Measuring the Accessibility of Domain Name Encryption and Its Impact on Internet Filtering

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Abstract. Most online communications rely on DNS to map domain names to their hosting IP address(es). Previous work has shown that DNS-based network interference is widespread due to the unencrypted and unauthenticated nature of the original DNS protocol. In addition to DNS, accessed domain names can also be monitored by on-path observers during the TLS handshake when the SNI extension is used. These lingering issues with exposed plaintext domain names have led to the development of a new generation of protocols that keep accessed domain names hidden. DNS-over-TLS (DoT) and DNS-over-HTTPS (DoH) hide the domain names of DNS queries, while Encrypted Server Name Indication (ESNI) encrypts the domain name in the SNI extension.
We present ***DNEye***, a measurement system built on top of a network of distributed vantage points, which we used to study the accessibility of DoT/DoH and ESNI, and to investigate whether these protocols are tampered with by network providers (e.g., for censorship). Moreover, we evaluate the efficacy of these protocols in circumventing network interference when accessing content blocked by traditional DNS manipulation. We find evidence of blocking efforts against domain name encryption technologies in several countries, including China, Russia, and Saudi Arabia. At the same time, we discover that domain name encryption can help with unblocking more than 55% and 95% of censored domains in China and other countries where DNS-based filtering is heavily employed.

Keywords: DNS · DoTH · ESNI · Domain-based Network Interference

1 Introduction

Despite its importance, the domain name system (DNS) [41] was not designed with encryption or authentication. Traditional DNS resolutions are transmitted in plaintext, allowing network-level adversaries to easily eavesdrop or tamper with the resolution process [29, 43, 48], jeopardizing user privacy and security.

Additionally, the domain name information is also visible in the Transport Layer Security (TLS) protocol [47]. During the TLS handshake, the client specifies the domain name in the Server Name Indication (SNI) in plaintext [17], signaling a server that hosts multiple domain names (name-based virtual hosting) to present the correct TLS certificate to the client. However, network observers can also use this information to surveil or interfere with a user's connection.

With the proliferation of network interference and Internet surveillance [25], users have become more aware of their online security and privacy. This has led to DNS and TLS improvements for enhancing user privacy. DNS-over-TLS (DoT) [32], DNS-over-HTTPS (DoH) [31], and Encrypted Server Name Indication (ESNI) [23] are recently proposed privacy-enhancing protocols, to which we refer collectively as domain name encryption technologies.

However, advances in domain name encryption technologies have not gone unnoticed to censors. For instance, China has been blocking ESNI since July 2020 [36]. Russia has also drafted laws to ban the adoption of domain name encryption [12]. Despite these reports, there has yet to be a comprehensive study to shed light on how common blocking of domain name encryption is; and whether domain name encryption approaches can help with evading network interference.

In this paper, we present ***DNEye***, a measurement system built on top of a network of vantage points, allowing us to study the accessibility of domain name encryption technologies and whether censors are interfering with them, and to evaluate their efficacy in bypassing network interference. Over a period of six months, ***DNEye*** conducted 315K measurements to examine the accessibility of 1.6K domains and DoT/DoH (hereafter: DoTH) resolvers around the globe.

While our data shows that DNS manipulation is widespread, we found no major DNS-based filtering of DoTH resolvers' domain names at the autonomous system (AS) level, except for *ordns.he.net*, which is blocked by the Great Firewall via DNS poisoning, and two Cloudflare servers (*cloudflare-dns.com* and *mozilla.cloudflare-dns.com*) blocked in Thailand's AS23969. We then examine whether connections destined for DoTH resolvers suffer from any interference (§4.2). We detect several ASes in China interfere with connections destined for different DoTH resolvers. We also found only 1.5–2.25% of the domains in the top-level domain (TLD) zone files with ESNI supported. Despite this small number of ESNI-supported domains, we find evidence that China and numerous network operators in Russia have started blocking connections to ESNI-enabled websites (§4.2).

Finally, we investigated whether domain name encryption can help with bypassing Internet filtering (§4.3), and found that it can help with unblocking many censored domains. Specifically, except from Iran, we could successfully fetch more than 55% and 95% of the blocked domains in China and other countries where DNS-based network filtering is widely employed.

2 Background

2.1 Common Internet Filtering Techniques

There are several Internet filtering techniques often employed by authoritarian governments to control the free flow of information.

DNS manipulation. Due to the unencrypted design of the original DNS protocol [41], any on-path network observer can monitor the domain name being queried by a user. The visibility into the plaintext domain name allows any on-path filtering system to trivially conduct DNS-based filtering. Specifically, an on-path observer can forge DNS responses containing non-routable IPs, an IP under its control, or a DNS error code. China's Great Firewall (GFW) is one of the most prominent filtering systems that injects such forged DNS packets in response to "sensitive" DNS queries [8, 29, 43].

