Large-scale Spatiotemporal Characterization of Inconsistencies in the World’s Largest Firewall

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Abstract—A nation-scale firewall, colloquially referred to as the “Great Firewall of China,” implements many different types of censorship and content filtering to control China’s Internet traffic. Past work has shown that the firewall occasionally fails. In other words, sometimes clients in China are able to reach blacklisted servers outside of China. This phenomenon has not yet been characterized because it is infeasible to find a large and geographically diverse set of clients in China from which to test connectivity.

In this paper, we overcome this challenge by using hybrid idle scan techniques that are able to measure connectivity between a remote client and an arbitrary server, neither of which are under the control of the researcher performing measurements. In addition to hybrid idle scans, we present and employ a novel side channel in the Linux kernel’s SYN backlog. We demonstrate both techniques by measuring the reachability of the Tor network which is known to be blocked in China. Our measurements reveal that 1) failures in the firewall occur throughout the entire country without any conspicuous geographical patterns, 2) a network block in China appears to have unfiltered access to parts of the Tor network, and 3) the filtering seems to be mostly centralized at the level of Internet exchange points. Our work also answers many other open questions about the Great Firewall’s architecture and implementation.

I. INTRODUCTION

More than 600 million Internet users are located behind the world’s most sophisticated and pervasive censorship system: the Great Firewall of China (GFW) [1]. Brought to life in 2003, the GFW has a tight grip on several layers of the TCP/IP model and is known to block or filter IP addresses [2], TCP ports [2], DNS requests [3], [4], [5], HTTP requests [6], [7], [8], circumvention tools, and even social networking sites [9].

This pervasive censorship gives rise to numerous circumvention tools seeking to evade the GFW by exploiting a number of opportunities [10]. Of particular interest is the Tor anonymity network [11] whose arms race with the operators of the GFW now counts several iterations. Once having had 30,000 users solely from China, the Tor network now is largely inaccessible from within China’s borders as illustrated in Figure 1.

The amount of users trying to connect to the Tor network indicates that there is a strong need for practical and scalable circumvention tools. Censorship circumvention, however, builds on censorship analysis. A solid understanding of censorship systems is necessary in order to design sound and sustainable circumvention systems. However, it is difficult to analyze Internet censorship without controlling either the censored source machine or its—typically uncensored—communication destination. This problem is usually tackled by obtaining access to censored source machines, finding open proxies, renting virtual systems, or by cooperating with volunteers inside the censoring country. In the absence of these possibilities, censorship analysis has to resort to observing traffic on the server’s side and inferring what the client is seeing.

Our work fills this gap by presenting and evaluating network measurement techniques which can be used to expose censorship while controlling neither the source nor the destination machine. This puts our study in stark contrast to previous work which had to rely on proxies or volunteers, both of which provide limited coverage of the censor’s networks. By being mostly independent of source and destination machines, we are able to shed light on entirely unexplored areas of the Internet. We evaluate our techniques by applying them to the Tor anonymity network, thereby handing the Tor Project practical tools to measure the reachability of their network. Such tools are needed because bridges† are frequently blocked in China without the bridge operators or the Tor Project noticing [12]. Our work makes it possible to test the reachability

†Bridges are “hidden” Tor relays which are not listed in the public network consensus.
of these bridges without having a vantage point in China. As a result, the Tor Project is able to learn which subset of bridges is still reachable and hence undiscovered by the GFW. This knowledge facilitates the optimization of bridge distribution [13], e.g., bridges blocked in China are only given out to users outside China.

Our techniques are currently limited to testing basic IP connectivity. Thus, we can only detect censorship on lower layers of the network stack, i.e., before a TCP connection is even established. This kind of low-level censorship is very important to the censors, however. For example, while social media controls on domestic sites in China, such as Weibo, can be very sophisticated, users would simply use alternatives such as Facebook if the low-level IP address blocking were not in place to prevent this. Also, deep packet inspection (DPI) does not scale as well in terms of raw traffic as does lower-level filtering. Nevertheless, we acknowledge that our techniques are not applicable if censors only make use of DPI to block Tor as it was or is done by Ethiopia, Kazakhstan, and Syria [14].

We are interested not only in finding patterns in the GFW’s failures, but also in gaining a better understanding of how the GFW is architected within China’s backbone and provincial networks and whether previously observed details of its implementation are observed throughout the country. To this end, we focus our efforts on testing the following hypotheses that will illuminate the GFW’s architecture and implementation. All hypotheses are with respect to the filtering of TCP/IP packets based on IP addresses and port numbers.

Hypothesis 1. In general, from any client to any destination if a SYN packet is filtered by the GFW then a RST with the same source, destination, and port numbers will also be filtered. For brevity, we refer to this hypothesis as “RSTs are treated the same as SYNs.”

Hypothesis 2. There are no conspicuous geographic patterns in the GFW’s failures. In other words, failures can occur in any part of the country. For brevity, we refer to this hypothesis as “No geographic patterns in failures.”

Hypothesis 3. In general, the GFW blocks Tor relays by dropping SYN/ACK segments with IP address and port information that matches known Tor relays. Other types of filtering seen for Tor relays in China (e.g., dropping SYN segments) are a negligible fraction of the censorship. For brevity, we refer to this hypothesis as “server-to-client blocking.”

Hypothesis 4. At least some of the failures of the GFW are persistent, meaning that the client and server are able to communicate throughout the day. Note that this could also be due to intentionally whitelisted destinations, but in this paper we refer to all cases where clients in China can access Tor relays as “failures.” For brevity, we refer to this hypothesis as “some failures are persistent.”

Hypothesis 5. At least some of the failures of the GFW exhibit diurnal patterns, where a client and blacklisted server can communicate at some times of the day but not others. For brevity, we refer to this hypothesis as “some failures have diurnal patterns.”

Hypothesis 6. In general, packets that are subject to censorship traverse at least one or two hops, and sometimes more, into China before they are dropped by the GFW. For brevity, we refer to this hypothesis as “blocking is in the backbone.”

By testing the above hypotheses, we further increase the public’s knowledge about the GFW and by presenting and evaluating our measurement techniques, we equip circumvention system developers with a set of tools to analyze and debug censorship incidents. In summary, this paper makes the following contributions:

- We describe the first real-world application of the hybrid idle scan [15], [16] to a large-scale Internet measurement problem, in which we measure the connectivity between the Tor anonymity network and clients in China over a period of four weeks.
- We present and evaluate a novel side channel based on the Linux kernel’s SYN backlog which enables indirect detection of packet loss.
- We increase the community’s understanding of how the GFW is architected and how its blocking of the Tor network looks from different clients all over China.
- We publish our code under a free license to encourage further research.

