From Single Lane to Highways: Analyzing the Adoption of Multipath TCP in the Internet

Florian Aschenbrenner*, Tanya Shreedhar†, Oliver Gasser§, Nitinder Mohan*, Jörg Ott*
*TUM Germany, †IIIT-Delhi India, §MPI-Informatics Germany

Abstract—Multipath TCP (MPTCP) extends traditional TCP to enable simultaneous use of multiple connection endpoints at the source and destination. MPTCP has been under active development since its standardization in 2013, and more recently in February 2020, MPTCP was upstreamed to the Linux kernel.

In this paper, we provide the first broad analysis of MPTCPv0 in the Internet. We probe the entire IPv4 address space and an IPv6 hitlist to detect MPTCP-enabled systems operational on port 80 and 443. Our scans reveal a steady increase in MPTCP-capable IPs, reaching 9k+ on IPv4 and a few dozen on IPv6. We also discover a significant share of seemingly MPTCP-capable hosts, an artifact of middleboxes mirroring TCP options. We conduct targeted HTTP(S) measurements towards select hosts and find that middleboxes can aggressively impact the perceived quality of applications utilizing MPTCP. Finally, we analyze two complementary traffic traces from CAIDA and MAWI to shed light on the real-world usage of MPTCP. We find that while MPTCP usage has increased by a factor of 20 over the past few years, its traffic share is still quite low.

I. Introduction

Despite significant advances in Internet infrastructure and connectivity, TCP’s connectivity model has remained largely unchanged over the last 30 years. Recent advances in network technologies have led to the rise of multi-homed devices, e.g., smartphones, with access to more than one networking interface. Multipath TCP (MPTCP) is an extension to TCP that allows endpoints to simultaneously utilize multiple interfaces for concurrent or backup data transmissions [1]. Standardized in early 2013, MPTCP has shown better resource utilization, higher aggregated throughput, and resilience to network failures in numerous research studies published over the years.

Due to the performance benefits of MPTCP over TCP, several known organizations have incorporated the protocol within their products and services. Apple uses MPTCP in its iOS devices to enhance user experience surrounding its system services, e.g., Siri, Music, Maps, Wi-Fi Assist [2]. In 2019, Apple provided APIs to third-party developers for making use of MPTCP in non-system iOS applications. Korea Telecom, in partnership with Samsung, uses MPTCP to provide Gigabit speeds over Wi-Fi and LTE to its customers [3]. In February 2020, MPTCPv1 was upstreamed to Linux and is now available to all users running Linux 5.6 or newer [4].

Despite significant interest in improving the protocol [1], [5], [6], the current state of MPTCP deployment in the Internet remains largely unexplored in research. We attribute this gap partially to the influence of middleboxes on the accuracy of such studies. The Internet is proliferated with a wide spectrum of specialized appliances and systems known as middleboxes, that meddles with user traffic before it reaches the target [7]. The intended operation of middleboxes is to offer valuable benefits, e.g., firewalls drop unintentional packets and proxies improve the performance of connection setup. However, certain middleboxes interact quite poorly with connections containing TCP header extensions. While some may strip the packet of any header additions before relaying it to the next hop, others might block the connection altogether [8]. Since MPTCP relies on TCP extensions for signaling, it is also susceptible to such middleboxes in the Internet. MPTCP designers incorporate several mechanisms into the protocol specification that allows the protocol to fall back to regular TCP for data transfers, if the connection is affected by middleboxes [9]. Despite that, middleboxes continue to hinder MPTCP studies, since scanning tools leverage the connection establishment mechanism to interact with targets and thus remain vulnerable to side-effects of middleboxes. In a study from 2015, the authors wanted to analyze the deployment of MPTCP in the Internet, it later became clear that the results include false-positives due to middleboxes echoing MPTCP options for non-MPTCP hosts [10]. However, despite significant measurement challenges, assessing the adoption of MPTCP in-the-wild is still pertinent since the protocol can only be employed if there is sufficient server-side support in the Internet.

This paper presents the first broad and multi-faceted assessment of MPTCPv0. We study both the infrastructure, in terms of MPTCP-capable IPv4 and IPv6 addresses, and the traffic share at two geographically diverse vantage points. We identify and remove middleboxes affecting MPTCP in-the-wild and investigate if they also negatively impact MPTCP application traffic. Specifically, our contributions are as follows.

I. We regularly probe the entire IPv4 address space and an IPv6 hitlist [11] for MPTCPv0 support since July 2020 using ZMap. Our scans target HTTP (port 80) and HTTPS (port 443) since they make up the largest traffic share in the Internet [12], [13]. We find that our scans are affected mainly by middleboxes that echo TCP extensions, indicating that traditional scanning methods are still ineffective in accurately evaluating the deployment of MPTCP. We also observe that the number of IPs reported to support MPTCP without replayed options increased fourfold over IPv4 port 443 since 2015.

