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Systemization of Pluggable Transports for Censorship Resistance

Abstract: An increasing number of countries implement Internet censorship at different scales and for a variety of reasons. In particular, the link between the censored client and entry point to the uncensored network is a frequent target of censorship due to the ease with which a nation-state censor can control it. A number of censorship resistance systems have been developed thus far to help circumvent blocking on this link, which we refer to as *link circumvention systems* (LCs). The variety and profusion of attack vectors available to a censor has led to an arms race, leading to a dramatic speed of evolution of LCs. Despite their inherent complexity and the breadth of work in this area, there is no systematic way to evaluate link circumvention systems and compare them against each other. In this paper, we (*i*) sketch an attack model to comprehensively explore a censor's capabilities, (*ii*) present an abstract model of a LC, a system that helps a censored client communicate with a server over the Internet while resisting censorship, (*iii*) describe an evaluation stack that underscores a layered approach to evaluate LCs, and (*iv*) systemize and evaluate existing censorship resistance systems that provide link circumvention. We highlight open challenges in the evaluation and development of LCs and discuss possible mitigations.

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1 Introduction

As the Internet becomes an increasingly important means to engage in civil society, those who wish to control the flow of information are turning to measures to suppress speech which they consider undesirable. While blocking can take place at

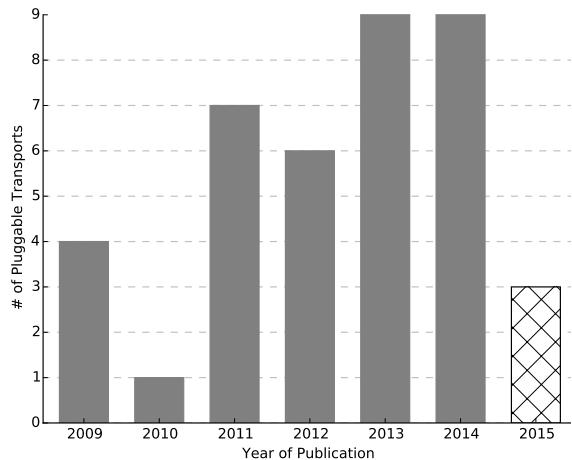


Fig. 1. Surveyed systems (literature and implementation) from the last five years related to censorship resistance systems with a focus on link circumvention.

a number of points on a network, the link between the censored client and entry point to uncensored part of the network has been a frequent target as the censor is typically a powerful nation-state adversary in control of network infrastructure within the censored region. A number of censorship resistance systems have emerged to help bypass such blocks which we call link circumvention systems or LCs (the scope of this systemization is limited to systems that resist censorship on the link). Due to the diversity of censorship mechanisms across different jurisdictions and their evolution over time, there is no one approach which is optimally efficient and resistant to all censors. Consequently, an arms race has developed resulting in the evolution of LCs to have dramatically sped up with resistance schemes becoming increasingly complex. This has been captured in Figure 1 which shows work in this area over the last five years as per our survey.

Despite the multitude of LCs that have been developed so far, there is no systematic way to evaluate them. The area lacks a comprehensive attack model of the censor which has led to systems assuming arbitrary threat models, some of which are misaligned with how real censors operate [1]. As a result of the disparate attack vectors these systems protect against, it is hard to assess the scope of circumvention offered by a system in isolation as well as in comparison with others.

We systematize and evaluate existing work by conducting a comprehensive survey of censorship resistance systems that offer link circumvention (we identify 41 such systems). To un-

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derstand effectiveness of various LCs under different censorship scenarios, we sketch a comprehensive attack model to understand a censor’s capabilities. Next we develop an abstract model of a link circumvention system that enables a client application in censored region to communicate with a server application over the Internet, even though direct connections are blocked.¹ We then present an evaluation stack that highlights capabilities of a LC in terms of the mechanisms employed to resist different censorship vectors.

Related Work: Existing work systematizes censorship and circumvention systems in a broader context. Elahi and Goldberg [3] present a taxonomy of censorship resistance strategies for different types of censors (e.g. ISP, government) with the decision-making process based on their resources, capabilities, limitations and utility. Tschantz *et al.* [4] argue that the evaluation of circumvention tools should be based on economic models of censorship. Köpsell *et al.* [5] present a classification of blocking techniques based on the communication layer involved, the content of communication (e.g. images, web) and metadata of the communication (e.g. IP addresses of participants, time of the communication, protocols involved). Perng *et al.* [6] classify circumvention systems based on the technical primitives and principles they build upon. Leberknight *et al.* [7] survey the social, political and technical aspects that underpin censorship. They also propose metrics that quantify their efficacy, i.e. scale, cost and granularity. Our work has a special focus on the link circumvention aspect of censorship resistance, and extends previous work by using a comprehensive attack model and evaluation stack to systematize link circumvention systems.

In this systemization of knowledge paper, we make the following contributions:

- present an attack model from a censor’s perspective that captures capabilities of a censor and the diversity of censorship mechanisms (Section 3).
- develop an abstract model of a link circumvention system that facilitates communication between a censored client and server in a censorship resistant fashion (Section 4).
- present an evaluation stack to assess scope of circumvention offered by various link circumvention systems (Section 4).
- survey 41 link circumvention systems and evaluate them using the proposed attack model and evaluation stack. We identify broad categories of resistance systems based on

the attack path(s) that these seek to protect (Sections 5, 6 and 7).

- discuss open challenges in the evaluation of link circumvention schemes and discuss possible solutions to mitigate these (Section 8).

2 Background

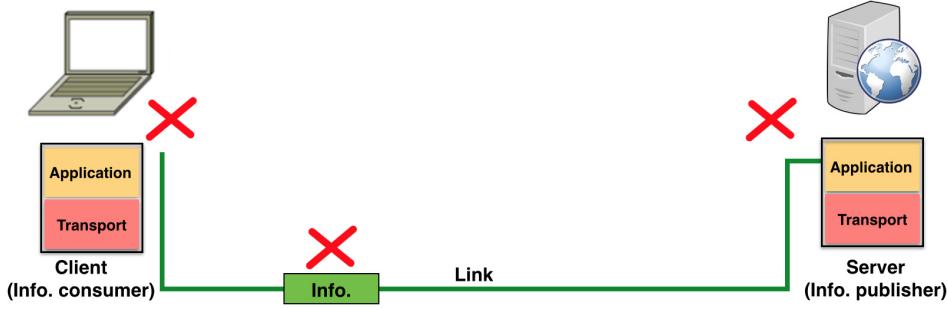
In its simplest form, an information dissemination network comprises an information consumer (the client), an information publisher (the server) and a link that connects the two (Figure 2a). A censor’s goal is to disrupt information dissemination. This can be done by directly targeting the information (through corruption, insertion of false information, deletion or modification), or by impairing access or publication of information.

A censorship resistance system thwarts a censor’s attempts to corrupt information, or its access or publication. While a censorship resistance system can encompass any part of the information network, in reality most systems offer circumvention on the link connecting information endpoints due to its flashpoint status in the censorship arms race. Link censorship is more prevalent because it is less intrusive, and convenient (the communication infrastructure is typically under the censor’s direct control).

