, Google still has a privileged network position, but the user's traffic patterns are no longer visible to the operators of a public app instance.

A censor can block meek by blocking access to Google entirely, but other systems can take the place of Google. An attractive alternative is CloudFlare, a large content delivery network, which supports domain fronting, dispatching requests based on the Host header rather than IP or SNI. We did not test deployment on CloudFlare, because their terms of service are not clear on whether this kind of use is allowed, and we got an ambiguous answer when we asked for clarification. A particular concern when using CloudFlare or other content delivery networks is the choice of front domain. If one domain is being used particularly as a front for circumvention traffic, it may find itself blocked by the censor, even though it is not itself involved in any circumvention. One good solution to this problem may be not to use a domain name at all, but only the IP address of one of CloudFlare's servers. The censor will then face the choice of allowing circumvention traffic, or else blocking a large number of unrelated web sites.

The code that runs on App Engine is very simple. It just statelessly copies HTTP requests and responses. Another possible deployment scenario uses a PHP implementation of the reflector, deployed on an ordinary web hosting service other than App Engine. In this scenario, domain fronting is not used; instead unblockability depends on there being many (individually blockable) PHP reflectors. In other words, it is roughly the same situation as exists today with Tor bridges, except that it can be much easier for a volunteer to upload a PHP file to a web host than to set up Tor bridge or other proxy. Such PHP bridges could potentially automatically report their own URLs, which could be distributed using a system like BridgeDB.

8 Future work

In future work we would like to implement pipelining of requests, so that more than one HTTP request can be outstanding at a time. This would have better performance compared to the current system, which serializes requests and responses in order to keep the underlying TCP stream in order. A system of sequence numbers and acknowledgments as used in OSS [10] could make this possible.

We would like to do more quantitative performance measurements, in order to measure the overhead in bandwidth and latency that meek has over plain Tor. We have done informal tests, such as browsing YouTube, but have not yet put numbers to our measurements.

9 Acknowledgments

We thank Vern Paxson, Nick Weaver, and Doug Tygar for inspiring conversation on this topic. Special thanks go to the members of the tor-qa and tor-dev mailing lists who responded to our design ideas, reviewed source code, and tested our prototypes.

References

[1] GoAgent. `https://github.com/goagent/goagent`.

[2] Jacob Appelbaum and Nick Mathewson. Pluggable transport specification. `https://gitweb.torproject.org/torspec.git/blob/HEAD:/pt-spec.txt`, October 2010.

[3] Common Vulnerabilities and Exposures. CVE-2014-0160 "Heartbleed". `https://cve.mitre.org/cgi-bin/cvename.cgi?name=CVE-2014-0160`.

[4] Roger Dingledine. Obfsproxy: the next step in the censorship arms race. `https://blog.torproject.org/blog/obfsproxy-next-step-censorship-arms-race`, February 2012.

[5] Roger Dingledine and Nick Mathewson. Design of a blocking-resistant anonymity system. Technical Report 2006-1, The Tor Project, November 2006. `https://svn.torproject.org/svn/projects/design-paper/blocking.pdf`.

[6] Kevin P. Dyer, Scott E. Coull, Thomas Ristenpart, and Thomas Shrimpton. Protocol misidentification made easy with format-transforming encryption. In *Proceedings of the 20th ACM conference on Computer and Communications Security (CCS)*, November 2013. `https://kpdyer.com/publications/ccs2013-fte.pdf`.

[7] D. Eastlake. RFC 6066: Transport Layer Security (TLS) extensions: Extension definitions. `https://tools.ietf.org/html/rfc6066`, January 2011.

[8] R. Fielding, J. Gettys, J. Mogul, H. Frystyk, L. Masinter, P. Leach, and T. Berners-Lee. RFC 2616: Hypertext transfer protocol — http/1.1. `http:`

//tools.ietf.org/html/rfc2616, June 1999. Updated by RFCs 2817, 5785, 6266, 6585.

[9] David Fifield, Nate Hardison, Jonathan Ellithorpe, Emily Stark, Roger Dingledine, Phil Porras, and Dan Boneh. Evading censorship with browser-based proxies. In *Proceedings of the 12th Privacy Enhancing Technologies Symposium (PETS)*. Springer, July 2012. https://crypto.stanford.edu/flashproxy/flashproxy.pdf.

[10] David Fifield, Gabi Nakibly, and Dan Boneh. OSS: Using online scanning services for censorship circumvention. In *Proceedings of the 13th Privacy Enhancing Technologies Symposium (PETS)*, July 2013. https://www.bamsoftware.com/papers/oss.pdf.

[11] John Geddes, Maxfield Schuchard, and Nicholas Hopper. Cover your ACKs: Pitfalls of covert channel censorship circumvention. In *Proceedings of the 20th ACM conference on Computer and Communications Security (CCS)*, November 2013. http://www-users.cs.umn.edu/~hopper/ccs13-cya.pdf.

[12] Amir Houmansadr, Chad Brubaker, and Vitaly Shmatikov. The parrot is dead: Observing unobservable network communications. In *Proceedings of the 2013 IEEE Symposium on Security and Privacy*, May 2013. http://www.cs.utexas.edu/~amir/papers/parrot.pdf.

