2020 Pandemic Network Performance

A BROADBAND INTERNET TECHNICAL ADVISORY GROUP
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About the BITAG

The Broadband Internet Technical Advisory Group (BITAG) is a non-profit, multi-stakeholder organization focused on bringing together engineers and technologists in a Technical Working Group (TWG) to develop consensus on how the Internet operates including broadband network management practices and other related technical issues that can affect users' Internet experience, including the impact to and from applications, content and devices that utilize the Internet.

The BITAG's mission includes: (a) educating policymakers on such technical issues; (b) addressing specific technical matters in an effort to minimize related policy disputes; and (c) serving as a sounding board for new ideas and network management practices. Specific TWG functions also may include: (i) identifying "best practices" by broadband providers and other entities; (ii) interpreting and applying "safe harbor" practices; (iii) otherwise providing technical guidance to industry and to the public; and/or (iv) issuing advisory opinions on the technical issues germane to the TWG's mission that may underlie disputes concerning broadband network management practices.

The BITAG Technical Working Group and its individual Committees make decisions through a consensus process, with the corresponding levels of agreement represented on the cover of each report. Each TWG Representative works towards achieving consensus around recommendations their respective organizations support, although even at the highest level of agreement, BITAG consensus does not require that all TWG member organizations agree with each and every sentence of a document. The Chair of each TWG Committee determines if consensus has been reached. In the case there is disagreement within a Committee as to whether there is consensus, BITAG has a voting process with which various levels of agreement may be more formally achieved and indicated. For more information please see the BITAG Technical Working Group Manual, available on the BITAG website at www.bitag.org.

BITAG TWG reports focus primarily on technical issues, especially those with the potential to be construed as anti-competitive, discriminatory, or otherwise motivated by non- technical factors. While the reports may touch on a broad range of questions associated with a particular network management practice, the reports are not intended to address or analyze in a comprehensive fashion the economic, legal, regulatory or public policy issues that the practice may raise. BITAG welcomes public comment. Please feel free to submit comments in writing via email at comments@bitag.org.

Executive Summary

The global COVID-19 pandemic emerged in the first few months of 2020 [1]. As work and school shifted to the home for millions of people, residential Internet services faced an unprecedented demand spike. Despite these extraordinary changes, the Internet has performed well: from user applications to content distribution infrastructure to all types of Internet access networks, the Internet proved resilient and reliable. This is likely due to a combination of the nature of the design of the Internet itself, open and interoperable standards, competent technical execution and operational execution, network capacity upgrades during the pandemic, and significant long-term investments across the entire Internet ecosystem [2].

This report is focused on the US and details how increased demand affected various parts of the Internet ecosystem, and how different organizations responded to these changes. Many reports have examined particular parts of the Internet ecosystem, such as Internet exchange points and a content delivery networks in depth. This report synthesizes a holistic view, explaining how the ecosystem as a whole - including Internet Service Providers (ISPs), transit providers, application providers, content providers, campus networks, and others - responded to these changes.

Overall, the available data suggests that the Internet has performed well during the pandemic, and continues to do so, despite unparalleled and rapid changes in traffic demands. Although individual end-users may have experienced isolated issues, we found no data or reports that suggest that the Internet did not perform to meet the needs of the end-users (e.g., slow page loads, excessive video buffering, video conferencing sessions aborting, etc.). This resilience is evident across many parts of the Internet ecosystem, from ISPs to content delivery networks and applications, and is a testament to the importance of continued investment in robust Internet infrastructure in all parts of the ecosystem, including access, transit, and content delivery.

The report highlights the following findings:

- ISPs saw significant growth in both downstream and upstream traffic, increasing at least 30% and as much as 40% during peak business hours and as much as 60% in some markets.
- The observed increase in traffic volume was not simply a consequence of a shift from organizational networks to residential ones. The shift caused local information resources on organizational sites to become remote ones, accessible only through the Internet. Therefore, net Internet traffic increased.
- Video conferencing traffic, while representative of a small overall percentage of traffic, increased substantially. Some networks saw more than 300% increase in the amount of video conferencing traffic from February to October 2020.
- Applications including gaming, web access and video streaming also saw substantial increases.
- Enterprise and campus networks saw an increase in the use of VPN services, leading in some cases to VPN capacity problems. However, the increase in VPN usage, particularly to campus networks, was less than expected, partially because many of applications are now hosted in the cloud and can be accessed directly rather than exclusively through a private network.
- Transit networks, content delivery networks, and Internet exchange points saw traffic volumes increase by 20-50%.
- Traffic over direct interconnection points also increased significantly. The extent of the increase in traffic demand varied across peers, with growth patterns ranging from modest to more than an order of magnitude or more.
- Traffic ratios between downstream and upstream traffic also shifted as a result of greater upstream consumption, although traffic ratios remained strongly asymmetric, with downstream traffic continuing to far outpace upstream traffic.
- The extent of growth in traffic demand tended to vary by the application or service of the corresponding peer. As a general pattern, ISPs augmented capacity to keep pace with this increase in demand.
- The growth in traffic varied widely by application, interconnect peer, and geographic region.