The rest of this paper is structured as follows. We discuss some background of the GFW in Section II and our measurement techniques in Section III, which is then followed by our experimental methodology in Section IV. We analyze the data we gathered and present results in Section V and proceed with a discussion of our results in Section VI. Related work is covered in Section VII and the paper is concluded in Section VIII.

II. MOTIVATION AND GFW BACKGROUND

The hypotheses enumerated in Section I were chosen because we wanted to address the following open questions about the GFW:

- Are there geographic or other spatial patterns in the GFW’s failures? This is important because such patterns could be exploited by evasion technologies if the patterns exist, but if no such patterns exist then evasion efforts should focus on other aspects of the GFW.
- Are there temporal patterns in the GFW’s failures? There are many different evasion efforts that periodically test their methods to see if they have been detected and blocked by the GFW. A solid understanding of temporal patterns (such as diurnal patterns) will help these projects to better understand the results of their tests.
- What kinds of packets are filtered in different parts of the country? This is important, because if an evasion technology is tested in, e.g., Beijing but then fails to work in another part of the country, the developers of the evasion technology need to understand why.
- Where in China’s Internet backbone does the filtering occur, and what is the role of routing? If an evasion technology is being tested from two different sources in China or two different destinations outside the country, the developers of the evasion technology may...
observe two different results for their tests and they need a good understanding of why this occurs.

Now we give more details about what was known before the work presented in this paper. A more comprehensive overview of previous work is given in Section VII.

A. Spatial patterns

Ensafi et al. [15], [16] found that a small percentage of tests showed no signs of censorship. Their tests, like ours, were taken between clients in China paired with Tor relays outside China. However, their experimental methodology was designed to test if the failures in the censorship observed by Winter and Lindskog [2] were also observed outside of Beijing or not. Ensafi et al. made no attempt to choose clients or servers so that spatial patterns could be identified. Our experiments were specifically designed to identify spatial and geographic patterns in the GFW’s failures.

B. Temporal patterns

Neither Ensafi et al. nor Winter and Lindskog attempted to characterize temporal patterns in the GFW’s failures. This kind of characterization is difficult because, for a general understanding of temporal patterns, spatial patterns must be fully understood. Otherwise temporal patterns may be specific to one location. Also, temporal patterns are difficult to extract from idle scan measurements because of noise. This is why, in our experiments, we used traceroutes from a Tor relay to analyze temporal patterns.

C. Details of the filtering

What kinds of packets are filtered? This is a key question, especially for evasion techniques that seek to evade the GFW via insertion and evasion in the IP and TCP layers. Winter and Lindskog described detailed results about what happens to SYN, SYN/ACK, ACK, and RST packets, but their results were specific to one location in China: Beijing. Also, any of their experiments that required observation on the server were only able to be carried out between Beijing and one Tor relay in Sweden. Ensafi et al. had more spatial diversity in their experiments, but because of the nature of their hybrid idle scan the only packets that can be tested are SYN/ACKs from server to client and RSTs from client to server. SYN packets or any kind of stateful connection cannot be tested with the hybrid idle scan. All of these limitations in previous approaches is why our experiments include another—previously unknown—idle scan that uses the SYN backlog to make more general inferences with a wider spatial variety.

D. Architecture of the GFW

There are generally regarded to be three theories about how the GFW is architected, posited in technical papers [17], [18], [6], [19] or other media [20], [21]. One theory posits that the filtering occurs at choke points where oversea cables carrying international Internet traffic enter the country. Another theory is that the majority of the filtering occurs in three big Internet exchange points in Beijing, Shanghai, and Guangzhou [22], near where international traffic enters the country but positioned more at central points in China’s backbone network. A third theory that has been discussed is the possibility that the filtering occurs—or may increasingly occur as the GFW evolves—at the provincial level [18].

Our results about where the filtering of SYN/ACKs from Tor relays occurs are largely congruent with Xu et al.’s results about where RST injection based on deep packet inspection occurs. In their results, CNCGROUP performed most of its RST injection in the backbone, while CHINANET performed this type of censorship at the provincial level. Since their study, CNCGROUP has bought CHINANET, but the censorship at both the backbone and provincial levels, in about the same proportions as reported by Xu et al., is also apparent in our results. This means that the routers that perform port mirroring for deep packet inspection are probably the same routers that enforce access controls such as blocking Tor by source IP address and TCP port. It also means that where the filtering occurs has not changed significantly since the study performed by Xu et al..

In addition to providing more information about where the filtering occurs, our work presented in this paper raises interesting questions about how the GFW is architected, both in terms of implementations at routers and in terms of the big picture. Winter and Lindskog observed that for Tor relays only the SYN/ACK from the server is blocked, not the SYN from the client to the server. One of our key results in this paper is that this observation also applies to China in general for a lot of different geographic locations. This raises a question: why block SYN/ACKs in the one direction, but not SYNs in the other?

One possible theory might be that the Border Gateway Protocol (BGP) plays a key role in the censorship by causing all international traffic to flow through the routers that implement the censorship. Because the GFW operators are presumably restricted to announcing BGP routes for autonomous systems (ASes) that are in China, they can only control routing in the direction of traffic that is entering China. Hence SYN/ACKs from Tor relays outside China to clients in China are blocked almost all the time, while SYNs from clients in China to Tor relays outside China are much less likely to be blocked.

Another theory is based on speculating about the way the GFW operators monitor traffic to decide what to block. In a description of the GFW written in Chinese by “Xylon Pan” [23], it is speculated that this is done because the server in an HTTP connection typically sends a lot more content to the client than the client sends to the server. Thus Netflow aggregation in the server-to-client direction works better, because there is more traffic to be sampled. One theory put forward by Xylon Pan is that since the GFW’s operators think about network flows in the server-to-client direction, so they also write access controls (such as the blocking of Tor by IP address and TCP port) for the server-to-client direction.

The reason why this one-way blocking property (where SYN/ACKs entering China are much more likely to be blocked than SYNs leaving China) exists is left for future work. The major contribution of our present work in this regard is to confirm that this property is a general property that is observed all over China, not just in the one or two locations where previous tests [2], [23] have been performed.
The research questions we seek to answer require high geographical diversity of clients in China. Typically, such a study would only be possible if we could find and control vantage points in all of China’s provinces. Instead, we exploit side channels allowing us to detect intentional packet dropping—without controlling the two affected machines. In particular, we use hybrid idle scans (see Section III-C) and SYN backlog scans (see Section III-A). The idea behind these side channels as well as their prerequisites are discussed in this section.

