

# Mind the IP Gap

## On the IPv6 Transition and the Emergence of DNS Censorship Inconsistencies

Paper #XXX

### Abstract

This is our abstract

## 1 Introduction

Internet censorship is a global problem that affects over half the world’s population. Censors rely on sophisticated network middleboxes to inspect and block traffic. A core component of Internet censorship is DNS blocking, and prior work has extensively studied how DNS censorship occurs, both for specific countries [5, 19] and globally [12, 21, 30, 33]. These studies generally perform active measurements of DNS resolvers for large sets of domains, and identify forged censorship responses from legitimate ones.

Unfortunately, prior work has focused exclusively on the IPv4 Internet, in part because scanning the IPv6 Internet for open resolvers is difficult [26], owing to its impossible-to-enumerate 128-bit address space. In this paper, we perform the first comprehensive global measurement of DNS censorship on the IPv6 Internet. We leverage a recent network measurement technique that can discover dual-stack IPv6 open resolvers from their IPv4 counterpart [18], and use these IPv4-IPv6 resolver pairs to study DNS censorship globally. By sending DNS queries to both the IPv4 and IPv6 interfaces of the *same resolver*, we measure the difference in censorship on the IPv4 and IPv6 Internet.

IPv6 is becoming more widely deployed, with nearly 35% of current Internet traffic being served over native IPv6 connections [3]. However, IPv6 has fundamentally different performance characteristics [13], network security policies [11], and network topologies [10].

While it may seem that censors either do or don’t support detecting and censoring IPv6 DNS, we find that there is a tremendous range of how well a censor blocks in IPv6 compared to IPv4. In particular, although nearly all of the countries we study have some support for IPv6 censorship, we find that most block less effectively in IPv6 compared to IPv4. For instance, we observe Thailand censors on average 80% fewer IPv6 DNS resources compared to IPv4 ones, despite a robust nation-wide censorship system [17].

Studying censorship in IPv6 can provide opportunities for circumvention tools. By identifying ways that censors miss or incorrectly implement blocking, we can offer these as techniques that tools can exploit. Moreover, because of the complex and heterogeneous censorship systems censors operate,

many of these techniques would be costly for censors to prevent, requiring investing significant resources to close the IPv4/IPv6 gap in their networks. For this reason, we believe IPv6 can provide unique techniques for circumvention researchers and tool developers, that will be beneficial in the short term, and potentially robust in the longer term.

We find a significant global presence of IPv6 DNS censorship – comparable, but not identical to well documented IPv4 censorship efforts. Censors demonstrate a clear bias towards IPv4, censoring A queries in IPv4 at the highest rates, and a propensity for censoring native record types (A in IPv4, AAAA in IPv6). At the country level we break down differences by resolver and domain across resource record and interface type. We find that multiple countries – Thailand, Myanmar, Bangladesh, Pakistan, and Iran – present consistent discrepancies across resolvers or domains indicating centrally coordinated censorship, where IPv4 and IPv6 efforts are deployed or maintained independently but managed centrally. Other countries show inconsistent discrepancies in the ways that resolvers censor IPv4 and IPv6 with resolvers that can be loosely grouped by AS connection type (for the AS where the resolver is located) and the set of domains that each resolver censors. This evidence supports a decentralized model of censorship coordination or deployment in countries like Russia and China.

We also identify behavior indicative of censorship oversight that can be advantageous to censorship circumvention. For example Iran censors queries that rely on 6to4 bridges at significantly lower rates presumably due to the encapsulation of an IPv6 DNS request in an IPv4 packet marked as type IPv6 encapsulation.

Taken all together, this study provides a first look at IPv6 DNS censorship and the policy gaps that arise from the IPv6 transition. We provide the following contributions:

- We conduct the first large-scale measurement of IPv6 DNS censorship in over 100 IPv6-connected countries. We find that while most censors support IPv6 in some capacity, there are significant gaps in how well they censor IPv6.
- We provide methodological improvements on measuring DNS censorship that avoids relying on cumbersome IP comparisons (that are not robust to region-specific DNS nameservers). Our methods are easily reproducible, and can be used in future measurement studies

- We characterize the difference in censorship of both network type (IPv4 and IPv6), and resource type (A and AAAA record), and identify trends in several countries.
- Using our findings, we suggest several new avenues of future exploration for censorship circumvention researchers, and censorship measurements.

The remainder of this paper is laid out as follows. §2 provides background information in DNS censorship, and the relation of IPv6 to relevant DNS infrastructure. We outline our compiled methodology and ethical design considerations in §3 before presenting our findings on the global prevalence of IPv6 censorship in §4. We then dig into per country analysis based on Resource Record types in §5 and IP protocol version in §6. We select several case studies to highlight in §7 before covering related work in §8. Finally §9 provides discussion and contextualization of this work before concluding.

## 2 Background

Our work is focused on uncovering differences in *Internet censorship* that occur from *DNS censorship* mechanisms’ failure to effectively adapt to the Internet’s *adoption of the IPv6 protocol*. In this section, we provide an overview of Internet censorship approaches (§2.1), DNS censorship mechanisms and infrastructure (§2.2), and the impact of IPv6 on DNS censorship (§2.3).

### 2.1 Internet censorship

**What constitutes Internet censorship?** Internet censorship can be broadly defined as the act of filtering or blocking access to Internet content [2]. Like previous work, we also use this definition when measuring censorship.

**Corporate and national censorship.** Our working definition of censorship applies to any Internet traffic filtering or blocking actions, regardless of the entities that perform them. With a few exceptions, much of prior work has largely focused on measuring censorship with a presumed attribution of measured events to national content access policies. However, it is important to note that corporate censorship, where businesses deploy information controls systems to prevent access to specific types of content, is also globally prevalent. Throughout our work, we take care to identify when it is likely that our measurements are reporting instances of corporate censorship rather than national censorship. This classification is done using Maxmind’s Connection Type database [1] which characterizes IP end-points as ‘Corporate’, ‘Cable/DSL’ (associated typically with residential networks), or ‘Cellular’. This distinction is important in order to provide context for some of our results. For example, from our study we find that 0.9% of our tests in the United States were censored. Without the additional context that: (1) more that 50% of all our measurement

vantage points in the US were placed in corporate networks and (2) these end-points were responsible for the identified censorship events, this finding would be confusing, assumed incorrect, or incorrectly attributed to a national censorship policy.

**Internet censorship techniques.** Blocking access to Internet content can occur in a variety of ways and at different layers of the networking stack, all of which require the ability to monitor network traffic passing through the censor’s borders. The simplest and most common approaches are: (1) IP-based blocking in which a censor maintains blocklists of IP addresses and prevent connections to these IP addresses; (2) DNS manipulation where censors inject (when the censor is a man-in-the-middle) or return (when the censor is the resolver) incorrect responses to domains that are to be censored; and (3) HTTP proxying in which a censor acts as a proxy to clients within its border with the intention of blocking access to intercepted ‘unsuitable’ content. While these censorship mechanisms are passive and possible to evade, it is known that countries such as China have deployed comprehensive censorship infrastructure that is capable of active probing, protocol inspection, and incorporates multiple approaches for censorship. In fact, there has been a large body of work to identify censorship techniques that are leveraged by state actors and globally prevalent [16, 28–30, 32–34] and specific to individual countries [6, 17, 19, 27, 31, 39]. Unfortunately, the impact of the growing deployment of IPv6 networks has not been previously studied — leaving gaps in our knowledge of how censors are handling the network transition and what opportunities exist for developers of circumvention tools. Our work fills this gap by studying how the transition to IPv6 impacts DNS censorship mechanisms.

### 2.2 DNS censorship

The Domain Name System (DNS) underpins the global internet by providing a mapping from human readable hostnames to routable IP addresses making domain name resolution the first step in almost all connection establishment flows. However, the widely deployed DNS system is implemented as a plaintext protocol allowing on-path eavesdroppers to inspect the hostnames as clients attempt to establish connections and in some cases inject falsified responses to interfere.

**On-path and in-path DNS censorship.** An on-path censor operates on a copy of the traffic that transits a specific network link. Operating on a copy allows the censor to make deeper inspections on the content of packets and respond accordingly. This approach has the limitation that censors cannot interfere with the packets that have already passed their vantage point. In the context of DNS censorship, on-path censors make censorship decisions based on the copy of a DNS request and inject a false response to the source of the request in the hopes that their response reaches the source before the actual

response from a resolver. Because the source will receive a response from the intended resolver as well as the injected response from the censor, on-path censorship can be identified by recording *all* DNS response packets that are received to a DNS query for a censored domain. Another censorship approach is in-path censorship in which a censor makes decisions about dropping or modifying packets on-the-fly and at line rate. Censoring of DNS queries by in-path censors can be identified either by the presence of timeouts (packet drops by censor) or incorrect responses (packet modifications by censors). The Chinese traffic inspection system, called the Great Firewall (GFW), is documented injecting falsified DNS responses as early as 2002 [9]. This censorship has been shown to be a packet injection from an on-path adversary monitoring for hostnames in DNS queries that match regular expressions [19].

