Impact of Evolving Protocols and COVID-19 on Internet Traffic Shares

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Abstract—The rapid deployment of new Internet protocols over the last few years and the COVID-19 pandemic more recently (2020) has resulted in a change in the Internet traffic composition. Consequently, an updated microscopic view of traffic shares is needed to understand how the Internet is evolving to capture both such shorter- and longer-term events. Toward this end, we observe traffic composition at a research network in Japan and a Tier-1 ISP in the USA. We analyze the traffic traces passively captured at two inter-domain links: MAWI (Japan) and CAIDA (New York–São Paulo), which cover ≈100 GB of data for MAWI traces and ≈4 TB of data for CAIDA traces in total. We begin by studying the impact of COVID-19 on the monitored MAWI link: We find a substantial increase in the traffic volume of OpenVPN and rsync, as well as increases in traffic volume from cloud storage and video conferencing services, which shows that clients shift to remote work during the pandemic. For traffic traces between March 2018 and December 2018, we find that the use of IPv6 is increasing quickly on the CAIDA monitor: The IPv6 traffic volume increases from 1.1% in March 2018 to 6.1% in December 2018, while the IPv6 traffic share remains stable in the MAWI dataset at around 9% of the traffic volume. Among other protocols at the application layer, 60%–70% of IPv4 traffic on the CAIDA link is HTTP(S) traffic, out of which two-thirds are encrypted; for the MAWI link, more than 90% of the traffic is Web, of which nearly 75% is encrypted. Compared to previous studies, this depicts a larger increase in encrypted Web traffic of up to a 3-to-1 ratio of HTTPS to HTTP. As such, our observations in this study further reconfirm that traffic shares change with time and can vary greatly depending on the vantage point studied despite the use of the same generalized methodology and analyses, which can also be applied to other traffic monitoring datasets.

1 INTRODUCTION

Technologies and services on the Internet (and their underlying building blocks) have changed drastically over the last decade. While many of the Internet protocols nowadays, such as IPv6 or HTTPS, had been proposed more than 15 years ago, their adoption has only recently evolved and gained traction. With more recent protocols such as Multipath TCP (MPTCP), QUIC [1], [2], or FB-Zero [3] joining the mix, today’s traffic composition is much different from what it was a few years ago. These evolving protocols are essential in shaping and advancing the Internet: IPv6 enables an increasing number of connected users, MPTCP supports seamless mobility, and QUIC and FB-Zero drive low-latency interaction, along with securing Web traffic together with HTTPS. As a result, these protocols have seen increasing adoption: Google measures 25–30% of its users accessing their servers via IPv6 [4], although its growth has slowed down since 2016 [5]. HTTPS support has increased significantly in the last few years, with 40% of the Alexa Top 1M websites offering HTTPS as of 2016 [6]. A study [7] from 2017 measures traffic from an Italian ISP network and found that both QUIC and FB-Zero each carry around 10% of the total Web traffic.

While these evolutions have significantly transformed the Internet traffic composition, especially over the last decade, more short-term events such as the recent COVID-19 pandemic have also affected the application mix, shifting traffic toward protocols and services which are related to remote work.

To this end, we first consider related studies (§2.1) on the impact of COVID-19 on network traffic, finding that these studies are biased regarding the observed network in terms of types and regions. Further, previous work has not focused on changes in source and destination Autonomous Systems (ASes) of traffic during the pandemic. As such, we analyze datasets from a Japanese Internet backbone, operated by the Measurement and Analysis on the WIDE Internet (MAWI) Working Group [8], [9] to study the impact of the COVID-19 lockdown on the MAWI traffic mix. We compare traffic from 2019 to 2020 (§4) in order to investigate the following research questions: How do restrictions for spread prevention affect the Internet traffic composition? Do popular source and destination ASes of traffic change during the pandemic, and if so, how?

Besides such sudden changes, the Internet has also become increasingly flat over the years, which results in most traffic only traveling one inter-AS link [10], [11]. Thus, it is also necessary to revisit and re-quantify the composition of Internet traffic (§2.2) in a broader scope. However, as aforementioned studies have shown, observations can differ quite significantly based on the location of the vantage point [12], [13], [6], and are thus not necessarily generalizable. Further, traffic over inter-domain links that capture such evolutions has not been extensively studied yet, although it is important to understand the usage (or lack thereof) of such evolving protocols for traffic engineering purposes. We focus on these evolving protocols, as they represent pressing issues of this decade, which is why trends of their evolution are of particular interest for the future of the Internet. Consequently, we pose the following research questions with respect to such links while contrasting two
different vantage points: What is the traffic share of IPv6? Has HTTPS already replaced HTTP? Have the newer transport layer protocols replaced traditional protocols and to what extent? What other applications contribute significantly to the application mix?

To answer these questions, we leverage monitoring data from an inter-domain link between New York and São Paulo, collected by the Center for Applied Internet Data Analysis (CAIDA) [14], [15] to focus on such evolving protocols, and contrast the results with traces collected in the same time period from the MAWI monitor.