A. Side channels in Linux’s SYN backlog

A performance optimization in the Linux kernel’s SYN backlog can be used to detect intentional packet dropping. Half-open TCP connections of network applications are queued in the kernel’s SYN backlog whose size defaults to 256. These half-open connections then turn into fully established TCP connections once the server’s SYN/ACK was acknowledged by the client. If a proper response is not received for an entry in the SYN backlog, it will be retransmitted the SYN/ACK several times. However, if the SYN/ACK and its respective retransmissions are never acknowledged by the client, the half-open connection is removed from the backlog. When under heavy load or under attack, a server’s backlog might fill faster than it can be processed. This causes attempted TCP connections to not be fully handled while pending TCP connections time out. The Linux kernel mitigates this problem by pruning an application’s SYN backlog. If the backlog becomes more than half full, the kernel begins to reduce the number of SYN/ACK retransmissions for all pending connections [24]. As a result, half-open connections will time out earlier which should bring the SYN backlog back into uncritical state. We show that the Linux kernel’s pruning mechanism—by design a shared resource—opens a side channel which can be used to measure intentional packet drops targeting a server. This is possible without controlling said server.

Our key insight is that we can remotely measure the approximate size of a server’s SYN backlog by sending SYN segments and counting the number of corresponding SYN/ACK retransmissions. Starting with version number 2.2, the Linux kernel retransmits unacknowledged SYN/ACK segments five times [25]. As a result, we expect to receive the full number of five retransmissions when querying a service whose SYN backlog is less than half full. If, on the other hand, the backlog becomes more than half full, we will observe less than five retransmissions. When applied to the problem of intentional packet dropping, this allows us to infer whether a firewall blocks TCP connections by dropping the client’s SYN or the server’s SYN/ACK segment.

It is worth mentioning that a server’s backlog state can also be inferred by coercing it into using SYN cookies [26]. A server using SYN cookies reveals that its SYN backlog is completely full. However, this measurement technique is effectively a SYN flood and TCP connections which were established using SYN cookies suffer from reduced throughputs due to the lack of flow control window scaling. In contrast to triggering SYN cookies, our technique has no negative impact on servers or other clients’ connections, when applied carefully.

B. The global IP identifier

IP identifiers (IPIDs) are unique numbers assigned to IP packets in case they are fragmented along a path. The receiving party is able to reassemble the fragmented packets by looking at their IPID field. Most modern TCP/IP stacks increment the IPID field per connection or randomize it, as opposed to globally incrementing it. A machine with a globally incrementing IPID keeps a global counter that is incremented by 1 for every packet the machine sends, regardless of the destination IP address. Being a shared resource, the IPID can be used by a measurement machine talking to a remote machine to estimate how many packets the remote machine has sent to other machines. Throughout this paper, we refer to machines with globally incrementing IPIDs as simply machines with “global IPIDs.”

C. Hybrid idle scan

Ensafi et al. [15], [16] discovered a new method for remotely detecting intentional packet drops on the Internet via side channel inferences. Their technique can discover packet drops (e.g., caused by censorship) between two remote machines, as well as infer in which direction the packet drops are occurring. The only major requirements for their approach are a client with a global IPID and a target server with an open port. Access to the client or the server is not required. Conceptually, the hybrid idle scan technique can turn approximately 1% of the total IPv4 address space [15] into conscripted measurement machines that can be used as vantage points to measure IP address-based censorship—without having root access on those machines. This is why we employ the hybrid idle scan technique for our geographic study of how Tor is blocked in China.

As shown in Figure 3, the hybrid idle scan implementation queues the IPID of the client to create a time series. By sending SYN/ACKs from the measurement machine and receiving RST responses, the IPID of the client can be recorded. The time series is used to compare a base case (when no traffic is being generated other than noise) to a period of time when the server is sending SYN/ACKs to the client (because of our forged SYNIs). Recall that the hybrid idle scan assumes that the client’s IPID is global and the server has an open port. By comparing two phases, one phase where no SYN packets are sent to the server and one phase where SYN packets are sent to the server with the return IP address spoofed to appear to be from the client, the hybrid idle scan technique can detect three different cases (plus an error case), shown in Figure 2, with respect to IP packets being dropped by the network in between the client and the server:

1) **Server-to-client-dropped**: SYN/ACKs are dropped in transit from the server to the client causing the client’s IPID to not increase at all (except for noise). See Figure 3(a).

2) **No-packets-dropped**: If no intentional packet dropping is happening, the client’s IPID will go up by exactly one. See Figure 3(b). This happens because the server’s SYN/ACK is unsolicited and answered by the client with a RST segment causing the server to remove the entry from its SYN backlog and not retransmit the SYN/ACK.
3) **Client-to-server-dropped:** The RST responses sent by the client to the server are dropped in transit. In this case, the server will continue to retransmit SYN/ACKs and the client’s IPID will get incremented by the total number of (re)transmitted SYN/ACKs, which is typically three to six. See Figure 3(c). This may indicate null routing, the simplest method for blacklisting an IP address.

4) **Error:** A measurement error happens if networking errors occur during the experiment, the IPID is found to not be global throughout the experiment, a model is fit to the data but does not match any of the three non-error cases above, the data is too noisy and intervention analysis fails because we are not able to fit a model to the data, and/or other errors.

Auto-regressive moving average (ARMA) models are used to distinguish these cases. This overcomes autocorrelated noise in IPID values (e.g., due to packet loss, packet delay, or other traffic that the client is receiving). More details about the ARMA modeling are described by Ensafi *et al.* [15], [16].

**D. The Tor network**

The Tor network [11] is an overlay network which provides its users with anonymity on the Internet. Tor clients expose a local SOCKS interface which is used to anonymize TCP streams such as web traffic. As of April 2014, the network consists of approximately 4,500 volunteer-run relays, nine directory authorities, and one bridge authority. While the relays anonymize the network traffic of Tor clients, the authorities’ task is to keep track of all relays and to vote on and publish the network consensus which Tor clients need in order to bootstrap. It is trivial for censors to download the hourly published network consensus and block all IP address/TCP port pairs found in it. Other circumvention systems suffer from the same problem [27].

All authorities are hard-coded in the Tor source code and their IP addresses remain static. As a result, they constitute attractive choke points for censors. In fact, blocking the IP addresses of all nine directory authorities is sufficient to
prevent direct connections to the Tor network. Our study focuses on the reachability of the authorities and relays, as it is known that the GFW is blocking them [2]. Our focus is on gathering more details about this blocking and characterizing it with a large-scale spatiotemporal study.

IV. EXPERIMENTAL METHODOLOGY

In this section, we describe the challenges our experimental methodology was designed to address, the data sets we collected, how our measurements help us to test the hypotheses enumerated in Section I, and other issues.

A. Encountered challenges

Over the course of running our experiments and analyzing our data, we faced a number of challenges which we discuss here.