**Distributed and centralized DNS censorship.** In a centralized DNS censorship mechanism, a single entity manages the ‘blocklists’ or filter-rules associated with DNS censorship decisions. This is the case in countries such as China where traffic inspection devices are housed at or near border gateways [38]. In contrast, countries such as India and Russia are known to delegate censorship orders to regional ISPs who may choose to implement them either via DNS (typically by reconfiguring their own resolvers) or other censorship approaches [31, 40]. The latter approach results in different implementations of DNS censorship and the possibility for inconsistencies across different ISPs.

## 2.3 IPv6 and DNS

As with other critical protocols, DNS has also adapted to the IPv6 protocol. The AAAA resource record type was introduced to aid in the resolution of domains to their IPv6 addresses. Further, the existing DNS protocol is IP-independent and can therefore be deployed on IPv4 and IPv6 networks. Therefore, it is now possible and common for IPv4 and IPv6-hosted DNS servers to receive both A and AAAA queries. This is in contrast to a IPv4-dominant Internet where A queries to IPv4 resolvers were the norm.

**Impact of IPv6 on DNS censorship.** The changes outlined above also influence the mechanics and success of DNS censorship operations. A theoretically comprehensive DNS censorship strategy using response injection requires traffic monitoring infrastructure to: (1) analyze both IPv4 and IPv6 traffic and (2) parse both A and AAAA queries accounting for hostnames that may not implement resource records of one type or the other. Our work which provides a snapshot documentation of contemporary censorship strategies through the IPv6 transition. In addition to helping circumvention tool developers exploit weaknesses made available through this transition, this work also improves our understanding of the reactivity of network censorship more broadly.

## 3 Dataset and Methodology

The analysis presented in the remainder of this paper is based on the results of 21.3M DNS A and AAAA resolution requests for 717 domains sent to 7,428 IPv4- and IPv6-capable resolvers located in a 106 countries. In this section, we explain our process for identifying resolver targets for our queries (§3.1), domains that are the subject of our queries (§3.2), and our process for identifying the occurrence of a censorship event from the results of each query (§3.3).

### 3.1 Selecting resolvers

Our work is aimed at characterizing the inconsistencies that exist in the handling of IPv4- and IPv6-related DNS queries — i.e., differences in the handling of A and AAAA query types over IPv4 and IPv6 connections. Therefore, we required that each resolver used for our measurements was IPv4- and IPv6-capable.

**Identifying resolvers with IPv4- and IPv6-capabilities.** Our approach, described below, borrows from the work of Hendricks et al. [18] who identified IPv6 open resolvers to measure the potential for IPv6-based DDoS attacks.

*Creating control domains.* We begin by creating two new domains, owned and controlled by us and used exclusively for this study. The Name Servers for each domain were also controlled by us. The Name Server for one of these domains was hosted on an IPv6-only network without the capability of communicating with IPv4. Note that because these domains were newly registered, they could not have been present on the blocklists of any censor. We refer to these domains as our control and and IPv6-only NS domains.

*Identifying IPv4-capable resolvers.* We then use `zmap` [15] to scan the entire IPv4 address space and issue a DNS A query on port 53 for our IPv4 control domain. This yields an initial list of IPv4 DNS resolvers.

*Verifying IPv6 capabilities of IPv4-capable resolvers.* Next, we issue a DNS A query for a resolver-specific subdomain of our IPv6 control domain to each of these IPv4 DNS resolvers. The subdomain encoded the IPv4 address of the resolver being targeted. Therefore, if our domain was `v6onlyNS.io` and our resolver target was `1.1.1.1`, our DNS query requested the A record for `1-1-1-1.v6onlyNS.io`. Since IPv4-only resolvers will not be able to communicate with our IPv6-only Name Server, we expect this resolution to fail. On the other hand, resolvers with any form of IPv6 connectivity will be able to connect to our IPv6-only Name Server. Thus, by examining the logs of our IPv6-only NS domain, we are able to identify the set of resolvers that successfully reached our server and their corresponding IPv4 addresses. The associated IPv6 address for each successful query is extracted from packet captures of the IPv6-only Name Server giving us an (IPv4, IPv6) address pair for each resolver.

**Filtering and geolocating resolvers.** The approach detailed above yields pairs that suggest the presence of ‘infrastructure’ resolvers — e.g., multiple IPv4 resolvers have the same IPv6 address associated with them. These are cases where the IPv4 resolver simply forwards requests to a dedicated multi-machine DNS infrastructure rather than performing the resolution by itself. Although this does not change the validity of our results regarding the IPv6-related inconsistencies of resolvers, we still remove these cases in order to minimize the influence of such infrastructure resolvers. Finally, to confirm the correctness of our list of IPv4/IPv6 resolver pairs, we: (1) perform a follow up scan by issuing A and AAAA requests for both our control domains using `zdns` [15] and filter out those pairs where an incorrect response was received, (2) we use the Maxmind GeoIP dataset [1] to geolocate the IPv4 and IPv6 addresses of a resolver pair and only those which belong to the same region. In total, we obtained 7,788 resolvers in 106 different countries. Table 7 illustrates how these resolvers were geographically distributed.

### 3.2 Selecting target domains

In order to identify inconsistencies in IPv4/IPv6-related DNS censorship we require that the domains we use are: (1) sensitive and likely to be censored in a large number of countries and (2) have valid A and AAAA records associated with them.

**Identifying sensitive domains.** Censored Planet’s ‘Satellite’ project, which performs global longitudinal measurements of DNS censorship, [34] maintains a list of domains that combines sensitive domains in each country with popular domains randomly chosen from the Alexa Top-10K. The sensitive domains in this list were gathered by the Citizen Lab using regional experts to curate lists for each country [23]. Given the input from experts and the availability of comparable validation data from Censored Planet, we utilize this list as the starting point for our study as well.

**Identifying usable domains.** Not all the domains on the Satellite list are usable in our study since they do not have IPv6 connectivity or AAAA records. We filter out unusable domains by using `zdns` to perform A and AAAA resource record requests from Google and Cloudflare’s four public DNS resolvers (8.8.8.8, 8.8.4.4, 1.1.1.1, and 1.0.0.1) and removing those with invalid A or AAAA records. A record is invalid if it does not contain valid IPv4 or IPv6 addresses. Finally, we follow-up by making TLS connections (using `zgrab2`), from our uncensored vantage point, to each of the IP addresses contained in the DNS responses. We locally verify the obtained TLS certificates and exclude all domains whose verification fails. This final list contains 717 sensitive domains whose TLS certificates and IPv4 and IPv6 addresses are valid. We use this list for all the measurements reported in this paper.

### 3.3 Identifying DNS censorship events

In general, our goal is to err on the side of caution and avoid false-positives in our censorship determination. We achieve this by accounting for unreliability of resolvers and domains in our lists.

**Removing unstable resolvers.** For each of the 7,788 (IPv4, IPv6) resolver pairs and 717 sensitive domains, we send a DNS A and AAAA resource record request for a domain to the IPv4 and IPv6 addresses associated with the resolver. We follow this up with a A and AAAA resource record request for a set of 3 control domains (owned and operated by us). We discard data from resolver pairs which failed to resolve any of our control domains correctly since this is a sign of resolver instability. This left us with data from 7,428 stable resolver pairs.

**Distinguishing censorship from domain instability.** For the remaining resolvers, we extract the IPv4 and IPv6 resource records returned for each domain. Next, we use `zgrab2` to establish TLS connections to the IP addresses contained in the resource records. In each of these connections, we set the TLS SNI (using the `-servername` option) to be the domain whose records were requested. We then verify the validity of the retrieved TLS certificates. Since the domains themselves might be unreliable, we repeat this verification procedure three times. Only if this step fails all three times do we conclude that the response from that resolver for that domain was censored.

### 3.4 Ethics

Our experimental design has incorporated ethical considerations into the decision-making process at multiple stages. We concern ourselves primarily with the security and autonomy of human users and their ability to securely access the internet. Given the prevalence of self-censorship, understanding and documenting the mechanisms and scope of censorship strategies can assist users in better evaluating their own risk. However, censorship measurement naturally entails interacting with and occasionally violating the rules of access control systems. We rely on The Menlo Report [14], its companion guide [7], and the censorship specific ethical measurement guidelines discussed by Jones et al. [20] to provide structure and guidance to our experimental design.