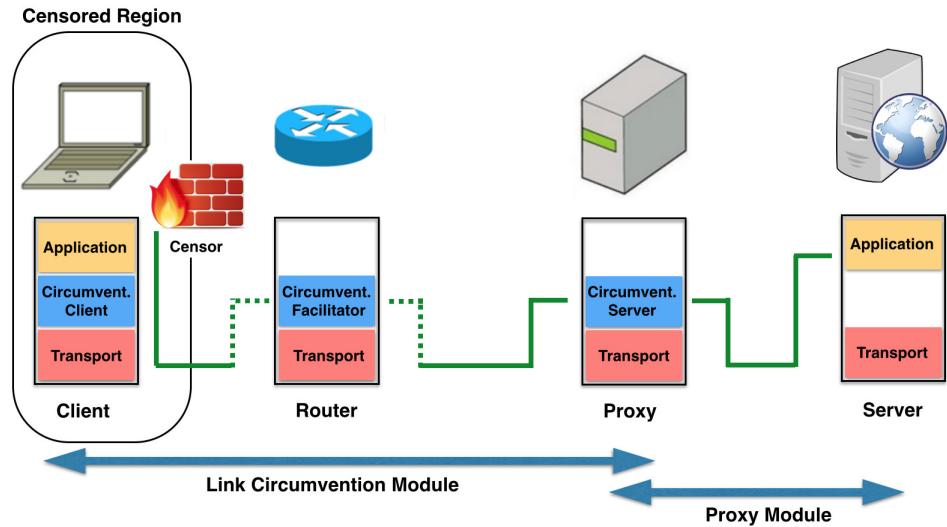
For circumvention on the information link, it is common to employ a proxy, an intermediate unblocked system that relays traffic back and forth between the client and server. A proxy divides the link between client and server into two distinct portions: (i) client to proxy (within censored region), and (ii) proxy to server (outside censored region). This has been illustrated in Figure 2b. Resistance systems increasingly treat these two portions separately (via *link circumvention module* and *proxy module*, respectively) as these lend themselves to different design, implementation, and software distribution practices.

The *proxy module*, being in uncensored region, may simply provide access to server, without offering any additional security properties and could be simply implemented as a HTTP or SOCKS proxy, or as a VPN. Alternatively, the proxy module may be an anonymity system like Tor [8] which not only provides access to the server but also prevents attackers from being able to identify which user is accessing which resource. In contrast, *link circumvention* being in the line of fire is a rapidly evolving but less mature area. In this paper, our focus is the link circumvention role of censorship resistance systems. Any reference to censorship resistance systems henceforth should be perceived within the scope of link circumvention.

¹ An instance of our abstract link circumvention (LC) model is the de facto API for anonymous communication systems to integrate with censorship resistance schemes [2], however, we purposely maintain a broad focus to accommodate LCs that have not been written strictly as a Pluggable Transport but can fit the broad model with minor adaptation.



(a) A typical information retrieval process involves an information consumer (the client), an information publisher (the server), and a link that connects the two. A censor's goal is to disrupt dissemination of information either by corrupting it, or by hindering its access or publication (indicated by red crosses in the figure).



(b) Circumvention software provides unfettered information retrieval despite censorship and may encompass any part of the information network. The process is typically facilitated by a *proxy* that relays traffic between a *client* in the censored region and an external server, and effectively divides the channel into two portions which circumvention tools handle separately via different modules: (i) client to proxy (*link circumvention module*), and (ii) proxy to server (*proxy module*). The *circumvention client* allows the client application to construct a communication channel to the server application through a *circumvention server*, which can optionally be facilitated by an intermediate device (*circumvention facilitator*).

Fig. 2. Information retrieval (a) without censorship, and (b) with censorship, aided by circumvention software.

3 A Censor's Attack Model

To understand the scope of circumvention offered by various tools, it is important to first understand the attack surface available to a censor (illustrated in Figure 3). While the link between client and server remains the focus of this paper, for the sake of completeness, we also include client and server-based censorship in the attack model. The model captures both direct and indirect forms of censorship. While direct censorship immediately targets information dissemination, indirect censorship (or *fingerprinting*) provides input to aid the censor's blocking decision. For example, a censor can identify a protocol by destination port (fingerprinting) and follow up by blocking IP addresses in the associated flows (direct cen-

sorship). For convenience, through the rest of this paper we refer to shorthands associated with direct censorship and fingerprinting activities described in Figure 3. We now discuss various censorship scenarios grouped under direct censorship and fingerprinting.

3.1 Direct Censorship

Censor on Client (CEN.CLI).

Client-side censorship can take place through direct or discrete (facilitated by malware or insider attacks) installation of surveillance software. This may lead to corruption of information as well as access disruption. China's Green Dam, a filtering software product purported to prevent children from harm-

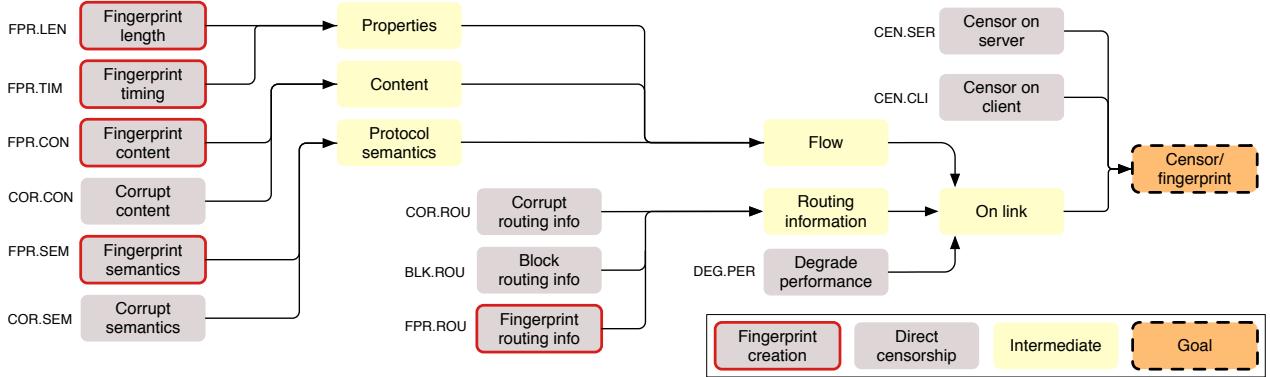


Fig. 3. Censor's attack model, showing both direct censorship (information corruption, or disabling access or publication) and indirect censorship (fingerprinting to develop and improve features for direct censorship)

ful Internet content, was mandated to be installed on all new Chinese computers in 2009 [9]. The software was found to be far more intrusive than officially portrayed, blocking access to a large blacklist of websites in diverse categories, and monitored and disrupted operation of various programs if found to be engaging in censored activity. TOM-Skype, a joint venture between a Chinese telephony company TOM Online and Skype Limited, is a Voice-over-IP (VoIP) chat client program that uses a list of keywords to censor chat messages in either direction [10].

Censor on Server (CEN.SER).

A censor can install software on the server-side to corrupt the information being published or disrupt the publication process. A number of studies investigate Chinese government's censorship of posts on the national microblogging site Sina Weibo. Bamman *et al.* [11] analyze three months of Weibo data and find that 16% of politically-driven content is deleted. Zhu *et al.* [12] note that Weibo's user-generated content is mainly removed during the hour following the post with ~30% of removals occurring within 30 minutes and ~90% within 24 hours. Another study observes posts from politically active Weibo users over 44 days and finds that censorship varies across topics, with the highest deletion rate culminating at 82%. They further note the use of *morphs*—adapted variants of words to avoid keyword-based censorship. Weiboscope [13], a data collection, image aggregation and visualization tool, makes censored Sina Weibo posts by a set of Chinese microbloggers publicly available.

Degradate Performance (DEG.PER).

Network performance degradation is a soft form of censorship that diminishes access to information while at the same time affording deniability to the censor. Anderson [14] uses a set of diagnostics data (such as network congestion, packet loss, latency) to study the use of throttling of Internet connectivity in Iran between January 2010 and 2013. He uncovers two

extended periods with a 77% and 69% decrease in download throughput respectively; as well as eight to nine shorter periods. These often coincide with holidays, protest events, international political turmoils and important anniversaries, and are sometimes corroborated by overt filtering of online services or jamming of international broadcast television.

Block Routing Information (BLK.ROU).

Censorship can leverage items of a connection tuple (source IP address, source port, destination IP address and destination port) to disable information access or publication. The block can continue for a short period of time to create a chilling effect and encourage self-censorship on part of the client. One study notes that the Great Firewall of China (GFW) blocks communication from a client IP address to a destination IP address and port combination for 90 seconds after observing 'objectionable' activity over that flow [15]. The GFW has been reported to drop packets originating from Tor bridges based on both source IP address and source port to minimize collateral damage [16].