IP blocking. Once a user obtains the correct IP(s) of the intended website, a TCP connection is established with the web server for data transmission. Upon observing a connection attempt to a forbidden IP, filtering systems often inject RST (reset) packets to interfere with the TCP stream [11, 46, 54]. In other cases, null routing [53] can also be used to discard traffic destined for certain IPs.

Application-level interference. After establishing the TCP connection, the user proceeds with sending an HTTP request with the HTTP Host field specifying the intended domain name. Similarly, for HTTPS-supported websites, clients specify the intended domain name in the SNI field of the TLS handshake [17]. Filtering systems can also monitor these fields to determine the domain name being visited to interfere with the connection, either by injecting RST packets or modifying the HTTP traffic to redirect the user to a blockpage [35, 42, 46, 52].

2.2 Domain Name Encryption Protocols

As discussed in §2.1, the exposure of the domain information in both DNS and TLS protocols has been widely exploited for network interference [13, 29, 46, 48].

Encrypted DNS. DoT [32] and DoH [31] were proposed to provide integrity and confidentiality for DNS resolutions by encrypting DNS packets between clients and DoTH resolvers. These protocols have been standardized and supported by many major Internet companies. Google [26] and Cloudflare [5] have provided public DoTH resolvers, while popular web browsers (e.g, Firefox [39], Chrome [9], Safari [14], and Edge [15]) have also supported DoH.

Encrypted SNI. The SNI extension [47] was introduced to enable name-based virtual hosting. Up until TLS 1.2 [17], clients indicate their intended domain name in the SNI field during the TLS handshake in plaintext so that the server can present the appropriate certificate. Encrypted SNI is one of the optional extensions of TLS 1.3 designed to conceal the domain name information [21]. ESNI has been reworked to Encrypted Client Hello (ECH) [22] since June 2020.

3 *DNEye* Design

Given that the visibility into plaintext domain information is lost due to the introduction of domain name encryption, we are interested in investigating how these new protocols impact Internet filtering systems. We developed *DNEye* to (1) assess the current situation of DNS-based network filtering, (2) examine the accessibility of domain name encryption protocols and whether they are interfered with across different network locations, and (3) evaluate whether these

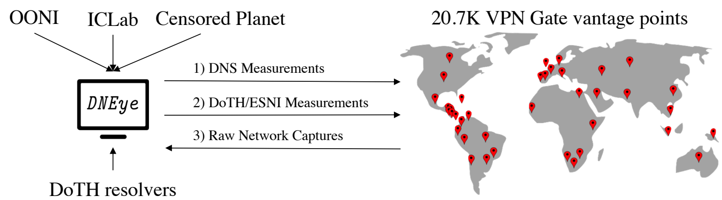


Fig. 1: *DNEye* architecture.

protocols can help with evading network interference. In this section, we first describe how we obtain testing vantage points, their limitations, and ethical considerations. We then explain the process by which we curate our test list of domains and how we use *DNEye* to perform various connectivity measurements. Figure 1 provides an overall view of *DNEye*'s architecture.

3.1 Vantage Points

Vantage points. The core component of *DNEye* is a network of vantage points (VPs) provided by VPN Gate [45]. VPN Gate is a public VPN relay service where any volunteer can register to be a VPN endpoint by running the SoftEther package [44]. Since these VPs are operated by volunteers around the globe, they often reside in residential networks, allowing us to observe filtering policies which would be usually unobservable via commercial VPNs in data centers [46]. However, since the infrastructure is volunteer-based, these VPs are often short-lived and unsuitable for testing a long list of websites. We describe how we account for this shortcoming by conducting a sliding-window analysis in §4.1.

Table 1 summarizes the geographical distribution of our VPs by continent and Internet freedom scores assessed by the Freedom House [1]. During six months of our study, VPN Gate VPs provide us with access to 34K unique IPs. We however exclude 13.3K short-lived VPs that were online for less than one day to eliminate unstable data points. In total, *DNEye* has access to about 20.7K VPs in 85 countries, with an average of 10 ASes per country. More importantly, we have access to more than twice the number of countries classified as "not free" than ICLab [42], which is a platform that also relies on VPN services for measuring network interference. Of these "not free" countries, there are 11 countries where we have access to VPs located in at least two different ASes, allowing us to observe centralized country-level filtering policies (if any).

Ethical considerations. Measuring Internet interference using volunteer-based VPs must be carried out in a thoughtful way that takes into consideration various ethical aspects [34]. There are commercial VPN services (e.g., Luminati [3]) that also provide residential VPs, meeting the measurement needs of our study. Nonetheless, studies have reported illicit activities of these services, e.g., malware hosting [40]. We, thus, opt to use VPN Gate for two primary reasons. First, to become a VPN server, the SoftEther VPN package [44] requires all volunteers to manually go through a process that reminds them about the associated risks

Table 1: Geographical distribution of ***DNEye***'s VPN vantage points indicated by the number of countries and ASes across continents. `NF`, `PF`, and `F` columns denote the number of *politically not free*, *partially free*, and *free* countries.