**Consent.** To align with the guiding principle of *respect for persons* we structure the data collection to implicate as few individuals as possible. Specifically we rely on open resolvers which typically have little or no direct association with individuals in lieu of measurement from client based software. While we cannot acquire direct or proxy consent from the operators of the open resolvers we consider the trade-off between the implied consent standard and the value in the measurements we make. Understanding the extent and mechanisms of censorship infrastructure can help to demystify and clarify risks to

real users seeking to safely access the internet. It is important to note that the goal of our ethical analysis is not to eliminate risk, but to minimize it wherever possible. As noted by Jones et al. in some cases acquiring consent from operators may not only be impossible, but increase the risk to operators as it introduces their acknowledgement of, or active participation in, the measurement at hand [20]. This analysis aligns with previous work relying on open resolvers to collect impactful results while minimizing risk on individuals [30, 33, 34].

**Privacy.** Our study collects no personal data about any end users or individual open resolver operators. The analysis completed herein uses resolver addresses, public Anonymous System (AS) identifiers, and country codes. All measurements are initiated from within the United States at little to no risk of repercussions to citizens in the countries that we examine. Beyond this, measurement domains are not drawn from any human browsing patterns or history as the suspected censored domains are a subset of the Satellite measurement results as discussed in §3.2.

**Resource usage.** The vantage that was used for data collection is connected to the internet with a 1 Gbps interface that scanned using the default rates for `zmap` and `zgrab2` tools (line rate). However, the structure of the scan was established such that individual resolvers and domains for the DNS probe and TLS certificate validation respectively would be accessed in round robin order — i.e., when probing the open resolvers every target would receive a preliminary request before any target would receive the subsequent request. Equivalently for validating TLS certificates, each of the 717 target domains would receive a preliminary attempted handshake before any target would receive a subsequent handshake. While we do not have an upper bound on the bandwidth that was sent to individual resolvers or TLS endpoints we believe this strategy provides a reasonable limitation to the impact of the measurements in this study.

## 4 Prevalence of DNS Censorship

**Overview.** In this section, we focus on *providing a high-level understanding on the prevalence of DNS censorship on IPv4 and IPv6 networks*. Specifically, we measure the global prevalence of DNS censorship that occur in the following four cases: (1) a DNS A query is sent over IPv4, (2) a DNS AAAA query is sent over IPv4, (3) a DNS A query is sent over IPv6, and (4) a DNS AAAA query is sent over IPv6. While much of prior work has focused on case (1), the increased adoption of IPv6 necessitates the analysis of cases (2-4) which are provided in our work. In each case, we use our collected dataset (*cf.*, §3) to summarize the base rate of censorship.

**How common is DNS censorship?** Our data shows the mean base rate of DNS censorship among the 106 countries included in our study, across all query and network types, for

Country	Resolver pairs	IPv4 A	IPv4 AAAA	IPv6 A	IPv6 AAAA	Avg.
China (CN)	194	29.27	32.32	28.41	32.08	30.52
Iran (IR)	277	25.12	24.49	21.95	21.45	23.25
Hong Kong (HK)	67	7.00	5.57	4.91	5.24	5.68
Russia (RU)	312	5.51	4.78	4.49	4.50	4.82
Ukraine (UA)	35	6.49	3.05	2.64	2.87	3.76
Indonesia (ID)	56	6.46	2.99	2.41	2.26	3.53
Argentina (AR)	47	5.20	3.51	2.22	1.28	3.05
Thailand (TH)	186	8.25	1.18	1.13	0.93	2.87
Malaysia (MY)	50	4.92	2.03	1.27	1.35	2.39
Mexico (MX)	150	3.78	2.05	1.75	1.94	2.38
Bangladesh (BD)	29	6.42	1.28	0.89	0.81	2.35
Colombia (CO)	27	3.39	3.28	1.45	1.14	2.31
Italy (IT)	38	2.36	2.10	2.25	2.52	2.31
Brazil (BR)	160	2.67	1.67	1.99	2.08	2.10
Bulgaria (BG)	30	3.24	2.91	1.15	1.06	2.09
Poland (PL)	48	2.00	1.13	2.90	0.96	1.75
South Africa (ZA)	93	2.41	1.60	1.18	1.33	1.63
Korea (KR)	632	2.33	1.06	1.24	1.22	1.46
Chile (CL)	65	2.67	0.70	1.10	0.79	1.32
Romania (RO)	44	2.30	1.03	0.83	0.93	1.27
Spain (ES)	49	0.91	0.75	1.40	1.94	1.25
India (IN)	226	1.27	1.52	1.04	1.16	1.25
Belgium (BE)	31	1.56	1.26	0.95	0.95	1.18
Turkey (TR)	114	1.29	0.96	1.27	1.02	1.14
Viet Nam (VN)	252	1.53	0.89	1.42	0.67	1.13
<b>Global</b>	7,428	3.10	1.83	1.77	1.60	2.07

Table 1: Top-25 countries with over 25 resolver pairs and the highest average rates of DNS censorship across both query types and network interfaces. Rates are expressed as the percentage of censored DNS queries over total number of DNS queries sent. Darker shaded cells indicate a higher rate of DNS censorship (compared to the country’s average) and lighter shaded cells indicate a lower rate of DNS censorship. The average rate of censorship for a country is computed across all four IP/query combinations. The global row contains the mean of each column and includes data from the countries with less than 25 resolvers. These means weigh the contribution of each country equally, rather than weighted by the number of resolvers used in tests. Countries are grouped together by their distance from this median.

our list of domains is 2.1%. A summary of the base rates observed in each of our four A/AAAA-IPv4/IPv6 combinations for the 25 countries which have at least 25 pairs of resolvers that were tested and perform the most censorship is illustrated in Table 1. In general, our results concur with prior work which has also found high levels of DNS censorship in China, Iran, Russia, and Hong Kong.

**Trends in censorship of IPv6-related queries in heavily censoring countries.** By measuring IPv6-related behaviors of censorship mechanisms, we uncover a large number of DNS censorship inconsistencies in heavily censoring countries. Because our dataset is balanced (i.e., all the domains have both A and AAAA records and all the tested resolvers have an IPv4 and IPv6 interface), if censorship is independent of the query type and interface, we expect to see a uniform rate of censorship across all query types and interface combinations in Table 1. However, we find that this is not true. We observe

Country	Resolver Pairs	IPv4 A	IPv4 AAAA	IPv6 A	IPv6 AAAA	Avg.
United States (US)	757	1.62	1.16	0.54	0.96	1.07
Germany (DE)	717	0.98	0.91	0.75	0.80	0.86
France (FR)	470	0.60	0.45	0.40	0.46	0.48
Great Britain (GB)	186	1.07	0.94	0.78	0.97	0.94
South Korea (KR)	177	2.49	1.37	1.38	1.57	1.70
Canada (CA)	165	0.84	0.39	0.26	0.33	0.45
Russia (RU)	117	4.67	4.36	4.01	4.00	4.26
India (IN)	101	1.19	1.76	0.81	0.99	1.19
Japan (JP)	79	1.71	1.82	0.90	1.57	1.50
South Africa (ZA)	74	2.09	1.62	1.10	1.31	1.53
Netherlands (NL)	71	1.08	0.94	0.84	0.85	0.92
Chile (CL)	53	2.10	0.73	1.12	0.77	1.18
Lithuania (LT)	51	0.95	0.80	0.51	0.78	0.76
Iran (IR)	48	25.50	24.66	22.34	21.69	23.55
Thailand (TH)	43	9.28	1.18	0.99	0.95	3.10
Singapore (SG)	41	1.56	0.85	0.65	0.78	0.96
Viet Nam (VN)	40	2.16	1.01	0.85	0.86	1.22
Hong Kong (HK)	37	6.20	5.44	4.55	5.38	5.39
Australia (AU)	35	2.53	1.16	1.77	1.14	1.65
Brazil (BR)	34	1.50	1.10	1.01	1.17	1.19
Finland (FI)	31	0.74	0.64	0.47	0.56	0.60
Malaysia (MY)	30	6.07	2.25	0.97	1.10	2.60
Spain (ES)	28	1.26	0.97	2.24	2.97	1.86
Turkey (TR)	25	1.72	1.29	1.20	2.17	1.60

Table 2: We highlight the countries with at least 25 resolver pairs in corporate ASes to showcase their censorship rates across interface and resource type. We see this is where the predominant censorship in the United States is present.

two trends common to many of the countries performing the most censorship. First, we see that, in comparison to any other query-interface combination, *A queries sent over IPv4 are the most heavily censored*. Second, we see that *AAAA queries are censored less than A queries, regardless of whether they are sent over IPv4 and IPv6 networks*. This immediately suggests that censorship apparatus in a large number of censoring regions are not fully IPv6-capable. Besides the possibility of misconfiguration of the DNS censorship mechanisms, this may also be because censors in these regions are not yet widely deployed on IPv6 networks in their country. The only exception to both these generalizations is China — the most censoring country in our data. China shows an unusual *preference towards blocking AAAA records regardless of whether they are sent over IPv4 or IPv6*. We explore China and several other countries with interesting patterns as specific case studies in §7.

**Corporate Censorship.** Predominantly the focus of DNS censorship is at the nation state level as discussed so far. However, corporate censorship i.e., businesses restricting employee access to certain domains is also highly prevalent across the internet.