II. We scrutinize targets that reportedly support MPTCP in our ZMap scans for middleboxes by using Trace-
box [14] and make two significant discoveries. First, most MPTCP-capable hosts in the IPv4 are transient; indicating experimental connotations attached to MPTCP usage in-the-wild. Second, we identify several middleboxes that interact in a much more complicated fashion than just echoing with MPTCP packets. Despite that, we observe a growing adoption of MPTCP reaching 7.4k/6.9k and 31/27 over port 80/443 on IPv4 and IPv6, respectively.

III. We initiate parallel HTTP(S) GET requests using MPTCP and regular TCP towards IPs identified in our ZMap and Tracebox measurements. Our results show that a majority of truly MPTCP-capable servers are indifferent to the choice of transport protocol for connection establishment. However, IP addresses affected by middleboxes take longer to successfully establish a connection using MPTCP vs. TCP, hinting at the potential impact of middleboxes on MPTCP’s perceived quality.

IV. We analyze usage of MPTCP for data transfers over the Internet by investigating four years of inter-domain traffic collected by CAIDA and MAWI. Our findings show that MPTCP data usage is still quite low compared to TCP (peaking at 0.4%), primarily due to the lack of widespread MPTCP support among clients, servers, and applications. Despite openly supporting MPTCP, Apple’s traffic share over the protocol is relatively small. However, since the past year, we observe a steadily rising popularity of MPTCP for large data transfers.

To foster reproducibility we publish datasets and scripts for this work [15]. Additionally, we continuously perform MPTCPv0 and MPTCPv1 scans and publish the results at https://mptcp.io.

II. BACKGROUND AND RELATED WORK

A. MPTCP Connection Establishment

We first detail the MPTCP connection establishment procedure as our measurement approach utilizes it inherently. We refer inclined readers to [1], [5] for more details on MPTCP machinery, features, and design choices.

Figure 1 shows the MPTCPv0 connection establishment process between an MPTCP-enabled client and server. The MPTCP handshake mechanism is derived from the TCP three-way handshake. In addition, MPTCP hosts use a random 64-bit sequence as keys to authenticate themselves when setting up new subflows [16]. Moreover, every packet in the handshake signals MPTCP support through the MP_CAPABLE option. The client (in our example Bob) initiates a connection by sending a SYN packet containing its key and the MP_CAPABLE option to the server (Alice). If the server also supports MPTCP, it replies back with a SYN-ACK including the MP_CAPABLE option and its own key. According to the specification [16], both key values in SYN and SYN-ACK are individually referred to as Bob’s and Alice’s sender’s key. In the first stage of our study, we use SYN packets to probe hosts that reply with MP_CAPABLE option in the SYN-ACK; recording their IP address and sender’s key value (for more details see §III-A).

Bob finally establishes the connection by sending an ACK with both keys and the MP_CAPABLE option. This allows regular MPTCP data transmissions between the two parties. Please note that the handshake procedure differs in MPTCPv1 [9] where Bob does not send its key in the SYN. In this paper, we study only the deployment of MPTCPv0, and for deployment results for MPTCPv1 readers are advised to the webpage: https://mptcp.io.

B. Related Work

Scanning the activity of different protocols in the Internet has been a long-lasting interest within the network measurement research community. In early 2008, Heidemann et al. [17] systematically probed a subset of 1% of IPv4 address space with ICMP pings. The state of active scanning research was pushed forward significantly by ZMap [18], which allows researchers to scan the entire IPv4 address space in less than an hour. Several works have since used the tool to investigate the deployment of different protocols and applications in the Internet, e.g., liveness [19], TCP initial window [20], and QUIC [21]. Others have looked into passive data traces for a different viewpoint on deployment measurements. Richter et al. [22] studied the IPv4 activity as observed from within the Akamai network and show that comparative active scanning studies miss up to 40% of the hosts that contact the CDN. Qian et al. [23] analyzed TCP behavior from multiple vantage points within a large tier-1 ISP. Wan et al. [24] discussed several factors that can impact the quality of scanning results e.g., geo-location, losses, blocking etc. We circumvent these biases to the best of our abilities by following best practices and scanning continuously for six months. Please refer to §III-A for our detailed measurement methodology.

The closest work to ours dates back to 2015 [10]. Mehani et al. proposed a scanning mechanism that probed every host on port 80 of the Alexa Top 1M with ZMap and classified IP addresses that responded with MP_CAPABLE as supporting MPTCP. Their results indicate that less than 0.1% of scanned
targets support MPTCP, with a majority located in China. However, the accuracy of the work was later found to be low as it falsely recognized middleboxes that echoed unknown TCP extensions as MPTCP hosts [25]. The authors later published an errata and tracked the non middlebox-affected MPTCP deployment for several months in 2015. In this work, we extend their methodology to identify middleboxes affecting MPTCP correctly, hence providing the most accurate picture of true MPTCP deployment to date. In addition, our study scans for MPTCP support over the two most popular services in the Internet, HTTP and HTTPS, over both IPv4 and IPv6.