Continent	Vantages	Countries	ASes	NF	PF	F
Asia	14K	32/48	367	17	8	6
Africa	13	4/54	9	2	0	2
N. America	2.7K	6/23	157	0	1	3
S. America	811	9/14	58	1	4	4
Europe	2.8K	32/50	271	2	3	27
Oceania	282	2/ 6	16	0	0	2
Total	20.7K	85/195	878	22	16	44

of joining the VPN Gate research network [6]. Therefore, it is reasonable to expect volunteers, who are willing to be VPN endpoints, to fully understand the potential risks before agreeing to share their network connection. Moreover, the University of Tsukuba and the VPN Gate software also record access logs which serve as an anti-abuse policy used by the project and to assist its volunteers in case of disputes [49]. Since the launch of ***DNEye*** we have not received any complaints.

3.2 Test List

While it is desirable to test many domains, due to the short-lived nature of VPs, we cannot test a large number of domains. OONI [24], ICLab [42], and Censored Planet [52] are measurement platforms actively monitoring Internet interference around the globe. Since these platforms have implemented testing modules to monitor DNS filtering, we opt to use their collected data as an input for ***DNEye***.

We first look for domains reported as censored by these platforms within the past 30 days and visit them to confirm their online status. We consider domains that are censored in at least two ASes per country and reported by at least two platforms. This helps eliminate unreliable data points that could have been caused by generic network errors. To that end, we obtain 1.5K domains that are commonly reported as censored by these prior platforms in 77 countries where we have VPs. Since one of our main goals is to examine the accessibility of domain name encryption protocols, we also add domains for 71 DoTH resolvers publicly available at the time of our study [19]. These resolvers are indexed in Table 4.

3.3 Measurements

Once connected to a VP, we instruct ***DNEye*** to capture all network traffic during each measurement. Monitoring traffic transmitted over the VPN tunnel enables us to observe network interference (if any) across all layers of the network stack.

Measuring DNS manipulation. After each VPN tunnel is established, ***DNEye*** first issues DNS queries for the domains in our test list. This allows us to not only obtain an updated view of DNS filtering across network locations, but also determine whether there are any filtering systems that block these DoTH resolvers via DNS tampering. ***DNEye*** sends DNS queries to both public DNS resolvers (e.g., Google and Cloudflare) and the local DNS resolver configured by each VP's network provider. Querying both types of resolvers helps us discern whether DNS tampering (if any) is conducted solely by the local resolver or by an on-path system between our clients and the selected public resolvers.

Measuring DoTH and ESNI connectivity. ***DNEye*** then uses `kdig` [18] to send encrypted DNS queries to 71 DoTH resolvers to resolve a control domain for which we know the correct answer. This test checks whether each DoTH server returns the control domain's correct IP. The ability to capture network packets allows us to detect at which stage of a connection (i.e., TCP or TLS handshakes) a filtering system tampered with the connection destined for the selected DoTH servers. In addition, to determine whether ESNI is blocked, ***DNEye*** also attempts to connect to an ESNI-supported website under our control.

Measuring filtering circumvention. Finally, to evaluate whether domain name encryption can help evade Internet filtering, ***DNEye*** instruments a customized web browser with DoH and ESNI enabled to crawl filtered domains from VPs where DNS filtering of these domains was observed in the first step.

However, as later shown in §4.2, many DoTH resolvers are being blocked in several countries. To prevent any filtering system from interfering with our DoH resolutions, we configure the crawler to use our private DoH resolver, which runs on a non-standard port (i.e., different from 443) and is hosted in an uncensored network. For an ESNI-supported website, the crawler will also obtain its ESNI key and establish an ESNI-enabled TLS connection. Simultaneously, we crawl the same website from an uncensored control environment for later comparison.

Between November 12, 2020, and May 12, 2021, ***DNEye*** has conducted 315K connectivity measurements for 1.6K domains and DoTH resolvers in 878 ASes across 85 countries. The aggregated dataset will be made available to the public to stimulate future studies in this domain at https://homepage.np-tokumei.net/publication/publication_2022_pam/.

4 Results

4.1 DNS-based Network Interference

To identify DNS tampering, we apply well-established heuristics in the literature on the data collected by ***DNEye*** (Appendix B). For each DNS query sent via a VP, we extract all DNS responses captured from that VP's network traffic. In case of a poisoned DNS response, the ability to analyze raw network packets allows us to discern whether it was injected by an on-path filtering system or directly served from the local DNS resolver. Specifically, if the tampering is conducted by an on-path filtering system when querying a public DNS resolver, we will be able to observe more than one DNS response, of which the one arrives the VP first is usually forged by the filtering system [20, 29]. In case of a forged response served directly from a local resolver, we will only observe that one response.