Given our wide breadth of resolvers we were able to break down our resolver pairs discovered (as discussed in §3.1) further into the the Autonomous System (AS) each resolver pair is in allowing us to get a more fine grained look at which resolvers are censoring access to sensitive domains.

Table 2 shows the censorship rates across resource and infrastructure type in countries that had at least 25 resolver pairs in corporate ASes.

## 5 Censorship of IPv4 and IPv6 Resource Records

**Overview.** In this section, we focus on *identifying and characterizing differences in the handling of IPv4 and IPv6 resource records* in DNS censorship deployments. Specifically, we seek to answer the following questions: (§5.1) In which countries is the censorship of IPv4 **resource records** (DNS A queries) significantly different than the censorship of IPv6 resource records (DNS AAAA queries)?, (§5.2) what are the characteristics of the **resolvers** which exhibit differences in the handling of A and AAAA queries?, and (§5.3) what are the characteristics of **domains** in which these differences are frequently observed?

### 5.1 A vs. AAAA resource censorship

We use the responses received from our A and AAAA queries sent to the same set of resolvers and for the same set of domains (*cf.*, §3 for data collection methodology). We then apply the censorship determination methods described in §3.3 to measure the prevalence of censorship on our A and AAAA DNS queries. Finally, we perform statistical tests to identify significant differences in the prevalence of censorship of A and AAAA queries within each country.

**Identifying differences within a country.** To measure differences in DNS query handling within a specific country, we compare the prevalence of censorship on A and AAAA queries by aggregating responses across each resolver within the country. This presents us with two distributions (one each for the group of A and AAAA queries) of the fraction of censored domains observed at each resolver in the country. We use a two-sample *t*-test to verify statistical significance of any observed differences between the two groups for each country. In our statistical analysis, we aim to achieve a significance level of 5% ( $p \leq .05$ ) *over all our findings*. Therefore, we apply a Sidak correction [4] to control for Type I (false-positive) errors from multiple hypothesis testing. This requires  $p \leq 1 - .05^{1/n_c}$  for classifying a difference as significant, where  $n_c$  is the total number of countries in our dataset (106). This approach reduces the likelihood of false-positive reports of within-country differences. The presence of a statistically significant difference for a specific country would imply that A and AAAA resource types appear to undergo different censorship mechanisms within that country (if a centralized mechanism for censorship exists) or that a significant number of resolvers within that country have inconsistencies in their censoring of each query type. A summary of our results are presented in Table 3.

**How many countries demonstrate large-scale inconsistencies in their handling of A and AAAA queries?** In total, only seven countries showed a statistically significant difference in the rate at which AAAA and A DNS requests were blocked.

Country	IPv4 resolvers	IPv6 resolvers	All resolvers
Thailand (TH)	-7.1 pp (-85.7%)	<i>ns</i>	-3.7 pp (-77.5%)
Bangladesh (BD)	-5.1 pp (-80.0%)	<i>ns</i>	-2.6 pp (-71.3%)
Pakistan (PK)	-2.1 pp (-73.6%)	-2.8 pp (-59.8%)	-2.5 pp (-60.2%)
Chile (CL)	-2.0 pp (-57.6%)	<i>ns</i>	-1.1 pp (-58.9%)
Vietnam (VN)	<i>ns</i>	-0.7 pp (-52.5%)	-0.7 pp (-47.1%)
Korea (KR)	-1.3 pp (-54.6%)	<i>ns</i>	-0.6 pp (-36.2%)
China (CN)	3.1 pp (+10.4%)	3.7 pp (+12.9%)	3.4 pp (+11.7%)
United States (US)	-0.5 pp (-33.2%)	0.4 pp (+72.3%)	<i>ns</i>
Myanmar (MY)	-2.9 pp (-58.9%)	<i>ns</i>	<i>ns</i>

Table 3: Differences in blocking rates of A and AAAA queries observed over IPv4, IPv6, and all resolvers in a country. ‘pp’ denotes the change in terms of percentage points (computed as AAAA blocking rate - A blocking rate) and the %age value denotes the percentage change in blocking rate (computed as  $100 \times \frac{\text{AAAA blocking rate} - \text{A blocking rate}}{\text{A blocking rate}}$ ). Only countries having a statistically significant difference are reported. A negative value indicates that A queries observed higher blocking rates than AAAA queries. *ns* indicates the difference was not statistically significant and thus omitted.

We note that this is a conservative lower-bound due to the statistical test used, which minimizes false positive errors at the expense of false negatives. This finding suggests the presence of independent censorship mechanisms for handling each query type in the seven countries (Thailand, Bangladesh, Pakistan, Chile, Vietnam, Korea, and China). Of these, six (China being the only exception) were found to have lower blocking rates for AAAA queries than A queries. In fact, the AAAA censorship rates were between 36-78% lower than the A censorship rate suggesting that their censorship mechanisms for AAAA queries that are associated with IPv6 connectivity are still lagging. Further analysis shows that the differences are mostly found on the IPv4 interfaces of our resolvers (*cf.*, *IPv4 resolvers* column in Table 3) where the AAAA censorship rates were up to 86% lower than the A censorship rates. This finding is indicative of a tendency for network operators to have focused efforts on maintaining infrastructure for censoring A queries sent to IPv4 resolvers, while paying less attention to the handling of AAAA queries and their IPv6 interfaces. It also presents an opportunity for circumvention tool developers to exploit. China presents the only exception with a preference for blocking AAAA queries on both IPv4 and IPv6 interfaces of resolvers with a 10% and 13% higher AAAA censorship rate, respectively. We investigate this anomaly in §7.

## 5.2 Characteristics of A/AAAA-inconsistent resolvers

Given our above results which suggest that there are a number of countries in which A and AAAA queries are censored differently, we now seek to understand the characteristics of the resolvers that cause these differences. We first focus on identifying the individual resolvers in each country that have statistically different behaviors for A and AAAA queries. Then, we compare the AS distributions of these resolvers with the

set of all resolvers in a country. This comparison tells us if the A/AAAA inconsistencies are specific to a subset of ISPs, or if the inconsistencies exist across the whole country (suggesting centralized censorship). Finally, we identify the types of networks hosting inconsistent resolvers to get a measure of whether users in residential networks may exploit these DNS inconsistencies for circumvention.

**Identifying differences in individual resolvers.** We begin our analysis by identifying the individual resolver pairs (i.e., we consider the IPv4- and IPv6-interfaces of a resolver as a unit), within each of the seven countries listed above that have a statistically significant difference in their censorship of A and AAAA queries. To measure differences in DNS query handling of individual resolvers, we compare the ratio of censored responses each resolver observes for A and AAAA queries.

We use a two-proportion  $z$ -test to verify the statistical significance of any observed difference in the ratios between the two groups for each resolver. Similar to our within-country analysis, we apply a Sidak correction to account for our testing of multiple hypotheses and use  $p \leq 1 - .05^{1/n_c}$  to classify a difference as significant, where  $n_c$  is the total number of resolvers in our dataset belonging to country  $c$ . A summary of our results is provided in Table 4.

**Which countries have the largest fractions of resolvers exhibiting A and AAAA resolution inconsistencies?** Immediately standing out from the other countries are Thailand, Bangladesh, and Pakistan. These countries have A and AAAA inconsistencies in 62-82% of their resolvers. In comparison, other countries with statistically significant differences have inconsistencies arising from anywhere between 3-30% of their resolvers.

### How spread out are the A/AAAA-inconsistent resolvers?

We calculate the entropy of the distribution of all resolvers in the country ( $S_{\text{query}}^{\text{all}}$ ) and compare it with the entropy of the distribution of the inconsistent resolvers in the country ( $S_{\text{query}}^{\text{inconsistent}}$ ). This serves as a measure of the diversity of ASes observed in both cases. In order to compare the two measures, we use the Kullback-Leibler divergence ( $V_{\text{query}}$ ) distance [22]. In simple terms, the KL-divergence between two distributions ( $X, Y$ ) measures the number of additional bits required to encode  $X$  given the optimal encoding for  $Y$ . In other words, it is the relative entropy of one distribution given another. This computation is helpful for hypothesizing the censorship infrastructure that causes the inconsistencies. Finding a small  $V_{\text{query}}$  value in a country signifies that the inconsistent resolvers had a similar distribution to all the resolvers in that country. This would suggest the presence of a centralized mechanism that (roughly) equally impacts all ASes in the country that is responsible for the inconsistencies. Conversely, a higher  $V_{\text{query}}$  value indicates that there is a strong change in the distribution of resolvers – i.e., a disproportionate number of inconsistencies arise from a smaller set of ASes. This



would be indicative of local configuration inconsistency (at the network or resolver level), rather than a centralized configuration inconsistency. We note that this does not provide a measure of how centralized censorship is within a country overall, but rather, it describes how uniform the A vs. AAAA inconsistencies are.

