Exploring the Design Space of Longitudinal Censorship Measurement Platforms

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Abstract

Despite the high perceived value and increasing severity of online information controls, a data-driven understanding of the phenomenon has remained elusive. In this paper, we consider two design points in the space of Internet censorship measurement with particular emphasis on how they address the challenges of locating vantage points, choosing content to test, and analyzing results. We discuss the trade-offs of decisions made by each platform and show how the resulting data provides complementary views of global censorship. Finally, we discuss lessons learned and open challenges discovered through our experiences.

1 Introduction

The last five years have cemented the Internet as critical infrastructure for communication. In particular, it has demonstrated high utility for citizens and political activists to obtain accurate information, organize political movements, and express dissent. This fact has not gone unnoticed, with governments clamping down on this medium via censorship and information controls. Consequently, there has been a surge of interest in measuring various aspects of online information controls. More specifically, data obtained from such measurements has been used by (1) political activists to understand the motivation for and the impact of such government policies and (2) researchers to build safer and more secure censorship circumvention tools by understanding the techniques used to implement these policies [1].

While there have been numerous efforts to characterize online information controls [2][7], the data gathered or used by these measurements have limited scope due to the specificity of locations and time-periods considered. In order to gain a nuanced understanding of the evolution of Internet censorship, in terms of policy and techniques, a measurement platform needs to be able to gather longitudinal data from a diverse set of regions while performing accurate analysis using robust and well-specified techniques. We present and compare two such platforms – ICLab and OONI – that represent different points in the censorship measurement design space.

In this paper, we first identify three primary design decisions made in the development of censorship measurement platforms. Then, we describe how ICLab and OONI address these decisions, while considering the impact of these decisions on the measurement results produced by the systems. Finally, we show how ICLab and OONI, when used together, provide a unique insight into the current state of information controls around the globe.

2 Design Decisions

We now discuss the choices of (1) where measurements are run, (2) how measurements are run, and (3) how data is interpreted. These three design decisions are central to the design of a global censorship measurement platform.

2.1 Where measurements are run

There are two options when considering vantage points: crowd-sourced and dedicated infrastructure vantage points. Platforms using a crowd-sourced approach rely on volunteers running measurement software. They have the ability to turn citizens in any location into vantage points. Dedicated infrastructure, on the other hand are distributed and operated exclusively for the platform. Both approaches have their own benefits and drawbacks.

Cost and availability. A hurdle in setting up a dedicated infrastructure is distributing infrastructure globally. However, once this infrastructure is in place, it has the capability of performing on-demand measurements; limited only by the reliability and uptime of the infrastructure. Crowd-sourced platforms, on the other hand, incur no setup cost but are dependent on the availability of...
volunteers to execute measurements. As a consequence, crowd-sourced platforms are unable to provide a reliable flow of measurements from a region.

**Representativeness and diversity of measurements.** Crowd-sourced platforms have the potential to obtain a view of the Internet from a wide variety of networks (e.g., residential, academic, and corporate). In contrast, dedicated infrastructure faces an uphill battle of distributing devices or may leverage existing infrastructure (e.g., academic networks, or dedicated hosting networks). Vantage point location can impact conclusions drawn from their measurements. As an example, measurements conducted from the UK academic network (JANET) do not observe the “Great Firewall of Cameron” [8], since they are placed outside of its purview. Crowd-sourced platforms can also leverage public interest and news coverage to introduce additional vantage points.

**Safety and risk.** Information controls measurements using humans in the field poses a significant and hard to quantify risk. In many regions (e.g., Syria) this risk has been determined to be too high for volunteers. Such risks impede crowd-sourced measurements, while infrastructure (such as VPN or hosting networks) allow for measurements while posing little to no risk to users.

### 2.2 Measurement autonomy

A censorship measurement platform can either use a central server to schedule experiments, or leave these tasks to each vantage point. This dichotomy has an impact on several capabilities of the platform.