Sliding-window analysis. Due to the short-lived nature of our VPs, we do not have access to all VPs on the same day. To reduce the impact of unreliable data points, we analyze the data by considering a sliding window of seven days for each measurement. In other words, for each domain tested in a measurement, we aggregate the data we have from the same VP within a window of ±3 days. Meanwhile, we also compute the average filtering rate (i.e., the number of measurements we mark as "tampering" divided by the total measurements for each VP and domain pair). If the filtering rate of a domain at a VP is higher than 80%, we consider that domain as "blocked" at that VP in that particular measurement. We conservatively choose the 80% threshold to avoid false positives caused by generic network errors instead of network interference.

Table 2: Top five countries where most DNS resolutions are tampered with.

(a) When querying local resolvers

Country	**Domains**
China	305
Russia	251
Japan	181
Iran	159
Indonesia	135

(b) When querying public resolvers

Country	**Domains**
China	300
Russia	205
Iran	147
Indonesia	134
India	98

Regardless of the introduction of DNS encryption protocols, our results confirm that DNS manipulation is still widely employed, aligning with prior reports [29, 33, 42, 48, 52]. Table 2 presents the top five countries where most DNS resolutions are tampered with. Japan is not a censorship country, as is evident by its "*free*" classification by the Freedom House [1]. The reason for the high number of DNS resolutions interfered by local DNS resolvers is that VPN Gate is a Japan-based project, thus providing us with a large number of VPs from many residential networks across Japan. Our collected data indicates that many of these VPs are configured with filtering services provided by local DNS resolvers. Hence, queries sent to these resolvers are often interfered with. More specifically, many DNS responses returned by these local DNS resolvers contain IPs redirecting to destinations within the same AS of the VPs where DNS queries were issued. On the other hand, we could still obtain the correct DNS records for our DNS resolutions when querying public resolvers from these same VPs. As a result, this is not a case of country-level DNS censorship.

DNS manipulation of DoTH domains. As laid out in §3.3, ***DNEye*** also performs DNS resolutions for domain names of 71 DoTH resolvers to determine whether there is any DNS tampering against these resolvers. Except for China, we did not observe any DNS-based filtering of DoTH domain names at country level. Specifically, `ordns.he.net` is blocked in China by the GFW via DNS tampering. In addition, ***DNEye*** detected DNS tampering against two

Cloudflare servers (*cloudflare-dns.com*, *mozilla.cloudflare-dns.com*) by AS23969 TOT Public Company Limited, Thailand. DNS resolutions for these two domains are poisoned with a forged IP address (i.e., 180.180.255.130), pointing to a blockpage.

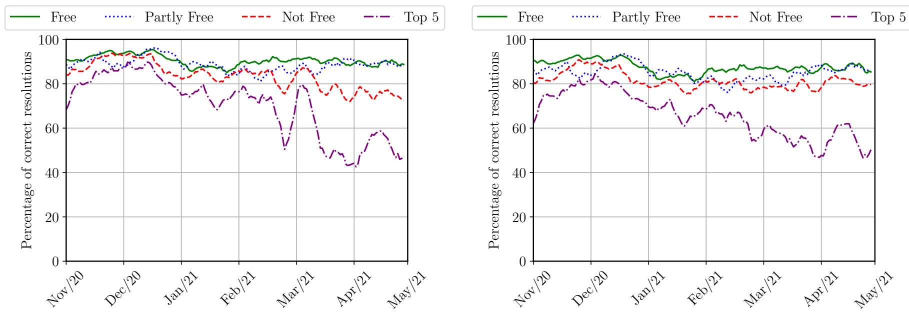
4.2 DoTH and ESNI Accessibility

DoTH accessibility. Since DoTH is still in its early stage of adoption while not all DoTH servers are well-provisioned, any of them may become unavailable during our measurement, e.g., due to maintenance. To determine if a resolver is unavailable due to a generic reason rather than network interference, we aggregate all daily resolutions from all VPs for that particular resolver. If more than 70% of the queries were successfully resolved, we consider that resolver as available on that day. We choose 70% as a conservative threshold to prevent intermittently available resolvers from causing false positives in our analysis.

Figures 2a and 2b show the percentages of correct resolutions performed daily using DoT and DoH resolvers, respectively. We consider a resolution as correct when the correct IP of our control domain is successfully returned. The result is clustered by country type defined by the Freedom House [1]. The percentages of correct resolutions obtained via VPs in *"not free"* countries are lower than those in *"partially free"* and *"free"* countries. To better highlight this finding, we add to both plots another dash-dot (purple) line, computed from data of the top five *"not free"* countries that have the most number of failed resolutions, namely China, Russia, Iran, Saudi Arabia, and Venezuela. It is visible on the plots that the number of successful resolutions for these five countries has decreased significantly since March. This decrease is driven by the blocking effort of China, where our system detected an increase in network interference with our DoTH resolutions issued from China VPs. In an earlier study, Lu et al. [38] reported successful rates of more than 84% and 99% for resolutions using Cloudflare and Quad9 DoT resolvers, respectively. However, since early March, ***DNEye*** has detected increasing network interference efforts by the GFW against DoT resolutions destined for several major resolvers, including Cloudflare, Quad9, AdGuard, and CleanBrowsing. Our findings corroborate several anecdotal reports from users in China about DoTH blocking around that same time [4].