Based on this analysis, we once again see that Thailand, Bangladesh, and Pakistan stand out with small  $\nabla_{\text{query}}$  values (0.14 - 0.48). This suggests a country-wide censorship mechanism is responsible for the inconsistent censorship of A and AAAA that impacts all ASes nearly equally. Korea, China, and the United States on the other hand demonstrate high  $\nabla_{\text{query}}$  scores suggesting the presence of network- or resolver-level misconfigurations are responsible. This is confirmed by inspecting the ASes hosting the resolvers with inconsistencies. For example, in the United States, resolvers in just 5 ASes (of 249 ASes with resolvers) account for 56% of all A and AAAA inconsistencies.

**What types of networks exhibit the most A and AAAA inconsistencies?** We use the Maxmind GeoIP2 connection type database (retrieved in 01/2022 [1]) to identify the connection type of the resolvers responsible for A and AAAA inconsistencies. We find that, in most countries, Cable/DSL network connections (typically associated with residential networks) were most likely to host a resolver exhibiting an inconsistency. Of the seven countries with statistically significant overall differences, only Thailand and China were found to have a high ratio of A/AAAA -inconsistent resolvers in corporate networks. Combined with our previous results which suggest the presence of an inconsistency in a centralized mechanism in Thailand, Bangladesh, and Pakistan, these results show that these inconsistencies are likely extending to residential networks — a promising sign for the citizen users of circumvention tools which exploit the A/AAAA gap.

### 5.3 Characteristics of anomalous domains

We now identify the category of domains that appear to exist in the gap of A and AAAA blocking. In addition to providing a general categorization of these domains, we also analyze whether their category distributions vary significantly from the category distribution of websites that received any blocking. We do this in order to identify the specific policies or mechanisms that differ between the censorship mechanisms for A and AAAA queries.

**Identifying differences in domain behaviors within a country.** We continue using our statistical approach for identifying differences within a country. We measure the ratio of blocking that occurs for a domain’s A and AAAA records within the country and then compare these using a two-proportion  $z$ -test with a Sidak corrected  $p$ -value of  $1 - .05^{\text{dom}}$  where  $\text{dom}$  is the total number of tested domains (717). We only label the behavior of a censor with regards to a domain as different

over A and AAAA queries if the  $z$ -test finds the difference to be statistically significant. Once again, we do this to err on the side of caution in order to minimize over-reporting and false-positives of censorship and, in this case, its corresponding policy differences over A and AAAA.

**Do these A/AAAA-inconsistent domains hint at policy gaps?** For each country, we begin our analysis by deriving domain categories, using the McAfee domain categorization service [?], for domains in the following two lists: (1)  $D_{\text{any}}$  which contains the domains which experienced any blocking events inside a country and (2)  $D_{\text{inconsistent}}$  which contains the A/AAAA-inconsistent domains identified by our  $z$ -test. Next, we compute the KL-divergence between the category distributions of the two lists (i.e.,  $\nabla_{\text{query}}^{\text{domains}} = \text{KLDivergence}(D_{\text{any}}, D_{\text{inconsistent}})$ ). A small  $\nabla_{\text{query}}^{\text{domains}}$  would signify that the domains that experience inconsistent treatment are not from a largely different category distribution than the set of all domains that experience any type of blocking. This would suggest that the inconsistencies do not arise from a specific content-specific policy gap that exists in the censorship mechanism implemented over A and AAAA queries. On the other hand, a large difference would signify that the category distributions are very different and that domains with specific types of content appear to have more inconsistencies — suggesting a content-based policy gap.

Based on this analysis, we find that the United States and Thailand have the smallest  $\nabla_{\text{query}}^{\text{domains}}$  scores (0.4-1.2). Conversely, Pakistan and Myanmar have high  $\nabla_{\text{query}}^{\text{domains}}$  scores ( $>2$ ). After manual inspection of these results, we attribute the low divergence in the United States to the fact that censorship observed in the US arise largely in a range of corporate networks (§4) which are fairly consistent in their blocking of domains belonging to McAfee’s ‘Potentially unwanted programs’, ‘Entertainment’, and ‘Pornography’ categories. On the other hand, in Thailand the low divergence appears despite the large number of residential networks. This suggests that there is no significant policy gap that causes the A/AAAA-inconsistencies. Rather, it suggests a simply incomplete implementation of any existing mechanisms for A query censorship. On the other hand, in Pakistan and Myanmar where the divergence scores were high, we found that the biggest contribution to the high divergence scores arose from the ‘Pornography’ and ‘Government/Military’ domain categories, respectively. This suggests the presence of a content-policy gap in the implementation of A/AAAA DNS censorship implementations that disproportionately allows sites in these categories to evade censorship.

## 6 Censorship of IPv4 and IPv6 DNS Traffic

**Overview.** In this section, we focus on *identifying and characterizing the differences in handling DNS queries sent over IPv4 and IPv6 networks* in DNS censorship mechanisms. Specifically, we answer the following questions: (§6.1) In



Country	Total pairs	Inconsistent pairs (% of total pairs)	Most inconsistent AS (# inconsistent pairs)	$S_{\text{query}}^{\text{all}}$	AS diversity $S_{\text{query}}^{\text{inconsistent}}$	$V_{\text{query}}$	Most inconsistent type (# inconsistent pairs)
Thailand (TH)	186	152 (81.7%)	AS9835 Government IT Services (40)	4.50	4.06	0.14	Cable/DSL (110)
Bangladesh (BD)	29	18 (62.1%)	AS 9230 Bangladesh Online (4)	4.10	3.61	0.48	Cable/DSL (18)
Pakistan (PK)	23	15 (65.2%)	AS 17911 Brain Telecom (3)	3.43	3.06	0.25	Cable/DSL (12)
Chile (CL)	65	20 (30.1%)	AS 27651 Entel Chile (13)	3.08	1.14	1.18	Corporate (13)
Vietnam (VN)	252	64 (25.4%)	AS 131353 NhanHoa Software (37)	3.89	2.22	0.71	Cable/DSL (59)
Korea (KR)	632	80 (12.7%)	AS 9848 Sejong Telecom (13)	3.12	4.17	1.30	Cable/DSL (58)
China (CN)	194	6 (3.1%)	AS 4538 China Education and Research Network (2)	3.89	2.25	2.56	Corporate (4)
United States (US)	1,228	175 (14.3%)	AS 30475 WEHOSTWEBSITES (35)	6.28	4.69	1.31	Corporate (129)
Myanmar (MY)	50	30 (60%)	AS 136170 Exabytes Network (10)	3.31	2.42	0.48	Corporate (26)

Table 4: Characteristics of the resolvers which demonstrated a statistically significant difference in their handling of A and AAAA queries in each country. ‘AS diversity’ denotes the entropies of (all) resolver distribution ( $S_{\text{query}}^{\text{all}}$ ) and A/AAAA-inconsistent resolver distribution ( $S_{\text{query}}^{\text{inconsistent}}$ ) across a country’s ASes, and ‘ $V_{\text{query}}$ ’ represents the Kullback-Leibler divergence of the distribution of inconsistent resolvers from the distribution of all resolvers in the country’s ASes (*cf.*, §5.2). ‘Most inconsistent type’ denotes the connection type with the most number of A/AAAA-inconsistent resolvers.

which countries are the DNS censorship mechanisms for IPv4 and IPv6 traffic significantly different?, (§6.2) what are the characteristics of resolvers that exhibit differences in the censorship of IPv4 and IPv6 traffic?, and (§6.3) what are the characteristics of the domains in which such differences are frequently exhibited?

## 6.1 Within-country differences in the censorship of IPv4 and IPv6 DNS queries

We use the responses received from the IPv4 and IPv6 interfaces of each of the resolvers in our dataset for the same set of domains. We then apply the censorship detection mechanism detailed in §3.3 to measure the prevalence of DNS censorship of queries sent over IPv4 and IPv6. Finally, we perform statistical tests to identify the countries that have significant differences in their censorship of IPv4 and IPv6 DNS traffic.

**Identifying differences within a country.** To measure differences in the censorship of DNS queries sent over IPv4 and IPv6, we compare the prevalence of censorship on each by aggregating their responses across each resolver within a country. This presents us with two distributions (corresponding to the IPv4 and IPv6 interfaces of resolvers) of the fraction of censored domains from resolvers within the corresponding country. We use a two-sample *t*-test to verify statistical significance of any observed differences between the two groups for each country. Similar to our approach in §5, we apply a Sidak correction to control for Type I errors from multiple hypothesis testing. This requires  $p \leq 1 - .05^{1/n_c}$  for classifying a difference as significant, where  $n_c$  is the total number of countries in our dataset (106). The presence of a statistically significant difference for a specific country would imply that the country appears to have different censorship mechanisms for IPv4 and IPv6 DNS traffic (if a centralized mechanism for censorship exists) or that a significant number of resolvers within that country are not consistent in their censorship of

IPv6 and IPv4 traffic. A summary of our results are presented in Table 5.