### III. Active Internet Scans

To identify support for Multipath TCP in the Internet, we actively scan for MPTCP options over the IPv4 and IPv6 address space. Our study probes the entire IPv4 address space over port 80 ($\approx 74M$ unique responsive IPs) and port 443 ($\approx 52M$ unique responsive IPs). In IPv6, we use the IPv6 hitlist [11] to probe both port 80 and port 443 due to the size of the address space. We find 746k and 544k responsive IPv6 addresses, respectively. Our results are over six months of data collection from July – December 2020.

#### A. Methodology

We use ZMap [26] to rapidly enumerate IPv4 and IPv6 addresses. To identify MPTCP hosts, we leverage the initial handshake mechanism, i.e., sending a SYN with the MP_CAPABLE flag along with a static sender’s key. As illustrated in Figure 1, a legitimate MPTCP host will reply back to an MPTCP SYN with a SYN-ACK containing MP_CAPABLE and its own sender’s key. If the target’s SYN-ACK response includes these values, we classify it as potentially MPTCP-capable. Previous research has shown that the accuracy of identifying MPTCP hosts via ZMap can be low due to middleboxes that replay or strip packets with TCP extensions [8], [10], [25]. To improve the reliability of our analysis, we probe potentially MPTCP-capable hosts with the well-known middlebox-detection tool Tracebox [14]. Tracebox allows us to detect the presence of MPTCP options modifications on the path, revealing IPs that truly support MPTCP.

Before conducting active measurements, we incorporate proposals by Partridge and Allman [27] and Dittrich et al. [28]. We follow best scanning practices [18] by limiting our probing rate, maintaining a blocklist, and using dedicated servers with informing rDNS names, websites, and abuse contacts. Furthermore, we diligently complied to any emails from organizations asking for their networks to be blacklisted.

#### B. Finding MPTCP Support In-The-Wild

Table I provides a month-wise summary of our scanning results over the IPv4 address space. The drop in responsive targets in August can be attributed to organizations that started blocking our scans—misidentifying it as a potential attack on their network. After taking corrective steps, the number of responsive targets increases again in October. Unfortunately, we were unable to perform any port 443 scans in September due to infrastructural reasons.

From almost 60M responsive targets on port 80 and 50M on port 443 in IPv4, about 200k addresses responded with the MP_CAPABLE flag in their SYN-ACK (potential MPTCP), making $\approx 3.3\%$ and $\approx 4.6\%$ of total responsive hosts on port 80 and 443, respectively. At first glance, it might seem that MPTCP is extensively supported, more so on port 443 than on port 80. However, we also observe that a large percentage of potential MPTCP hosts are inconsistently active across our six-month scanning period, signaling at the existence of transient hosts. In IPv6, we find a very small number of addresses responding with the MP_CAPABLE option: 43 on TCP/80 and 165 on TCP/443. Similar to IPv4, we see more MP_CAPABLE addresses on port 443 (0.03%) compared to port 80 (0.005%). The numbers increase to 44 and 168 until December 2020 on port 80 and 443, respectively.

**Impact of middleboxes on correctness of scans.** To examine if our scans are affected by interfering middleboxes, we
analyze the MPTCP sender’s key we receive from targets in their SYN-ACK response. A true MPTCP host generates a random 64-bit sequence to use as the key (see §II-A). According to the central limit theorem, the sum of independent random variables tends toward a normal distribution. In that case, the sum of all bits in the sender’s key — i.e., the Hamming weight — should follow the normal distribution $\mathcal{N}(32, 16)$. Figure 2 shows the Hamming weight distribution of the sender’s key from potential MPTCP hosts on port 443 in IPv4 and IPv6. We find that a large number of sender’s keys do not follow the normal distribution. In fact, the Hamming weight 16, i.e., the exact Hamming weight of the key that we send in our SYN probes, is heavily over-represented. This indicates a prevalence of middleboxes that mirror MPTCP options in our ZMap scans. On port 443, the phenomenon is much more prominent in IPv4, where almost 80% of the sender’s keys are mirrored compared to 8% of keys on IPv6. On port 80 (not shown), we find that middlebox interference is even more elevated, with almost 90% and 30% of received sender’s keys identified as being mirrored for IPv4 and IPv6, respectively.

