ABSTRACT
The Explicit Congestion Notification (ECN) field has taken on new importance due to Low Latency, Low Loss, and Scalable throughput (L4S) technology designed for extremely latency-sensitive applications (such as cloud games and cloud-rendered VR/AR). ECN and L4S need to be supported by the client and server but also all devices in the network path. We have identified that “ECN bleaching”, where an intermediate network device clears or “bleaches” the ECN flags, occurs and quantified how often that happens, why it happens and identified where in the network it happens.

In this research, we conduct a comprehensive measurement study on end-to-end traversal of the ECN field using probes deployed on the Internet across different varied clients and servers. Using these probes, we identify and locate instances of ECN bleaching on various network paths on the Internet. In our six months of measurements, conducted in late 2021 and early 2022, we found the prevalence varied considerably from network to network. One cloud provider and two cellular providers bleach the ECN field as a matter of policy. Of the rest, we found 1,112 out of 129,252 routers, 4.17% of paths we measured showed ECN bleaching.

1 INTRODUCTION
RFC 3168 [29] specifies the incorporation of Explicit Congestion Notification (ECN) to TCP/IP, which allows routers to signal impending congestion to endpoints before buffers overflow or packets get dropped by routers. The IP header contains a 2-bit field known as the ECN field to enable such an end-to-end notification of impending network congestion without dropping packets. To enable ECN, a sender marks its packets as ECN-Capable and then reacts to congestion signaled by the network. As packets traverse the network, congested devices mark ECN-enabled packets to indicate congestion rather than dropping those packets. The receiver monitors received packets for ECN congestion signals and sends congestion feedback to the sender. ECN relies on the network devices to either pass along packets with the ECN information unmodified if there is no congestion or to indicate congestion by marking the ECN bits. It only takes one misbehaving device in a network path to eliminate the benefit of ECN – if any network device between a sender and receiver clear the ECN bits, the sender and receiver will not learn about the impending congestion.

There are several benefits to ECN [12], particularly as a congestion signal that reduces application latency by foregoing dropping packets to signal congestion. Congestion control algorithms treat ECN congestion signals identically to packet drops as far as congestion response. Most OSs have ECN enabled by default [22, 23], meaning they respond to and use ECN if requested by the sender.

Recently, the L4S (Low Latency, Low Loss, and Scalable throughput) standard proposal [6] recognized that the original definition of ECN could be improved to significantly reduce latency and latency variation, and could improve the scalability of congestion control designs for wide-area networks using the mechanisms previously used in Datacenter TCP [2, 4] while coexisting with the existing TCP and QUIC traffic on the Internet. L4S aims to enable high-bandwidth, extremely latency-sensitive applications, such as cloud games and cloud-rendered VR/AR, to achieve their performance objectives to a degree that has not been practically feasible with existing congestion feedback mechanisms and is a key element of proposed access network technologies such as Low-Latency DOCSIS. L4S uses the ECT(1) codepoint as an
identifier for ‘L4S’ packets to be distinguished from ‘classic ECN’ packets and has a separate treatment of L4S packets via an independent queue to reduce queuing delay [31]. Unfortunately, some network devices clear or “bleach” the ECN bits, limiting the benefit of ECN and also L4S.

ECN is widely available since most server OSs have ECN enabled by default [22, 23]. Studies [3, 23, 33] using path traversal of ECN using a traceroute-based method have shown that path traversal of ECN has become close to universal (as long as two endpoints have ECN enabled), but there are still a non-trivial fraction of paths along which network nodes wipe the ECN field of packets. In 2019, Roddav et al. [30] used passive measurements to show that only 5.23% of traffic is using ECN codepoints, possibly because of ECN “bleaching”.

It remains largely unknown where such bleeding paths are prevalent in the Internet in terms of ISPs and geographical regions, and why they exist or if ECN signaling is being used. Mandalari et al. [23] observed that more than half of the mobile carriers that they tested bleach the ECN field to zeros, and the ECN bleeding cases happen in the first hop from mobile clients. Two recent studies [5, 14] indicate that there are a few networks that have enabled ECN congestion signaling, but the majority have not.

In light of significant interest in the new L4S ECN architecture, it is now the time to revisit the usability (i.e. traversal) of ECN in cellular as well as wired networks. We conducted a study of a 24 hour passive trace of network traffic at a single vantage point within a University network, looking at the prevalence of the different values within ECN fields in the IP and TCP packet headers. We also have conducted an active measurement study on end-to-end traversal of the ECN field using probes deployed on the Internet across different locations and providers using two forms of active measurements. First, we used PATHspider [22] to determine which HTTP/HTTPS servers have ECN enabled to better understand ECN adoption. Then, using a tool we developed, we identified and located instances of ECN bleeding on various network paths on the Internet.