DoTH filtering. To examine how filtering systems interfere with connections destined for DoTH resolvers, we analyze packets captured by ***DNEye*** for measurements in which failed resolutions were observed. The ability to process raw network packets allows us to pinpoint the stage at which a connection was interfered with, thus being able to identify the employed filtering technique (i.e., TCP packet injection, SNI-based filtering, or packet dropping).

We employ the same sliding-window technique defined in §4.1 to determine blocking cases of DoTH resolvers. Given a VP, an average failure rate of a DoTH resolver is calculated by dividing the number of failed resolutions by the total number of resolutions performed at that VP within a seven-day window. If the failure rate exceeds 80%, we label the DoTH resolver as "probably blocked" at



(a) Resolutions using DoT

(b) Resolutions using DoH

Fig. 2: Percentage of correct DoTH resolutions over time.

that VP. To determine whether a DoTH resolver is actually blocked at a VP, we then compute the 90th percentile value of all failure rates for that DoTH resolver at that particular VP. If the value is greater than 80%, we can be confident that there is network interference with connections destined for that resolver at that VP. We employ this 90th percentile threshold in combination with the sliding-window analysis to account for failed resolutions caused by sporadically available VPs and unstable DoTH resolvers rather than actual network interference.

Next, we consider a DoTH resolver to be blocked by an AS if ***DNEye*** detects network interference from at least two VPs from different subnets of that AS on two separate days. Table 5 in Appendix C depicts the top countries where most AS-level DoTH filtering was detected. China has the most number of ASes that interfere with DoTH connections. The filtering of different DoTH resolvers detected at different ASes indicates that DoTH filtering is implemented by individual Internet service providers rather than a centralized policy (e.g., centralized DNS-based filtering by the GFW [29]).

Another advantage provided by the VPN Gate VPs is that having access to multiple ASes per country allows ***DNEye*** to identify cases of country-level filtering where multiple ASes interfere with the same domains. For instance, ***DNEye*** detects SNI-based network interference against the same set of DoH resolvers across different ASes in Saudi Arabia, indicating a centralized filtering policy.

In Iran, we also observe filtering of multiple DoTH resolvers. Notably, SNI-based filtering of TLS connections, destined for both DoT and DoH servers of `dns.google`, were detected from several subnets of AS58224. This same filtering was also detected at AS39501 and AS56402, which are not considered in Table 5 since we did not have VPs from more than one subnet in these two ASes.

Filtering of some DoTH resolvers was also detected in the US, South Korea, and Singapore (Table 5). However, upon verifying the organization information of the filtering ASes, we find that these are filtering cases implemented by corporate and institutional firewalls instead of a country-wide filtering policy.

ESNI adoption. For ESNI to provide any meaningful privacy and filtering resistance benefits, it needs to be supported by many websites, since if there are only a few ESNI-supported websites, connections to their servers are trivially distinguishable [27, 28]. Therefore, we first measure the adoption of ESNI on the web by looking up the ESNI TXT record for more than 350M domains from TLD zone files [2].

Over the course of our measurement period, we find that only about 1.5–2.25% of domains from TLD zone files have a valid ESNI key format (see Appendix D). Of these ESNI-supported domains, 15.4K and 143.3K domains are within the top 100K and 1M popular domains ranked by the Tranco list [37], respectively. We have also measured the deployment of Encrypted Client Hello (ECH) by probing for HTTPS resource records [22] but did not find any evidence of ECH deployment in the wild.

ESNI filtering. As described in §3.3, *DNEye* also measures the filtering of ESNI by visiting our control website that has ESNI enabled. This website will reflect the visiting client's IP if the client can successfully connect to our server. Employing the same sliding-window technique defined in §4.1 in combination with the 90th percentile threshold described above, we detect ESNI filtering in China, Russia, and Iran.

Following a TLS client hello whose SNI field is encrypted, we observe RST packets being injected by China's GFW to tear down connections destined for our ESNI-supported web server. This observation aligns with previous anecdotal reports that China has started filtering all ESNI traffic since July 2020 [36].

Unlike the centralized ESNI filtering policy of China, Internet service providers in Russia are known to implement blocking mechanisms independently in a decentralized manner [50]. Among the networks where we have VPs in Russia, we detect ESNI filtering in AS28890, AS52207, and AS41754, where RST packets are injected to disrupt ESNI connections to our website.

DNEye has also detected ESNI filtering from VPs in Iran's AS56402, AS31549, and AS16322. However, since we did not have measurements from more than one subnet in each of these ASes, we cannot conclude these cases as AS-level filtering with high confidence.