The MAWI backbone carries a mix of traditional and experimental research traffic; the CAIDA monitor captures traffic from a Tier-1 ISP backbone link in both directions and, thus, carries more conventional traffic (§3). Analyzing the traffic monitored on these links allows us to investigate the usage and impact of evolving protocols on the Internet traffic composition, while also highlighting that trends differ based on the observed link, and even on the observed link direction (§5). In our analysis, we focus on byte shares to denote the traffic percentages. We then discuss limitations (§6) before concluding the study (§7). Our primary findings are:

— **Impact of COVID-19:** Comparing the MAWI traffic mix from April 2019 to the one from April 2020, we find that although the overall number of flows has increased, the number of bytes transmitted over the research network link has reduced by 47.3% over IPv4 and 38.5% over IPv6. Further, differences in traffic volume between weekdays and weekend have become less pronounced in 2020. For the heavy-hitting applications, we observe that the volume differences of protocols related to remote access (§4.1) such as OpenVPN and rsync increase significantly over both address families when comparing 2019 and 2020 (by up to 3082.7%), although ssh and X11 exhibit lower traffic volume in 2020 (lower by 63.7–84.0%). In terms of source ASes for both 2019 and 2020 (§4.2), we find that traffic is primarily received from Content Delivery Networks (CDNs) and cloud providers, although the volume drastically decreases from 2019 to 2020. However, traffic volume incoming from Dropbox (AS19679) increases in 2020, along with increases of traffic sent toward Cisco Webex (AS13445), which indicate a shift to remote work among users.

— **Impact of Evolving Protocols:** On the CAIDA link, IPv6 accounts for 4% of the traffic (byte share) on average in both directions, although the IPv6 traffic shares are highly asymmetric when comparing the individual directions of the link. In comparison, the MAWI link shows a significantly higher IPv6 traffic share (9% average in 2018, however, increasing to 12.2% in 2020) (§5.1). Further, the MAWI IPv6 mix converges to its IPv4 mix, which indicates that both address families are used similarly.

TCP is still the dominant transport protocol (91.5% of traffic share) on the monitored links. Although, TCP usage is declining at the expense of evolving transport protocols, such as FB-Zero and QUIC, since QUIC already achieves 7% traffic share. Further, we only find 1.5% of the traffic being carried over UDP (besides QUIC), indicative of its usage primarily for carrying DNS traffic or as a multiplexer to support the deployment of new transport protocols on top of its stack (§5.2).

We notice a growth of HTTPS traffic, while HTTP traffic declines. Thus, the ratio of HTTPS to HTTP increases, reaching ratios of 2-to-1 up to 3-to-1 in favor of encrypted Web traffic. As QUIC and FB-Zero primarily carry encrypted Web traffic and simultaneously experience higher usage, the traffic share of HTTPS increases consequently (§5.3).

Overall, our study is directly relevant for network and operational communities, since knowledge of both short-term and long-term trends in Internet traffic composition is crucial not only for better management of networks and traffic engineering, but also for predicting future trends to allow ISP networks and content providers to be better prepared either via reconfiguration or via increasing network capacity. The respective contributions and novelty of the paper are three-fold:

1) The first contribution is the evaluation of how traffic shares change on the Internet due to both short-term (COVID-19 lockdown measures) and long-term (evolving protocols) effects. Previous work has majorly evaluated either effect, however, not both in the same study. We show that studies need to observe both effects together, to be able to provide a more comprehensive view on Internet traffic shares.

2) Second, analyses should consider different vantage points on the globe. For this, we compare the Internet traffic shares at two distinct vantage points (West and East) on the globe during the same time period, after which we show that traffic shares vary significantly based on location, which also applies to the evolving protocols in these regions. Previous work has majorly focused on traffic shares by analyzing dataset of a particular location or an AS.

3) Lastly, despite observing different trends for the two different traces, we demonstrate that our method and analyses are generalized and can be applied to other traffic monitoring datasets. This is a valuable contribution to the community, since the method and analyses are not tailored to a specific dataset.

## 2 Related Work

### 2.1 Effects of the COVID-19 on Internet Traffic

After the outbreak of the COVID-19 pandemic, several studies have investigated the impact of countermeasures to the pandemic on the Internet traffic.

Favale *et al.* [16] analyze the effect on the campus network of an Italian university, which implemented e-learning solutions for classes. They specifically focus on passive traces and application logs of collaborative tools such as Microsoft Teams and tools for remote access such VPN and remote desktop services. They find that the amount of incoming traffic has decreased significantly, whereas the outgoing traffic (to the student’s homes) has increased by more than a factor of two.

A similar picture is shown by Böttger *et al.* [17], who use Facebook’s edge network around the globe to reveal that different regions have been affected differently by the lockdown measures. Similarly, the traffic demand in terms of volume increased, whereas the traffic demand in terms of application type also shifted toward live streaming and messaging, both following changes in user behavior at the edge.
In contrast, Lutu et al. [18] study the effect of the COVID-19 pandemic on a mobile network in the UK. Due to the limited mobility of users as a result of lockdown measures, they identify that both mobility and download traffic volume decreased, although these changes also differ between geographical locations and social backgrounds of users. Moreover, they see an increase in voice traffic, which overall indicates that the types of used services have shifted.

Feldmann et al. [19] leverage multiple datasets from a set of IXPs, an ISP, an educational network to study implications of the outbreak on the Internet traffic. In general, they find an increase in traffic volume of 15–20% in a week, as well as traffic shifts away from hypergiants and toward applications typically used at home and for remote work (like VPNs or Web conferencing).

Gives these different observations from different networks around the world, e.g., in Italy, where the initial outbreak was more severe, an additional study regarding the impact on the Japanese research networks monitored by MAWI provides a complementary view for the overall picture of the pandemic’s effect on Internet traffic. However, note that observations are not directly comparable due to inherent differences of the monitored networks.