We learned different things from our passive and active measurements. In our six months of measurements, conducted in late 2021 and early 2022, aside from one cloud provider that bleaches the ECN field as a matter of policy, we found 1,112 out of 129,252 routers, and 4.17% of paths showed ECN bleeding and many networks have no bleeding. However, previous studies [30] using passive measurements showed that only 5.23% of traffic is using ECN, which is a perplexing result given that ECN is enabled for most modern OSs. We found that although ECN is enabled by receivers for incoming packets, ECN is not requested for outgoing packets by senders by default. In other words, many networks and servers are ready for ECN but client devices [15] or applications [26] need to enable ECN for it to be used.

The remainder of this paper is structured as follows. First, we describe the old (classic) and new (L4S) schemes of ECN in Section 2. Then, in Section 3, we present the probes we use and the data collection methodology. Next, using the results from our methodology, we characterize the current state of ECN traversal and compare it to previous studies in Section 4. We discuss additional results in Section 5. Finally, Section 6 reviews related work before Section 7 concludes with a summary of our findings.

2 BACKGROUND

2.1 Explicit Congestion Notification

The original ECN specification (i.e. Classic ECN) was standardized in 2001 to allow routers to provide end-to-end notification of incipient network congestion instead of using packet drops as an indication of congestion [29]. The basic idea behind ECN is to provide an unambiguous signal of congestion without additionally causing a degradation (i.e. packet loss) in the transfer of data. In a router, ECN is implemented via an active queue management (AQM) mechanism that evaluates queue depth and/or queue latency, and when the queue exceeds a threshold it marks the packet to indicate congestion has been experienced. The benefits of ECN include reducing packet loss in the Internet, which in turn leads to avoiding an increased application-layer latency caused by packet retransmissions. As a result, ECN improves the user experience in latency sensitive applications.

We provide a brief overview of how ECN works with TCP (on top of IP), assuming that two endpoints and all the intermediate routers between the endpoints are ECN-capable. ECN uses an ECN field of two bits in the IP header, which are the last two bits of the type of service (TOS) field originally

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Table 1: Dataset types and descriptions.

| Type     | Data collection         | # of paths | Data size |
|----------|-------------------------|------------|-----------|
| Active   | Server measurement      | 2,656,935  | 3.4 GB    |
| Active   | Traceroute localization | 530,795    | 2.4 GB    |
| Passive  | 1-day traffic trace data| -          | 9.8 GB    |

Table 2: ECN codepoints and their meanings.

| ECN codepoint | Binary | L4S meaning            |
|---------------|--------|------------------------|
| Not-ECT       | 00     | Not ECN-capable transport |
| ECT(0)        | 10     | Classic ECN-capable transport |
| ECT(1)        | 01     | L4S-capable transport |
| CE            | 11     | Congestion experienced |

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1 The ECT(1) codepoint was originally defined along with ECT(0) to indicate ECN-Capable Transport (ECT) in the ECN specification [29].
defined in the IP header. The codepoints of the ECN field and their meanings are shown in Table 2. The ECT codepoints '10' and '01' – ECT(0) and ECT(1) – were originally equivalent in the ECN specification [29], but ECT(1) has been repurposed to indicate L4S packets under the L4S service architecture [6], leaving ECT(0) to indicate Classic ECN packets. ECN also requires support from the transport protocol (i.e., TCP) in addition to the functionality provided by the ECN field of IP packets.

The endpoints, i.e., TCP client and server, first negotiate ECN capability during the establishment of their connection. After successful negotiation, a Classic ECN sender sends IP packets with ECT(0) set in the ECN field to indicate that they are ECN-capable. If a router detects impending congestion (with the help of an AQM mechanism) when a Classic ECN-capable packet arrives at the router, it marks the ECN field of the packet with the CE codepoint, and forwards the packet instead of dropping it. When the receiver receives this packet with CE set in the ECN field, it informs the sender of the congestion indication by sending its next TCP ACK with the ECN-Echo (ECE) flag marked in the TCP header. Upon receiving this TCP ACK, the sender then reacts to the congestion as if a packet has been dropped and sends the next packet with the Congestion Window Reduced (CWR) flag marked in the TCP header to acknowledge the receipt of the congestion indication. Note that the ECE and CWR flags in the TCP header are also used for the negotiation of ECN capability during connection establishment. See [29] for more details.

| OS and version       | Default ECN setting                                      |
|----------------------|---------------------------------------------------------|
| Linux kernel 2.4.20  | Enabled for incoming ECN connections                    |
| Mac OS X 10.11, iOS 9| Enabled for incoming ECN connections                    |
| Windows Server 2012 | Enabled for both incoming and outgoing ECN connections  |

Table 3 shows default ECN settings in the current major OSs. Most modern OSs use ECN and echo incoming ECN connections, but do not initiate the use of ECN on outgoing connections. In other words, many networks and servers are ready for ECN. However, client devices [15] or applications [26] need to enable ECN for it to be used.