4.3 Network Filtering Circumvention

For the top five countries where most on-path DNS tampering was detected, Table 3 summarizes the number of domains that we (1) could fetch by employing domain name encryption, thus evading network filtering, and (2) could not fetch due to other filtering mechanisms at multiple layers of the network stack.

Note that we focus our analysis on those domains tampered with by on-path filtering systems (i.e., Table 2b), rather than those blocked by local resolvers. This is because, instead of using domain name encryption, simply changing to a public resolver is already sufficient to evade filtering employed by a local resolver for some domains. This is the reason why *DNEye* observes fewer filtered domains when querying public resolvers (Table 2b) compared to local resolvers (Table 2a).

Except for Iran, we could successfully unblock more than 50% and 95% of filtered domains in China and other countries, respectively, where on-path DNS filtering is heavily employed.

Table 3: Number of domains that could evade filtering as a result of domain name encryption employment. The filtering technique column indicates the number of domains that fail to evade filtering due to other filtering techniques (i.e., TCP packet injection), HTTP-only site, SNI-based filtering of domains without ESNI support, and server-side blocking.

Country	Circumvented/Total crawled	Filtering technique			
		TCP	HTTP	TLS	SS
China	130/230	11	2	84	3
Russia	53/56	1	1	1	0
Iran	0/49	1	1	47	0
Indonesia	93/98	2	2	0	1
India	20/20	0	0	0	0

There are three reasons why some domains fail to evade filtering. First, filtering systems can have several mechanisms deployed at different network layers, as discussed in §2.1. Thus, domain name encryption alone is not enough to cope with other filtering mechanisms. Second, a few domains are still serving HTTP sites only, allowing straightforward network interference. The third reason, which is also the main one, is because many domains do not support ESNI (see Appendix D). Domain name information of websites without ESNI support is still visible via the TLS handshake and thus susceptible to SNI-based filtering.

Note that DNS-based and SNI-based filtering modules of China's GFW have been shown to maintain different blocklists. Some domains, therefore, are filtered via DNS tampering but not SNI-based interference [46]. There are three domains that we could evade filtering in China but experience server-side blocking.

5 Related Work

The adoption trend of domain name encryption technologies by major Internet companies in the last couple of years has prompted several measurement studies to examine how these new technologies are treated by Internet filtering systems.

Basso [10] created a testing module to detect the blocking of DoTH services for the OONI probe [24]. The author analyzed one-month data of measurements for 123 DoTH resolvers conducted by OONI volunteers at three separate ASes in Kazakhstan, Iran, and China, finding that the most frequently blocked DoTH resolvers belong to Cloudflare and Google. While this study presents some preliminary insight into DoTH filtering, ***DNEye*** conducts comprehensive measurements from more VPs at many network locations over an extended period of time, providing a more complete view of how filtering systems are treating domain name encryption technologies around the globe. Specifically, the extensive and continuous measurements conducted by ***DNEye*** have enabled us to discover exactly when a major filtering system like the Great Firewall started blocking a domain name encryption protocol (§4.2).

Jin et al. [33] conducted a one-off measurement to examine whether DoTH resolvers perform any DNS tampering themselves. Our system, ***DNEye***, is designed to also detect on-path filtering systems that interfere with connections destined to DoTH servers. The authors also examined whether encrypted DNS can help with bypassing Internet filtering by using commercial VPNs running in data centers for testing. However, this has several drawbacks, including VPN locations being falsified [55] and limited visibility into residential networks that often have different filtering policies [46]. The paper concludes that the effectiveness of encrypted DNS in evading network interference varies by country.

Chai et al. [13] study the adoption of ESNI and whether it can help bypass Internet filtering in China. They found that 10.9% of the Alexa top 1M domains supported ESNI in 2018. By enabling ESNI in their web crawler, the authors could unblock 66 websites filtered by the GFW based on SNI [13]. Unfortunately, that has not gone unnoticed to China's filtering systems. From July 2020, the GFW has been reported to block all ESNI traffic [36]. Our work complements this earlier work by verifying the support of ESNI for all domains from TLD zone files, finding an increase to almost 15% of top 1M popular domains supporting ESNI (§4.2).

6 Discussion

From a technical perspective, it is obvious that domain name encryption technologies can help to improve security and privacy for Internet users. Our measurements, however, show mixed results when it comes to the resilience of these technologies to Internet filtering. Specifically, while we found that encrypting DNS resolutions could help evade DNS-based filtering for many domains, almost half of the domains filtered in China and all domains filtered in Iran could not evade filtering despite the use of DoH (§4.3). This is primarily because the vast majority of domains on the Internet do not have ESNI supported.