2.2 Traffic Share of Protocols

Felt et al. [6] analyzed HTTPS and HTTP measurements between 2014 and 2017 from different viewpoints, one of which was the MAWI monitor that we also use in this work. They saw an ongoing increase in HTTPS traffic and a decrease in HTTP traffic over the three years, similar to previous measurements [20]; for example, the percentage of HTTPS traffic grew from 20% to 40% of Web traffic. Chan et al. [21] present similar results for their analysis of the same traces between 2009 and 2017. Further, they classified the HTTPS traffic per major AS in the time span, where Amazon showed to be the main HTTPS contributor with Facebook right after.

Transport protocols have seen multiple advancements in the last decade [22]. As for QUIC [1], previous measurement studies [23], [24], [25], [26], [27] primarily focused on the performance aspects, with only a few studies looking into measuring the usage and adoption of QUIC. Rüth et al. [28] studied the usage of QUIC within the IPv4 address space, finding traffic shares of 2.6%–9.1% for different vantage points. They further showed that Google is the main driver of QUIC. Trevisan et al. [7] used data from an Italian ISP gathered between 2012 and 2017 to give an overview of the Internet evolution. They noticed that Internet giants such as Google and Facebook could quickly deploy new transport protocols (namely QUIC [1] and FB-Zero [3]), leading to them together carrying around 20-25% of Web traffic at the end of the measurement period. Regarding MPTCP, a recent study [29] reveals a steady increase in MPTCP-capable IPs. While the MPTCP usage has increased, its traffic share remains fairly low.

There are varying reports regarding the IPv6 adoption on the Internet, as the use of different metrics leads to different observations [30]. Akamai reported 11% IPv6 traffic in July 2017 [31]. Google measured 19% IPv6 connectivity on their clients in July 2017 and around 30% in January 2021 [4]. They also detect a 44.4% IPv6 capability in the USA and 36.8% in Brazil for January 2021. At the same time, the Asia Pacific Network Information Centre (APNIC) measures a 53.7% (USA) and 36.7% (Brazil) IPv6 capability, respectively [13]. Although IPv6 has exponentially grown since 2012 [30], [20], the growth has slowed down substantially since 2016 [5]. On the other hand, reports based on global corporate data [32], [33] primarily focus on other metrics, such as number of connected users or performance, and application usage, rather than traffic shares of underlying protocols. Moreover, note that protocol support is different from protocol usage.

Considering the varying numbers observed by different studies, it is important revisit the traffic composition while considering differences due to the selection of vantage points. Thus, we attempt to highlight this by contrasting two datasets of different traffic monitors in this study. We further dissect the data of one monitored link by its two directions to show similarities and differences within a single link, since Internet traffic can be asymmetric as well.

3 Datasets and Methodology

For the analysis of short-term changes, we first discuss the impact of the restrictions imposed by the current COVID-19 pandemic on the traffic composition monitored by MAWI (§4), for which we compare datasets collected by the MAWI monitor from April 2019 and April 2020.

We then analyze two sets of publicly available traffic traces to study the natural evolution of the composition of Internet traffic at two different geolocations. To directly contrast the two datasets with each other, we limit the study period to monthly traces collected between March 2018 and December 2018 to align the timeline of both datasets: For comparison of the traffic seen at the monitors (§5), we consider traces for the days on which both CAIDA and MAWI monitors have collected data, i.e., within the same timeframe. Note that the CAIDA monitors stopped capturing data after January 2019, as the link upgraded to 100 Gbps, which the monitoring cards are not capable of handling anymore, which is why the common time period of the data is limited to 2018.

Moreover, parts of the MAWI datasets from April 2019 and 2020 are not anonymized (see §4.2), in contrast to the public datasets from 2018 in which source and destination endpoints are anonymized. Thus, analyses in §4 and §5 are inherently different. Nevertheless, despite the data being available in the public domain, the observable trends derived from the data analysis are not necessarily known, which represents the novel contribution of this study.

MAWI – The Measurement and Analysis on the WIDE Internet (MAWI) Working Group monitors network traffic as part of the Widely Integrated Distributed Environment (WIDE) project. The WIDE project [34] runs an Internet backbone in Japan, which is an operational network and simultaneously serves as an experimentation ground for new applications. We download the collected traces for samplepoint-F (≈ 100 GB in size for March to December 2018), which is a 1 Gbps transit link of WIDE to the upstream ISP. The traffic traces are collected via tcpdump, with confidential information being removed via TCPdPriv [8]. Since
2007, MAWI publishes 15-minute captures (14:00–14:15 local time) of this link every day. They release compressed pcap files for each trace, along with a summary of the packets and bytes observed per IP protocol.

**CAIDA** – The dataset collected by CAIDA consists of anonymized Internet traces [35] captured from a passive monitor [14] located in an Equinix data center in New York City. The monitor connects to a 9953 Mbps Tier-1 ISP backbone link between New York and São Paulo. The packets are captured by two machines, each of them using an Endace 9.2 DAG network monitoring card to capture one direction of the full-duplex fiber optics link: direction “A” from São Paulo to New York and direction “B” from New York to São Paulo, which we refer to as SPNY and NYSP, respectively, for the remainder of this work, in which we present separate observations for each direction. After collecting the data, CAIDA strips the payload from the packets and anonymizes the IP addresses through CryptoPan prefix-preserving anonymization [36]. For IPv4, all 32 bits are preserved, while for IPv6 addresses, only 64 bits are preserved. The traces considered in this study were recorded between March 15, 2018, and December 20, 2018 (= 4 TB in size); the monitor records the traces on the third Thursday of each month for both directions at 13:00 UTC for 1 hour. The corresponding local time of the traces is 08:00–09:00 AM in New York and 10:00–11:00 AM in São Paulo. The recorded pcap files contain the anonymized traces with header information up to the transport layer (L4) and timestamps truncated to microsecond precision.