Churn in the Tor network: While the size of the Tor network does not vary considerably over a short period of time, the network’s churn rate can render longitudinal studies difficult. For example, the median size of Tor’s network consensus (i.e., the number of Tor relays in the network) in March 2014 was 5,286. In total, however, March has seen 13,343 unique relays—many of which were online for only hours. To minimize the chance of selecting unstable Tor relays for longitudinal studies, only relays having earned the “Stable” flag should be considered [28]. Furthermore, the relay descriptor archives could be examined to calculate a relay’s reachability over time [29]. We selected only Tor relays that had an uptime of at least five days, and filtered out all data points where a node appeared to have left the network. After having run our experiments, we removed one Tor relay in Argentina from our data because its Tor and web ports switched during our experiments.

Geolocation of routers: For geolocating routers, we used MaxMind’s GeoIP2 City database [30]. As of April 2014, this database lacks accurate geolocation information for backbone routers in China. While provincial routers can typically be mapped to their province based on whois records, backbone routers are all mapped to the same bogus location at latitude 35 and longitude 105 which resides in an unpopulated area in central China. We also used MaxMind for geolocating clients, for which it is fairly accurate. For the location of routers, we used a combination of whois information and round-trip delays per hop. We discarded hops in our data that have whois records from China but are actually in Hong Kong or Pasadena, CA (where ChinaNet has a Point of Presence).

Diurnal patterns: For most measurements in this paper, we measured once per hour throughout the day. This avoids bias and distortion. For example, if we measured one set of clients in the morning and one set at night, differences between the two sets of clients may be due to different traffic patterns at the different times of day and not a property of the different set of clients. Thus we always randomize the order of our experiments when possible and repeat all measurements every hour for at least one full day.

Note that the Tor Project designed and implemented so-called bridges to tackle this very problem but the details are outside the scope of this work.

B. Experimental design and setup

Over the course of our experiments, we made use of three sets of Linux-based measurement machines in the U.S., China, and Europe. These three sets of machines correspond to the three main datasets that we collected.

Machines in the U.S.: The three machines used for our hybrid idle scans (see Section III-C) and SYN backlog scans (see Section III-A) were located at our university campus (UC) at the University of New Mexico. All machines had a direct link to a research network which is free from packet filtering and does not conduct egress filtering to block spoofed return IP addresses. Furthermore, the UC measurement machines have IP addresses that are not bound to any interfaces in order to eliminate unsolicited network packets. For example, a measurement machine’s kernel should never send a RST when it receives a SYN/ACK. The data set collected using the hybrid idle scan from these machines is a large-scale geographic pairing of many clients (in China and other countries) with many Tor relays and web servers around the world (mostly outside China). It complements the other data sets discussed below because it gives a complete cross-section of censorship between many clients and many servers. This data will be used to test Hypotheses 2 (no geographical patterns in failures) and 4 (some failures are persistent).

VPS in China: We rented a virtual private system (VPS) in China. The system was located in Beijing (AS 23028) and was used for our SYN backlog scans discussed in Section III-A. Our VPS provider employed a transparent and stateful TCP proxy in front of our VPS which silently dropped unsolicited segments. We carefully implemented our SYN backlog scans so they first established state whenever necessary to be unaffected by the TCP proxy. These SYN backlog scans provide a dataset that speaks to our assumptions about how China blocks Tor. It complements the hybrid idle scan data set because, although the measurements are from a single client in China, it allows us see exactly how that client experiences the censorship. This data will be used to test Hypotheses 1 (RSTs are treated the same as SYNs) and 3 (server to client blocking).

Tor relay in Europe: We used a long-established Tor relay at Karlstad University in Sweden for our traceroute measurements discussed in Section IV-B3. The relay has been part of the Tor network for several months, and using our VPS we manually verified it to be blocked in China. This data set shows blocking between one Tor relay and many clients in China. It complements the hybrid idle scan data set because access to the Tor relay allows us to collect more details about the blocking. This data will be used to test Hypotheses 4 (some failures are persistent), 5 (some failures have diurnal patterns), and 6 (blocking is in the backbone).

We now present our probing infrastructure as well as our measurement methodology used to investigate the theories posited in Section III.

1) Hybrid idle scans: Recall that by using hybrid idle scans, we have more freedom in choosing clients in different regions to test their reachability to different servers. Our goal is to determine blocking of Tor relays (outside of China) from the perspective of a large and geographically diverse set of clients (within China).
We are interested in knowing whether there exist different experiences of the censorship of Tor for different users in different regions. Past work showed that a small fraction of all Tor relays was accessible from a single vantage point in Beijing [2], but what about the rest of the country? Key questions are: how does the GFW’s architecture and China’s routing affect censorship in different regions?

**IP address selection**: We selected clients in China (CN), North America (NA), and Europe (EU). In order to be able to select random IP addresses in China without favoring specific locations—especially large cities featuring a vast number of allocated IP addresses—we divided the map of China into 33 x 65 cells corresponding to one degree of latitude and longitude. We filled this grid with all IP addresses in MaxMind’s database that were documented to be in China. Then, we collected IP addresses by randomly selecting a cell from our grid after checking that they employed global IPIDs. In an analogous manner, clients from the EU and NA were chosen by horizontally scanning these regions. After 24 hours, we gathered a pool of IP addresses that belonged to machines with a global IPID. Then, we continually checked the selected IP addresses for a 24-hour period to discard IP addresses that changed global IPID behavior, went down, or were too noisy. At the end we had 11 NA, 7 EU, and 161 CN clients to use for our measurements.

Servers were chosen from three groups: Tor relays, Tor directory authorities, and web servers. Tor relays were downloaded from a Tor relay status list [31]. We only selected relays with an uptime greater than five days. In order to select Tor relays in geographically diverse regions, we selected 10 Tor relays from Europe, 13 from the United States, 20 from Russia, and 101 from other countries. This way, our selected Tor relays were not biased toward Europe or the U.S., which exhibit more relays per capita than other regions. The 10 Tor authorities were obtained from the Tor source code. Web servers were chosen randomly from Alexa’s top 50 websites in China [32]. All web server and Tor relay IP addresses were checked hourly to make sure that they stayed up for at least 24 hours before being selected for our measurement.

The geographic distribution of our Tor relays as well as all clients in China is illustrated in Figure 4.

**Creating a complete bipartite graph**: We used three machines at UC (our university campus) to run the hybrid idle scan experiments. We started the experiments with 180 clients and 176 servers. Each day 20 clients and approximately 20 servers were selected for each of the machines. For 22 hours³, every hour, we performed the hybrid idle scan for each possible pair of client and server. Every “scan round” performs: 1) two minutes of hybrid idle scans, 2) 30 seconds of sending SYN to clear the server’s backlog, and 3) five seconds of testing the client to assure that they remained online and kept their global IPID. Similar checks are performed to ensure that servers remain online throughout each experiment. At any given time, each IP address (client or server) was involved in only one test. After 27 days, each client’s reachability was tested to all servers, i.e., our clients and servers created a bipartite graph. For more details about the experiment design refer to Ensafi et al. [15], [16].