**Which countries demonstrate large-scale inconsistencies in their handling of IPv4 and IPv6 DNS traffic?** In total, we find only five countries (Thailand, Iran, Bangladesh, Myanmar, and the United States) with statistically significant differences in their handling of DNS queries over IPv4 and IPv6 traffic — suggesting the use of independent censorship mechanisms for IPv4 and IPv6. Interestingly, all these countries appear to have gaps in their IPv6 censorship apparatus — i.e., IPv4 rates of blocking are higher than IPv6 rates in all countries with significant differences. These differences result in IPv6 queries experiencing between 12% and 78% less censorship than their IPv4 counterparts. Once again, this suggests a tendency for network operators to more effectively maintain IPv4 DNS censorship infrastructure than IPv6 infrastructure. These gaps present opportunities for the success of circumvention tools with IPv6 capabilities. Further analysis shows that these differences primarily arise due to the fact that DNS type A queries are significantly more likely to be blocked over IPv4 connections than over an IPv6 connection. However, this is not the case for AAAA queries, with the exception of Iran. Taken together, these findings are particularly noteworthy for circumvention efforts in Thailand, Myanmar, and Iran where IPv6 adoption rates are high (between 15% and 45%) and dual-stack tools may be used for circumvention of DNS censorship.

## 6.2 Characteristics of IPv4/IPv6-inconsistent resolvers

Our previous results demonstrate the promise of using IPv6 channels for DNS resolution to bypass IPv4 DNS censorship. We now focus on identifying the distribution and connection-type of resolvers demonstrating inconsistencies in their handling of IPv4 and IPv6 traffic. This serves two purposes. First, our analysis on the distribution of IPv4/IPv6-inconsistent re-

Country	A queries	AAAA queries	All queries
Thailand (TH)	-7.1 pp (-86.3%)	<i>ns</i>	-3.7 pp (-78.1%)
Iran (IR)	-3.2 pp (-12.6%)	-3.0 pp (-12.5%)	-3.1 pp (-12.5%)
Bangladesh (BD)	-5.5 pp (-86.1%)	<i>ns</i>	-3.0 pp (-77.9%)
Myanmar (MY)	-3.6 pp (-74.2%)	<i>ns</i>	-2.1 pp (-62.3%)
United States (US)	-0.9 pp (-64.8%)	<i>ns</i>	-0.5 pp (-42.6%)
Korea (KR)	-1.1pp (-46.5%)	<i>ns</i>	<i>ns</i>
Chile (CL)	-1.6pp (-58.7%)	<i>ns</i>	<i>ns</i>

Table 5: Differences in blocking rates of DNS queries sent to IPv4 and IPv6 interfaces of each resolver in a country. ‘pp’ denotes the change in terms of percentage points (computed as blocking rate of IPv6 - blocking rate of IPv4) and the %age value denotes the percentage change in blocking rate (computed as  $100 \times \frac{\text{IPv6 blocking rate} - \text{IPv4 blocking rate}}{\text{IPv4 blocking rate}}$ ). Only countries having a statistically significant difference are reported. A negative value indicates that queries sent over IPv4 observed higher blocking rates than those sent over IPv6. *ns* indicates the difference was not statistically significant and thus omitted.

solvers provides evidence-driven hypotheses about how information controls deployments are structured in different countries. Second, studying the connection-types of IPv4/IPv6-inconsistent resolvers sheds light on whether the gaps in censorship are visible to users in residential networks. This serves as an indicator for the potential gains to be had by circumvention tools that begin exploiting the IPv4/IPv6 gap.

**Identifying IPv4/IPv6-inconsistent resolvers.** Our approach is similar to the methods used to identify A/AAAA-inconsistent resolvers (*cf.*, §5.2). We compare the ratios of censored responses received from a single resolver pair’s IPv4 and IPv6 interfaces. We test whether these ratios are statistically different using a  $z$ -test with a Sidak corrected  $p \leq 1 - .05^{1/n_{rc}}$  being required for a statistically significant difference. A summary of the characteristics of the inconsistent resolvers identified in each country is illustrated in Table 6.

**Which countries have the largest fraction of IPv4/IPv6-inconsistent resolvers?** Two countries from our previous analysis on A/AAAA-inconsistencies once again appear with a large fraction of IPv4/IPv6-inconsistent resolvers — Thailand (81%) and Bangladesh (65%). Myanmar presents a new addition with 60% of its resolvers demonstrating IPv4/IPv6-inconsistencies. Other countries were found to have smaller fractions ranging from 12-26%.

**How spread out are the IPv4/IPv6-inconsistent resolvers?** In order to characterize the spread of IPv4/IPv6-inconsistent resolvers within a country, we compute the entropy of the AS distribution of all resolvers and IPv4/IPv6-inconsistent resolvers within a country ( $S_{\text{net}}^{\text{all}}$  and  $S_{\text{net}}^{\text{inconsistent}}$ ) and then compute the KL-divergence of the distribution of inconsistent resolvers from the distribution of all resolvers in that country ( $\nabla_{\text{net}}$ ). Similar to before, a large change in  $\nabla_{\text{net}}$  means that the IPv4/IPv6-inconsistencies arise from a small fraction of ASes and would suggest that the gaps exist due to

local network/resolver misconfigurations — as would be the case if regional operators implement their own DNS censorship mechanisms. Conversely, a small change means that the gaps that exist roughly equally impact all the ASes having resolvers and would suggest that the gaps exist due to misconfigurations in a centralized DNS censorship mechanism. Our results once again suggest the presence of a centralized blocking mechanism in Thailand, Bangladesh, and Myanmar ( $\nabla_{\text{net}} \in [0.13, 0.48]$ ) which causes the IPv4/IPv6-inconsistencies. The United States has the highest  $\nabla_{\text{net}}$  observed which indicates that regional policies are responsible for the IPv4/IPv6-inconsistencies.

**What types of networks exhibit the most IPv4 and IPv6 inconsistencies?** An overwhelming majority of the inconsistent resolvers in Thailand, Iran, and Bangladesh (77%-100%) are found to be present in networks with (Maxmind categorized) Cable/DSL connection-types that are typically associated with residential networks. Put in the context of our previous result which suggests the presence of a centralized DNS censorship mechanism in Thailand and Bangladesh, this suggests that the IPv4/IPv6 gaps that exist in this mechanism also extend to residential networks in the country. Myanmar and the United States experience such inconsistencies primarily due to their corporate networks which contain between 67-87% of their inconsistent resolvers.

### 6.3 Characterization of anomalous domains

We now seek to understand the category of domains that get through the infrastructural gap between DNS queries over IPv4 and IPv6. We provide a general categorization of these domains and further compare this category distribution with that of domains that received any blocking. We do this in order to identify specific mechanisms that might differ for censorship of certain categories over IPv4 and IPv6.

**Identifying differences in domain behaviors within a country** We use an approach similar to the one defined in §5.3 for identifying domains that get through the gap in between IPv4 and IPv6. For each domain, we measure the ratio of blocking that occurs over IPv4 and IPv6. We then apply the  $z$ -test with a corrected  $p$ -value (as described in §5.3) to these ratios. This gives us all domains which had significant differences in censorship over IPv4 and IPv6.

**Do these IPv4/IPv6-inconsistent domains hint at policy gaps?** For each country, we derive domain categories for the following two lists; (1)  $D_{\text{any}}$  which contains the domains which experienced any blocking events inside a country and (2)  $D_{\text{inconsistent}}$  which contains the IPv4/IPv6-inconsistent domains identified by our  $z$ -test. We again used KL-divergence between to compare these two category distributions. A small  $\nabla_{\text{query}}^{\text{domains}}$  would signify that the two category distributions are not largely different suggesting the policy gap over IPv4/IPv6 is not content specific; A large  $\nabla_{\text{query}}^{\text{domains}}$

Country	Total pairs	Inconsistent pairs (% of total pairs)	Most inconsistent AS (# inconsistent pairs)	AS diversity			Most inconsistent type (# inconsistent pairs)
				$S_{net}^{all}$	$S_{net}^{inconsistent}$	$V_{net}$	
Thailand (TH)	186	151 (81.2%)	AS 9835 Government IT Services (39)	4.50	4.10	0.13	Cable/DSL (108)
Iran (IR)	277	74 (26.7%)	AS 208161 PARSVDS (11)	5.03	3.81	0.87	Cable/DSL (57)
Bangladesh (BD)	29	19 (65.2%)	AS 9230 Bangladesh Online (4)	4.10	3.72	0.39	Cable/DSL (19)
Myanmar (MY)	50	30 (60.0%)	AS 136170 Exabytes Network (10)	3.31	2.42	0.48	Corporate (26)
United States (US)	1,228	151 (12.3%)	AS 30457 WEHOSTWEBSITES (36)	6.28	5.22	1.44	Corporate (102)
Korea (KR)	632	101 (16.0%)	AS 9848 Sejong Telecom (13)	3.12	4.14	0.95	Cable/DSL (73)
Chile (CL)	65	16 (24.6%)	AS 27651 Entel Chile (12)	3.08	1.19	1.04	Corporate (11)

Table 6: Characteristics of the resolvers which demonstrated a statistically significant difference in their handling of DNS queries over IPv4 and IPv6 each country. ‘AS diversity’ denotes the entropies of (all) resolver distribution ( $S_{net}^{all}$ ) and IPv4/IPv6-inconsistent resolver distribution ( $S_{net}^{inconsistent}$ ) across a country’s ASes, and ‘ $V_{net}$ ’ represents the Kullback-Leibler divergence of the distribution of inconsistent resolvers from the distribution of all resolvers in the country’s ASes (*cf.*, §6.2). ‘Most inconsistent type’ denotes the connection type with the most number of IPv4/IPv6-inconsistent resolvers.

would signify that the category distributions are indeed very different suggesting a content-based policy gap.