**Methodology** – To investigate the distribution of IP versions, we extract the relevant meta information provided by both datasets, which includes the bytes observed per IP version. To obtain the transport layer information, namely the transport protocol (such as TCP/MPTCP/UDP/QUIC), port numbers, and IP addresses (source and destination) of the packets, we analyze the pcap files using the SILK analysis suit [37] and TShark network protocol analyzer [38]. For both MAWI and CAIDA traces, a small fraction (around 0.5%) of packets are lost during the conversion due to incomplete packet headers. Note that the CAIDA data collected in October 2018 has around 50% incomplete headers; for those, we manually extracted the pcap files of this month instead.

Throughout our results, we refer to the number of bytes transferred when we mention quantities of traffic. To extract the information on applications in the dataset, we apply a heuristic that maps tuples of transport protocol and port to known applications (e.g., UDP and port 53 are mapped to DNS). We first extract the top 50 combinations of transport protocol with source and destination ports from all traces for each month and count the monthly occurrence of every combination. Note that for the CAIDA dataset, we consider and process the two directions SPNY and NYSP separately. For the top 50 combinations, we further normalize the data between the CAIDA and MAWI data and also discard applications that have only become popular over a brief period of time. Note that not all combinations can be mapped to one specific application; e.g., some combinations can be mapped to several applications, while others cannot be mapped to any application. Many applications often use a wide range of ports (several hundred), making it difficult to classify with anonymized headers. We thus map the port/protocol combinations on a best effort basis.

### 4 Impact of COVID-19

Before considering “natural” evolutions of the application mix, we first investigate sudden changes to the traffic composition: The COVID-19 pandemic has resulted in a drastic shift in Internet traffic from work environments to home networks. Governments and various institutions are recommending people to work from home to limit the spread of the virus. Recent studies [16], [18], [19], [17] investigate how COVID-19 has impacted the Internet and traffic from different networks and vantage points, primarily from Europe. In this section, we investigate the change in traffic composition on the MAWI link (samplepoint-F) in April 2019 and April 2020; recall that this link carries a mix of traditional and experimental traffic from research networks in Japan. Furthermore, Japan did not have a lockdown for the general public (other than most countries where the vantage points of the aforementioned studies were located). Instead, Japan has put preventive measures into place starting April 2020; on-campus operations have been shut down at major universities in Tokyo [39], [40], [41], from whose research network the MAWI data is collected. Thus, for countries which implemented more strict and limiting regulations, the observed impact of the COVID-19 pandemic on the Internet traffic are likely more extreme (cf. [19], [18]). As the CAIDA link stopped monitoring data after January 2019, traffic data collected from the link between New York and São Paulo cannot be included in this analysis.

To this end, we aggregate the traffic traces across all of April for 2019 and 2020 (referred to as 2019 and 2020 in the following). We find 838.9M flows overall for 2019, whereas for 2020, we observe 1.26B flows in total, i.e., an increase by roughly 50%. On the other hand, the number of packets has remained similar with 3.1B in 2019 and 2.8B in 2020. Nevertheless, we observe packet sizes (i.e., bytes per packet) to be smaller, as the total number of bytes has reduced drastically. Moreover, the common weekday-weekend patterns with respect to traffic volumes become less pronounced in 2020 (cf. [19]). The aggregates in terms of traffic volume in bytes are shown in Table 1 over IPv4 (left) and IPv6 (right), along with the relative changes to the previous year (highlighted cells show substantial changes from 2019 to 2020). Overall, we see traffic volume has dropped significantly by 47.3% over IPv4 and 38.5% over IPv6 when comparing 2019 to 2020, which is expected, as traffic from the WIDE network has likely moved to residential networks due to home office regulations. The table further indicates that IPv6 traffic share was 10.7% in 2019 and has increased to 12.2% in 2020, suggesting continuous growth in IPv6 adoption since 2018 (when the share was around 9%).

#### 4.1 Application Mix and Remote Work

We focus on a subset of applications that we have seen to be prominent in previous sections or which are related to remote access. In particular, the volume of Web traffic (HTTPS and HTTP) over IPv4 decreases by 55.7% and 41.8%, respectively, although the difference in traffic share
only changes substantially for HTTPS (−8.6 percentage points (p.p.)). Traffic volume attributed to ssh drops by 84.0%, which also affects X11 (−63.7%), although both protocols are typically used for remote work. Nevertheless, we observe that the traffic volume of rsync and OpenVPN has increased manifold by 129.9% and 973.4%; especially the high increase in OpenVPN traffic volume indicates that clients likely connect to the WIDE network through a VPN, which then carries other applications.

Regarding IPv6, we find that HTTPS traffic volume decreases massively by 86.6%, resulting in a traffic share difference of −56.4 p.p.. In contrast, however, HTTP traffic increases by 57.4%, increasing traffic share by 25.9 p.p..