Corrupt Routing Information (COR.ROU).

A censor can disrupt access by corrupting information that supports correct routing of packets. This can be done by changing routing entries on an intermediate censor-controlled router, or by manipulating information that supports the routing process, e.g. BGP hijacking and DNS manipulation. The Border Gateway Protocol (BGP) is the de facto protocol for inter-AS routing. A censor can block a network's connectivity to the Internet by withdrawing previously advertised network prefixes or re-advertising them with different properties (rogue BGP route advertisements). A number of countries have attempted to effect complete or partial Internet outages in recent years by withdrawing their networks in the Internet's global routing table (Egypt [17], Libya [18], Sudan [19], Myanmar [20]). DNS is another vital service that maps names given to different Internet resources to IP addresses. The hi-

archical distributed nature of DNS makes it vulnerable to censorship. Typical forms of DNS manipulation involve redirecting DNS queries for blacklisted domain names to a censor-controlled IP address (DNS redirection or poisoning), a non-existent IP address (DNS blackholing) or by simply dropping DNS responses for blacklisted domains. China’s injection of forged DNS responses to queries for blocked domain names is well known, and causes large scale collateral damage by applying the same censorship policy to outside traffic that traverses Chinese links [21].

Corrupt Flow Content (COR.CON).

A censor can compromise information or disrupt access by corrupting flow content (COR.CON), i.e. the application layer payload. For example, a censor can inject HTTP 404 Not Found message in response to requests for censored content and drop the original response, or modify the HTML page in the body of an HTTP response.

Corrupt Protocol Semantics (COR.SEM).

A censor can corrupt information or disrupt access by manipulating protocol semantics (COR.SEM). A censor can leverage knowledge of protocol specification to induce disruption on a flow (for example, injecting forged TCP reset packets into a flow will cause both endpoints to tear down the connection).

3.2 Fingerprinting

Fingerprint Routing Information (FPR.ROU).

A flow can be associated with a protocol based on items of the connection tuple. The destination port is a typical target of censorship (e.g. 80 for HTTP). Flows addressed to IP addresses known to be associated with a blocked service can be disrupted by implication. Flow fingerprinting of this kind can form part of a multi-stage censorship policy, possibly followed by a blocking step. Clayton examines the hybrid two-stage censorship system *CleanFeed* deployed by British ISP, BT. In the first stage, it redirects suspicious traffic (based on destination IP and port) to an HTTP proxy. In the next stage it performs content filtering on the redirected traffic and returns an error message if requested content is in the Internet Watch Foundation (IWF) list [22].

Fingerprint Content (FPR.CON).

Flows can be fingerprinted by checking for the presence of protocol-specific strings, blacklisted keywords, domain names and HTTP hosts etc. A number of deep packet inspection (DPI) boxes can perform regex-based traffic classification [23–26], however it remains unclear what are the true costs of performing DPI at scale [27, 28]. Alternatively, flows can be fingerprinted based on some property of the content being carried. For example, a censor that does not allow encrypted content can block flows where content has high entropy [29].

Fingerprint Flow Properties (FPR.LEN and FPR.TIM).

A censor can fingerprint a protocol by creating its statistical model based on flow features such as packet length, and timing-related features (inter-arrival times, burstiness etc.). Once a model has been derived, a censor can fingerprint flows based on their resemblance or deviation from this model [30, 31]. Wiley [32] used Bayesian models created from sample traffic to fingerprint obfuscated protocols (Dust [33], SSL and obfs-openssh [34]) based on flow features, and found that across these protocols length and timing detectors achieved accuracy of 16% and 89% respectively over entire packet streams, while the entropy detector was 94% accurate using only the first packet. A host’s transport layer behavior (e.g. the number of outgoing connections) can be used for application classification. Flow properties can also be used to fingerprint the website a user is visiting even if the flow is encrypted [35–38].

Fingerprint Protocol Semantics (FPR.SEM).

A censor can fingerprint flows based on protocol behaviour triggered through different kinds of active manipulation, i.e. by dropping, injecting, modifying and delaying packets. The censor’s goal is to leverage knowledge of a protocol’s semantic properties to elicit behaviour of a known protocol. Alternatively, a censor can perform several fingerprinting cycles to elicit the information on which to base subsequent blocking decision. In 2011, Wilde [39] investigated how China blocked Tor bridges and found that unpublished Tor bridges are first scanned and then blocked by the Great Firewall of China (GFW). Wilde’s analysis showed that bridges were blocked in the following fashion: (i) When a Tor client within China connects to a Tor bridge or relay, GFW’s DPI box flags the flow as a potential Tor flow, (ii) random Chinese IP addresses then connect to the bridge and try to establish a Tor connection; if it succeeds, the bridge IP/port combination is blocked.

4 Link Circumvention

We now turn our attention from a censor’s attack landscape to censorship resistance systems. In Section 2, we mentioned that the link between information client and server (*On Link* in Figure 2b) is a frequent target of censorship and hence the assumed threat model of most resistance systems. It is common for resistance systems to employ an intermediate proxy that divides the link into two parts, (i) client to proxy (*link circumvention*) and (ii) proxy to server. The focus of this work is link circumvention: we first present an abstract model of link circumvention, followed by an *evaluation stack* that represents functional components of link circumvention as a multi-layer stack. The evaluation stack can be used as a common bench-

mark to visualize capabilities of different link circumvention systems.

4.1 Abstract Model of a Link Circumvention System

We present an abstract model of a link circumvention system (LC), which lends itself well to analysis through the attack model outlined in Figure 3. The goal of a LC is to enable a client application to communicate with a server application over the Internet, even though direct connections are blocked (Figure 2b). The LC-client exposes an API whereby the client application can request that a communication channel to the server application be opened. The LC-client then connects to the LC-server over a blocking-resistant communication channel, and the LC-server connects to the server application. The client application can then communicate with the LC-client as if it is communicating directly with the server.

The communication channel provided by the LC-client and server has similar properties to TCP. Data sent through the channel will either be delivered to the other end without corruption in the same order as it was sent, or an error will be reported to the sender. It is the responsibility of the LC to route communications between the LC-client and LC-server, avoid blocking, and recover from any corruption of data (whether by the censor or due to other network disruption).

The LC-client and LC-server may be able to communicate directly over the Internet, in that any intermediate networks or routers are not aware of the protocol the LC is using. However in some cases there may be a LC-router which implements part of the LC protocol so as to facilitate the blocking resistant communication channel.

The LC communication channel does not offer authenticity, so it is the responsibility of the client and server applications to confirm that data received on the channel originated from the expected party and has not been corrupted in transit. However many practical LCs will provide some degree of authenticity so as to meet the goal of blocking resistance.

Ideally the latency of the communication channel will not be much higher than that of the direct communication channel, but in some cases a much higher latency is unavoidable in which case a client application which is designed for a normal TCP connection may malfunction.

This abstract model is implemented through the de-facto Pluggable Transport standard [2]. This API specifies how modules are invoked (i.e. as separate executable), how the communication channel is implemented (i.e. as an extension to the SOCKS protocol), how configuration and status information is communicated between client/server applications and Pluggable Transport client/server (i.e. through a combination

of environment variables, command-line parameters, and standard in/out/error descriptors). Although this specification was written for the Tor anonymity system, it is also implemented in the Lantern [40] and Psiphon [41] simple proxy CRSSs.

4.2 Evaluation Stack

In order to defend against the multiple avenues of attacks available to a censor, a link circumvention system (LC) is typically designed as a series of components, with each component defending against one or more attacks, either by itself or in conjunction with other components. In order to describe the capability of each LC, we map each of them to a generic set of components shown in Figure 4, arranged in layers analogous to a network protocol stack.

The primary flow of payload information is between adjacent layers in the stack, with the client/server application at the top and network at the bottom. However just as with real-world network stacks, control information does not always exactly follow this abstraction and may skip layers. Also not all layers will be present in all LCs, as some exclude certain attacks from their threat model.