### 2.2 L4S

L4S is a service architecture that uses ECN as an integral component to achieve high bandwidth and low latency for Internet applications and is currently undergoing standardization [6]. The main idea behind L4S is to take advantage of the fact that the congestion signal in ECN isn’t a degradation in the way that packet drops are, and thus congestion signals can be sent much more frequently in order to provide high-fidelity congestion information. As mentioned above, L4S redefines the ECT(1) codepoint to indicate L4S-Capable Transport, and in the context of an L4S flow it redefines the CE codepoint to provide this fine-grained congestion feedback.

L4S supports incremental deployment, via a classic congestion control response to packet drops, and via in-network isolation of classic traffic from L4S traffic. L4S routers isolate these two types of traffic from one another so that the queuing latency caused by classic traffic doesn’t impact L4S traffic, and so that the two types can each be provided their appropriate congestion signals. Two queuing mechanisms have been defined for this purpose. One is referred to as Dual-Queue Coupled AQM, the other is an L4S-aware flow queuing approach.

Dual-Queue Coupled AQM routers have two separate queues at the network bottleneck one for L4S traffic and one for classic traffic, where the ECN field is used as an identifier for L4S packets to be distinguished from classic packets. The queue for L4S traffic has a shallower (or smaller) buffer size, which allows the L4S packets to experience very low queuing delay. Additionally, packets in the L4S queue are marked with CE in the ECN field (to notify the endpoints of impending congestion) as soon as they start building up in the queue (e.g. when the queue delay exceeds a low threshold of 500 µs or 1 ms). However, the queue for classic traffic has a larger buffer to maintain full utilization since the queue needs to be large enough to cope with large saw-tooth rate variations by a classic congestion control. In addition, despite the use of separate queues, the congestion signaling is coupled between the queues so that the two types of traffic share the bottleneck bandwidth in a fair manner. See [6, 32] for more details.

The L4S-aware flow queuing approach provides a separate queue for each individual flow based on a hash of the header 5-tuple, and then provides CE-marking of ECT(1) packets via a shallow queue delay threshold (e.g. 1 ms) while ECT(0) or Not-ECT packets are CE-marked or dropped (respectively) using a classic AQM algorithm.

L4S is not limited to a certain type of network but can be implemented in different types of networks. However, the implementation of L4S in different networks poses different sets of obstacles, especially when L4S is implemented in 5G [7, 37] and WiFi [27].

### 3 MEASUREMENT METHODOLOGY

In this section, we explain the details of our methodology for active and passive measurements to examine the status quo
of the deployment and traversal of ECN in a wide range of wired and cellular networks. Specifically, we use a ‘request and respond’ method and a traceroute-based method for active measurement to test or probe specific paths to measure ECN capability. To complement the active measurement results, we also passively collect and analyze a 24-hour trace of network traffic at a vantage point within a large university campus network to understand what fraction of traffic is ECN-enabled or how widely ECN is currently being used in practice.

3.1 Active Measurement

3.1.1 Request and Respond Method. We use the active measurement tool called PATHspider [22] for the request and response method to investigate the server-side deployment of ECN and the traversal of ECN over the paths to servers. There are two phases in this method, namely ECN negotiation phase and data transmission phase.

First, the ECN negotiation phase allows us to confirm the ECN support of a target web server if the negotiation with the server succeeds. Specifically, a probe attempts to negotiate ECN capability with a targeted server while establishing a TCP session with the server. The probe first sends to the server a TCP SYN segment with ECE and CWR flags set in the TCP header. The server then sends back to the probe a SYN-ACK segment with ECE flag set, if the server supports ECN. Otherwise, the server just sends a plain SYN-ACK segment. After that, the server responds with an ACK to finalize the negotiation and establish a new session with the probe. It is worth noting that the ECN negotiation is invisible to routers in the path between the probe and the server since it is done at the transport layer. In other words, the routers do not affect the ECN negotiation even if there is a router in the path that bleaches the ECN field of IP packets.

Second, the data transmission phase allows us to check whether ECN bleaching happens along the path from the probe to the server, assuming that the server supports ECN. The probe starts with sending an HTTP request to the server, where the IP packet carrying the HTTP request has ECT(0) marked in the ECN field. The server then sends an HTTP response back to the probe. The ECN field of the IP packet carrying a part of the HTTP response has either ECT(0) or CE marked, where ECT(0) is 0b10 and CE is 0b11. While the former is for normal cases, the latter happens when a router in the path signals impending congestion by setting the ECN field of the packet with CE. However, if ECN bleaching happens at a router in the path (i.e., the router clears the ECN field to 0b00), the IP packets received by the probe lose the ECN marking. Therefore, we can identify the presence of ECN bleaching by looking at the ECN field of incoming IP packets from the server.

3.1.2 Traceroute Method. To investigate whether the ECN-marked IP packets traverse the network without any illegitimate modifications, we use the traceroute-based method that has been used in the literature [3, 10, 23, 34]. For a source
when its TTL expires. In this case, the router also generates
A Fresh Look at ECN Traversal in the Wild,,

3.1.3 Measurement Probes. For the above active measurements, we use three types of probes, which are crowdsourced probes, cellular probes, and cloud probes.