We now analyze the share of hosts that are affected by middleboxes mirroring MPTCP options in our measurements. Figure 3 shows the aggregate number of unique potential MPTCP targets scanned over IPv4 for which the sender’s key was mirrored (in orange) and different from ours (in blue) for port 80 and 443. It is evident that middleboxes affect ZMap scans quite significantly as a large percentage of hosts on both ports have mirrored keys. Interestingly, we find that the presence of middleboxes is far greater on port 80 than on port 443, as port 80 has 96% of hosts with mirrored keys compared to 81% on port 443. In contrast, 6484 and 42294 hosts send back different sender’s keys on port 80 and 443, respectively. For IPv6, we received different sender’s key responses from 31 IP addresses on port 80 and 157 on port 443 (not shown).

The result is quite intriguing as it hints at HTTPS having far more support for MPTCP than HTTP over IPv4. We also investigate whether any hosts that are middlebox-affected on port 80 are MPTCP-capable on port 443, but we find no intersection. This leads us to believe the following contrasting possibilities. First, HTTPS traffic is end-to-end encrypted at the application layer; it is possible that a large number of middleboxes do not modify the transport layer options of user traffic. This results in a much smaller percentage of hosts that are affected by middleboxes that inject replayed TCP extensions. Second, the result may still include non-MPTCP end-hosts, which are affected by middleboxes that also modify the sender’s key value of SYN-ACK packets.

C. Finding Interfering Middleboxes

While our ZMap analysis in the previous section filters out hosts that are affected by middleboxes simply mirroring TCP options, it still does not entirely capture the true state of MPTCP deployment in the Internet. First, our filtering mechanism assumes that all hosts which reply with the same sender’s key as ours are middlebox-affected and do not support MPTCP. However, this excludes the possibility of legitimate MPTCP hosts whose MPTCP options in the SYN-ACK are either stripped or overwritten by middleboxes—thus resulting in false negatives. Second, our analysis may also include false positives due to middleboxes that may perform a complex operations on packets with extended TCP options, e.g., modifying sender’s keys. Therefore, we detect the presence of interfering middleboxes by running Tracebox [14] towards all targets that sent the MP_CAPABLE option in our ZMap scans.

Methodology. Similar to our ZMap methodology, we issue Tracebox requests with the MP_CAPABLE option towards a target address. In the reply, we receive responses from intermediate routers on the path, including any modifications made. Overall, we observe the following different behaviors in Tracebox responses.

I. Only the target IP modifies the MP_CAPABLE option.
II. An intermediate hop modifies the MP_CAPABLE option.
III. The target was unresponsive or the query timed out.

Based on these three categories, we classify MPTCP support as follows. Since category I responses are caused by IPs...
Observations on the traffic�

Figure 5 shows the overview of our IPv4 Tracebox analysis for IPv4.

Despite reducing the input dataset, we observe that a large share of IPv4 targets over port 443 are still unreachable and the absolute number of responsive addresses is similar on both port 80 and 443. Contrary to our initial assessment based on the ZMap results, we find true MPTCP support to be slightly higher on port 80 (7.5k hosts) than on port 443 (6.9k hosts). Furthermore, the end-to-end encrypted nature of HTTPS does not seem to prevent middleboxes to interfere with traffic on the path as the number of middlebox-affected hosts is ≈ 3× larger on port 443 compared to port 80. In IPv6, we find not a single middlebox-affected target address. In fact, after removing the large share of unresponsive port 443 addresses, the number of true MPTCP-capable targets is similar on both protocols: 31 on TCP/80 and 27 on TCP/443.

Figure 6 shows the monthly distribution of truly MPTCP-capable IPv4 addresses. In IPv6, the number of MPTCP-capable addresses remains almost constant during the study period, varying only by a maximum of two addresses. We observe that the support for MPTCP on IPv4 has been steadily increasing for both port 80 and 443 and almost doubled for port 80 over our six months study period. As of December 2020, we identify almost ≈ 5.5k and ≈ 4.5k active MPTCP-capable IPv4 addresses on port 80 and 443, respectively. Compared to 7.5k and 6.8k true MPTCP hosts reported across six months (see Figure 5), the monthly distribution suggests significant transience in the MPTCP deployment. We likely attribute these short-lived hosts to enthusiasts, system tinkerers, or researchers that may use MPTCP for short time periods. The monthly Tracebox results are also in stark contrast to ZMap results discussed earlier (see Figure 4) as the MPTCP support over port 80 exceeds port 443 in October 2020.

We also observe that the number of middlebox-affected hosts remains almost consistent across months, hinting at an unevenly set of IPv4 addresses affected by interfering middleboxes on the path. Of the 402 and 1.27k middlebox-affected end-hosts on port 80 and 443, only 6 are found to truly support MPTCP. However, since MPTCP options are stripped for a large fraction of middlebox-affected end-hosts, we cannot accurately assess the true support for MPTCP within this group. We attempt to investigate the deployment nature of middleboxes that impact MPTCP traffic using Nmap fingerprinting. Unfortunately, this did not lead to fruitful results due to the following hindrances. First, the majority of middleboxes that impact our study do not respond to Tracebox probes, and hence we are unable to identify their IP address. Second, for the handful of middleboxes that we positively identified, the accuracy of Nmap is too low (around 85%)...
to confidently identify their hardware and OS characteristics. While most middleboxes are geo-located in China (the rest being located in Asia, North America, and Europe), their AS information does not reveal any defining traits or commonalities between organizations managing them. We leave the thorough analysis of such middleboxes to future work.