Before data can be sent over the LC communication channel, a session must be established. The **Session Initialisation (SI)** is responsible for the handshake between the LC-client and LC-server. This may involve negotiating connection parameters, performing authentication, and deriving session keys.

On the same uppermost layer is the **Encryption (ENC)** which takes application traffic data and encrypts it so as to look random to an adversary. The key for performing the encryption is provided by the SI layer.

Next is the **Multiplexing (MUX)** layer, which allows multiple application sessions to be multiplexed over a single LC channel, or a single application session to be split over multiple LC channels. This layer is also responsible for error detection and re-assembly, if the lower layers do not provide this.

Then the **Content Obfuscation (OBF)** formats the ‘random’ data stream so as to mimic the content of a different protocol, e.g. HTTP or VoIP.

Next **Timing Obfuscation and Length Obfuscation (TIM-LEN)** hide the application’s timing and packet length patterns. The layer may perform the obfuscation itself, or may just compute the changes which are necessary and transmit this as control data to other layers which actually delay and/or pad payload data.

Finally **Transport (TRN)** is responsible for taking the transformed payload data and sending it to the other side of the LC client/server pair.

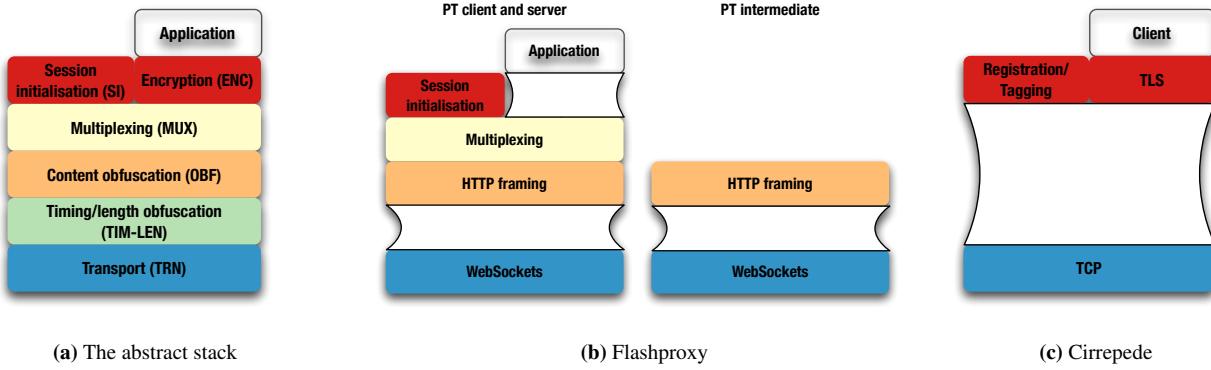


Fig. 4. The Abstract Stack and Evaluation Stacks for Flashproxy and Cirrepede.

We conduct a comprehensive survey of censorship resistance systems that offer link circumvention (LC). We identify 41 such systems which we broadly classify as ones that resist IP address/host blocking (Section 5), flow fingerprinting (Section 6) and composite systems that combine the last two (Section 7). We further classify these high-level categories where relevant. For each category, we discuss one representative LC in *depth* with respect to the LC evaluation stack (Figure 4) and the attack model (Figure 3). To capture the *breadth* of systems in a given category, we also provide a brief discussion of other relevant systems (under the title *Miscellaneous*).

5 IP Address/Host Filtering Resistance Systems

A censor can disrupt access to a service by blocking the server’s IP address, or a key hop directly on path to the server (corresponding to BLK.ROU in Figure 3). A number of tools have emerged to resist IP address filtering which we further classify based on the circumvention approach they take. Techniques under *censorship surface augmentation* hide the censorship target (e.g. IP address) among a crowd such that censoring the target incurs larger collateral damage than if it is blocked in isolation. In *decoy routing*, a cooperative hop between client and server applies circumvention-friendly treatment to packets containing a special steganographic mark.

5.1 Censorship Surface Augmentation

The accuracy of a censor’s blocking decision depends on a number of factors, such as the blocking mechanism employed and the quality of target set to block. In particular, the censor’s policy must make consideration for the acceptable false positive rate as these have political and economic ramifications [4].

Mechanisms under this category obfuscate the censorship target in such a way that censoring it incurs large collateral damage in terms of false positives.

5.1.1 Flashproxy

Simple proxies with long-lived IP addresses that circumvent IP blocking by relaying traffic between a client and censored server suffer from the problem of being enumerated and subsequently blocked by a censor (FPR.ROU, COR.ROU and BLK.ROU nodes in the attack diagram in Figure 3).

To protect against these attacks, Flashproxy introduces two new entities, i.e. *facilitators* and *flashproxies* (Figure 4b, left and right, respectively). A *facilitator* is a volunteer website outside the censored region which may be blocked by the censor, yet remains reachable through low-bandwidth channels such as email. Over this channel, the *Session Initialisation* module (*SI*) of a censored user registers itself by sending its IP address and a port where it awaits incoming connections. On the *facilitator* side, the *SI* adds a special *badge* in all the web pages it serves to uncensored users, typically a piece of Javascript. When an uncensored user visits a web page on the *facilitator* website, the *badge* turns the visitor’s web browser into a *flashproxy*. The *SI* of a *flashproxy* (running in the web browser of an uncensored user) connects to the *facilitator* to retrieve an IP-port pair for a censored user and initiates a connection to it. The *SI* of the censored user accepts the connection to complete the rendezvous between the two entities. Thereafter, the *Content Obfuscation (OBF)* of the *flashproxy* relays censored content for the censored user through HTTP (“HTTP framing” in Figure 4b).

Flashproxy offers resistance against IP address blocking only, consequently leaving a number of paths on the attack diagram exposed. A censor could block traffic based on content (COR.CON), use statistical traffic properties (FPR.LEN and

FPR.TIM) to detect the protocol or content to block, or observe characteristic patterns in incoming connections to censored hosts (FPR.SEM). The authors suggest using Flashproxy in combination with Tor to thwart COR.CON attacks.

5.1.2 Miscellaneous

VPN-Gate [42] is a public VPN service that randomizes the IP addresses of its VPN servers through a pool of volunteer-run VPN-Gate proxies. To prevent a censor from harvesting all proxies, VPN-Gate (i) only gives a fraction of the entire pool to each client, (ii) includes decoy IP addresses (belonging to vitally important hosts on the Internet, such as Windows Update servers) in the pool, and (iii) by aggregating data across VPN-Gate proxies to flag probes from a censor. One design trend is to use a widely used service as a proxy to fetch censored content. Meek [43] employs a technique called *domain fronting* [44] to evade host-based censorship by using an innocuous domain name (*front domain*) in the unencrypted request header (*TLS Server Name Indication header* – SNI), while hiding the domain of a proxy (*inside-domain*) in the encapsulated encrypted request (*HTTP Host header*). The front domain (the only one visible to a censor) is an intermediate web service hosting many domains (typically a CDN) which decrypts the inside-domain and internally routes the traffic to the relevant host within its network. This host serves as a proxy for censored clients to access blocked servers. OSS [45] turns any existing Online Scanning Service (OSS) (web services that take a URL as user input and then fetch the web page behind that URL e.g. PDFmyURL [46]) into a proxy to fetch censored content. A variation of this scheme is for clients and servers to rendezvous on an intermediate host, blocking which incurs significant collateral damage. CloudTransport [47] clients and bridges (i.e. proxies) share a common account on a cloud storage which they use to share files containing client requests and bridge responses in real time. Collage [48] peers exchange data through social networking and photo sharing websites by embedding hidden messages in user-generated content such as posts and images. MIAB [49] improves Collage's rendezvous by leveraging *blog pings*, i.e. real-time notifications a blog sends to a centralized network service (a ping server) when content is updated. By monitoring ping servers, MIAB peers automatically learn when a new message is available. Defiance [50] allocates ephemeral IP addresses to its gateways and bridges from a large pool of diverse IP addresses. The transience and diversity of IP addresses make it hard for a censor to block or enumerate them. To access blocked websites, the Defiance client must connect to a shorted-lived bridge which acts as a proxy. To learn an ephemeral bridge location, a client must successfully complete a *dance*; that is, make a sequence

of pre-agreed timed short-lived connections to ephemeral gateways.