[13] Amir Houmansadr, Giang T. K. Nguyen, Matthew Caesar, and Nikita Borisov. Cirripede: Circumvention infrastructure using router redirection with plausible deniability. In *Proceedings of the 18th ACM conference on Computer and Communications Security (CCS)*, October 2011. http://hatswitch.org/~nikita/papers/cirripede-ccs11.pdf.

[14] Amir Houmansadr, Thomas Riedl, Nikita Borisov, and Andrew Singer. I Want my Voice to be Heard: IP over Voice-over-IP for Unobservable Censorship Circumvention. In *Proceedings of the 20th Network and Distributed System Security Symposium (NDSS)*. Internet Society, February 2013. http://www.cs.utexas.edu/~amir/papers/FreeWave.pdf.

[15] Amir Houmansadr, Edmund L. Wong, and Vitaly Shmatikov. No direction home: The true cost of routing around decoys. In *Proceedings of the 21st Network and Distributed Security Symposium (NDSS)*. Internet Society, February 2014. http://www.internetsociety.org/sites/default/files/01_2_1.pdf.

[16] George Kadianakis and Nick Mathewson. obfs2 (the twobfuscator). https://gitweb.torproject.org/pluggable-transports/obfsproxy.git/blob/HEAD:/doc/obfs2/obfs2-protocol-spec.txt, January 2011.

[17] George Kadianakis and Nick Mathewson. obfs3 (the threebfuscator). https://gitweb.torproject.org/pluggable-transports/obfsproxy.git/blob/HEAD:/doc/obfs3/obfs3-protocol-spec.txt, January 2013.

[18] Josh Karlin, Daniel Ellard, Alden W. Jackson, Christine E. Jones, Greg Lauer, David P. Mankins, and W. Timothy Strayer. Decoy routing: Toward unblockable internet communication. In *Proceedings of the USENIX Workshop on Free and Open Communications on the Internet (FOCI)*, August 2011. http://www.usenix.org/events/foci11/tech/final_files/Karlin.pdf.

[19] Karsten Loesing. Counting daily bridge users. Technical Report 2012-10-001, October 2012. https://research.torproject.org/techreports/counting-daily-bridge-users-2012-10-24.pdf.

[20] Hooman Mohajeri Moghaddam, Baiyu Li, Mohammad Derakhshani, and Ian Goldberg. SkypeMorph: Protocol obfuscation for Tor bridges. In *Proceedings of the 19th ACM conference on Computer and Communications Security (CCS)*, October 2012. https://cs.uwaterloo.ca/~iang/pubs/skypemorph-ccs.pdf.

[21] Tor Project. #4744: GFW probes based on Tor's SSL cipher list. https://trac.torproject.org/projects/tor/ticket/4744, December 2011.

[22] Tor Project. #7167: Combine traffic obfuscation with address diversity of flash proxy. https://trac.torproject.org/projects/tor/ticket/7167, October 2012.

[23] Tor Project. Bridge users using transport meek. https://metrics.torproject.org/users.html?graph=userstats-bridge-transport&transport=meek#userstats-bridge-transport, May 2014.

[24] David Robinson, Harlan Yu, and Anne An. Collateral freedom: A snapshot of Chinese users circumventing censorship. Technical report, Open Internet Tools Project, May 2013. https://openitp.org/pdfs/CollateralFreedom.pdf.

[25] Qiyan Wang, Xun Gong, Giang T. K. Nguyen, Amir Houmansadr, and Nikita Borisov. CensorSpoofer: Asymmetric communication using IP spoofing for censorship-resistant web browsing. In *Proceedings of the 19th ACM conference on Computer and Communications Security (CCS)*, October 2012. https://netfiles.uiuc.edu/qwang26/www/publications/censorspoofer.pdf.

[26] Zachary Weinberg, Jeffrey Wang, Vinod Yegneswaran, Linda Briesemeister, Steven Cheung, Frank Wang, and Dan Boneh. StegoTorus: A camouflage proxy for the Tor anonymity system. In *Proceedings of the 19th ACM conference on Computer and Communications Security (CCS)*, October 2012. http://www.owlfolio.org/media/2010/05/stegotorus.pdf.

[27] Tim Wilde. Great Firewall Tor probing circa 09 DEC 2011. Technical report, Team Cymru, January 2012. https://gist.github.com/da3c7a9af01d74cd7de7.

[28] Philipp Winter and Stefan Lindskog. How the Great Firewall of China is blocking Tor. In *Proceedings of the USENIX Workshop on Free and Open Communications on the Internet (FOCI)*, August 2012. https://www.usenix.org/system/files/conference/foci12/foci12-final2.pdf.

[29] Philipp Winter, Tobias Pulls, and Juergen Fuss. ScrambleSuit: A polymorphic network protocol to circumvent censorship. In *Proceedings of the Workshop on Privacy in the Electronic Society (WPES)*. ACM, November 2013. http://www.cs.kau.se/philwint/pdf/wpes2013.pdf.

[30] Eric Wustrow, Scott Wolchok, Ian Goldberg, and J. Alex Halderman. Telex: Anticensorship in the network infrastructure. In *Proceedings of the 20th USENIX Security Symposium*, August 2011. http://www.usenix.org/events/sec/tech/full_papers/Wustrow.pdf.