**Time and context sensitive measurements.** The time and political context of measurements are important for understanding evolving and abrupt policy changes. As an example, during the rise of ISIS in 2014, the Indian government blocked (and subsequently unblocked) access to 32 websites including GitHub, Vimeo, and Paste-Bin for propagating “Anti India content” [9]. Centrally controlled measurement platforms have the advantage of being able to evolve existing and schedule new measurements in response to changing political and social situations. Locally controlled platforms, however, do not have this capability. Instead they are dependent on the update schedule of the local vantage point.

**Infrastructure requirements.** The ability to remotely schedule experiments and aggregate data centrally allows for the use of computationally constrained infrastructure, not needing technically savvy local maintenance efforts. This comes with the cost of bandwidth requirements associated with shipping unprocessed data to a central server. Locally controlled platforms require local management of the platform infrastructure to ensure up-to-date experiments, higher computational capabilities for processing gathered data, and lower bandwidth for communicating processed results of measurements.

### 2.3 Gathering and interpreting data

A censorship measurement platform must specify data collected and how it will identify censorship in this data.

**Type and quantity of data gathered.** A platform may record packet captures of entire tests or selectively gather data such as packet headers and responses. While complete packet captures are ideal for deep aposteriori analysis and to identify censorship not visible at the application layer. However, they require root privileges, high storage and bandwidth requirements, and may accidentally collect data of other system users.

**Identifying censorship events.** Another challenge that arises during the processing of gathered data is defining when “censorship” has occurred. This task is complicated by strange protocol implementations (e.g., load balancers that cause gaps in TCP sequence numbers), server side blocking [10], and regular network failures.

### 3 The ICLab and OONI Platforms

In this section we describe the design decisions made during the development of the ICLab and OONI platforms.

#### 3.1 Vantage points

The most fundamental difference between the ICLab and OONI platforms is the approach each system takes to recruit vantage points. ICLab relies on a dedicated infrastructure to perform measurements. This allows measurements that require permissions that may not be compatible with software to be run on end-user systems. As a consequence, the system has thus far focused on deployment on VPN vantage points and a limited deployment of Raspberry Pi’s installed with ICLab software. In contrast, OONI takes a lighter-weight software-based approach and assumes some amount of technical savvy on the part of volunteers.

This leads to differences in the availability and representativeness of measurements from each platform. In Figure 1a we see that as a result of the decision to use VPN end points, ICLab is able to provide vantage points for measurements in significantly more countries than OONI (151 for ICLab and 46 for OONI in the last 100 days[1]). However, we found that that OONI’s crowd-sourced model is able to provide more AS-level diversity — i.e., OONI provides vantage points from an average

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1. Since its release in 2012, OONI has received nearly 10M measurements from volunteers in 95 countries.
of 3.15 different networks (ASes) in each country, compared to ICLab’s average of 1.46 networks per country.

Both platforms have measurements

|       |       |       |       |
|-------|-------|-------|-------|
| ICLab | OONI  | ICLab | OONI  |
| >40   | >40   | >10   | >10   |

(a) Global availability of measurements.

(b) Country-level temporal availability. Green and red indicate the availability of measurement data from ICLab and OONI, respectively. Black indicates the availability of measurements from both platforms from the same region on the given day.

Figure 1: Availability of measurements from the ICLab and OONI platforms in the last 100 days.

3.2 System architecture

In terms of system architectures, ICLab uses a central controller to schedule experiments while OONI processes data both on the vantage point and inside of its data processing pipeline. This introduces several key differences in how each platform handles its vantage points.

**Measurement scheduling.** ICLab takes a centralized approach to scheduling experiments, leveraging a single server that is able to schedule experiments on all deployed nodes (e.g., VPNs, Raspberry Pis) or a subset thereof (e.g., a given country). This facilitates the execution of ongoing or one-off measurements. In contrast, OONI takes a decentralized approach. Recommended measurements are hard-coded into the OONI platform source-code and require vantage points (technically savvy volunteers) to regularly download updates in order to execute new measurements. Repetition of measurements is dependent on individual volunteer availability. Volunteers also have the option to add their own tests and modify inputs to existing tests (e.g., they may change the set of URLs being used by a test).