5.2 Decoy Routing

In this approach, clients covertly signal a cooperating intermediate router to deflect their traffic meant for a non-blocked destination (to evade the censor) to a blocked one. To deflect traffic, deflecting routers must be located on the forward network path from the client to the non-blocked destination. These routers must therefore be strategically positioned to optimise the number of censored users that can be served [51]. It is theoretically possible for a censor to defeat decoy routing by routing traffic around the deflecting routers [52]. However, in practice this is believed to be too costly for a censor because of business relationships with other ISPs, and monetary, performance and quality of service degradation issues thereby induced [53].

5.2.1 Cirripede

Cirripede offers resistance against IP address filtering (BLK.ROU, FPR.ROU and COR.ROU in the attack diagram in Figure 3). In addition to this, it also resists content-based fingerprinting (FPR.CON) and content tampering/blocking (COR.CON) through its authenticated encryption layer. Its corresponding evaluation stack is presented in Figure 4c.

To use Cirripede, a censored user must first register its IP address and a shared secret with a Registration Server (RS). The registration is facilitated by a friendly ISP that deploys Deflecting Routers (DRs) that redirect non-registered client traffic to the Registration Server. To register, the *Session Initialisation (SI)*, *Transport (TRN)* and *Encryption (ENC)* module of a client coordinate to encode a covert registration signal into the *TCP Initial Sequence Number (ISN)* of a series of packets destined to a non-blocked destination. The registration packets are deflected by the Deflecting Routers (DRs) and reach the Registration Server where they are inspected. If the Registration Server successfully recognises the signal in the packets, its *SI* instructs all Deflecting Routers within the ISP network to deflect subsequent client traffic to a Service Proxy (SP). After sending the registration packets, a client selects an innocuous non-blocked destination and initiates a TLS handshake to it which is taken over by the Service Proxy that acts as a web proxy to censored content thereafter.

A censor could still attack unprotected nodes of the attack diagram in Figure 3. Traffic from/to different websites generally has different characteristic patterns, therefore a censor could determine that traffic feigned to originate from a

non-blocked website actually comes from a blocked website (FPR.LEN and FPR.TIM). It could also detect protocol implementation inconsistencies due to the non-blocked and blocked destination running different software stacks (FPR.SEM).

5.2.2 Miscellaneous

Telex [54], TapDance [55] and Curveball [56, 57] can selectively *tag* individual connections on-the-fly (in contrast to Cirrepede that deflects client traffic after registration). Telex and Curveball embed their tag in the random nonce of a TLS handshake with a non-blocked destination. TapDance encodes the tag in a connection’s incomplete HTTPS request to a decoy server using a novel steganography scheme. Cirrepede, TapDance and Curveball support asymmetric flows where upstream and downstream traffic do not follow the same path because of ISP’s internal routing. TapDance is the only solution that does not require active inline flow blocking to prevent further decoy-server client communication. This property makes it easier to be deployed by ISPs without disturbing existing traffic and quality of service. IBS [58] improves decoy routing solutions in general by simplifying key distribution and providing forward secrecy. These are achieved with the use of identity-based encryption instead of traditional public-key cryptography.

6 Flow Fingerprinting Resistance Systems

These systems obfuscate blocked traffic such that it cannot be fingerprinted by a censor, some by offering resistance against *fingerprinting of protocol semantics*, while others *mimic* a supposedly whitelisted category. Another approach to censorship evasion is to transform flows leveraging a censor’s analysis limitations (*monitor-driven flow transformation*).

6.1 Fingerprinting of Protocol Semantics

A number of schemes offer resistance against protocol scanning, i.e. techniques used by a censor to confirm that a machine is indeed part of an anti-censorship system. Typically, a censor probes for an open port and attempts to “speak” the anti-censorship protocol. To defeat protocol scanning, a SilentKnock [60] server accepts incoming connections on a particular port only from clients that authenticate with a special “knock” (a one-way authentication mechanism embedded in TCP headers). BridgeSPA [61] (originally known as SPA-

Tor [62]) builds upon SilentKnock’s design but relaxes server-side memory constraints associated with per-client housekeeping. It replaces counters with rounded-to-the-minute UTC timestamps and long-lived keys with short-lived ones. Defiance [50] imposes several levels of address indirection to prevent unauthenticated access to bridges from protocol scanning censors. Keyspace-Hopping [63] discloses only a fraction of its proxies to each client. It defeats protocol scanning probes through the use of shared secrets. It forces a censor to dedicate more resources to discover proxies by requesting clients to solve computational problems.

6.2 Mimicry

Mimicry-based mechanisms transform traffic to look like whitelisted communication, such that the transformed traffic resembles the syntax or content of an allowed protocol or randomness.

6.2.1 Mimic Existing Protocol or Content

A large body of work evades censorship by imitating an innocuous protocol (e.g. HTTP) or content (e.g. HTML). Typically the mimicry is based on widely-deployed protocols or popular content thus complicating a censor’s task by (i) increasing the censor’s workload as there is more volume of traffic to inspect, and (ii) increasing the collateral damage associated with wholesale protocol blocking.

StegoTorus.

StegoTorus obfuscates packet length and inter-packet timing of Tor traffic thus thwarting fingerprinting of flow properties (FPR.LEN and FPR.TIM nodes in the attack diagram in Figure 3). It also prevents content fingerprinting (FPR.CON) and content tampering/blocking (COR.CON) with authenticated encryption. Optionally it can mimic a set of innocuous protocols over which covert traffic is sent. The corresponding evaluation stack is presented in Figure 5b.

StegoTorus comprises two modules, both of which can be implemented by a combination of LC components. To start a session, the *SI* of a client and server (i.e. proxy) first establish a shared key through a key-exchange that only contains random bytes: this thwarts content-based filtering (FPR.CON). Once a session is established, the *TIM-LEN* module chops fixed-length input packets into random-sized messages. Sizes are taken from a trace of an innocuous protocol session pre-recorded by the user or bundled with the software (FPR.LEN). A 32-byte ID is added to messages so they can be re-ordered by the recipient. The *ENC* module then encrypts messages individually (COR.CON and FPR.CON) and passes them again

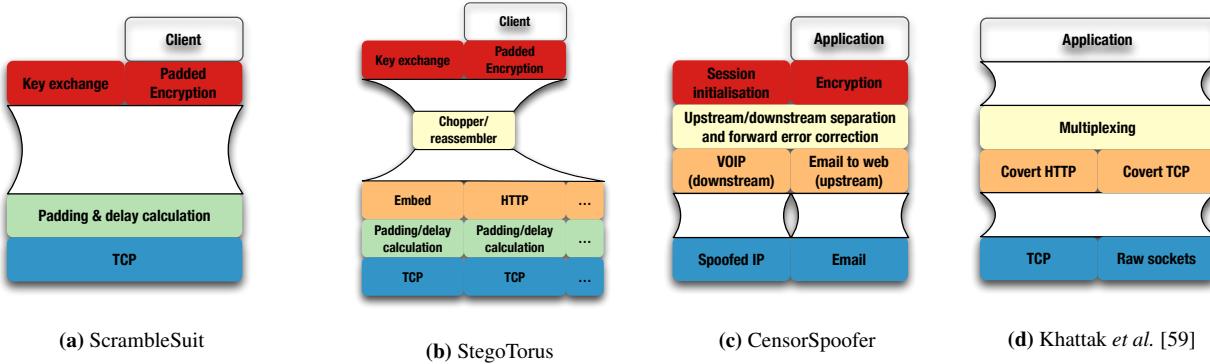


Fig. 5. Evaluation Stacks for ScrambleSuit, StegoTorus, CensorSpoof and Khattak *et al.* [59].

to the *TIM-LEN* module which adjusts their sending time in accordance with packet inter-arrival times derived from a pre-recorded traffic trace (FPR.TIM). Optionally, the *Content Obfuscation (OBF)* component of StegoTorus can mimic a known protocol such as unencrypted HTTP. For example the *OBF* of a client may embed the encrypted messages into the *HTTP Cookie* header and url part of requests, and the *OBF* of a server may reply by steganographically embedding content into the body of HTTP responses.