Crowdsourced probes. We deployed the ECN measurement probes within the home and work ISP networks of 11 volunteers who participate in this study. The majority of the volunteers are located in the U.S., and the others are in Canada, Argentina, and Germany. Specifically, the 11 volunteers from four countries installed measurement probes in 10 different home and work ISP networks, namely, Armstrong, Charter, Comcast, Cox, Rogers, Shaw, Telecom Argentina, Verizon business, and Vodafone. Many of the probes are deployed behind NAT/firewall in which case they only function as source probes for the traceroute-based method. Note that we did not use PATHspider with the crowdsourced probes since the volume of the traffic generated by PATHspider can be a burden to the volunteers.

Cellular probes. We set up laptops with USB tethering as cellular probes to connect to cellular networks in order to examine ECN capability in cellular networks. We consider the cellular networks of six major US and South Korean carriers in this study, namely AT&T, Verizon, T-mobile, KT, LGU+, and SKT. The cellular probes do not have public IP addresses to be connected from the outside of a network, so they only act as source probes for the request and respond method.

Cloud probes. We placed 37 cloud probes (or vantage points) in 33 geographic regions around the world and within the cloud servers operated by five different cloud service providers, namely, AWS, Azure, GCP, DigitalOcean, and Cloudlab. Cloudlab [11] is the only non-profit cloud service that provides high-performance computing and networks across several states in the U.S. We set up a virtual machine (VM) server at each one of multiple cloud servers for each provider. The VM servers installed in multiple locations are to reflect the presence of multiple cloud servers across different geographical regions. In addition, each VM server has a public IP address, which allows it to be connected from other probes.

It is worth noting that we would not get meaningful results if we only use cloud probes, as most of the primary cloud service providers, such as Amazon, Google, and Microsoft, have massive private WANs, which hide tenant traffic from the public Internet.

3.2 Passive Measurement

While the above two active measurement methods allow us to examine the status quo of the ECN readiness in various types of networks, they cannot be used to reveal how widely ECN is currently being used in practice. To this end, we collected and analyzed a 24-hour trace of network traffic, whose data size is 10GB, at a vantage point within a large University campus network, from which we can see how widely ECN is currently being used among the traffic over the campus network.

We post-processed the traffic data as follows. We first obtained packet traces that only contain the IP and TCP/UDP headers of packets by stripping out their actual payloads. We next identified a packet trace per flow. The flow information that we collected includes the source and destination IP addresses and their country codes, port number, the ECN codepoint of the ECN field in the IP header, and the ECE and CWR flags in the TCP header, if the flow is a TCP flow. From the per-flow information, we were able to obtain the overall distribution of the ECN codepoints in the IP header as well as that of the ECE and CWR flags in the TCP header. We were also able to find the separate distributions of the ECN codepoints per port number. We finally investigated possible causes for the case when ECN(0) or ECN(1) is set in the ECN field of IP header while its upper transport protocol is not TCP.

4 MEASUREMENT RESULTS

In this section, we closely examine the ECN field in the wild. We first present the ECN support results from our vantage points to public websites. We then use the traceroute-based method to understand how many Internet paths support ECN and pinpoint where ECN bleaching happens. Lastly, we examine the overall usage of ECNs from traffic traces collected on a University campus.

4.1 ECN-enabled Public Websites

4.1.1 Methodology. To consider CDN deployment of popular websites listed as Alexa 100K website domains [1], we chose 16 different vantage points out of 25. We then obtained
404,382 unique IP addresses for these websites by removing duplicate ones. We use the request and response method using PATHspider to check if ECN is supported from each vantage point to each website, where our probe in each vantage point sends an HTTP request and checks the response. We ensure that a middlebox or the network where each vantage point is hosted is not mangling TCP and IP headers.

Figure 2: Geographic locations of tested Alexa 100K web servers. Since popular domains provide their service from geographically distributed clouds, the total number of unique IPs 404,382 is much more than the number of listed domains. U.S. accounts for most of the IPs by 53.6%, followed by Germany (4.8%), Russia (4.3%), and Canada (3.8%).

Web server locations. We are interested in understanding where these websites are geographically located. We use whois command to locate each IP address. Figure 2 shows the locations of Alexa 100K websites by using the location information (i.e., City, StateProv, and Country) from each whois query. The majority of Alexa 100K websites are located in the U.S. (56%), followed by Germany (4.8%), Russia (4.3%), and Canada (3.8%).

Web server hosting providers. We are also interested in service providers hosting these websites. We classify each IP address based on the service providers’ names using the whois response. Figure 3 shows the top 10 providers for Alexa 100K websites. We obtained around 10,950 providers serving these websites. We found that many web servers are hosted in major data centers in the U.S. with Cloudflare and Amazon being the top 2 providers, serving 21.1% and 17.1%, respectively.