As a result, unless ESNI is universally deployed, DNS encryption alone is not enough to resist Internet filtering. Moreover, filtering systems in China and Russia have been blocking ESNI traffic because the collateral damage of this blocking is not substantial enough, since only a small fraction of domains on the Internet have ESNI supported. Even when more websites support ESNI, they should be co-hosted instead of being hosted on separate IPs to increase the potential collateral damage (if being blocked) [30] and to avoid IP-based blocking [27, 28].

Another issue with DoTH is the chicken-and-egg problem of resolving the domains of DoTH resolvers. Specifically, the domain of a DoTH resolver would still need to be first resolved via an unencrypted DNS resolution. Although we did not observe any major DNS-based filtering against the domains of DoTH resolvers, the blocking cases of `ordns.he.net` and two Cloudflare DoH resolvers in §4.1 show that this is a critical problem in the current implementation of most DoTH resolvers. Although a client can instead use a fixed IP of a DoTH resolver (e.g., `8.8.8.8` or `1.1.1.1`), this setting is then susceptible to IP-based blocking unless the DoTH resolver's identity is obfuscated similarly to our own DoH resolver in §3.3. There have been studies demonstrating the possibility of using machine learning models to detect and filter encrypted DNS resolutions based on network traffic signatures [7, 16], we however did not experience such blocking efforts. This is evident by the fact that we could still use our private DoH resolver in all countries where we have measurement vantage points.

7 Limitations

Prior work has shown that an advanced Internet filtering system such as the GFW could block hundreds of thousands of domains [29]. Although it is desirable to test as many domains as possible to obtain a more general view about the filtering mechanisms used against various types of domains, we could not test a large number of domains due to the short-lived nature of VPN Gate vantage points (§3.2). Another limitation of using VPN Gate is that VPN endpoints often rewrite the packet header, taking away the capability of using incremental IP time-to-live values to pinpoint the location of filtering devices.

8 Conclusion

We present *DNEye*, a measurement system built on top of a distributed network of vantage points, to examine the accessibility of domain name encryption technologies and whether they are interfered with by filtering systems across different network locations. Over a six-month period, *DNEye* conducted 315K measurements from more than 20K vantage points in 85 countries, detecting blocking efforts against domain name encryption technologies in several countries, including China, Russia, and Saudi Arabia.

Measuring the prevalence of ESNI adoption, we find that only 1.5–2.25% of the domains from TLD zone files have a valid ESNI key, indicating that ESNI has not been widely adopted yet. Finally, to evaluate the efficacy of domain name encryption in evading Internet filtering, we instrument a customized browser with DoH and ESNI enabled to crawl a list of filtered domains detected by *DNEye*. Except for network locations where SNI-based filtering is also employed, we could unblock more than 55% and 95% of the blocked domains in China and other countries where DNS-based filtering is employed.

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A DoTH Resolvers

Table 4 indexes 71 DoTH resolvers publicly available at the time of our study.

B DNS Tampering Detection

To identify cases of DNS-based network interference, we employ the following well-established consistency heuristics in the literature [24, 42, 48, 51].

Multiple responses with different ASes. We receive multiple responses for a DNS query that belong to different ASes. Previous studies have identified cases where on-path filtering systems inject packets carrying false IP addresses that often are publicly routable [8, 29, 43].

NXDomain or non-routable address. We receive an NXDomain or non-routable IP in response to a DNS query from a vantage point while receiving a routable address from the majority of vantage points and our control node.

Different responses from control and aggregate. When a vantage point receives a globally routable IP but different from the IP observed at the control node. We first check whether they belong to the same AS. If both IPs are under the same AS, this is due to the use of CDN and/or DNS-based load balancing but not censorship. If the IP observed by the vantage point belongs to an AS

Table 4: The list of DoTH resolvers that is used in our measurement.