³Two hours per day were reserved for server data synchronization.

**Pruning the data**: We used the selected IP addresses throughout our experiments. Naturally, some of the hosts went down or were occasionally too noisy. Also, the host behind an IP address can change, e.g., a client with a global IPID might lose its DHCP lease and get replaced with a client running a random IPID. To account for these issues, we perform tests throughout our experiments which cull out data points where basic assumptions are not met. For every server involved in the experiment, we had two checks: liveliness and the stable TOR flag test. After each scan, for five seconds we sent five SYN segments per second using UC’s unbound IP address. The data point passed the liveliness test only if it retransmits three or more SYN/ACKs. Also, if the server was a Tor relay, we verified that the relay was assigned the “Stable” flag (cf. Section IV-A).

For every client, for five seconds, we sent five SYN/ACKs per second using UC’s unbound IP address. We expect the client to respond with RST segments totaling in number to more than half the number of sent SYN/ACKs. If this is the case then the data point passes the client’s liveliness test. The results of a scan were allowed into the data set only if both the client and server passed their checks. Note that each data point is one client and one server tested one time in a given hour. There was a several-hour network outage that caused a hole in a portion of one day of our data.

After culling out data that did not meet our basic assumptions, we were left with 36% of the total data collected. This 36% is the data described in Section V and used for our analysis.

**SYN scan**: The SYN scan—depicted in Figure 5(a)—is started by MM by sending five SYN segments to Tor in order to infer the relay’s backlog size when under stress.⁴ After a delay of approximately 500 ms, VPS proceeds by sending 145 SYN segments whose purpose is to fill the relay’s backlog by more than half. Recall that the backlog size defaults to 256, so we only fill the backlog to 59%. That way, we can make the relay’s kernel prune MM’s SYN segments, thus reducing their retransmissions. Finally, MM knows that VPS’s SYNs reached the relay if the number of SYN/ACK retransmissions for its five SYNs is lower than five. Otherwise, VPS’s SYNs did not reach the relay. This type of inference is necessary because, most of the time, China’s GFW drops SYN/ACKs from known Tor relays.

**RST scan**: Our RST scan incorporates an additional step but is based on the same principle. As illustrated in Figure 5(b), MM starts by sending 10 SYN segments whose purpose is,

⁴We transmit five SYN segments rather than just one to account for packet loss.
Fig. 4. The geographic distribution of all tested Tor relays (shown as onions) and of our global IPID clients in China (shown as red marks). Note that outside of Xinjiang the west of China has very little Internet penetration, which is why we have few data points in this region and the distribution is biased towards the eastern parts of China. (Map data © 2014 Google, INEGI)

(a) SYN scan to infer whether SYN segments from VPS reach Tor. "MM" is our measurement machine.

(b) RST scan to infer whether RST segments from VPS reach Tor. "MM" is our measurement machine.

Fig. 5. The two types of backlog scans we employ. The purpose of these scans is to verify if 1) SYN segments from China reach a Tor relay and if 2) RST segments from China reach a Tor relay.

analogous to the SYN scan, to monitor the relay’s backlog size. Afterwards, MM proceeds by sending 145 spoofed SYN segments with VPS’s source address. Note that we cannot send the SYN segments from VPS as they might be blocked. By sending spoofed SYN segments from an unfiltered network link, we can ensure that the segments reach the Tor relay. Upon receiving the SYN segment burst, the relay replies with SYN/ACK segments which we expect to be dropped by the GFW. In the final step, VPS sends a burst of RST segments to the Tor relay. The RST segments are crafted so that every RST segment corresponds to one of the relay’s SYN/ACK segments. The purpose of the RST burst is to terminate all half-open connections, thus clearing the relay’s backlog. Based on how many retransmissions we observe for the 10 “probing SYN”, we can infer whether the RST segments were dropped by the GFW or not. Receiving five retransmissions means that the backlog was not cleared and the RST segments were dropped. Receiving less than five retransmissions means that the backlog was successfully cleared and the RST segments were not dropped by the GFW. This kind of inference is necessary because machines outside China cannot measure directly what happens to RST packets sent from China, and machines inside China are very limited in their ability to infer what is happening on blocked IP address/TCP port pairs.

Implementation: We implemented our scans using a collection of bash scripts and a patched version of the tool hping3 [33]. Accurate timing was crucial for our experiments. To keep the clock of our machines synchronized, we used the tool ntp which implements the network time protocol. Recall that the SYN backlog behavior we are exploiting is limited to Linux kernels (cf. Section III-A). As a result, our scans targeted the subset of 94 out of our 144 Tor relays which are known to run Linux. Tor relays periodically publish their server descriptors—which includes their operating system—to all directory authorities so there is no need for us to guess the operating system of Tor relays.

Pruning the data: By pruning the backlog scan data, we aim to make sure that the relay runs an unmodified Linux TCP/IP stack. After scanning a relay, we send three “baseline SYN” to it in order to query its original amount of SYN/ACK
retransmissions. First, we discard scans in which the relay never sent five SYN/ACK retransmissions. Linux’s default value since version 2.2. For example, we found embedded Linux relays which always retransmit SYN/ACK segments four times, regardless of their backlog size. Second, we also discard scans whose SYN/ACK retransmissions do not exhibit Linux’s exponential backoff behavior. Third and finally, we discard scans where the relay was offline or other networking problems occurred. These three pruning steps discarded 774 out of all 2,094 scans (37%).

3) Traceroutes into China: We want to learn if there are unfiltered routes leading into China. To investigate this question, we used our Tor relay in Europe to run traceroutes to numerous destinations in China. After a country-wide scan, we obtained a list of 3,934 IP addresses in China that responded to SYN/ACKs and were distributed geographically in a diverse way, which served as our traceroute destinations. For every IP address, we ran two TCP traceroutes; one whose TCP source port was equal to the filtered Tor port 9001 and one whose TCP port was set to the unused and unfiltered port 9002. The traceroutes had both their SYN and ACK bit set. We used a slightly modified version of the tool hping3 [33] to run the traceroutes as it allowed us to send TCP segments with a source port which is short for China, CN means No-packets-dropped, C → S means Client-to-server-dropped, and Error simply means Error. In the table’s rows, CN is short for China, EU means Europe, and NA means North America. As for the server types, Tor−Dir is a Tor directory authority, Tor−Relay is a Tor relay, and Web is a web server. Our results confirm that, in general, SYN/ACKs entering China from blacklisted IP address/TCP port pairs are blocked. Some web servers were censored, and some Tor nodes were censored outside China. This is to be expected because even in countries that do not perform nation-scale Internet censorship, organizations frequently take steps to filter material such as pornography or file sharing sites. Note that highly popular websites often contain material that is subject to censorship.