We suspect that the decrease of HTTPS traffic volume in the network is likely linked to the decrease of Web service usage (e.g., YouTube, Facebook, and Netflix that are known to be drivers of IPv6 traffic), which has reduced together with the number of users (see §4.2). On the other hand, similar to IPv4, we observe the largest changes for rsync (+3082.7% traffic volume), FTP (+249.9%), OpenVPN (+219.6%), and IPSec NAT Traversal (+126.9%), with the traffic share of rsync even increasing by 10.2 p.p. as a result.

Overall, we find that the traffic composition over IPv4 remains roughly the same during the prevention measures. However, over IPv6, the composition and rankings change, as HTTP and HTTPS switch places in terms of the highest traffic shares. Moreover, rsync contributes more than 10.4% of the traffic over IPv6 in 2020, whereas in 2019, it only amounted to a percentage of 0.2%, showing a significant increase.

### 4.2 Source and Destination ASes

We are further given access to non-anonymized traffic trace headers from MAWI for April 2019 and 2020, which allows us to identify the traces’ source and destination ASes from the real IP addresses for these months specifically. To map the ASes, we use BGP Routing Information Base data collected by RouteViews for the respective months. On top of that, we lookup the types of the ASes based on the CAIDA AS classification dataset [42], which differentiates between transit/access (T/A), content (C), and enterprise (E) ASes in particular. However, note that the non-anonymized dataset only covers Wednesdays and Sundays of the months and is therefore a subset of the previously discussed traffic traces. We aggregate the data for these days across the whole month and group bytes by AS. In 2019, this subset covers 551.7 GiB of traffic, whereas in 2020, the subset covers only 292.4 GiB of traffic instead. We inspect the top 10 source (i.e., incoming traffic) and top 10 destination (i.e., outgoing traffic) ASes by traffic volume, shown in Tables 2 and 3 (highlighted cells discussed in detail).

#### 4.2.1 Source ASes

We observe that for source ASes (see Table 2), the composition of ASes remains roughly the same: The majority of incoming traffic volume is received from popular CDNs and cloud providers, i.e., Akamai, Apple, Amazon, Dropbox,
and Cloudflare. However, while we also observe larger amounts of traffic to be received from other prominent services and CDNs such as Google, Edgecast, Facebook, or Netflix in 2019, these ASes disappear from the top 10 in 2020. We suspect that this is due to university staff and students being moved off-campus, resulting in a substantial decrease of popular end user content served from Facebook (AS32934) and Netflix (AS2906), as they drop from 25.8 GiB (ranked 7th) and 9.49 GiB (ranked 10th) to less than 1 GiB of traffic volume each (ranked 25th and 26th).

On the other hand, Google (AS15169) drops from 119.25 GiB (ranked 1st) to 17.8 MiB (ranked 169th), i.e., a decrease by more than 99%; similarly, Edgecast (AS15133) drops from 26.23 GiB (ranked 6th) to 6.15 MiB (ranked 291st). Therefore, these substantial decreases are likely due to changes in the AS topology, rather than due to the pandemic.

However, although the overall traffic volume has decreased from 2019 to 2020 as shown in Table 1, we find more traffic incoming from within the WIDE network (AS2500), increasing from 70.87 GiB to 132.77 GiB, as well as from Dropbox (AS19679), increasing from 19.2 GiB to 24.31 GiB. Considering the COVID-19 restrictions, the latter observation indicates that clients in the WIDE network are increasingly pulling data from their Dropbox storage, likely to synchronize with work done remotely; note that this might also result in policy violations depending on the classification of information, e.g., if sensitive datasets are stored on such third-party servers.

### 5 Impact of Evolving Protocols

As shown in the previous section, the Internet traffic composition can change drastically depending on recent, life-changing events. However, the Internet also evolves over time naturally, resulting in a shift regarding protocols and services used, which we will focus on in this section.

#### 5.1 IPv4 and IPv6 Traffic Analysis

##### 5.1.1 IPv4 Traffic

Fig. 1a shows the traffic distribution over the source and destination ports for IPv4 on SPNY. Around 80% of the traffic originates from source ports of the well-known port range (1–1024), which indicates that most of the traffic on SPNY comes from servers running the associated services. On the other hand, the destination ports have no such distinct behavior in the well-known port range. Instead, we see a mostly linear trend, with three minor spikes in the CDF: The first cluster is located at around port 28000, though cause and purpose are not clear. The second spike starts from port 32768 onwards, where the standard ephemeral port range for Linux starts. The third begins at port 49152, which is the start of the ephemeral port range for Windows since Windows Vista [43].

For NYSP, Fig. 1b shows the traffic distribution for source and destination ports. About 40% of traffic ends in
TABLE 3: Top 10 destination ASes (w.r.t. traffic volume by bytes) in April 2019 (left) and 2020 (right) for samplepoint-F.