Index	DoTH Servers	Index	DoTH Servers	Index	DoTH Servers
1	1dot1dot1dot1.cloudflare-dns.com	25	dns.switch.ch	49	doh.xfinity.com
2	cloudflare-dns.com	26	dns.twnic.tw	50	family.cloudflare-dns.com
3	dns10.quad9.net	27	dns-unfiltered.adguard.com	51	fi.doh.dns.snopyta.org
4	dns11.quad9.net	28	doh-2.seby.io	52	free.bravedns.com
5	dns9.quad9.net	29	doh.applied-privacy.net	53	jp.tiarap.org
6	dns.aa.net.uk	30	doh.centraleu.pi-dns.com	54	jp.tiar.app
7	dns.adguard.com	31	doh.cleanbrowsing.org	55	mozilla.cloudflare-dns.com
8	dns.alidns.com	32	doh-de.blahdns.com	56	odvr.nic.cz
9	dns.containerpi.com	33	doh.dnslify.com	57	ordns.he.net
10	dns.digitale-gesellschaft.ch	34	doh.dns.sb	58	resolver-eu.lelux.fi
11	dns.dnshome.de	35	doh.eastas.pi-dns.com	59	security.cloudflare-dns.com
12	dns.dns-over-https.com	36	doh.eastau.pi-dns.com	60	1dot1dot1dot1.cloudflare-dns.com (DoT)
13	dns.dnsoverhttps.net	37	doh.eastus.pi-dns.com	61	adult-filter-dns.cleanbrowsing.org (DoT)
14	dnses.alekberg.net	38	doh.familyshield.opendns.com	62	dns.adguard.com (DoT)
15	dns-family.adguard.com	39	doh.ffmuc.net	63	dns-family.adguard.com (DoT)
16	dns.flatuslifir.is	40	doh-fi.blahdns.com	64	dns.google (DoT)
17	dnsforge.de	41	doh-jp.blahdns.com	65	dns-nosec.quad9.net (DoT)
18	dns.google	42	doh.libredns.gr	66	dns.quad9.net (DoT)
19	dns.hostux.net	43	doh.northeu.pi-dns.com	67	dns-unfiltered.adguard.com (DoT)
20	dnsnl.alekberg.net	44	doh.opendns.com	68	dot.xfinity.com (DoT)
21	dns-nosec.quad9.net	45	doh.pi-dns.com	69	family-filter-dns.cleanbrowsing.org (DoT)
22	dns-nyc.aaflalo.me	46	doh.tiarap.org	70	one.one.one.one (DoT)
23	dns.quad9.net	47	doh.tiar.app	71	security-filter-dns.cleanbrowsing.org (DoT)
24	dns.rubyfish.cn	48	doh.westus.pi-dns.com		

which is different from the response AS we observe at the control node and the majority of other vantage points, this behavior indicates DNS interference by a filtering system that aims to redirect the client to a different server (e.g., for displaying blockpages). However, there are also cases in which different ASes are managed by large CDN providers (e.g., Akamai). We look up organization information of those ASes to exclude cases where different response ASes belong to the same organization to avoid false positives.

C AS-level DoTH Filtering

Table 5 shows the top five countries where most connections to DoTH resolvers were interfered with. The DoTH server names are indexed in Table 4.

D ESNI Prevalence

Over the course of our measurement period, we frequently query for ESNI TXT records of more than 350M domains from TLD zone files [2]. Only 3%–4.5% of domains respond to our ESNI TXT queries. And, only 48–51% of these TXT records have a valid ESNI key format defined in the Internet drafts [21, 23]. Analyzing the key lengths of all ESNI TXT records obtained, we find that the majority of them have 92 characters. These ESNI-supported domains are hosted by Cloudflare, which is the only Internet company supporting ESNI to the best of our knowledge. For domains whose ESNI TXT records that do not have a correct ESNI key format, we find that their authoritative nameservers are configured with a wildcard setup (i.e., `*.example.com`), thus responding to our ESNI TXT query for `_esni.example.com` despite not having an actual ESNI key. To that end, only around 1.5%–2.25% of domains on the Internet have ESNI supported.

Table 5: Top five countries where most AS-level DoTH filtering was detected. * indicate cases where both TCP and TLS handshakes were completed but we could not obtain the correct IP of our control domain being resolved.

Country		China						United States				S. Korea			Singapore			Saudi Arabia			Iran
ASN		4134	4837	9808	37963	45090	140314	7155	20473	31898	36352	17870	20473	38121	14061	20473	55430	25019	35819	35753	58224
Index of blocked DoH resolvers	1			X										X				X	X	X	X
	2			X			X											X	X	X	
	4																				X
	5						X														
	6			X			X														
	9			X			X														
	10			X			X														
	11						X														
	13			X																	
	14			X			X														
	16			X			X														
	18	X	X	X	X	X	X														X
	19			X			X														
	20			X			X														
	22			X																	
	23			X																	X
	25			X																	
	26				X		X														
	27						X														
	28			X			X														
	32			X																	
	33			X	X	X															
	34			X			X														
	37			X			X														
	38			X	X	X	X	X			X	X			X	X	X				X
	39			X			X														
	40			X	X	X	X														
	41			X	X	X															
	42			X			X														
	44			X	X	X	X	X		X	X	X	X		X	X	X				
	45	X	X		X	X															
	47			X			X		X							X					
	48			X			X														
	50													X				X	X	X	X
	51			X			X														
	54						X		X							X					
	55			X	X	X	X											X	X	X	
	59													X				X	X	X	X
Index of blocked DoT resolvers	60			X			X							X							
	61			X			X														
	62			X			X														
	63			X			X														
	64																				X
	65			X			X														
	66			X			X														
	67			X			X														
	68			X			X														
	69			X			X														
	70			X			X							X							
	71			X			X														
Block	TCP	98.3	97.8	44.8	4.8	95.3	96.2	0*	100	0*	0*	100	0*	100	0*	50	0*	0	0	0	10
(%)	TLS	1.7	2.2	55.2	95.2	4.7	3.8	0*	0	0*	0*	0	0*	0	0*	50	0*	100	100	100	90