StegoTorus uses long-lived server locations. So if a censor manages to harvest them, it could block them by injecting TCP *RST* packets or erroneous DNS responses (COR.ROU, BLK.ROU and FPR.ROU).

Miscellaneous.

FOE [64] and MailMyWeb [65] proxies send users static web pages as email attachments in response to censored URLs they receive in an email *Subject* field (assuming that SMTP is not monitored or email traffic is encrypted). SWEET [66] creates a bi-directional communication channel by encapsulating censored traffic into email attachments such as images. To prevent a censor from blocking all emails sent to the proxy, each client sends requests to a unique email address. SkypeMorph [67] shapes inter-packet timing and packet size distribution so as to mimic a Skype video call. TransTeg [68] negotiates an *overt codec* during a VoIP call initialisation, but thereafter encodes the raw voice stream with a different lower-bitrate codec (the *covert codec*), thus reducing the length of packets to transmit. The freed space is filled with low-bandwidth covert traffic. FTE [69] extends conventional symmetric encryption with the ability to specify the format of the ciphertext with a regex. This thwarts protocol fingerprinting by transforming a blocked *source* application-layer protocol into an unblocked *target* application-layer protocol.

Protocol imitation has a number of limitations that make it possible to distinguish imitated traffic from legitimate traffic [70, 71]. To avoid the above pitfalls, a number of recent

mimicry-based circumvention systems reuse genuine software and libraries and tunnel covert traffic through them. Facet [72] streams potentially censored videos over video-conferencing calls of popular applications such as Skype, Google Hangout and FaceTime. Freewave [73] modulates traffic into acoustic signals and streams them directly into an existing VoIP application such as Skype. JumpBox [74] feeds HTTP request directly into a web browser's stack in order to ‘emulate’ the networking characteristics of the HTTP protocol. Castle [75] provides obfuscation for low-bandwidth application (e.g. chat and emails) through real-time strategy (RTS) video games. It encodes data as player actions in the game and uses desktop-automation software to feed player actions directly to the game’s user interface. Rook [76] leverages First Person Shooter (FPS) video games to obfuscate chat sessions of users within a censor region. It identifies packet fields of high entropy and replaces them with other legitimate game values before they are sent. Marionette [77] mimics a protocol’s stateful semantics and statistical properties by composing probabilistic state machine automata through flexible plugins and domain-specific languages. Content obfuscation is achieved through template grammars built using probabilistic context-free grammars.

6.2.2 Mimic Unknown Protocol or Content

Another approach is to make traffic look like an unknown protocol, either by imitating randomness or arbitrarily deviating from a known blocked protocol. This idea is motivated by the general assumption that a censor implements blacklisting of known protocols and is unwilling to incur high collateral damage associated with whitelisting.

ScrambleSuit.

ScrambleSuit [78] obfuscates a censored protocol with random-looking bytes for all its traffic including session ini-

tialisation thus thwarting fingerprinting based on flow content (FPR.CON in the attack diagram in Figure 3). Encryption of content provides content obfuscation (FPR.CON), confidentiality and resistance against tampering (COR.CON). Packet lengths and inter-arrival times are also randomised (FPR.LEN and FPR.TIM). ScrambleSuit uses a special protocol for session bootstrapping that resists tampering (COR.CON) and protocol scanning (FPR.SEM). The corresponding evaluation stack is presented in Figure 5a.

To connect to a ScrambleSuit proxy, the *SI* of a client redeems a short-lived ticket retrieved from a low-bandwidth out-of-band channel. After the first authentication, the server gives the client a ticket for the next connection. This ticket provides mutual authentication and therefore resistance against protocol scanning from a censor (FPR.SEM). Furthermore, it only contains random bytes to evade content-based detection (FPR.CON). Once a session is initialised, the *ENC* component turns all traffic into random-looking bytes, thereby thwarting content-based fingerprinting and blocking (FPR.CON). It also provides authentication and confidentiality (COR.CON). The *TIM-LEN* component randomises packet lengths (FPR.LEN) and timing of flows (FPR.TIM) using discrete probability distributions provided by the *ENC* module.

ScrambleSuit protects against most attacks in the attack diagram (Figure 3). One limitation is that the IP addresses of ScrambleSuit proxies are known, and therefore vulnerable to being enumerated and subsequently blocked by a server (COR.ROU and BLK.ROU).

Miscellaneous.

MSE [79] is the de-facto obfuscation mechanism used by Bit-Torrent. Both the key exchange and traffic session contain only random-looking bytes. Padding is added to all traffic including the handshake. Dust [33] is a similar system with the capability to shape packet sizes based on an arbitrary distribution. obfs2 [80] obfuscates traffic content with encryption, but the key exchange does not provide authentication against passive and active attackers. obfs3 [81], initially adopted by ScrambleSuit, improves obfs2 by negotiating keys using anonymous Diffie Hellman (DH) with a special encoding so as to be indistinguishable from a random string. This forces a censor to actively probe the server or perform a man-in-the-middle attack to detect the key exchange. obfs4 [82] adds authentication to obfs3 using the ntor handshake [83, 84] and is now used by ScrambleSuit. Unlike ScrambleSuit, obfs2 and obfs3 do not randomise packet lengths and inter-packet timings.

6.3 Monitor-driven Flow Transformation (MDFT)

Systems under this category shape traffic in a way that exploits the limitations of an adversary’s traffic fingerprinting model. Effectively, this mechanism can provide unobservability to even cleartext traffic, which is particularly useful for countries that prohibit encrypted traffic.

6.3.1 Khattak *et al.* [59]

This work explores protection against content-based filtering (FPR.CON and COR.CON in the attack diagram in Figure 3) by exploiting limitations of the implementation of Deep Packet Inspection (DPI) boxes. The evaluation stack is presented in Figure 5d.

Being operationally similar to Network Intrusion Detection Systems (NIDS), DPI boxes grapple with the same issues that make them vulnerable to evasion: when to create state for a flow to monitor, when to tear down state for a flow being monitored, how to interpret a packet stream in the presence of multiple routing paths, divergent header fields, and overlapping IP fragments and TCP segments. The authors intermingle a number of specially crafted packets in their regular packet stream to fetch Web content from a server outside China using a client inside China, and highlight a number of vulnerabilities in the Great Firewall of China (GFW)’s traffic analysis model. For example, one observation was that by sending a TCP reset packet with low *TTL* value for an existing connection, subsequent packets containing blacklisted keywords are no longer censored.

Most nodes of the attack diagram (Figure 3) are not protected by this approach. Even without a clear view of the entire stream, a censor could still block traffic on a per-packet basis, for example by filtering packets destined to known server IP addresses (FPR.ROU, COR.ROU and BLK.ROU) or by fingerprinting packet length (FPR.LEN).

6.3.2 Miscellaneous

GoHop [85] breaks the notion of ‘flow’ used by Deep Packet Inspection (DPI) boxes by sending traffic over a set of randomized ports. Clayton *et al.* [86] note that the GFW terminates offending connections through injection of TCP reset packets. A client can circumvent this form of censorship by ignoring all the TCP reset packets it receives. West Chamber [87–89] forces the GFW to purge state for a connection and exclude it from censorship analysis by exchanging specially crafted TCP reset packets between the client and server. These packets are

ignored by TCP stacks of the client and server, but considered by the GFW.