**Performing measurements.** ICLab and OONI also differ in their approach to performing measurements. ICLab takes a “simple node” approach, with nodes largely being responsible for collecting data and transmitting it back to the central server for later analysis. This lowers the computational requirement of the vantage points but increases demands on bandwidth. In contrast, OONI performs measurements and analysis on the device and ships processed data back to a central server. Importantly, OONI allows volunteers to opt-out of submitting measurement reports to the OONI publishing server, while ICLab takes an informed approach with vantage points opting into participate in the system.

Figure 1b shows the impacts of these decisions on the platforms. OONI has a core set of vantage points that continuously measure and a few opportunistic measurements. ICLab on the other hand exhibits large coordinated testing as a result of its VPN vantage points.

3.3 Tests and analysis

Both platforms perform a battery of tests to identify censors that may be blocking or manipulating content. The ICLab test infrastructure is extensible, allowing new tests to be scheduled on vantage points without the need for updating their software. In addition to custom tests, the ICLab platform periodically schedules a baseline test on each vantage point. This baseline experiment tests connectivity to a set of URLs that are composed of the Alexa Top 500 websites and a country-specific list of potentially blocked URLs (obtained from the CitizenLab). In contrast, tests on the OONI platform are not scheduled remotely and new tests need to be obtained by software updates. Existing tests, however, do not require software updates to evolve the list of domains that they test connectivity to. The default experiments included in the OONI platform test connectivity to the global and country-specific lists of potentially blocked URLs (also obtained from the CitizenLab).

In terms of analysis, the ICLab platform does not perform analysis on the vantage points, rather it leaves all post-processing to the centralized servers. This allows ICLab to perform retroactive analysis on existing results. The OONI platform, on the other hand, performs data analysis on the vantage points. This allows independent and private deployments by in-country watchdog groups.

We now briefly describe the tests conducted to identify censorship by each platform.

**DNS anomaly detection.** For each URL to be tested on a given vantage point, the ICLab and OONI vantage
points perform DNS name resolution queries for the domain name associated with that URL using both the default DNS resolver configured on the machine as well as Google’s DNS at 8.8.8.8. The ICLab platform concludes that an anomaly (e.g., DNS injection, tampering, etc.) has occurred if a second DNS response is received within 2 seconds of the first. The OONI platform on the other hand, makes several requests at once and does not wait between requests. Requests are also made to control resolver that binds to a non standard DNS port. The client is able to report failures to resolve directly, and resolutions are included in the generated report to allow further analysis by the central analysis infrastructure.

**HTTP tampering, proxy, and blockpage detection.** For each URL to be tested on a given vantage point, the ICLab and OONI vantage points issue HTTP GET requests and record received responses, with ICLab to follow redirects. The responses received from these tests are processed to identify blockpages and evidence of HTTP tampering. The ICLab platform uses regular expression pattern matching to identify known blockpages and responses obtained by the same test executed from a censor-free vantage point in the US to identify instances of content manipulation. The OONI platform uses metadata (e.g., status codes, response sizes, etc.) obtained from a Tor control channel to identify HTTP tampering. Additionally, the OONI platform is also able to detect the presence of HTTP proxies. It does this by generating malformed HTTP requests that cause proxies on the vantage point network to reveal their presence (e.g., by modifying the malformed headers). The data processing pipeline is then capable of identifying specific types of proxy software based on known fingerprints.

**TLS man-in-the-middle detection.** The ICLab platform also performs tests on HTTPS compatible URLs. For each such URL, a TLS handshake is performed and all server certificates that are received are checked for validity. If they are found to have expired or signed by an untrusted certificate authority, a TLS anomaly is reported.