| Top 10 Destination ASes (April 2019) | AS Type | Tfc. Vol. [GiB] | Top 10 Destination ASes (April 2020) | AS Type | Tfc. Vol. [GiB] |
|-------------------------------------|---------|----------------|-------------------------------------|---------|----------------|
| AS2500 WIDE-BB                      | T/A     | 438.64         | AS2500 WIDE-BB                      | T/A     | 135.72         |
| AS23799 National Defense Academy     | T/A     | 38.13          | AS17676 GIGAINFRA Softbank          | T/A     | 56.68          |
| AS17676 GIGAINFRA Softbank          | T/A     | 15.42          | AS4837 CHINA169-BACKBONE            | T/A     | 26.21          |
| AS715 WOODYNET-2                    | C       | 12.72          | AS8068 MICROSOFT-CORP-MSN           | C       | 11.61          |
| AS7922 COMCAST-7922                 | T/A     | 5.29           | AS715 WOODYNET-2                    | C       | 10.68          |
| AS64238 ASN-OARC                    | T/A     | 4.12           | AS7922 COMCAST-7922                 | T/A     | 5.18           |
| AS8075 MICROSOFT-CORP-MSN           | C       | 2.21           | AS4717 WIDE-BB                      | T/A     | 4.67           |
| AS2510 INFOWEB FUJITSU               | T/A     | 1.73           | AS8075 MICROSOFT-CORP-MSN           | C       | 3.55           |
| AS2518 BIGLOBE                      | T/A     | 1.47           | AS16276 OVH                        | C       | 2.61           |
| AS4725 ODN SoftBank Corp.           | T/A     | 1.44           | AS13445 CISCO Webex LLC             | C       | 2.22           |

destination ports which are in the well-known port range, which is expected as it represents the respective client traffic to the opposite direction (SPNY). In addition, we see around 80% of traffic coming from ports above 1024. This leaves 20% that come from ports below 1024, indicating that there is a moderate share of server-to-client traffic on NYSP as well. Again, the increase of the curve at the start of the Windows ephemeral port range can be observed, this time for both source and destination ports. The destination ports curve further exhibits a step-wise pattern up to port 10000, which we observe due to popular applications within the registered ports range.

Fig. 2 shows the distribution for the MAWI link and exhibits a similar distribution as SPNY. This indicates that it mostly carries server-to-client traffic over the upstream link.

5.1.2 IPv6 Traffic

Fig. 3 visualizes the traffic distribution by ports in NYSP over IPv6. We do not include the graphs for IPv6 on SPNY here, as IPv6 traffic on SPNY only accounts for 0.5% of overall traffic at its peak (see Fig. 4). For MAWI, the distribution of ports over IPv6 is similar to its IPv4 distribution, thus also not shown. The distribution of NYSP over IPv6, however, shows an interesting pattern when compared to its IPv4 counterpart: Around 20% of the source ports are in the well-known port range; traffic shares increase linearly from port 1024 onward, with a visible spike after port 49152. Regarding destination ports, we observe significant spikes on the same two ports inside the registered port range every month, namely ports 5443 and 9501; traffic on these ports almost has the same source and destination IP prefixes.

Fig. 4 shows the distribution of IPv6 traffic for CAIDA
(SPNY, NYSP, and total) and MAWI. IPv4 is by far the more popular address family; the IPv6 traffic share on the CAIDA traces is just 1.1% in March 2018 but eventually grows to 6.1% despite some fluctuations at the end of the measurements in December 2018. Traffic coming from São Paulo (SPNY) barely carries any IPv6 packets; with values between 0.1% and 0.5%, this is even lower than observed worldwide years ago in 2013 [30]. Nevertheless, we notice that destination port 5443 accounts for a large traffic share in this direction. We suspect that the traffic is related to DNS services, as the flows originate from port 53, and as port 5443 is further used for DNSCrypt services. In the other direction, traffic coming from New York (NYSP) reaches up to 11% of IPv6 traffic share. CAIDA offers insights on the packet sizes for IPv6 [44], from which we can see that IPv6 traffic on NYSP has a very low median packet size between 70 and 100 bytes but a much bigger mean packet size that is 3–5 times higher. For IPv4, we see the opposite (not shown in the figure), where the mean packet size is almost half the median packet size. Therefore, we assume that the applications using ports 5443 and 9501 carry few but big packets and almost solely push the IPv6 traffic share (defined by the number of transferred bytes) on NYSP. This large volume of intra-AS traffic is used to synchronize data between content replicas across data centers (further analysis withheld to preserve the anonymity of the trace); note that IPv6 is known to be heavily used for content delivery purposes [30]. On the other hand, the MAWI traces already start off with 7.1% IPv6 traffic, but do not show a growing trend over time. Although some months have over 10% of IPv6 traffic, the percentage is even slightly less in December than at the beginning of March. When compared to up to date IPv6 measurements mentioned in §2, both datasets show much less IPv6 adoption overall. As explained in previous work [30], quantifying IPv6 adoption relies heavily on the metric used, as well as the vantage point location: Google [4] as well as APNIC [13] use different metrics, e.g., counting the number of users accessing their service via IPv6 in Google’s case. The same work measures 0.68% of traffic over IPv6 in 2014. When we compare this to the most recent percentages on the CAIDA dataset, this is an approximate 800% increase in four years. When compared to MAWI’s 6.9% in December 2018, this even represents a growth of more than 900%. In contrast, Czyz et al. [30] observed a yearly 400% increase in IPv6 traffic between 2012 and 2014.

5.2 Transport Layer Traffic Analysis
For the different transport protocols, we determine the traffic volume shares in terms of bytes within the MAWI dataset (CAIDA omitted for brevity). Since FB-Zero runs over TCP and uses the same port as HTTPS, we cannot distinguish FB-Zero from TCP in our traces. As expected, TCP traffic dominates with more than 90% traffic share. This is followed by QUIC with an average of 7% traffic share, which is a very high share for being a relatively new protocol; this observation is in-line with prior work [7], [32], [1]. UDP (besides QUIC) has a depleting traffic share of around 1.5%. However, we do not observe much MPTCP traffic in our analysis (~1%): No clear longitudinal trend is visible in the results across the months; the traffic share of MPTCP remains similar with slight variations, which can likely be attributed to the short (15 minutes) time frame of the traces.