Since an MPTCP-capable machine can offer different services concurrently, we now examine the overlap between TCP/80 and TCP/443 end-hosts. Figure 7 shows the port breakup of all truly MPTCP-capable IP addresses throughout our study, including transient IP addresses. As shown in the figure, most IPv4 MPTCP hosts provide complementary services over either of the ports. Only 16.4% of IPv4 addresses support MPTCP over both port 80 and 443, while 22.3% only support MPTCP over HTTP and 61% over HTTPS. The picture is very different for IPv6, where more than 80% of addresses support MPTCP on both ports.

**Geo-distribution of MPTCP-capable hosts.** We now shed some light on the physical deployment locations and operational zones of end-hosts that truly support MPTCP. Figure 8 visualizes the top 10 countries with the most MPTCP-capable host densities on IPv4, arranged in decreasing fashion. We use the MaxMind database [30] for our analysis and only show country-level breakup since more fine-granular IP geolocation is not very accurate [31]–[33]. Table II provides further insights, as it shows the top 10 ASes with most IPv4 MPTCP hosts on port 80 and 443. The table also lists the associated organization name, country and AS rank, which we obtain from CAIDA’s AS database [34].

We find that almost half of all IPv4 MPTCP hosts are deployed in the US and the country dominates its closest competitors with a total of 5300 unique MPTCP-capable hosts. Table II shows that with the US, Apple has the largest deployment of MPTCP servers operational on both port 80 and 443, totaling more than 2000 unique IPv4 addresses. The result is unsurprising since Apple has been known to publicly use MPTCP for several iOS services, e.g., Siri, Music, Maps, and has recently allowed third-party developers to utilize MPTCP for non-system-native apps [2]. The second-largest support for MPTCP over IPv4 comes from Australia, mainly due to servers hosted by Telstra, a major telecommunications company in the region. We observe that many network operators and ISPs across the globe are utilizing MPTCP within their networks to enhance several of their client-facing services. For example, Korea Telecom, in partnership with Samsung, uses MPTCP to provide Gigabit speeds over Wi-Fi and LTE [3]. Interestingly, we also observe from Figure 8 that in certain countries such as Austria and France, MPTCP deployment favors one port over the other, showcasing an organization’s tendency to utilize MPTCP for serving specific application traffic. In Table III we show the AS distribution of truly MPTCP-capable IPv6 addresses. Compared to IPv4, MPTCP support in IPv6 is much more evenly distributed over ASes. We find that most of the small number of MPTCP hosts in IPv6 are located in hosting providers and ISPs. Overall, we find that the current MPTCP deployment spans more than 80 countries across the globe.
D. Middlebox Impact on MPTCP Perceived Quality

Our analysis in §III-C revealed a widespread prevalence of middleboxes that modify extensions MPTCP relies on. Previous research has shown that certain middleboxes, such as firewalls or load balancers, manipulate packets that do not fit pre-defined rule sets, e.g., by marking them low-priority or forwarding them on longer paths [8]. In this section, we want to answer whether middleboxes treat MPTCP application traffic any different from regular TCP traffic.

We investigate this by initiating HTTP(S) GET requests using MPTCP from AWS in Germany towards IPv4 addresses that are marked potential-MPTCP in §III-B. We conduct the same measurements over regular TCP from the same data center in parallel. For each successful GET response, we record (1) the TCP handshake time (a.k.a. connect time), (2) the TLS handshake time, (3) time to first byte (TTFB), and (4) the total completion time (roughly equates to website load time). We run each measurement set, composed of 10+ runs, for almost two weeks. Overall, ≈80% and ≈27% targets responded to our GET requests on port 80 and 443, respectively.

Figures 9a and 9b show the distribution of Δ time difference between responses from truly MPTCP IPs identified in §III-C. Keep in mind that these targets are not affected by middleboxes on the path. Δ values less than zero denote targets that are faster using MPTCP while Δ > 0 are hosts that are faster over TCP. Values centered around zero indicate that both protocols perform similarly. The symmetric upper and lower distributions in Figure 9a shows that the clients observe no discernible difference using (MP)TCP if connecting to targets that support MPTCP over port 80. MPTCP-capable targets on port 443 (shown in Figure 9b) show similar results for all timing values except completion time, for which the distribution tilts slightly in favor of TCP.