4.1.2 ECN deployment status on the servers. Figure 4 shows the ECN deployment ratio over the last two decades in chronological order. Measurement studies [20, 25, 28] before 2010 reported an almost negligible number of ECN-enabled web servers. The study in 2015 [24] reported that ECN deployment had rapidly increased to 80%. Our measurement study shows that the percentage of ECN-supported web servers is now 86.4%, following the trend shown in the 2015 study. These servers offer successful ECN negotiation to the client during TCP session establishment; this percentage still includes the cases where a TCP session with successful ECN negotiation is bleached in IP packets by some intermediate routers.

Table 4 shows the details of this measurement results. Among 349,188 (85.4%) ECN-enabled Web servers completing successful ECN negotiation in TCP session establishment, 37,798 (10.8%) hosts show ECN bleaching in IP packets; we conjecture that these paths have ECN bleaching points between the vantage points and these Web servers. The 0.2% percentage of CE marking on ECN-enabled connections matches the results by Apple in 2017 [5] that the percentage of CE marking in the packets between two ECN-enabled devices in the U.S. shows 0.2% while it varies from country to country.

4.1.3 ECN-enabled paths within or across continents. By sending a request from the vantage points hosted in cloud
Table 4: ECN-enabled web servers obtained from one vantage point to the list of public websites (404,382 IPs).

| Codepoint | Enabled (pct) | Disabled (pct) |
|-----------|---------------|----------------|
| Total     | 349,188 (86.4%) | 55,194 (13.6%) |
| 00: Not-ECT | 37,798 (10.8%) | 55,141 (99.9%) |
| 10: ECT(0) | 259,634 (74.4%) | 48 (0.99%) |
| 01: ECT(1) | 50,898 (14.6%) | 3 (0.01%) |
| 11: CE     | 858 (0.2%) | 2 (0.004%) |

providers where no local ECN bleaching is observed to public websites, we measure the percentage of ECN-enabled paths showing successful ECN negotiation in TCP sessions. Figure 5(a) visualizes ECN-enabled paths within or across continents. –1 indicates no available measurement data. Interestingly, no particular region supports ECN better than the others. We conjecture that ECN-enabled paths depend largely on the OS version and settings of hosting web servers which may not correlate with geographical locations. If we average for each destination continent, the ECN-enabled path ratio becomes close to 86.4% of the ECN deployment ratio in Figure 4.

Figure 5: ECN-enabled and ECN-bleaching path ratios within and across continents. –1 represents no results available. ECN-enabled paths are less correlated with the geographical locations of clients and web servers (a). Europe (EU) and South America (SA) show the highest bleaching ratio within the same continent. The requests sent from vantage points in North America (NA) show higher ECN bleaching rates (over 40%).

4.1.4 ECN-bleached paths within or across continents. From each ECN-enabled path of successful ECN negotiation in TCP sessions (Figure 5(a)), we show the ECN bleaching ratio where ECN bits are wiped in IP packets (Figure 5(b)). Europe (EU) and South America (SA) show the highest bleaching ratio within the same continent. North America (NA) was the highest ECN bleaching source among the other continents. The Africa (AF) websites show relatively low bleaching rates except for NA-originated traffic, while Oceania (OC) websites show the lowest ECN bleaching rates. These results illustrate that the ECN bleaching points are located primarily in North and South America and Europe.

4.1.5 ECN bleaching from different access networks. We check the impact of different access networks when clients located in each access network connect to public websites. Table 5 shows the summary of ECN negotiation and bleaching percentages for different types of access networks and providers. In wired access networks, Comcast shows a 51.35% ECN bleaching percentage among the ECN-enabled paths with successful ECN negotiation (86.8%). In contrast, the other providers show around 10% ECN bleaching percentage, which matches the overall ECN deployment percentage in Table 4.

In cellular networks, AT&T shows ECN negotiation responses come from the middleboxes at the TCP connection establishment phase, not by the destination web servers. We confirmed this behavior by sending an ECN negotiation packet to ECN-disabled web servers. Surprisingly, the client successfully negotiates ECN with any web server (99.8%)2, indicating the presence of performance-enhancing proxies (PEPs) in the network. On the other hand, SKT in South Korea bleaches 100% of ECN-negotiated sessions; it wipes ECN bits in all IP headers.

4.1.6 ECN bleaching from different cloud providers. We now check if cloud providers support ECN when clients in their cloud connect to public websites. Table 6 shows the results. Interestingly, clients in Azure failed 100% in ECN negotiation. We conjecture that PEPs in its network change

We confirm that this is not because of the USB tethering.
the ECN field without following the standards. We confirmed the alteration at the middleboxes with additional testing with our own servers with ECN enabled and disabled, respectively. Another key observation is that GCP bleaches 100% in IP headers even after successful ECN negotiation in TCP headers. We conjecture that Google removes ECN in IP packets to use it internally in their datacenters.

4.2 ECN-supported Internet Paths

4.2.1 Methodology. The trends in Subsection 4.1 highlight that the ECN deployment ratio in public websites is reaching 90% and is already well used on the Internet, while the network bleaches 10% of those ECN-enabled websites. To understand and pinpoint where in the network ECN fields are being altered or bleached, we use the traceroute-based method mentioned in Section 3.1.2 towards each ECN-enabled public website. We further categorize the types of ECN violations and seek potential causes of ECN bleaching.