**Sequence number, TTL, and RST anomaly detection.** For each of the above tests, the ICLab platform analyzes raw data (packet captures) of TCP streams to identify inconsistent sequence number and TTL values in packet headers. Additionally, the presence of pre-mature RST packets is also recorded. If any of these are identified, the ICLab platform reports anomalies that may be the result of a censor injecting packets into a TCP stream.

**TCP connectivity test.** The OONI platform attempts to establish TCP connections to a specified set of hosts to validate that the handshake can be completed and detect instances of IP level blocking. In this test, the vantage point attempts to establish a connection to the end host directly and also via a Tor control channel. If the control channel succeeds, while the direct connection fails, an anomaly is reported.

**Circumvention protocol tests.** Finally, the OONI platform also includes a set of tests designed to detect the availability of several circumvention system by (1) mimicking the protocols involved and (2) by launching bundled instances of the actual tools and checking whether they are able to successfully complete connections. Currently the test considers the connectivity of all Tor pluggable transports (scramblesuit, meek, fteproxy, obfsproxy versions 2 to 4), Psiphon, Lantern, and the OpenVPN protocol.

### 4 Comparing results of ICLab and OONI

In this section, we provide results from our analysis of measurements generated by the ICLab and OONI platforms. In particular, we use measurements from each platform to (1) understand which countries are the least free – i.e., have the highest amounts of censorship and (2) to demonstrate challenges in finding ground truth when conducting censorship measurements. We use these results to demonstrate how the ICLab and OONI platforms can provide complementary insights into censor behavior.

#### 4.1 Identifying the least free countries

Using the tests described in Section 3, we now report the countries found to be the least free based on measurements obtained from the ICLab and OONI platforms.

Figure 2 illustrates the fraction of URLs that were censored in each of the six least free countries – Iran (IR), Saudi Arabia (SA), India (IN), Cyprus (CY), China (CN), and Russia (RU) – based on tests conducted by the ICLab platform; and Iran (IR), Saudi Arabia (SA), India (IN), Greece (GR), Qatar (QA), and Turkey (TR) according to OONI’s measurements. We note that the remaining countries only displayed marginal amounts of censorship – i.e., under 5% of all tested URLs were censored. We find that both platforms find the most censorship in Iran, Saudi Arabia, and India.

In the specific case of Iran, both the ICLab and OONI platforms show comparably high levels of censorship. We see that both platforms are able to detect the large fraction of blockpages served by Iranian censors and that in addition to identifying the Iran blockpage, the TTL and RST anomaly detectors in the ICLab platform are also triggered. We attribute the extremely high levels of blocking observed to the fact that the measurements from both platforms were carried out around the same time period as the Iranian parliamentary elections. We investigate further using past data from the OONI platform.
and confirm that in October 2015, four months before the elections, a sharp rise in censorship was observed. This is illustrated in Figure 3. The URLs tested by the OONI platform during this time included content relating to political news and speech, social media, censorship circumvention tools, and pornography.

Analyzing the results for Saudi Arabia and India we find that measurements performed on the ICLab platform see significantly less information controls than on the OONI platform. In particular, while measurements from the ICLab platform detected a number of blockpages and RSTs in each of these countries, we find that it did not encounter the large number of DNS anomalies and incomplete TCP connections that are observed by the OONI platform. We attribute this to the fact that measurements from the OONI platform are usually obtained from residential networks where covert censorship is observed (i.e., censorship without explicitly serving a blockpage).

Finally, the results from both platforms also provide an insight into the censorship infrastructure in place in each country. The presence of a single dominant method of censorship in Iran and Saudi Arabia are indicative of the presence of a central censorship apparatus, while the case of India – where multiple equally dominant methods are observed – is indicative of censorship being implemented by local ISPs rather than the central government.