Based on this analysis, we see that Bangladesh, US and Iran have the smallest  $\nabla_{query}^{domains}$  scores (0-1.3) suggesting that there was little to no difference in the distribution of the two categories. This suggests that for these countries, there is no content-based policy gaps. On the other hand, Pakistan, China and Myanmar had the highest  $\nabla_{query}^{domains}$  scores (2.7-4.3). These scores suggest that some categories of domains get through the IPv4/IPv6 censorship gap much more than others. "Gambling" is the category most likely to get through this gap for China and Pakistan and "Government/Military" is the most likely to get through this gap in Iran.

## 7 Country-Specific DNS Censorship Trends and Mechanisms

**Thailand** One prominent example is Thailand, where 8.2% of A records were blocked by IPv4 resolvers, compared to around 1% for AAAA records or IPv6 resolvers in the country. The reason for this is that many instances of IPv4 resolvers predominantly (or exclusively) saw blocking on only A records, while their IPv6 pair saw little or no blocking on either A or AAAA records. For instance, one of the larger resolvers by blocked domains had an IPv4 endpoint that blocked 240 A records, but only 15 AAAA records from our domain list. Meanwhile, its IPv6 counterpart did not block any domains (either A or AAAA records).

**China** China shows an unusual preference toward blocking AAAA records over A records. While it is known that the Great Firewall can block AAAA records and injects IPv6 traffic, it is not clear why it would block those records more than A records. Manual investigation reveals 21 domains that almost exclusively have their AAAA record blocked, but not their A record. For example, *gmail.com*’s AAAA record is blocked by over 95% of resolvers in China, but the corresponding A record for *gmail.com* is only blocked by 1% of resolvers. The other 20 domains have similar patterns, leading to China’s

slight preference in blocking AAAA records over A records. We do not find any instances of domains in China that are similarly exclusively blocked by A record but not AAAA.

**Iran** While Iran supports both IPv6 and IPv4, it is more effective at blocking IPv4 resolvers (both A and AAAA records). We find this is due to the fact that many of the IPv6 resolvers in Iran are actually **6to4 bridges**: these are IPv6 addresses that are not native IPv6, but instead an encoding of an IPv4 address. For example, sending an IPv6 packet to `2002:0102:0304::` will send the packet encapsulated in an IPv4 packet to 1.2.3.4 (at the 6to4 gateway), whose 32-bit address is encoded in the IPv6 address (0102:0304). However, this can result in the packet passing encapsulated past the censor, who will observe an IPv4 packet with a protocol field denoting IPv6 encapsulation, instead of the usual UDP-carrying DNS. A naive censor may ignore such packets, allowing the domain lookup through unchecked and uncensored. We observe 272 IPv6 resolvers are actually 6to4 bridges in Iran, all of which block at lower (but non-zero) rates, compared to their corresponding IPv4 resolver.

**Trends** We observe two general trends that apply to many censoring countries in our data. First, **IPv4 resolvers are more heavily censored than IPv6 resolvers**. This may be because censors in those regions only inspect IPv4 packets, or that censors are more widely deployed on IPv4 networks. Second, **Native record types are more heavily censored than non-native records**. In other words, an A record requested from an IPv4 resolver is more likely to be censored than a AAAA record from the same interface. But conversely, we find that AAAA records are also more often censored on IPv6 resolvers than A records. This could be because a censor only supports detecting AAAA records in IPv6 traffic, and only A records in IPv4.

## 8 Related Work

There is a significant body of previous work investigating DNS based censorship strategies which can be generally broken down along a few major fault lines. The first is duration: snapshot studies as compared with longitudinal measurements. Many initial investigations into censorship techniques and proposals for measurement methodology provide an evaluation of DNS censorship during a single snapshot in time [5, 9, 30, 33, 35]. Similarly, a snapshot can capture DNS censorship centering around a specific event like an election or social uprising [6]. Established methodology can then be used to gain perspectives on the way that censorship evolves over time as part of a longitudinal measurement [16, 19, 28, 34].

The second major fault line that studies split across is scope: studies that focus in on the DNS censorship strategies used by individual countries as contrasted with global measurement. Censorship strategies are not universal and each censor is unique to some degree. Targeted measurement studies contribute to a better understanding of block-list infrastructure [19, 31] and explain blocking phenomena [5, 9]. Global studies provide high level view on the use of DNS censorship internationally providing context and understanding of prevalence to specific censorship techniques [28, 30, 33–35].

This work describes a methodology for collecting global measurement of IPv6 DNS censorship data and provides a snapshot analysis of several countries of interest.

**Using Open Resolvers.** Open DNS resolvers provide a unique vantage point from which to study the internet and a significant number of past measurement studies rely on their potentially censored traversals to measure suspect or adversarial behavior. Here we present a non-exhaustive timeline to distinguish methodology and describe primary contributions of related work relying on open resolvers over last two decades.

In 2007 Lowe et al. queried open resolvers hosted within China eliciting injected responses to characterize Chinese censorship infrastructure and strategy [25]. In 2008 Dagon et al. performed a survey of open DNS resolvers looking for resolvers that would intentionally provide incorrect or malicious DNS records relating to phishing attempts [12]. In 2012 anonymous authors focused in more closely on the explicit censorship of the GFW DNS injection and the collateral poisoning effect that it had on open resolvers around the world [24]. In 2014 Wander et al. used open resolvers to look more broadly for global poisoning of DNS resolution by any censoring country finding that spoofed addresses were leaking primarily from China and Iran [36]. Similar to Dagon et al., in 2015 Kührer et al. performed a global study of the reliability of open DNS resolution finding evidence of censorship, injected advertisements, and other suspicious or malicious behavior by returned addresses [21].

Satellite (2016) outlines a methodology for regularly discovering the set of available open resolvers and querying

hosts in order to detect paths that return incorrect or inconsistent resource records [33]. Iris (2017) relies on a very similar scanning methodology but develops a set of metrics using follow-up scans and requests that allow the authors to differentiate between inconsistency, misconfiguration, and manipulation [30]. These metrics are based on things like address consistency, TLS certificate validation, HTTP content hash, geolocation, DNS PTR lookup, and AS information. These supplemental elements allow Iris to handle cases like CDNs, virtual hosting, distributed / forwarded resolution requests and more. The 2020 Censored Planet project incorporates and extends the methods of the Satellite and Iris as part of a comprehensive and longitudinal global censorship measurement study [34]. The measurement platform improves the filtering of open resolvers using a set of trusted resolvers as a base of truth and validates TLS certificates for returned resource records. However as with Satellite and Iris, resolvers are discovered using `zmap`, limiting the measurement to the IPv4 address space.

**IPv6 Censorship Measurement.** Previous censorship studies primarily focus on measurements in IPv4 assuming that the mechanisms and block-lists are largely equivalent or finding that results were close enough to be considered noise relative to the independent question at hand. However, several efforts explicitly cover IPv6 results.

In March 2020 Hoang et al. began collection of DNS records injected by the GFW in order to classify the addresses provided, block-pages injected, and the set of hostnames that receive injections [19]. Their analysis investigates the commonality of addresses injected by the GFW, finding that all injected AAAA responses are drawn from the reserved teredo subnet `2001::/32`. The longitudinal study does not directly compare the injection rates of A vs AAAA or differences in injection to DNS queries sent over IPv4 versus IPv6.

A 2021 investigation of HTTP keyword block-lists associated with the GFW found that results are largely the same between IPv4 and IPv6 [37]. However, the authors note that the GFW failed to apply the temporary 90 second “penalty box” blocking subsequent connections between the two hosts described by numerous previous studies [8, 38]. This supports our finding that for now the GFW infrastructure supporting IPv4 and IPv6 are implemented and/or deployed independently.