4.2.2 ECN deployment status in the network. Table 7 shows the number of ECN violating paths and bleaching IP addresses obtained from the traceroute method.

| Input → Output | # of Path (pct) | # of IP (pct) |
|----------------|-----------------|---------------|
| # of Total Case | 534,077         | 129,252       |
| # of Violation  | 22,305 (4.17%)  | 1,112 (0.8%)  |
| Any → ØØ       | 22,111 (99.1%)  | 1,070 (96%)   |
| 10 → Ø1        | 171 (0.76%)     | 33 (2.9%)     |
| 11 → 10 or Ø1  | 24 (0.1%)       | 9 (0.7%)      |

4.2.3 ECN bleaching IPs and locations. To understand where those bleaching IP addresses are located, we use the whois command to locate each IP address. Table 8 shows the geographical distribution of those bleaching points. Europe and South/North America have proportionally higher bleaching points than the others.

4.2.4 ECN bleaching network paths per source ISP. By leveraging our probes in each ISP, we obtain the percentage of ECN bleaching paths among the total number of paths initiated from each ISP. Table 9 shows the results. While it is hard to generalize as we only had a few probes in each ISP, traffic initiated from probes installed in Rogers and Vodafone wired networks and Google Cloud show 100% ECN bleaching.
Figure 6: ISPs of bleaching points. The X-axis represents the ISP name of the bleaching IP addresses. From 1,112 bleaching IP addresses, ISPs in the EU have the highest ECN bleaching percentage.

Table 9: The percentage of bleaching network paths per source ISP.

| Type   | Provider     | location | Bleaching Percentage |
|--------|--------------|----------|----------------------|
| Wired  | Armstrong    | US       | 69.73%               |
|        | Charter      | US       | 53.2%                |
|        | Comcast      | US       | 3.58%                |
|        | Cox          | US       | 38.2%                |
|        | Rogers       | US       | 100%                 |
|        | Shaw         | US       | 19.14%               |
|        | Telecom Argentia | Argentina | 16.57%         |
|        | University A | US       | 9.41%                |
|        | Vodafone     | Germany  | 100%                 |
| Cellular | AT&T        | US       | 48.2%                |
|          | Tmobile      | US       | 5.63%                |
|          | Verizon      | US       | 11.06%               |
| Cloud   | AWS          | 16 Locations | 2.69%           |
|          | Google       | 10 Locations | 100%            |
|          | DigitalOcean | 8 Locations | 5.38%           |
|          | Cloudlab     | Wisconsin | 16.53%           |
|          | Cloudlab     | Clemson  | 5.38%               |
|          | Cloudlab     | Utah     | 2.69%               |

4.2.5 ECN bleaching hops. The bleaching hop number represents where ECN bleaching occurs in the network path. Figure 7 shows the percentages of ECN bleaching observed at relative hops in the paths. We divided a hop number, where we find ECN bleaching, from the total number of hops until the destination. Based on our results, we found that a large portion of bleaching happens in the access network. Also, if ECN bleaching occurs in the access network, the bleaching hop number is no longer than seven hops. The overall bleaching hops are well distributed, but 50% of ECN bleaching occurs in 30% of the total distance between the source and destination.

4.3 Usage of ECN from Traffic Traces

4.3.1 Methodology. We first classify ECN-negotiation succeeded, failed, and no attempt for each TCP session where we further check the ECN field in the IP headers. For UDP,
Table 10: Overall results from passive measurement. ECN is negotiated during TCP connection establishment. Note that the ECN percentage in TCP counts only within successful ECN negotiation flows. For UDP, we only collect the number of UDP flows with ECN codepoints since UDP does not have ECN negotiation standards.