### 4.2 The elusive ground truth

Ground truth plays a crucial role in analyzing censorship measurement data, and there are several challenges associated with gathering ground-truth censorship data at scale. In absence of a reliable baseline, inferring censorship becomes really challenging. This issue is exacerbated by the fact that automated measurements have a higher chance of triggering blocking from the websites themselves due to them not looking like real user traffic, or the website blocking access from VPNs. Table 1 shows websites with the highest number of TCP RST packets in their streams across ICLab’s vantage points.

| URL       | # of VPs | URL       | # of VPs |
|-----------|----------|-----------|----------|
| battle.net| 1459     | uol.com.br| 842      |
| 163.com   | 1417     | alibaba.com| 748  |
| baidu.com | 1350     | yahoo.com | 700      |
| hao123.com| 1333     | directrev.com| 564 |
| youth.cn  | 918      | roblox.com| 415      |

Table 1: Websites with the highest number of TCP RST packets in ICLab.

Among the list of websites with many observed RSTs are several websites hosted in China (e.g., 163.com and baidu.com) that exhibit anomalous TCP behaviors when queried by ICLab – i.e., they have incrementing IPID values and often end their connections with RSTs. This anomaly is hard to distinguish from anomalous traits that are caused by the Great Firewall of China. Similarly, gaming websites roblox.com and battle.net aggressively block VPN users, while yahoo.com and directrev.com (an ad marketplace website) do the same to a lesser degree. Other websites can also respond unexpectedly (e.g., due to server misconfiguration) and trigger false alarms. As an example, the Iranian retail website digikala.com shows sequence number anomalies as tested by 587 of ICLab’s vantage points, but is not censored in any of them.

OONI faces a similar problem in determining ground truth. Many of the ‘control’ measurements used by the
local client to determine what sites should look like are conducted through Tor. In practice, many websites either fully deny, or display substantially different content to visitors through the Tor network, making it difficult for the probe to determine if the local result is correct or not.

An additional challenge arises due to websites that are suddenly unavailable for non-censorship reasons – e.g., a dead website with a registered domain and unavailable webserver. For these cases, the ICLab platform verifies if the webpage could be loaded from any one of its other vantage points. If the page was unable to be loaded successfully, it is discarded from the test outputs. Figure 4 illustrates the URLs that were censored in the 20 least free countries. We observe several vertical bands in this figure. These are indicative of dead websites, ones which could not be loaded from any vantage point.

Figure 4: URLs censored in the 20 least free countries according to ICLab. Colors are indicative of the type of blocking observed (see Figure 2). The black vertical lines show websites that are either no longer available or have blocked access to all of the ICLab vantage points.

5 Conclusions

In this paper we presented the fundamental design decisions faced by developers of large-scale longitudinal censorship measurement platforms – where to obtain vantage points, how to use these vantage points to collect measurements, what measurements to collect, and how to analyze them. We then described the decisions that were made in development of the ICLab and OONI platform and their influence on the measurements obtained by these platforms.

In particular, we find that the ICLab platform is able to provide a more reliable and global picture of censorship by harnessing dedicated global VPN infrastructures in addition to on-the-ground volunteers. However, we also find that this dependence on VPNs can result in measurements being carried out on vantage points further away from residential networks which impacts the conclusions drawn from the platform. For example, the ICLab platform sees significantly less censorship than the OONI platform in India and Saudi Arabia. To this extent, it is important to work with representatives in affected countries, and the responsive nature of OONI has been successful in gaining support to measure several important political events. The challenge of obtaining representative, global, reliable, and response measurements remains a goal we continue to aspire to.

In addition, we showed how the results obtained from each of these platforms can be used to provide a deeper insight into understanding regional censorship at a global scale. By analyzing the types of censorship observed in several countries we were able to identify characteristics of the implemented censorship apparatus – i.e., results obtained by both platforms suggest the presence of a decentralized censorship infrastructure in India and a mostly centralized infrastructure in Iran and Saudi Arabia.

Finally, our current investigation also uncovers open challenges that remain in being able to distinguish censorship from anomalies that arise from phenomena such as misconfigured webservers, network outages, endpoint discrimination, and unresponsive websites. Our platforms plan on addressing these limitations in future work.

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