## 9 Discussion and Conclusions

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## A Full list of countries / resolvers

Country	Resolver pairs	IPv4 A	IPv4 AAAA	IPv6 A	IPv6 AAAA	Avg.
United States (US)	1228	1.40	0.94	0.49	0.85	0.92
Germany (DE)	753	1.00	0.92	0.75	0.81	0.87
Korea (KR)	632	2.33	1.06	1.24	1.22	1.46
France (FR)	560	0.56	0.47	0.39	0.54	0.49
Russia (RU)	312	5.51	4.78	4.49	4.50	4.82
Iran (IR)	277	25.12	24.49	21.95	21.45	23.25
Viet Nam (VN)	252	1.53	0.89	1.42	0.67	1.13
Taiwan (TW)	248	1.16	1.03	0.86	0.95	1.00
India (IN)	226	1.27	1.52	1.04	1.16	1.25
Canada (CA)	199	0.74	0.36	0.23	0.30	0.41
United Kingdom (GB)	196	1.14	0.92	0.77	0.97	0.95
China (CN)	194	29.27	32.32	28.41	32.08	30.52
Thailand (TH)	186	8.25	1.18	1.13	0.93	2.87
Brazil (BR)	160	2.67	1.67	1.99	2.08	2.10
Japan (JP)	152	1.12	1.18	0.56	1.01	0.97
Mexico (MX)	150	3.78	2.05	1.75	1.94	2.38
Turkey (TR)	114	1.29	0.96	1.27	1.02	1.14
Netherlands (NL)	97	1.17	0.78	0.72	0.70	0.85
South Africa (ZA)	93	2.41	1.60	1.18	1.33	1.63
Australia (AU)	72	1.56	0.70	0.95	0.66	0.97
Hong Kong (HK)	67	7.00	5.57	4.91	5.24	5.68
Chile (CL)	65	2.67	0.70	1.10	0.79	1.32
Switzerland (CH)	60	0.32	0.34	0.28	0.34	0.32

Indonesia (ID)	56	6.46	2.99	2.41	2.26	3.53
Lithuania (LT)	52	0.95	0.80	0.51	0.78	0.76
Singapore (SG)	50	1.76	0.86	0.64	0.78	1.01
Malaysia (MY)	50	4.92	2.03	1.27	1.35	2.39
Spain (ES)	49	0.91	0.75	1.40	1.94	1.25
Poland (PL)	48	2.00	1.13	2.90	0.96	1.75
Argentina (AR)	47	5.20	3.51	2.22	1.28	3.05
Romania (RO)	44	2.30	1.03	0.83	0.93	1.27
Czechia (CZ)	41	1.60	1.06	0.50	0.51	0.91
Italy (IT)	38	2.36	2.10	2.25	2.52	2.31
Ukraine (UA)	35	6.49	3.05	2.64	2.87	3.76
Sweden (SE)	34	0.36	0.29	0.51	0.25	0.35
Finland (FI)	34	0.68	0.59	0.43	0.52	0.56
Belgium (BE)	31	1.56	1.26	0.95	0.95	1.18
Bulgaria (BG)	30	3.24	2.91	1.15	1.06	2.09
Bangladesh (BD)	29	6.42	1.28	0.89	0.81	2.35
Colombia (CO)	27	3.39	3.28	1.45	1.14	2.31
Saudi Arabia (SA)	24	2.21	1.81	1.60	1.60	1.81
Pakistan (PK)	23	3.74	1.59	4.64	1.86	2.96
Hungary (HU)	22	0.29	0.27	0.23	0.31	0.27
Ecuador (EC)	21	3.29	2.94	0.38	0.77	1.84
Greece (GR)	20	0.49	1.15	0.41	0.53	0.64
Kazakhstan (KZ)	19	2.90	2.01	2.42	2.21	2.38
Philippines (PH)	18	4.34	2.36	2.45	1.96	2.78
Norway (NO)	16	0.27	0.32	0.31	0.40	0.32
Slovakia (SK)	14	0.22	0.24	0.22	0.26	0.24
Egypt (EG)	14	5.59	4.12	3.05	3.47	4.06
Denmark (DK)	13	1.68	1.26	0.93	1.05	1.23
Portugal (PT)	11	2.16	0.39	0.23	0.27	0.76
Peru (PE)	11	2.04	0.81	0.69	0.65	1.05
Nigeria (NG)	9	3.42	1.38	1.65	1.43	1.97
Austria (AT)	8	0.11	0.19	0.07	0.14	0.13
Kenya (KE)	8	7.79	1.40	1.14	1.07	2.85
Moldova, Republic of (MD)	7	5.46	3.58	2.90	3.04	3.75
Serbia (RS)	7	0.18	0.12	0.14	0.10	0.14
Nepal (NP)	7	1.10	1.22	0.80	0.98	1.03
Slovenia (SI)	7	3.48	0.24	0.14	0.16	1.01
New Zealand (NZ)	7	4.30	0.20	0.46	0.16	1.28
United Arab Emirates (AE)	6	1.61	0.86	1.10	0.89	1.11
Estonia (EE)	6	1.61	0.42	0.28	0.42	0.68
Costa Rica (CR)	6	8.57	2.45	2.19	2.10	3.83
Uruguay (UY)	6	0.70	0.42	0.23	0.19	0.39
Macao (MO)	6	4.44	4.48	4.44	4.51	4.46
Mongolia (MN)	5	1.88	0.67	0.59	0.70	0.96
Libya (LY)	5	1.40	0.76	0.39	0.42	0.74
Sudan (SD)	5	4.59	4.48	2.38	2.32	3.45
Venezuela (VE)	5	6.67	1.62	0.81	0.73	2.46
Belarus (BY)	5	1.01	0.73	0.45	0.62	0.70
Panama (PA)	5	3.75	3.98	0.31	0.45	2.12
Armenia (AM)	5	0.87	0.64	0.59	0.73	0.71
Uzbekistan (UZ)	4	0.53	0.85	0.82	0.74	0.74
Belize (BZ)	4	5.92	0.53	0.42	0.39	1.81
Latvia (LV)	4	0.11	0.11	0.14	0.14	0.12
Luxembourg (LU)	4	1.86	0.07	0.07	0.21	0.55
Albania (AL)	4	0.70	0.56	0.42	0.42	0.53
Iraq (IQ)	4	3.57	2.45	2.14	2.14	2.57
Bosnia and Herzegovina (BA)	4	2.21	0.70	0.63	0.70	1.06
Guatemala (GT)	4	0.60	0.56	0.39	0.21	0.44
Jordan (JO)	4	0.28	0.21	0.14	0.42	0.26
Bolivia (BO)	4	1.16	0.53	0.32	0.28	0.57
Lebanon (LB)	3	0.61	0.33	0.28	0.33	0.39
Dominican Republic (DO)	3	4.76	0.75	0.28	0.47	1.56
Honduras (HN)	3	1.49	1.45	0.65	0.61	1.05
Croatia (HR)	3	0.14	0.23	0.19	0.14	0.18
Afghanistan (AF)	3	2.24	1.12	1.91	1.82	1.77
Cambodia (KH)	3	3.17	0.90	0.47	0.43	1.24
El Salvador (SV)	2	0.84	0.35	0.14	0.21	0.39
Nicaragua (NI)	2	3.78	0.28	0.35	0.07	1.12
Lao (LA)	2	9.24	0.56	0.21	0.28	2.57
Oman (OM)	2	5.46	0.70	0.42	0.70	1.82
Israel (IL)	2	2.73	2.94	2.73	2.66	2.77

Guam (GU)	2	8.05	0.35	0.00	0.35	2.19
Georgia (GE)	2	1.19	1.26	1.40	0.98	1.21
Trinidad and Tobago (TT)	2	0.35	0.14	0.07	0.00	0.14
Chad (TD)	2	2.73	1.05	0.63	1.12	1.38
North Macedonia (MK)	2	9.52	6.44	4.69	4.83	6.37
Ethiopia (ET)	2	0.14	0.28	25.56	0.21	6.55
Uganda (UG)	2	0.49	0.49	0.56	6.65	2.05
Tunisia (TN)	2	0.35	0.42	0.35	0.49	0.40
Cyprus (CY)	2	4.83	0.70	0.35	0.21	1.52
Paraguay (PY)	1	3.26	1.56	1.28	1.13	1.81
Kyrgyzstan (KG)	1	0.57	0.71	0.43	0.85	0.64
Seychelles (SC)	1	0.28	0.43	0.28	0.57	0.39

<b>Global</b>	7,428	3.10	1.83	1.77	1.60	2.07
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Table 7: Full list of measured rates of DNS censorship across both query types and network interfaces. Rates are expressed as the percentage of censored DNS queries over total number of DNS queries sent. Darker shaded cells indicate a higher rate of DNS censorship (compared to the country’s average) and lighter shaded cells indicate a lower rate of DNS censorship. The average rate of censorship for a country is computed across all four IP/query combinations. The global row contains the mean of each column. These means weigh the contribution of each country equally, rather than weighted by the number of resolvers used in tests.