- There was a significant increase in the purchase of new consumer devices, including tablets and laptops, in some cases (e.g., webcams) outpacing supply of these devices.
- Some providers saw modest and temporary decreases in downstream traffic speeds, especially during earlier parts of 2020. Overall median download speeds decreased by less than 5%, while remaining above advertised speeds. Latency also increased modestly and temporarily for certain providers.
- Home Wi-Fi networks, in particular those with customer supplied home gateways and/or Wi-Fi access points, experienced performance challenges often due to the combined effects of increased traffic demand, a larger number of connected devices, and outdated devices and home network equipment.

While the report aims to be as comprehensive as possible in its view of traffic demand changes, certain aspects do remain difficult to characterize. We caution that this report does not shed light on every aspect of Internet behavior and user experience during the pandemic. In particular, the report focuses on directly observable metrics and characteristics, such as traffic demand (utilization), as well as network performance metrics such as throughput and latency, which can typically be directly measured. Other important metrics, such as user quality of experience for specific applications, are more difficult to measure and characterize, particularly at scale. Much of that data is simply not readily available. In many cases, for clarity of presentation, we have presented distributions of statistics, as opposed to individual measurements. Whenever possible, we have presented the results as distributions that show the full range of performance effects for which data is available, opting for percentiles, medians, and complete distributions as opposed to averages (which can obscure outliers).

In light of the above observations, the report offers several recommendations:

- End users should examine their home network when experiencing performance issues, particularly their devices and home Wi-Fi equipment, and consult with various online resources that contain helpful guidance on how to improve the network performance experienced in their home.
- Home Wi-Fi equipment that uses 802.11b (or older) should be retired, and users should be encouraged to upgrade to Wi-Fi 6 when it becomes widely available.
- If they are not already doing so, operators of campus and enterprise networks should consider enabling cloud-based applications to use Single-Sign On (SSO) to allow direct, secure access to applications without requiring the use of a VPN.
- Network operators should continue to provision network infrastructure with enough excess capacity to prepare and account for future possible systemic "shocks" and rapid changes in traffic demand patterns.
- Finally, Internet stakeholders should continue with open communication and collaboration for the continued success of the Internet as the Internet ecosystem worked together effectively and quickly to meet the massive increase in demand for Internet access and Internet applications. This enabled many millions of people to work and learn from home, kept society informed, kept people connected to family, friends and loved ones, and facilitated access to other important services during challenging this time [3].

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1 Introduction

In late 2019, the World Health Organization (WHO) identified the emergence of the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-COV-2) which causes the Coronavirus Disease 2019 (COVID-19). In the first few months of 2020, a global COVID-19 pandemic emerged [1], which eventually led to a significant portion of the population to quarantine or otherwise remain at home. Such events are also referred to as lockdowns, shutdowns, or shelter-in-place orders, and in this report, we use the term "shelter-in-place" to refer to these events.

Some studies estimated up to half the workforce shifted their work activities online [4], and most schools shifted to online formats [5]. This caused a significant change in Internet usage as people moved to working and/or studying from home and more generally spending much more time at home than usual. Society broadly embraced interpersonal video communications and other tools to support this new home-centric way of life. The entire end-to-end Internet ecosystem responded to the many technical challenges that emerged from this increase in demand.

The purpose of this report is to describe what changed in usage or demand as observed across different parts of the Internet ecosystem, and what steps different organizations took in response to support the increase in demand [2]. Existing reports typically cover the experiences of individual organizations or of a small trade group of similar organizations [6], but this report seeks to tell the broader arc of the story across the entire Internet ecosystem, from home networks to ISPs, transit providers, application providers, content providers, and others. This report focuses primarily on the time period from late February 2020 when the first shelter-in-place orders were being issued to June 2020 when many of the shelter-in-place orders were being lifted or relaxed but is not limited to that time window as there were still some events of interest in the second half of 2020.

We believe it is important to paint the bigger picture and to do so before the many day-to-day operational experiences are lost in our collective memory as we naturally move onto solve future challenges. This report should be of interest to a wide range of readers, from policymakers and regulators, to lawmakers, academic researchers, network engineers, historians, and many others.

The report begins with a brief summary of the major changes observed across the Internet ecosystem. It then examines the impacts and responses by each major part of the ecosystem, starting from the end user's home network and working out from the ISP providing access to the Internet all the way to applications and content at the other end. We close with summary observations and recommendations.

In this report, we attempt to present various metrics using aggregate representations to reflect the characteristics of data that often have millions of samples (e.g., throughput, latency, or other performance measurements across time and a large number of users)[1]. BITAG acknowledges aggregates can sometimes obscure the effects of certain factors, such as the congestion experienced by an individual subscriber, a group of subscribers in a particular service tier or region, or a group of subscribers using a particular access technology. In some cases, the effects are significant; in others, no significant effects have been observed. That does not mean that these factors do not exhibit significant effects, it only means that no study has yet identified significant effects from those factors. For example, we discuss in the report some performance effects that are visible in the "tail" observation periods of certain distributions of certain ISPs. When possible, we have attempted to show aggregate statistics that reflect the relevant or interesting effects. It should also be noted, not all organizations shared the same measurements and when sharing the same measurement may not have used the same unit nor over the exact time periods and thus it is not always possible to compare the response of different organizations by simply comparing the measurements. For example, some organizations shared percentage of peak utilization while others shared growth in data consumption.