We now investigate the impact of middleboxes on MPTCP traffic. In Figure 9c we show the responses from MPTCP-capable targets found to be affected by middleboxes. As can be observed, middleboxes act selectively on MPTCP application traffic differently. For ≈30% of all timing values, MPTCP is slower than TCP while TCP is slower for only 10% of measurements. Notice the difference in x-axis ticks of Figure 9c and Figure 9a; indicating that middleboxes can expand TTFB and load time of MPTCP connections by several seconds. Likely, the MPTCP client falls back to TCP before initiating data transfer for these targets since middleboxes strip away MPTCP options from the header [9]. As a result, such middleboxes only affect the TCP handshake phase, which also justifies large connect time values recorded for these targets. However, not all middleboxes have a deleterious impact on MPTCP traffic, as seen in Figure 9d. The result shows that middleboxes that simply replay unknown TCP extensions have no discernible effect on MPTCP traffic. Keep in mind that data transfers over these connections end up using TCP since none of the end-targets in this group were found to support MPTCP.

### Takeaway
- Using Tracebox we find a large share of middlebox-affected MPTCP addresses in IPv4, while IPv6 MPTCP support remains largely unaffected. Backed by Apple and major ISPs globally, IPv4 boasts of 9k+ truly MPTCP-capable hosts, compared to a few dozen on IPv6.

IV. MPTCP INTERNET TRAFFIC SHARE

We quantify the real-world MPTCP traffic share by analyzing two traffic traces from geographically diverse vantage points: (1) four years of traffic (from 2015 to 2019) on a Tier 1 ISP backbone link in North America (CAIDA traces [35]) and (2) seven years of traffic (from 2014 to 2020) captured at the uplink of a Japanese university network (MAWI traces [36])

**CAIDA.** The CAIDA dataset includes bidirectional traffic captured at an Equinix data center connected to an ISP backbone link (we only consider single direction “dir-A” traffic in our analysis). For 2015 and 2016, the monitor captures traffic of the ISP backbone connecting Chicago and Seattle, while for 2018 and 2019, the backbone links New York and São Paolo. The dataset includes a one-hour trace per month for four months of 2015 and 2016, each, ten months for 2018 and January 2019. No data is available for 2017 and after January 2019 since the monitored links have been upgraded to 100 Gbps and exceed capturing capacity.

**MAWI.** The MAWI dataset includes traffic captured at samplepoint-F, a 1 Gbps transit link of the WIDE working
group to an upstream ISP. We analyze 15 minute captures of the third Thursday of each month, from January 2014 to December 2020. This technique allows for better comparison between months, ensuring that weekday traffic is analyzed.

Both CAIDA and MAWI datasets are anonymized, disallowing us to identify participating endpoints accurately. However, since our objective is to understand the popularity of MPTCP in real-world Internet traffic, this does not hinder our analysis. We remove all flows with less than five packet exchanges to prevent possible scanning traffic from influencing our study.

A. MPTCP Traffic Characteristics

Figures 10a and 11a show the share of MPTCP flows and bytes over TCP at the CAIDA and MAWI vantage points, respectively. We observe that the MPTCP share remains fairly and consistently low in the CAIDA dataset, making up only 0.00006% of TCP byte and 0.0003% of TCP flow traffic. However, there is a clear uptick in MPTCP flow share at the start of 2018 that increases as the year progresses, reaching 0.005%. Interestingly, the trend is mostly missing on MPTCP byte share, indicating a simultaneous rise of TCP traffic on the link. By the end of 2018 (and beginning of 2019), both MPTCP flow and byte share within the CAIDA dataset escalate significantly and peak at 0.02% and 0.002%, respectively. Figure 10b paints the complementary picture of the dataset in absolute numbers. The bars (attached to the left y-axis) denote the aggregate amount of MPTCP bytes, and the line (to the right y-axis) shows the mean of MPTCP flows over four years. We observe a $\approx 8.6 \times$ jump in MPTCP bytes from 2016–2018 and an increase of 64% within 2018–2019. However, the concurrent increase in the number of MPTCP flows hints that MPTCP is largely being used for short-lived mice transfers. Unfortunately, we cannot analyze the after-effects of MPTCP upstreaming in Linux at the beginning of 2020 from the CAIDA dataset as no trace data is available beyond 2019. Hence we turn our attention to the MAWI traces.

From Figure 11a we observe that the share of MPTCP traffic flows captured by MAWI stays relatively constant over time, making up less than 0.1% of all TCP traffic flows. The share of MPTCP bytes is even smaller, until the end of 2019, as we begin to see it increase significantly, peaking at upwards of 0.4% in June 2020. Interestingly, the number of flows remains low and does not increase. We further investigate this phenomenon by looking at the flow size distribution over time. To convey this distribution, we show the traffic share of the top flow, the top five flows, and the top 50% of flows in Figure 11b. If all flows had the same size, the green top 50% line would be at 0.5. Right around the end of 2019, we see a drastic change in flow size distributions. A single flow makes up 50% of all MPTCP traffic at times, and the top five flows make up almost all of MPTCP traffic. This indicates that MPTCP is starting to be used and carries actual data. We also evaluate the duration of these elephant flows and find that they last about 30s. That relatively short duration also explains the few dips in the top 5 in 2020 as seen in Figure 11a. If an elephant MPTCP flow is not present within MAWI’s 15 min capturing window, the distribution and traffic share drops.