7 Composite Censorship Resistance Systems

These systems offer resistance against filtering of both IP addresses and hosts (Section 5), and flow-based censorship (Section 6).

7.1 CensorSpoof

CensorSpoof provides resistance against IP address harvesting (BLK.ROU, COR.ROU and FPR.ROU nodes in the attack diagram in Figure 3) using spoofed source IP address, and resistance against content-based blocking (FPR.CON and COR.CON) by mimicking encrypted VoIP traffic. The evaluation stack is presented in Figure 5c.

CensorSpoof client sends requests for censored content to a CensorSpoof server (*spoof*) over email, which then serves blocked content to the client over a VoIP call. The *SI* of a CensorSpoof client creates four accounts: two email accounts (one from a local provider and one from a foreign one), and two VoIP accounts (one from a local registrar and one from a foreign one). The local accounts serve as client agents, while the foreign accounts act as server agents. A client registers with the *spoof* by sending a registration message containing information related to its accounts and a shared cryptographic key. The *spoof* logs in to the foreign accounts (VoIP and email) and monitors incoming messages from the client’s local accounts. Once registered, the *SI* of a client initiates a session by calling the *spoof*’s VoIP account. The *spoof* accepts the call and provides a dummy IP address and port. The client then sends dummy UDP traffic to the IP address provided by the *spoof*, while sending censored requests to the *spoof*’s email account. Upon receiving a request, *spoof* serves the blocked content in encrypted UDP traffic by spoofing source IP address of the dummy host. The *ENC* module of CensorSpoof prevents content-based censorship (FPR.CON) and provides data confidentiality and authentication (COR.CON).

As CensorSpoof does not shape traffic, a censor may be able to detect discrepancies between a real voice call and the web traffic sent over UDP (FPR.LEN and FPR.TIM in Figure 3). Furthermore, there may be an indicative correlation between the timing of a VoIP call and SMTP traffic (FPR.SEM).

7.2 Miscellaneous

Freewave [73] mimics VoIP traffic while also hiding proxy IP addresses. It modulates traffic into acoustic signals and sends them over a VoIP network such as Skype, Vonage or iCal. To hide the IP address of a proxy, client traffic is relayed through multiple VoIP peers. For Skype, this is achieved by configuring the Freewave proxy as an ordinary node so that VoIP traffic is routed via Skype *super nodes*. Infranet [90] thwarts IP blocking by turning a non-blocked cooperative website into a proxy. Besides relaying censored content, proxy websites continue to serve their usual uncensored content. For its upstream channel, Infranet encodes covert traffic in sequences of HTTP requests; for its downstream channel, it steganographically embeds content in uncensored images.

8 Discussion and Challenges

In Table 1, we provide a summary of link circumvention systems (LCs). For each LC, we note components of the evaluation stack (Section 4.2) that the system implements to offer protection along various path(s) in the attack diagram (Figure 3). We note that a large number of systems resist content-based blocking and fingerprinting (FPR.CON and COR.CON), with relatively less focus on routing-based censorship (BLK.ROU, COR.ROU and FPR.ROU). Only a few systems protect against flow fingerprinting based on length and timing (FPR.LEN and FPR.TIM), while none address attacks related to manipulation of protocol semantics (COR.SEM). The heavy emphasis of existing LCs on content-based circumvention is in contrast to how censors have historically implemented blocking in practice, i.e. through blocking or corruption of routing information [1]. Furthermore, LCs tend to cluster around specific evasion styles making them vulnerable to unprotected paths in the attack diagram (Figure 3).

Our systemization highlights two main limitations in the area of link circumvention, i.e. lack of (*i*) common evaluation criteria, and (*ii*) modularity and flexibility. Currently each LC uses its own evaluation criteria which makes it hard to assess the scope of circumvention offered by a system in isolation as well as in comparison with other systems. Testing and benchmarking LCs is complicated due to the absence of a suitable testbed, and involves separately downloading, compiling and using systems with potentially different (and conflicting) build and run environments. This has led to a situation where research and development efforts are concentrated on proposing new schemes instead of improvising existing systems. Related to the testbed issue, there is no environment to simulate adversaries. Consequently, most adversarial assumptions are theo-

Table 1. A summary of link circumvention systems. Columns represent a node of the attack diagram (Figure 3). Within each column, different symbols denote components of evaluation stack (Figure 4) that a system implements to protect against the attack represented by the column. Symbols map to the evaluation stack as follows: \blacktriangle Session Initialisation (SI), \spadesuit Encryption (ENC), \clubsuit Multiplexing (MUX), \blacksquare Content Obfuscation (OBF), \blacklozenge Timing Obfuscation (TIM-LEN), \blacktriangledown Length Obfuscation (TIM-LEN) and \star Transport (TRN).

		Section #	Blocking				Fingerprinting				
			COR.CON	COR.SEM	COR.ROU	BLK.ROU	FPR.LEN	FPR.TIM	FPR.SEM	FPR.ROU	FPR.CON
Mimicry	MSE	6.2					\blacktriangledown				$\blacktriangle\spadesuit$
	FOE	6	\blacktriangle		\star	\star			\blacksquare	\star	\blacksquare
	MailMyWeb	6	\blacktriangle		\star	\star			\blacksquare	\star	\blacksquare
	Traffic Morphing	6.2					\blacktriangledown				
	TransTeg	6	$\blacktriangle\spadesuit$								\blacksquare
	Dust	6.2				\blacktriangledown					$\blacktriangle\spadesuit$
	SkypeMorph	6	$\blacktriangle\spadesuit$		\star	\star			\star		\blacksquare
	StegoTorus	6	$\blacktriangle\spadesuit$				\blacktriangledown	\blacklozenge			$\clubsuit\blacksquare$
	obfs2	6									$\blacktriangle\spadesuit$
	obfs3	6	$\blacktriangle\spadesuit$						\blacktriangle		$\blacktriangle\spadesuit$
	obfs4	7	$\blacktriangle\spadesuit$				\blacklozenge	\blacktriangledown	$\blacktriangle\spadesuit$		$\blacktriangle\spadesuit$
	SWEET	6	$\blacktriangle\spadesuit$		\star	\star				\star	\blacksquare
	FTE	6	\spadesuit								$\blacktriangle\blacksquare$
	TRIST	6									\blacksquare
	Rook	6	$\blacktriangle\spadesuit$					\star	\star	\star	$\blacktriangle\blacksquare\star$
	Castle	6	$\blacktriangle\spadesuit$		\star	\star	\star	\blacklozenge	$\blacktriangle\star$	$\blacktriangle\star$	
	Marionette	6	$\blacktriangle\spadesuit$				\blacktriangledown	\blacklozenge	\blacksquare	$\blacktriangle\spadesuit$	
	JumpBox	6					\star	\star	\star		
Prot. Fingprt. MDFT	Khattak	6.3									$\blacksquare\star$
	GoHop	6.3	$\blacktriangle\spadesuit$				\blacktriangledown				$\blacktriangle\spadesuit\star$
	SilentKnock	6.1							$\blacksquare\star$		
	SPATor	6.1							$\blacksquare\star$		
	BridgeSPA	6.1							$\blacksquare\star$		
	Keyspace-Hopping	6.1						$\blacktriangle\spadesuit$			
IP Filtering	Cirrepede	5	$\blacktriangle\spadesuit$		$\blacktriangle\spadesuit\star$	$\blacktriangle\spadesuit\star$				$\blacktriangle\spadesuit\star$	$\blacktriangle\spadesuit$
	Curveball	5	$\blacktriangle\spadesuit$		$\blacktriangle\spadesuit\star$	$\blacktriangle\spadesuit\star$				$\blacktriangle\spadesuit\star$	$\blacktriangle\spadesuit$
	Telex	5	$\blacktriangle\spadesuit$		$\blacktriangle\spadesuit\star$	$\blacktriangle\spadesuit\star$				$\blacktriangle\spadesuit\star$	$\blacktriangle\spadesuit$
	TapDance	5	$\blacktriangle\spadesuit$		$\blacktriangle\spadesuit\star$	$\blacktriangle\spadesuit\star$				$\blacktriangle\spadesuit\star$	$\blacktriangle\spadesuit$
	Defiance	5			$\blacktriangle\spadesuit\blacksquare$	$\blacktriangle\spadesuit\blacksquare$				$\blacktriangle\spadesuit\blacksquare$	
	Flashproxy	5			$\blacktriangle\star$	$\blacktriangle\star$				$\blacktriangle\star$	\blacktriangle
	OSS	5	$\blacktriangle\spadesuit$		$\blacktriangle\spadesuit\star$	$\blacktriangle\spadesuit\star$				$\blacktriangle\spadesuit\star$	\blacksquare
	MIAB	5	$\blacktriangle\spadesuit$		\blacktriangle	\blacktriangle				\blacktriangle	$\blacktriangle\spadesuit$
	IBS	5	$\blacktriangle\spadesuit$								$\blacktriangle\spadesuit$
	Meek	5	$\blacktriangle\spadesuit$		$\blacktriangle\spadesuit\star$	$\blacktriangle\spadesuit\star$				$\blacktriangle\spadesuit\star$	$\blacktriangle\spadesuit$
	CloudTransport	5	$\blacktriangle\spadesuit$		$\blacktriangle\star$	$\blacktriangle\star$				$\blacktriangle\star$	$\blacktriangle\spadesuit$
	VPN-Gate	5	$\blacktriangle\spadesuit$		\star	\star				\star	$\blacktriangle\spadesuit$
Composite	Infranet	7	$\blacktriangle\spadesuit$		\star	\star				\star	\blacksquare
	Collage	7	$\blacktriangle\spadesuit$		\star	\star				\star	$\blacktriangle\blacksquare$
	CensorSpoofer	7	$\blacktriangle\spadesuit$		$\blacktriangle\star$	$\blacktriangle\star$				$\blacktriangle\star$	$\blacktriangle\spadesuit$
	Freewave	7	$\blacktriangle\spadesuit$		\blacktriangle	\blacktriangle				\blacktriangle	$\blacktriangle\spadesuit$
	ScrambleSuit	7	$\blacktriangle\spadesuit$				\blacktriangledown	\blacklozenge	$\blacktriangle\spadesuit$		$\blacktriangle\spadesuit$