| Type | Port | Protocol | Flow Pct | ECN Negotiation Succeeded | Within ECN Negotiation Succeeded |
|------|------|----------|----------|--------------------------|---------------------------------|
|      |      |          |          |                          | Non-ECT (0b00) ECT(1) (0b01) ECT(0) (0b10) CE (0b11) |
| TCP  | ALL  | (21,888,015) | 100%     | 7.52% 4.85% 87.63%       | 6.14% 0.94% 92.92% 0.005%     |
|      | 443  | HTTPS     | 79.87%   | 8.09% 5.56% 86.35%       | 6.05% 0.9% 93.04% 0.003%      |
|      | 80   | HTTP      | 6.66%    | 4.58% 1.87% 93.55%       | 5.66% 0.4% 93.94% 0.002%      |
|      | 993  | IMAP-SSL  | 0.84%    | 4.88% 19.89% 75.23%      | 8.8% 0.41% 90.79% 0%          |
|      | 25   | SMTP      | 2.13%    | 5.91% 0.32% 93.77%       | 3.04% 2.45% 94.35% 0.163%     |
|      | 22   | SSH       | 1.33%    | 0.28% 0.72% 99.00%       | 6.61% 2.71% 90.68% 0%         |
|      | 5223 | APNs      | 0.09%    | 48.17% 0.47% 51.36%      | 21.44% 0% 78.56% 0%           |
|      | 8443 | HTTPS     | 0.47%    | 18.48% 0.2% 81.32%       | 6.76% 0% 93.24% 0%            |
|      | 53   | DNS       | 0.56%    | 0.01% 0.12% 99.87%       | 0% 0% 100% 0%                 |
|      | 5228 | Android   | 0.09%    | 0.08% 12% 87.92%         | 5.6% 0% 94.4% 0%              |
|      | 587  | SMTP      | 0.62%    | 55.79% 1.73% 42.48%      | 6.2% 5.6% 88.2% 0%            |
| UDP  | ALL  | (81,076,465) | 100%     | - - -              | 99.92% 0.005% 0.07% 0.005%    |
|      | 53   | DNS       | 59.95%   | - - -              | 99.99% 0.0001% 0.007% 0%      |
|      | 123  | QUIC      | 15.75%   | - - -              | 99.72% 0.001% 0.275% 0%       |
|      | 6881 | Game      | 8.53%    | - - -              | 100% 0.001% 0% 0%             |
|      | 51413| P2P       | 0.54%    | - - -              | 99.99% 0.006% 0.002% 0.004%   |

we check the usage of the ECN field in the IP header since UDP does not have any standard for ECN negotiation. Table 10 shows overall statistics of traffic traces. We observe 227,538,956 TCP and 81,076,465 UDP flows. We list the top 10 TCP applications and top 5 port UDP applications from these flows. We map each port number into the corresponding protocol and the usage percentage, as shown in Table 10. We also show the percentage of ECN negotiation failed and succeeded rate in TCP and ECN codepoint for TCP and UDP.

4.3.2 ECN usage in TCP and UDP. We observed that 7.52% of TCP flows negotiated ECN between source and destination, 4.85% of flows failed ECN negotiation during the TCP connection establishment, and the rest (87.6%) did not attempt ECN negotiation. Among the TCP flows of successful ECN negotiation (7.52%), ECT(0), ECT(1), and CE account for 92.9%, 0.94%, and 0.005%, respectively. Overall, more than 87% of TCP flows did not attempt ECN negotiation, which is perplexing considering that most OS versions now support ECN by default, supported by our active measurement (86.4% of ECN-enabled Web servers). We found that although most servers enable ECN for incoming packets, ECN is not requested for outgoing packets by senders by default. Another interesting observation is that Apple’s APNs (Port 5223) and the default port for SMTP submission on the modern web (Port 587) heavily use ECN for their services, while more than 20% of APNs flows are ECN bleached in IP headers.

From the 81,076,465 UDP flows, we found some portions of flows are using ECN in ports 53 and 443. QUIC uses UDP port 443, and DNS uses UDP port 53. QUIC published as RFC 9001 [16] is a UDP-based, stream-multiplexing, and encrypted transport protocol. While a recent measurement study on QUIC [39] did not mention the use of ECN for QUIC, our results confirm that some QUIC flows are now using ECN.

5 DISCUSSION

Although our results discover the current ECN deployment status and violations on the path, there are still some avenues for future measurement and improvements.

Possible causes of ECN bleaching. We have revealed that there are paths to mangling ECN, and the bleaching percentages vary along with the providers. Aside from two exceptional cases of bleaching 100%, the ratio of the bleaching ECN field varies from 3.1% to 51.35%. We discuss two possible explanations for this observation.

There could be a bug in the router software leading to ECN bleaching. We got this clue from the correlation between ECN and DSCP in their bleaching. When ECN bleaching happens, a router overwrites two bits of the ECN field and
the preceding six bits of the DSCP field. These two fields used a single field named ToS, which is deprecated. To figure out the cause, we provided the list of bleeding IPs to the ISPs who own those IPs. One of the ISPs shared information about a bug in an NPU (Neural Processing Unit) that bleaches ECN bits when it rewrites DSCP.

We also conjecture that the complete bleeding is caused by proxies/middleboxes in the provider network. As mentioned in Section 4.1.1, we found two providers which completely bleach ECN. One is a cellular provider, and the other is a Cloud provider. According to recent papers, the cellular network uses a performance-enhancing proxy to improve its network performance. Furthermore, the cloud provider operates its proxy or middlebox, balancing the load from/to the data center.

**Potential impact of ECN bleeding to L4S performances.** Our measurements have identified multiple ECN bleeding cases. As mentioned in Section 2.2, L4S is using ECN as a classifier between a classic queue and an L4S queue. In typical cases, if a packet has ECT(1) or CE, a scheduler puts packets into the low latency queue. However, if an intermediate router has bleached packets marked with ECT(1), those packets will be put into the normal queue instead of the low latency queue. Furthermore, if CE marking is zeroed from one router, the congestion signal cannot reach the destination, potentially causing additional latency for the sender to get the loss signal.