The most interesting result from the hybrid idle scans is that the No-packets-dropped case was measured all over the country without any noticeable geographic pattern. The geographic distribution of observed No-packets-dropped cases is shown in Figure 6. The case distribution closely matches the geographic Internet penetration patterns of China. (Map data © 2014 Basarsoft, Google, ORION-ME, SK planet, ZENRIN)

Table 1 shows the results of our hybrid idle scans. The column $S \rightarrow C$ is short for Server-to-client-dropped, None means No-packets-dropped, $C \rightarrow S$ means Client-to-server-dropped, and Error simply means Error. In the table’s rows, CN is short for China, EU means Europe, and NA means North America. As for the server types, Tor−Dir is a Tor directory authority, Tor−Relay is a Tor relay, and Web is a web server. Our results confirm that, in general, SYN/ACKs entering China from blacklisted IP address/TCP port pairs are blocked. Some web servers were censored, and some Tor nodes were censored outside China. This is to be expected because even in countries that do not perform nation-scale Internet censorship, organizations frequently take steps to filter material such as pornography or file sharing sites. Note that highly popular websites often contain material that is subject to censorship.

V. ANALYSIS AND RESULTS

We now analyze the three data sets we gathered; the hybrid idle scans, the backlog scans, as well as the traceroutes into China.

A. Hybrid idle scans

The hybrid idle scan data was collected from 15 March 2014 to 10 April 2014. One client was removed from the data because we determined that it was in Hong Kong and as a result not subject to the GFW’s filtering.
traceroute results reveal that CERNET does not perform the type of blocking we are measuring at all so later in this section we will discuss similar failures in commercial networks. Clients 58.193.0.0 and 121.194.0.0 are part of the Chinese Educational and Research Network (CERNET). Server 198.96.155.3 is a long-established Tor exit relay at the University of Waterloo. 161.53.116.37 and 128.173.89.245 are Tor relays in Croatia and the U.S., respectively. There were also many instances where client/server pairs showed Server-to-client-dropped for most of the day but also showed No-packets-dropped once or a handful of times.

B. Temporal and spatial association

We now seek to answer the question of whether there are any temporal or spatial associations among the No-packets-dropped cases observed for Tor relays tested from within China.

Temporal association is shown in Figure 7. The probabilities are computed by a simple counting technique. We have the hourly count of the number of No-packets-dropped cases for each source. For each occurrence of No-packets-dropped, we check if there are other No-packets-dropped cases in the subsequent hours. We use 151 sources for this calculation, excluding the educational sources, which contained 353 No-packets-dropped cases in total. The final probabilities are averaged over all sources. With the increase in the lag amount in the $x$-axis, the probability decreases. This shows that No-packets-dropped cases generally happen in bursts of hours.

Spatial association is shown in Figure 8. We use the latitude and longitude of the sources as two-dimensional coordinates. The curvature of the earth is ignored while computing the distance between sources. For every source, we find the geographically K-nearest neighboring sources and average their count. We compute the Pearson’s correlation coefficient between the count of No-packets-dropped cases for a source and the average of the same for the neighboring sources. Note that Pearson’s correlation has a range of −1.0 to 1.0. Our maximum observed correlation value of 0.26 is, therefore, a very weak positive correlation and supports the fact that there is no significant geographical association between sources and their neighbors. With the increase of the neighborhood radius, the correlation decreases to below 0.1. Together with the fact that the cases of No-packets-dropped are distributed fairly evenly in all geographic regions (see Figure 6), this is strong support for Hypothesis 2.

C. SYN backlog scans

We began our backlog scans on 24 March 2014 and ran them twice a day with approximately 12 hours in between the scans until 10 April 2014. We gathered a total of 2,094 scans and after pruning, this effort yielded 1,320 scans (63%).

1) Reachable Tor relays: Out of all 1,320 backlog scans, 33 scans (2.5%) to 12 unique IP addresses contained the respective Tor relay’s SYN/ACK segments, indicating that no filtering was happening. Interestingly, 19 of these 33 scans targeted the directory authority 128.31.0.39 on port 9131. Only the RST scan and not the SYN scan yielded SYN/ACKs from the directory authority.

The results in Table II show that, in general, if a RST packet passes through the GFW then a SYN packet also will. This confirms one of the basic assumptions behind the hybrid idle scan, and confirms Hypothesis 1. Also, the fact that most SYNs were allowed to pass through the GFW confirms Hypothesis 3.

D. Traceroutes

Table III shows the results of our traceroute measurements. In the table, “EDU” indicates that the first hop in China in the traceroute is the educational and research network backbone, CERNET (210.250.0.0/16 or 101.4.112.0/24) or another scientific network called CSTNET (159.226.0.0/16). “COM” indicates that the first hop in China was a commercial backbone, one of: CNCGROUP (219.158.0.0/16), China Telecom/CHINANET (202.97.0.0/16), China Mobile Communications Corporation (211.136.1.0/24 or 221.176.23.0/24), or the China Telecom Next Carrying Network backbone (50.43.0.0/16). All other entry points were thrown out because they were actually in Hong Kong or Pasadena, and that usually indicated that the destination IP address was not in China or non-Chinese routing hops had not been properly culled. “Tor” means that the source port of the SYN/ACKs sent in the
TABLE I. RESULTS FROM THE HYBRID IDLE SCAN MEASUREMENT STUDY.

| Client   | Server | $S \rightarrow C$ (%) | None (%) | $C \rightarrow S$ (%) | Error (%) |
|----------|--------|------------------------|----------|------------------------|-----------|
| CN Tor−Relay | 116,460 (81.52) | 555 (0.39) | 786 (0.55) | 25,061 (17.54) |
| CN Tor−Dir   | 8,922 (64.91) | 31 (0.23) | 2,696 (19.61) | 2,097 (15.25) |
| CN Web       | 306 (1.23) | 15,663 (62.95) | 2,688 (10.80) | 6,226 (25.02) |
| EU Tor−Relay | 18 (0.20) | 8,589 (96.79) | 22 (0.25) | 245 (2.76) |
| EU Tor−Dir   | 2 (0.25) | 776 (96.76) | 0 (0.00) | 24 (2.99) |
| EU Web       | 19 (1.23) | 1,333 (86.28) | 95 (6.15) | 986 (6.34) |
| NA Tor−Relay | 45 (0.39) | 11,022 (94.48) | 33 (0.28) | 566 (4.85) |
| NA Tor−Dir   | 4 (0.37) | 1,025 (94.73) | 3 (0.28) | 50 (4.62) |
| NA Web       | 32 (1.52) | 1,794 (85.06) | 98 (4.65) | 185 (8.77) |