Takeaway: Overall, we find that the CAIDA dataset has an average of 4% IPv6 traffic share, consistently lower to that of the MAWI dataset (~9%). We further notice the CAIDA link to carry different traffic depending on the observed direction: SPNY carries primarily server-to-client traffic, whereas NYSP carries client-to-server traffic instead. Regarding transport protocols, TCP to accounts for 91.5% of the traffic and UDP for 1.5%. As an evolving protocol, the traffic share of QUIC is already seen to be at 7%.

5.3 Web Browsing Traffic Analysis
Fig. 5 presents the top applications from the CAIDA (top) and MAWI (bottom) datasets over IPv4 and IPv6 in terms of traffic shares. Classified applications other than the ones displayed in the legend are grouped into the category “misc”; applications that could not be mapped are subsumed under “unclassified” instead. Note that XMPP is only popular over IPv4, while NTP (CAIDA) and rsync (MAWI) are only
5.3.1 IPv4 Application Mix

In this section, we look into the applications observed over IPv4 (see Fig. 5, blue boxes). The CAIDA IPv4 mix primarily consists of HTTPS, followed by HTTP, both together accounting for 60–70% of traffic. Note that encrypted Web traffic such as HTTP/2 and FB-Zero is subsumed under HTTPS in our results. When compared to the 2013 application mix from Richter et al. [20], where HTTPS contributes less than 10% to the overall traffic, it is clear that HTTPS has been growing at the expense of HTTP. Nevertheless, HTTPS and HTTP together still account for a similar fraction of all traffic. In the previous study [20], the ratio between HTTPS to HTTP was 1-to-6 in 2013, however, we see an approximately 2-to-1 HTTPS to HTTP ratio in the current data. More recent work also measured a 3-to-1 HTTPS to HTTP ratio in the current data. The MAWI data presents a different view: On average, the HTTPS to HTTP ratio is around 3-to-1, which is higher than in the CAIDA traces. Previous research on the same MAWI monitor showed a 2-to-3 HTTPS to HTTP ratio in 2017 [6], which means that the MAWI traffic is trending toward more encrypted Web traffic. HTTP and HTTPS are also accountable for a much larger fraction of traffic compared to the CAIDA data, with more than 90% of traffic share in some months. This dominance of Web-related traffic can be clearly seen in the MAWI traces, whereas the CAIDA traces exhibit a more diverse application mix.

We further inspect the application mix for both directions SPNY and NYSP of the MAWI monitor separately by month. We observe that traffic on SPNY carries more HTTPS and HTTP than its counterpart: Web traffic accounts for consistently more than 70% on SPNY but always less than 60% on NYSP, in December 2018 even less than 50%. The discrepancy for HTTP in particular is striking here: Direction SPNY is composed of around 20%-30% of HTTP traffic, whereas there is only 10%-20% on NYSP. NYSP traffic sees a relatively large fraction of XMPP, BitTorrent, DNS, and other classified applications instead, which indicates asymmetry between the two directions regarding the application mix.

5.3.2 IPv6 Application Mix

The application mixes over IPv6 (see Fig. 5, red boxes) exhibit a different behavior. With respect to the CAIDA dataset and Fig. 4, we see that the majority of IPv6 traffic is carried on NYSP. As such, CAIDA’s IPv6 application mix is mainly determined by traffic in that direction. We notice more than 50% of unclassified traffic across all months (except for April and May 2018), which comes from two applications on ports 5443 and 9501, following the aforementioned reasoning. This part of the traffic also increases over time, to a point where it is over 90% of IPv6 traffic in December 2018. The rest is mainly HTTPS and DNS, with a much higher HTTPS to HTTP ratio than seen over IPv4. The largest part of the DNS traffic on IPv6 comes from traffic in SPNY, as more than half of SPNY’s IPv6 traffic is DNS. Earlier measurements show similar behavior to our observations for SPNY, where IPv6 is mainly used for DNS queries (85% DNS traffic on average in 2009 [45]). The overall picture of the IPv6 traffic in the CAIDA dataset is contrary to the trend observed by Czyz et al. [30], who suggest that the IPv6 application mix is adapting to the one of IPv4.

When we look at the MAWI IPv6 mix in Fig. 5, HTTPS and HTTP together account for more than 90% of traffic in the median case over the months, which is even a larger share than observed in the IPv4 mix. Furthermore, DNS accounts for a very small part of the traffic only, similar to IPv4. The results we see head more toward the direction of Czyz et al.’s observations [30]. Note that the plot displays rsync instead of NTP for CAIDA but shows rsync for MAWI over IPv6 in Fig. 5, as rsync does not appear at all in the CAIDA IPv6 mix, whereas it is popular in the MAWI traces. At its peak in July 2018, rsync even reaches 12.5% of IPv6 traffic volume.

Takeaway: In terms of Web traffic, we find the HTTPS to HTTP ratio growing overall, ranging from 2-to-1 up to 3-to-1. Evolving transport protocols, such as QUIC and FB-Zero, increasingly contribute to Web traffic at the expense of TCP, which further increases the HTTPS traffic share. Moreover, comparing the MAWI and CAIDA data (including both directions), highlights how different the traffic composition can be depending on the selected samples.