retical and in some cases disconnected from how real censors operate [1]. A number of systems protect against a censor capable of fingerprinting flow properties and content. Evaluation of such systems will greatly benefit from a repository of traffic capture files. Systems that perform traffic shaping use various protocols in a ‘correct’ manner and require labelled datasets against which to validate their schemes. Adversary Lab [91] has done some preliminary work on developing a standard environment to evaluate systems resistant to flow fingerprinting by subjecting them to a range of adversaries. Another important but overlooked aspect of evaluation is performance and usability. This is particularly important because LCs often rely on help from volunteers for deployment who are naturally interested in the system’s performance and maintenance costs. We note lack of principled performance evaluation, with some metrics being misaligned to a given use case. For example, some systems use file download to approximate web browsing performance. There has been preliminary work recently on conducting user studies to evaluate LC’s performance [92].

The ability to quickly develop link circumvention systems (LCs) for particular locations (spatial agility) and in response to changes (temporal agility) is particularly important for censorship resistance because there is no one approach which is optimally efficient and resistant to all attackers. However, building a new LC is a significant undertaking, in particular if it must include several classes of blocking-prevention techniques (e.g. scanning-resistance, traffic-analysis resistance, encryption) and robustness techniques (e.g. flow control, error detection and recovery). In many situations having several schemes in operation is more effective than using any one [93] (for example, Tor dealt with TLS handshake fingerprinting of January and September 2011 by modifying its protocol to protect against the vulnerable attack path). Recently, there has been a case for combining multiple LCs (particularly in the context of Tor’s Pluggable Transports which are essentially an instantiation of our abstract model of link circumvention systems) with the goal to offer circumvention tailored to different censorship scenarios. So far, the sharing of Pluggable Transport features has happened not in a black-box way, but through the sharing of source code. LibFTE is in use by Tor (in its fteproxy Pluggable Transport form) and a number of other projects. Similarly, Meek which was originally developed for Tor now also exists in a fork by Psiphon [41] with minor adaptations. Fog [94] uses multiple proxies to chain Pluggable Transports in a black box fashion. This approach is not suitable for practical deployment due to a number of limitations. For example, not all combinations of Pluggable Transports make sense: the chain obfs3 (flow fingerprinting resistance) followed by Flashproxy (IP address filtering resistance) offers more comprehensive resistance, but the reverse,

i.e. Flashproxy followed by obfs3 breaks the former’s network layer assumptions.

The evaluation stack described in Section 4.2 was designed to help understand and evaluate link circumvention schemes (LCs), as well as assist the rapid development of new schemes. We propose a framework to build link circumvention schemes out of reusable components following the evaluation stack architecture which we call *Tweakable Transports* (we are currently writing the design specification [95]).

Tweakable Transports provide a modular and flexible platform for writing link circumvention systems (LCs), while simplifying evaluation. Following the evaluation stack, components from a link obfuscation scheme can be extracted so that each component complies with the abstract model the stack defines. This approach assists the design process by providing a set of patterns to follow, and a methodology for evaluating the censorship resistance features which are offered. Just as abstractions for components have been developed for compiler design (lexer, parser, code generator) or GUI design (model, view, controller), a systematic approach to design reduces development time and improves quality of code. A particular instance of a Tweakable stack may be designed by an expert familiar with the properties of each component and a censor’s blocking techniques and so allow the trade-off between performance and censorship resistance. Alternatively instances could be automatically generated and tested against the real censorship system or a simulation of one, so as to quickly find an adequate link circumvention scheme.

Tweakable Transports facilitate combining different link circumvention (LC) features. Each component can be replaced with another which is compatible and components can be inserted or removed. This approach allows code-reuse because a component developed for one Tweakable Transport can be used for another. In so doing, more collaboration opportunities are allowed, better testing can be performed on frequently required components improving reliability and both spatial and temporal agility. As a result Tweakable Transports exponentially increases the number of possible link obfuscation scheme. The development effort to add one component adds not just one new link obfuscation scheme, but creates a whole new family of schemes, each one of which the censor will need to test against any proposed fingerprinting or blocking technique. The increased development cost and possibility of false-positives reduces the likelihood that a censor will be able to effectively block the resulting LCs.

From the link obfuscation schemes summarised in this paper, adapting their implementations to be Tweakable Transports allows weaknesses to be addressed. Missing layers (e.g. resistance to timing and packet-length fingerprinting) leave some schemes open to attack. Rather than developing a component from scratch, a component can be imported from an-

other link obfuscation scheme. New schemes can also be created, such as combining the content obfuscation and timing/length obfuscation with a common session initialisation and encryption component, via a multiplexing component.

One way to build link obfuscation scheme designs following the principles of Tweakable Transports is to create a common API specification that allows components to communicate [95]. This approach has the advantage of allowing existing code to be re-used, which is particularly important when protocols to be impersonated are not specified and only available as binary modules. However components need to be modified to fit the API specification. An alternative approach taken to creating Tweakable Transports is taken by Marionette where the full link obfuscation scheme is written in a domain specific language (DSL) optimised for this case [77], reducing flexibility but also reducing effort for cases when the DSL is sufficient.

9 Conclusion

As censorship attempts have concentrated on disrupting the link between a censored client and server, a multitude of censorship resistance schemes have been built to bypass such blocks which we call link circumvention schemes (LCs). We bring clarity to the complex and rapidly evolving field of link circumvention by conducting a systematic survey of LCs in terms of the threat-model defended against and their evaluation in terms of an abstract evaluation stack. We have highlighted open challenges in the area of LCs with respect to common evaluation criteria and modular/flexible development of systems. These insights have motivated the case for a new framework to efficiently compose LCs out of reusable components following the evaluation stack presented in this paper.

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