TABLE III. THE RESULTS OF OUR TRACEROUTE MEASUREMENTS.

| EDU Randport | EDU Torport | COM Randport | COM Torport |
|--------------|-------------|--------------|-------------|
| Stalled      | 1,061       | 1,045        | 111,133     | 163,095     |
| Finished     | 428         | 433          | 53,479      | 429         |

Fig. 9. The amount of hops (log scale) in China, our filtered traceroutes could traverse. For example, a hop count of five means that a traceroute could successfully reach the fifth router inside China.

traceroute was the Tor port, and “rand” means that the source port was another port that the GFW does not filter. Thus, “Tor” traceroutes should always stop before the destination host if the filtering is effective on that route, and “rand” should reach the destination unless there are other types of filtering in play, such as ICMP filtering or firewalls not related to censorship. The elements in the table are the number of times that a traceroute reached all the way to the destination.

Surprisingly, the educational and research networks, in particular CERNET, do not seem to be implementing this type of filtering at all. The “Tor” and “rand” columns are nearly identical for the “EDU” traceroutes. The “COM” traceroutes, however, show that commercial networks are clearly censoring Tor by dropping SYN/ACKs. The “rand” traceroutes reached their destination 53,479 times, while the “Tor” traceroutes aimed at the same destinations only reached the destination end host 429 times. Similar to the hybrid idle scan results, these failures were all over the country and for any destination IP address where at least one failure was observed, the number of failures ranged from 1 to 48 (i.e., all 48 hours of measurements). The number of failures in the most prominent destinations where the traceroute entered China on a commercial background included one instance where 48 failures were observed and two where 47 were observed. This means that sometimes the failures are relatively persistent, confirming Hypothesis 4.

Figure 9 shows the amount of hops into China, filtered “Tor” port traceroutes traversed before stalling. For each measurement of each hour of each day, we only add the data to Figure 9 if the “rand” traceroute reached the destination and the “Tor” traceroute did not. In most cases, the filtered packets make it two hops into China, confirming Hypothesis 6.

Figure 10 shows the number of failures for traceroutes that entered China on the commercial network backbone, per hour. The diurnal patterns apparent in the figure confirm Hypothesis 5. Note that 02:00 UTC is 10:00 (or, 10:00 am) in Beijing.

VI. DISCUSSION

We discuss three different aspects of our work in this section: what we learned about the filtering of Tor in China, what we learned about the architecture of the GFW, and ethical considerations.

A. Filtering of Tor in China

Our results suggest that the filtering of Tor in China has several interesting aspects, some of which may even be useful for circumvention efforts. We showed that the failures in the filtering occur in every part of the country, and they are sometimes intermittent and sometimes persistent. A historical example of intermittent failures is illustrated in Figure 11. The diagram shows the amount of directly connecting Tor users in China in the first seven months of 2013. A relatively stable
“valley” in between March an May is clearly visible. This valley is surrounded by significantly higher usage numbers.

We also showed that this type of filtering does not occur on CERNET, the educational and research backbone of China’s Internet. This might suggest that CERNET users can reach the Tor network, or it might suggest that CERNET employs a more sophisticated method for detecting and interfering with connections to the Tor network, perhaps something stateful and based on deep packet inspection.

Our results raise additional questions such as “is it possible to run a Tor relay in China?” In general, the Tor network represents a complete graph. As a result, every relay should be able to connect (and generally maintain connections) to all other relays in the network. Furthermore, relays must be able to connect to the directory authorities in order to upload their server descriptors. If CERNET is indeed whitelisted, a Tor relay inside CERNET might be able to successfully join the Tor network. In addition, previous research suggested that domestic Tor traffic in China is not subject to blocking [2]. If filtering indeed happens at the Internet exchange point (IXP) level, as suggested by our data, it is not surprising that the GFW is generally unable to filter domestic network traffic as it typically does not reach IXP level and is of significantly higher volume than international traffic. As a result, functioning Tor relays or bridges inside CERNET might be able to connect users in China to the rest of the Tor network.

B. The architecture of the GFW

Our results also shed light on the architecture of the GFW, at least with respect to the mechanism that blacklists IP address/TCP port pairs. As discussed in Section III, the three theories about how the GFW is architected are that 1) the filtering occurs at choke points where undersea cables enter the country, 2) the filtering occurs in the backbone in large IXPs, and 3) the filtering occurs at a regional level. While our results show some filtering occurring many hops into China and some filtering occurring before packets can even enter China, the majority of the filtering happens about two hops into China (presumably at the large IXP in Beijing). Thus, Hypothesis 6 is most consistent with the theory that the filtering occurs in the backbone. Note that this observation is in accordance with other recent research efforts which focused on the GFW’s DNS injection [19]. The small amount of routes that are filtered at the provincial level, which were also observed by Xu et al. [18], can be explained by the strategy employed by China’s formerly second-largest ISP, CNCGROUP, which was recently bought by the largest (CHINANET).

While whitelisting would appear as persistent failures in the filtering and the filtering apparatus getting overloaded with traffic would appear as intermittent failures, the mix of intermittent failures and diurnal patterns with persistent failures suggests that routing is a major reason why the filtering fails. Hypotheses 4 and 5 are most consistent with the theory that the filtering occurs in the backbone, because provincial networks in China are very hierarchical [34] and undersea cables are few in number [35]. Hypothesis 2 is also most consistent with backbone-level filtering for this reason.

C. Ethical considerations

Our work has two ethical considerations that need to be discussed. First, our SYN backlog scans briefly fill a Tor relay’s backlog in order to be able to observe packet drops. A full backlog can prevent a relay from accepting new TCP connections or cause the use of SYN cookies which can lead to reduced throughput. To prevent relays from using SYN cookies, we adapted our scan parameters to minimize the risk of completely filling a relay’s SYN backlog. SYN cookies typically do not support scaled flow control windows, which is why we made every effort to avoid them. In general, the rate at which we are sending SYN packets, without intention of completing a connection, is not enough to create a denial-of-service condition on any modern network stack. For an interesting discussion about ethical issues related to port scans in general, we refer the reader to Durumeric et al. [36].

Second, our idle scans create unsolicited traffic between a client and a server. This traffic—which can be observed by the censor—is only SYN/ACKs from the server to the client and RSTs from the client to the server. As a result, we are not causing any meaningful communication other than background noise as it is also caused by port scanning activity. While one may conceptualize the hybrid idle scan technique as providing the ability to conscript a client into performing tests for us, in reality the traffic between the server and the client is no different from if the server chose to send SYN/ACKs to the client. Thus, in terms of the traffic that the censor sees, the hybrid idle scan technique is no different from if Tor relay operators performed simple connectivity measurements by directly sending SYN/ACKs.