B. MPTCP Application Usage

To better understand the applications used in MPTCP traffic, we map transport port numbers for MAWI and CAIDA traces to well-known port numbers used for specific services [37]. Additionally, we leverage Apple’s list of ports used in their services to identify Apple service traffic [38]. We are able to successfully map all flows to well-known ports in MAWI; except one flow with both high-ports and two flows with reserved value zero as the source port. The latter could be attributed to misconfigured devices [39]. For CAIDA, we find more than 80% of source ports in the well-known range and a majority of destination ports as ephemeral; indicating that the link mostly carries server-to-client upstream traffic.

Overall, we observe six different applications utilizing MPTCP in MAWI: HTTPS, HTTP, Ident, SMB, Siri, and RDP. The overwhelming majority of all MPTCP traffic, however, is HTTPS traffic, whose lowest share is 99.5%. On the other hand, the application mix in the CAIDA dataset is more diverse than MAWI as we find 15+ services using MPTCP; including HTTPS, HTTP, Spamtrap, and Microsoft services. However, similar to MAWI, HTTPS traffic eclipses all other applications with 99.91% being its lowest share. Moreover, other than very small traces of Siri in 2018, we did not discover any other instances of Apple services using MPTCP in both datasets.
Takeaway — The MPTCP traffic share remains consistently low over time. Since mid 2019, MPTCP traffic has shown a steady increase and now includes larger flows, indicating that MPTCP has started to see actual deployment. With more than 99% of all MPTCP traffic, HTTPS is the dominant application using MPTCP in-the-wild.

V. DISCUSSION AND CONCLUSION

This paper presented the first broad multi-faceted assessment on MPTCPv0. We studied both the infrastructure, by probing the entire IPv4 address space and an IPv6 hitlist for MPTCP-capable IPs, and traffic share at two geographically diverse vantage points. We identified middleboxes that impact both MPTCP scanning attempts and user traffic during the course of our study, hence providing the most accurate picture of true MPTCP deployment to date. We observed a steady growth in MPTCP-enabled IPs that support HTTP and HTTPS in our six-month investigation period, reaching ≈ 9k and 30+ in December 2020 for IPv4 and IPv6, respectively. The growth is primarily driven by Apple and ISPs across the globe that rely on the protocol to enhance their services.

The rise in infrastructure size is not yet reflected in MPTCP’s traffic share as MPTCP’s byte share peaks at a low 0.4%, however showing an apparent increase in 2020. Combined with MPTCP’s susceptibility to middleboxes, the path to wide-spread adoption of the protocol encounters several roadblocks. We identified the presence of middleboxes, which can aggressively degrade the perceived quality of applications employing MPTCP. Compare it to multipath alternatives being developed in parallel using substrates such as QUIC that remain largely unaffected by middleboxes, the popularity of MPTCP in the future is still unknown. Interestingly, MPTCP seems to encounter fewer hurdles over IPv6 compared to IPv4, as the new Internet Protocol lacks middleboxes that interfere with the protocol’s operation. We envision the wide-spread adoption of MPTCP to be possible only if it is embraced by both middlebox developers and service-providing organizations simultaneously.

Limitations: In this study, we focus on the evaluation of MPTCPv0 deployments over the Internet. Our methodology does not capture client-side MPTCP deployments, including MPTCP proxy solutions that work only when the client establishes an MPTCP connection. The passive data analysis (cf. §IV) only focuses on MPTCP support and not MPTCP usage. We plan to plug these limitations in a future study, with MPTCPv1 results being already available at https://mptcp.io.

Acknowledgments: We thank the reviewers and Olivier Bonaventure for the feedback and comments on this paper.