**ECN in cellular networks.** Recently, ECN-based congestion control algorithms such as ABC [13] and ECLAT [17] are introduced to fix a large queue problem in cellular networks. ABC modifies a typical ECN mechanism to use two-bit feedback as a congestion signal for increasing or decreasing the congestion window (CWND). This approach allows the router to explicitly inform how many CWNDs it needs to lower or raise, rather than implicitly notifying the network congestion in the typical ECN mechanism. As a result, performance degradation such as throughput loss and large queuing caused by wide CWND fluctuations is alleviated. ECLAT strictly limits queuing delays within an acceptable time by proactively forwarding ECN feedback to ensure that the CWND does not exceed a certain level for delay guarantees. To do this, ECLAT analyzes ECN policies that determine when to transmit ECN feedback based on CWND growth pattern analysis and network calculus. As long as ECN is well supported without bleeding, these ECN-based techniques have the potential to improve the network performances in cellular networks significantly.

### 6 RELATED WORK

#### 6.1 ECN Measurement Study

Prior measurement studies, as compared in Table 11, have investigated the server-side ECN capability among the major web servers as ranked by Alexa and its usability (or traversal) along the paths to the servers [3, 18, 22, 23, 33]. Padhye et al. [28] first revealed very little (server-side) deployment ratio of ECN, which is only 1.3% of the probed web servers. Bauer et al. [3] later presented a comprehensive measurement study of the ECN readiness in the Internet. They found that ECN was enabled in 14%–17% of web servers and 0.1%–4% of clients, and 6%–28.4% of paths cleared the ECN field of packets. Kühlwind et al. [18] also tested 22,487 hosts and reported that ECN was not usable for 9% of the hosts, due to the middleboxes along the paths to the hosts.

In a similar vein, Trammell et al. [33] found that when testing 326,743 hosts that can negotiate the ECN capability during connection establishment, 0.03% of the hosts (i.e., 107 hosts) experienced the failure of ECN negotiation due to the paths to the hosts, which mangle the ECE and CWR flags in the TCP header. In addition, Learmonth et al. [22] developed a measurement tool named PATHspider to measure the Internet path transparency for various protocol features of TCP (see Section 3.1.1 for more details). McQuistin et al. [24] conducted an Internet path transparency measurement study for UDP traffic. Learmonth et al. [21] also presented a measurement study of the ECN capability on mobile access networks, but this work is limited to checking the ECN negotiation with public websites. It is worth noting that the ECN negotiation is possible, even if the paths to the websites bleach the ECN field of IP packets, as the ECN negotiation is done based on the ECE and CWR flags of the TCP header during the TCP connection establishment.

#### 6.2 Inferring Proxies in Cellular Networks

There are a few measurement studies on inferring middleboxes in the Internet, especially cellular networks. Wang et al. [36] conducted a measurement study for commercial cellular networks and observed that various types of packet modifications happen due to middleboxes. Detal et al. [10] revealed the presence of middleboxes along the Internet paths from an experimental study using Tracebox. Xu et al. [38] used an experimental testbed to investigate transparent web proxies in the four major US mobile providers and see how they behave in the presence of real web workloads. Chung et al. [8] presented Luminati, an HTTP proxy network, for measuring the network infrastructure to demystify the end-to-end violations. Zullo et al. [40] proposed Mobile Tracebox, which sends crafted packets to validate intermediate boxes to see if they modify the packets or alter the path between...
source and destination. However, none of the prior studies have evaluated the ECN violations in wired and cellular networks.

7 CONCLUSION
In this work, we conducted a large-scale measurement study on the traversal of ECN in the Internet, involving a wide range of cellular and wired networks. In particular, we were able to provide detailed analysis results on the instances of ECN bleaching, including how often and where in the network the bleaching instances happen. We observed that 1,112 out of 129,252 routers and 4.17% of paths showed ECN bleaching, and only few networks bleach as a matter of policy. We have already shared our measurement results with ISPs and received a response from some of them, showing their willingness to fix the issue with ECN bleaching.

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| Methodology | 2000 [28] | 2004 [9] | 2011 [3] | 2013 [18] | 2015 [24] | 2017 [21] | 2018 [19] | 2019 [30] | Our work |
|-------------|-----------|---------|---------|---------|---------|---------|---------|---------|---------|
| Percentage of ECN-capable web servers (TCP) | 1.3% | 2.2% | 17.2% | 29.5% | 56.4% | 78.5% | 86.4% | | |
| Percentage of ECN marking changes | | | | | | | | | |
| Bleaching localization | | | | | | | | | |
| End-to-end testing | | | | | | | | | |
| Aggregated flow data | | | | | | | | | |
| Cellular networks | | | | | | | | | |

Table 11: Comparison with prior ECN measurement studies (●): partially meet the criterion; ●: has good results with details; Blank: not mentioned in the literature.)
A Fresh Look at ECN Traversal in the Wild

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A ETHICS

This work does not raise any ethical issues.