6 LIMITATIONS AND FUTURE DIRECTIONS

We are aware that traffic varies for different hours and weekdays [7], and that traffic captures from both CAIDA and MAWI links are different in length. While similar results have been already observed by previous work for the same links, our study updates, combines, and continues these studies by putting the monitored traffic in contrast with
each other. However, we also acknowledge that different types of traffic are carried by the monitored links. Thus, the presented results are specific to these links and cannot be generalized. Simultaneously, finding differing observations due to inherent differences of vantage points is also a point we aim to highlight with this study.

Future studies should further look into the different types of end users. While the MAWI datasets largely cover users from an educational/research network, the constellation of end users is unknown and cannot be determined for the CAIDA data due to header anonymization.

Moreover, the heuristic used for identification is limited, as it can only identify well-known protocols and applications. We acknowledge that a port-based identification will underestimate the observed traffic shares, however, an exhaustive application identification method is not the focus of this work. Due to the datasets anonymizing IP prefixes and addresses at the cost of the report transparency [35], we cannot incorporate additional information of the traces, such as sources and destinations, over a more extended period of time for a more fine-grained identification. As such, this does not allow us to draw conclusions for the endpoints of the measured traces, e.g., regarding potential geographic relationships. The analysis of source and destination ASes is only possible for §4.2 due to the support from MAWI, who provided us with non-anonymized data. The AS-based analysis can, therefore, not be extended to the whole monitoring period of the MAWI monitor. We are aware of other evolving protocols and protocol extensions/updates, such as HTTP/2 [46], TLS 1.3 [47], DNS over TLS (DoT) [48], [49], or DNS over HTTPS (DoH) [50]. However, traffic using HTTP/2, TLS 1.3, or DoH cannot be accurately identified based on the public trace data, as the monitors drop all packet information above the transport layer. In addition to this, the mentioned protocols do not yet contribute meaningfully to Internet traffic shares, as we find DoT traffic shares to be negligible (< 0.1%), for instance.

Regarding future directions, extending the analysis by considering a vantage point in Europe would add further insights. However, a similar dataset is not available in the public domain due to GDPR regulations. Further, the datasets that are indeed online are a bit dated. To this end, operators can consider making more recent datasets available in the public domain to allow researchers better provide insights into the trends of Internet traffic composition.

Additionally, an online dashboard to visualize and present the trends in real-time would be very valuable for planning of future short-term events (similar to COVID-19) that dramatically led to change in Internet usage behavior. Operators reactively adapted to such changes but an online dashboard can help visualize such changes more quickly, leading to a more proactive approach to network capacity planning for future events.

7 Conclusion

Evaluating the impact of the COVID-19 lockdown, we observed that the overall traffic volume decreased on the MAWI link over both address families, although we saw a surge in traffic volume from Dropbox and toward Cisco Webex ASE; we similarly observed a substantial relative increase in traffic volume for applications (OpenVPN and rsync) that facilitate remote work. More surprisingly, we found that although the application mix over IPv4 remained similar, it changed substantially over IPv6 during the lockdown in favor of HTTP over HTTPS.

We further presented a longitudinal view of the Internet by analyzing two trace datasets from Brazil/USA (CAIDA) and Japan (MAWI). The traffic distribution to the different source and destination ports on the CAIDA traces revealed that most of the traffic in these traces come from servers in São Paulo and clients in New York. SPNY carries more Web traffic on the application layer, but NYSP has a higher HTTPS to HTTP ratio. We saw that IPv6 usage is increasing on CAIDA’s traces and is increasingly stable for MAWI’s, with peak values of 10.1% IPv6 traffic share in 2018 (12.2% in 2020). Regarding the transport layer, we find that TCP dominates the transport layer traffic with 90% of the traffic. QUIC achieves 7%, despite being a relatively new protocol. For applications, we discovered that the traffic mix for IPv4 consists mostly of Web traffic in both datasets, with a higher and still growing part of HTTPS. In the CAIDA data, the HTTPS to HTTP ratio is 2-to-1, whereas the ratio is 3-to-1 in the MAWI dataset. Earlier traces on the same MAWI monitor from two years ago showed different results with HTTP in the lead [6]. In the MAWI traces, HTTP and HTTPS also dominate the application mix with more than 90% of traffic in some months, indicating the high share of Web traffic. We saw a vastly different application mix for the CAIDA dataset over IPv6 when compared to its IPv4 counterpart, with the majority of traffic utilized to synchronize content replicas. In the MAWI data, we instead notice that the shape of IPv6 traffic is more similar to that of IPv4 traffic.

In conclusion, our analysis provided a relative comparison of evolving protocols from two very different vantage points across the globe during the same time period. We demonstrated that the evolution trends can vary based on where the observations are made, despite applying the same methods and analyzes to the datasets. This further presents a novel perspective on related work that largely reported trends collected from datasets in one particular region, such as Europe or North America. Future work, particularly on evolving protocols and short-term sudden effects, should therefore take such aspects into consideration.

Reproducibility Considerations

The CAIDA [14] and the MAWI [8] datasets analyzed in §4.1 and §5 are publicly available. The scripts and Jupyter notebooks used for processing, aggregating, and analyzing the data will be released on Github to facilitate reproducibility of results.

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