REFERENCES

[1] O. Bonaventure et al., “An Overview of Multipath TCP,” ; login, 2012.
[2] Apple. (2017) Use Multipath TCP to create backup connections for iOS. [Online]. Available: https://support.apple.com/en-us/HT201373
[3] Android Authority. (2015) South Korea’s KT launches 1.17Gbps GiGA LTE. [Online]. Available: https://www.androidauthority.com/kt-launches-1gbps-giga-lte-617147/
[4] Netdev Group. (2020) MPTCP Linux kernel upstream. [Online]. Available: https://git.kernel.org/pub/scm/linux/kernel/git/netdev/net-next.git/commit/?id=f870fa8f857b68b42b6e9001c11f19228731ae6d
[5] C. Paasch et al., “Experimental Evaluation of Multipath TCP Schedulers,” in ACM SIGCOMM Workshop on Capacity Sharing, 2014.
[6] T. Shreedhar et al., “QAware: A Cross-Layer Approach to MPTCP Scheduling,” in IFIP Networking, 2018.
[7] J. Sherry et al., “Making Middleboxes Someone Else’s Problem: Network Processing as a Cloud Service,” ACM SIGCOMM CCR, 2012.
[8] B. Hemsans et al., “Are TCP Extensions Middlebox-proof?” in ACM HotMiddlebox, 2013.
[9] A. Ford et al., “RFC 8684: TCP Extensions for Multipath Operation with Multiple Addresses.”
[10] O. Mehani et al., “An Early Look at Multipath TCP Deployment in the Wild,” in ACM HotPlanet, 2015.
[11] O. Gasser et al., “Clusters in the Expanse: Understanding and Unbiasing IPv6 Hitlists,” in ACM IMC, 2018.
[12] M. Trevisan et al., “Five Years at the Edge: Watching Internet From the ISP Network,” IEEE/ACM ToN, 2020.
[13] A. Feldmann et al., “The Lockdown Effect: Implications of the COVID-19 Pandemic on Internet Traffic,” in ACM IMC, 2020.
[14] G. Detal et al., “Revealing Middlebox Interference with Tracebox,” in ACM IMC, 2013.
[15] F. Aschenbrenner et al. (2021) Dataset: From Single Lane to Highways: Analyzing the Adoption of Multipath TCP in the Internet. [Online]. Available: https://doi.org/10.14459/2021imp1610028
[16] A. Ford et al., “RFC 6824: TCP Extensions for Multipath Operation with Multiple Addresses.”
[17] J. Heidemann et al., “Census and Survey of the Visible Internet,” in ACM IMC, 2008.
[18] Z. Durumeric et al., “ZMap: Fast Internet-wide Scanning and Its Security Applications,” in USENIX Security Symposium, 2013.
[19] S. Bano et al., “Scanning the Internet for Liveness,” ACM SIGCOMM CCR, 2018.
[20] J. Rüth et al., “Large-Scale Scanning of TCP’s Initial Window,” in IMC, 2017.
[21] J. Rüth et al., “A First Look at QUIC in the Wild,” in PAM, 2018.
[22] P. Richter et al., “Beyond Counting: New Perspectives on the Active IPv4 Address Space,” in ACM IMC, 2016.
[23] F. Qian et al., “TCP Revisited: A Fresh Look at TCP in the Wild,” in ACM IMC, 2009.
[24] G. Wan et al., “On the Origin of Scanning: The Impact of Location on Internet-Wide Scans,” in ACM IMC, 2020.
[25] O. Bonaventure. (2015) Measuring the adoption of Multipath TCP is not so simple... [Online]. Available: http://blog.multipath-tcp.org/blog/html/2015/1027/adoption.html
[26] TUM. (2015) ZMap: The Internet Scanner. [Online]. Available: https://github.com/tumii/zmap
[27] C. Partridge and M. Allman, “Ethical Considerations in Network Measurement Papers,” Communications of the ACM, 2016.
[28] D. Dittrich et al., “The Menlo Report: Ethical Principles Guiding Information and Communication Technology Research,” US DHS, 2012.
[29] G. Lyon, (2020) Nmap. [Online]. Available: https://nmap.org/
[30] MaxMind. (2020) GeoLite2 Free Geolocation Data. [Online]. Available: https://dev.maxmind.com/geoip/geoip2/geolite2/
[31] I. Livadarui et al., “On the Accuracy of Country-Level IP Geolocation,” in ANRW, 2020.
[32] Q. Schettil et al., “HLOC: Hints-Based Geolocation Leveraging Multiple Measurement Frameworks,” in TMA, 2017.
[33] Y. Shavitt and N. Zilberman, “A Geolocation Databases Study,” IEEE JSAC, 2011.
[34] CAIDA. (2020) ASRank. [Online]. Available: https://asrank.caida.org/
[35] CAIDA, “Anonymized Internet Traces Dataset,” 2020. [Online]. Available: https://www.caida.org/data/passive/passive_dataset.xml
[36] MAWI Working Group, “MAWI Working Group Traffic Archive,” 2020. [Online]. Available: http://mawi.wide.ad.jp/mawi/
[37] IANA, “Service Name and Transport Protocol Port Number Registry,” 2020. [Online]. Available: https://www.iana.org/assignments/service-names-port-numbers/service-names-port-numbers.xhtml
[38] Apple, “TCP and UDP ports used by Apple software products,” 2020. [Online]. Available: https://support.apple.com/en-us/HT202944
[39] A. Maghsoudlou et al., “Zoeting in on Port 0 Traffic in the Wild,” in PAM, 2021.