VII. RELATED WORK

As our work employs network inference techniques in order to measure the reachability of the Tor anonymity network, we divide related work in two subsections. The first subsection focuses on similar network inference techniques, and the second discusses the Great Firewall of China and Internet censorship measurements in general.

A. Network inference techniques

There has been a fair amount of work on utilizing side channels in TCP/IP network stacks. Antirez’s seminal IPID idle scan from 1998 [37], [38] and other work on idle scans [26] focus on network security. Qian et al. [39] show that some
firewalls exhibit behavior that can be used to infer sequence numbers and hijack connections. Chen et al. [40] use the IPID field to perform advanced inferences, such as the amount of internal traffic generated by a server, the number of servers in a load-balanced setting, and one-way delays. Morbitzer [41] explores idle scans in IPv6. Queen [42] utilizes recursive DNS queries to estimate the packet loss between a pair of arbitrary hosts by measuring the packet loss between their respective DNS servers. Reverse traceroute [43] is an interesting application of indirect methods for Internet measurement.

Passively identifying hosts that have no routable IP address and are hidden by network address translation [44], [45] is a related problem to inferring connectivity of hosts.

iPlane [46] sends packets from PlanetLab nodes to carefully chosen hosts, and then compounds loss on specific routes to estimate the packet loss between arbitrary endpoints. The view of the network is fundamentally limited to the perspective of the measurement machine, however. Queen [42] utilizes recursive DNS queries to measure the packet loss between a pair of DNS servers, and extrapolates from this to estimate the packet loss rate between arbitrary hosts.

To the best of our knowledge, our work is the first use of idle scan inference techniques for a large-scale Internet measurement study where the data collected gives a view of the network from the perspective of a very large number of clients distributed over a large country. Platforms such as DIMES [47], M-Lab [48], PlanetLab [49], and RIPE Atlas [50], [51] have traditionally been the only way to measure from the perspective of a large number of clients, but they can be very limited, especially in non-Western regions of the Internet such as China. Our work overcomes a fundamental limitation of Internet measurement: that measurements traditionally have only been possible from the perspective of the measurement machines controlled directly by researchers.

B. The Great Firewall of China

The Great Firewall of China was first described in an article in 2600 magazine [52]. In 2006, Clayton, Murdoch, and Watson investigated the firewall’s keyword filtering mechanism and demonstrated that it can by circumvented by simply ignoring the firewall’s injected RST segments [6]. Clayton et al.’s study was limited to how the filtering works. What it filters was covered by Crandall et al. in 2007 [17], along with more details about routing. Using latent semantic analysis, the authors bootstrapped a set of 122 keywords which were used to probe the firewall over time. The study also shows that filtering is probably not happening at the border of China’s Internet. Xu, Mao, and Halderman made an effort to pinpoint where exactly the filtering is happening [18]. The authors came to the conclusion that most filtering is happening in border ASes but some filtering is also happening in provincial networks. Park and Crandall revisited the GFW’s keyword filtering mechanism and discussed why the filtering of HTML responses was discontinued in late 2008 [7].

In addition to topology and HTTP filtering, another direction of research focused on how the GFW operates on the TCP/IP layer. In 2006, Clayton et al. already showed that the GFW is terminating suspicious HTTP requests using injected RST segments. Weaver, Sommer, and Paxson showed that it is possible to not only distinguish genuine from injected RST segments but also to fingerprint networking devices injecting the segments [53]. More recently in 2013, Khattak et al. probed the GFW in order to find evasion opportunities on the TCP/IP layer [54]. Resorting to techniques first discussed by Ptaszek and Newsham in 1998 [55], the authors showed that there are numerous evasion opportunities when crafting TCP and IP packets. Similarly, Winter and Lindskog showed in 2012 that packet fragmentation used to be sufficient to evade the GFW’s deep packet inspection [2].

In addition to the design and topology of the GFW, some work focused on how the GFW blocks application protocols other than HTTP. In 2007, Lowe, Winters, and Marcus showed that the GFW is also conducting DNS poisoning [3]. A more comprehensive study was conducted by anonymous authors in 2012 [4] and 2014 [19]. The authors sent DNS queries to several million IP addresses in China, thereby demonstrating that the GFW’s DNS poisoning causes collateral damage, i.e., interferes with communication outside China. A follow-up study was conducted in 2014—also by anonymous authors [19]. The authors probed a large body of domain names to determine how filtering changes over time. Furthermore, the authors approximated the location of DNS injectors. Interestingly, their results are similar to ours and they write that “In most cases, the injecting interface manifested at either 2 (18.3%) or 3 (54.6%) hops inside China” (cf. V-D).

Most work discussed so far treated the firewall as a monolithic entity. Wright showed in 2012 that there are regional variations in DNS poisoning, thus suggesting that censorship should be investigated on a more fine-grained level with attention to geographical diversity in measurements [5]. In addition to DNS and HTTP, the GFW is known to block the Tor anonymity network. Using a VPS in China, Winter and Lindskog [2] investigated how the firewall’s active probing infrastructure is used to dynamically block Tor bridges.

In terms of Internet censorship measurements not aimed at the GFW, there is a growing body of work but two works in particular are notable from an Internet measurement perspective. Dainotti et al. [56] analyze several Internet disruption events that were censorship-related using various data sources from both the control and data planes. Dalek et al. [57] present a method for identifying externally visible evidence of URL filtering.

The most notable difference to previous work is that our measurement techniques do not require control over either machine which is part of censored communication. While that enables large-scale distributed studies, it comes at the cost of reduced flexibility.

VIII. Conclusion

In this paper, we have characterized the mechanism that the Great Firewall of China uses to block the Tor network using a hybrid idle scan that can measure connectivity from the perspective of many clients all over China. We have also presented a novel SYN backlog idle scan that can infer packets received by a server without causing denial of service. These novel Internet measurement techniques open up whole new possibilities in terms of being able to measure the Internet from the perspective of arbitrary clients and servers. This
is extremely important when it comes to characterizing and documenting Internet censorship around the world, because of the difficulty in finding volunteers geographically dispersed throughout a country.

We also evaluated our techniques which led to several new insights about the inner workings of the Great Firewall. Our data shows that 1) at least seven machines inside CERNET (China Education and Research Network) are able to connect to Tor relays, 2) filtering seems to be centralized at the IXP level, and 3) filtering is quite reliable with the Tor network being either almost completely reachable or almost completely blocked in different parts of the country.

Our code is available at: http://cs.unm.edu/~royaen/gfw/.

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