[1] Data sources vary from independent measurement systems to self-reported internal company sources. BITAG did not independently validate each and every source that has been cited, relying instead on each company to understand their critical key performance indicators, on academic journals or conferences that may have peer reviewed papers, on the long experience of well-known measurement platforms, and so on. That being the case, the BITAG does believe that many of these sources tend to agree or correlate in terms of the high-level timeline of how the Internet has changed as a result of COVID-19. Of course, given the diversity of devices, users, networks and applications, the general findings explained herein will not apply to every possible individual situation or experience. In many cases, the datasets we rely on are public and we have included pointers to those datasets and our analysis of those public datasets.

2 The COVID-19 Pandemic Significantly Changed Internet Usage

The changes noted above caused a dramatic shift in Internet usage [7]. At a high level, the typical diurnal pattern of peak and off-peak times shifted as the peaks started earlier in the day and lasted longer into the evening. The number of people and devices connected to and simultaneously using the network increased. Finally, the types of applications shifted as most users embraced conferencing applications such as Zoom, Microsoft Teams, and Cisco WebEx.

Nokia Deepfield reported [8] that most service provider networks saw 30-60% growth in traffic in the first four weeks of the shelter-in-place orders [9], a shift to earlier start times for peak streaming video hours, a rise [10] in video conferencing (350-700% for some services), tremendous increase in weekend traffic, and more than 30% increase in the upstream traffic [11].

OpenVault, a provider of technology solutions and industry analytics for broadband providers, reported that daily consumption during local business hours (9am to 5pm) grew by nearly 42% (4.45 GB/day to 6.35 GB/day) in the downstream and just over 82% (0.215 GB/day to 0.392 GB/day) in the upstream [12]. Peak hours downstream consumption grew 21% and the upstream peak hours grew 35%. Many reported observing a shift in diurnal patterns, noting that their downstream peak moved from 9 PM to between 7 PM and 8 PM, while the upstream peak shifted from 9 PM to between 8 AM and 6 PM [13] [14] [15].

3 COVID-19 Impacts & Responses from the Internet Ecosystem

We next looked at the impacts and responses by each major part of the Internet ecosystem starting from the end user's home network and working out from the first-hop networks (ISPs, enterprise networks, campus networks) to the applications and content at the other end as shown in the figure below.

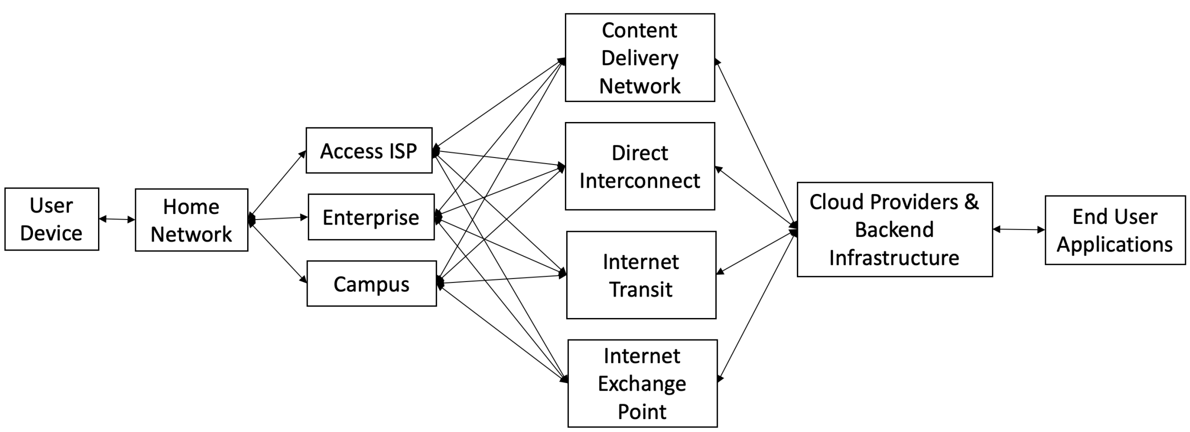

Figure 1. Simplified End-to-End Internet Ecosystem

3.1 COVID-19 Impacts and US Preparation

In the United States (US), government organizations recognized the potential impact of shifting a majority of the non-essential workforce and student population to home. To prepare millions of Americans for this change, two agencies separately took action to support telecommunications as part of critical infrastructure: the Federal Communications

Commission (FCC) and the Cybersecurity & Infrastructure Security Agency (CISA). The support from the FCC and CISA to keep consumers on the network facilitated the communications industry response activities [16].

The FCC posted tips and guidelines to its website [17] to guide consumers through service level network optimization. Consumers were advised to review broadband plans, execute connection speed tests, and explore options intended to maximize the performance of the home-based network. The FCC encouraged network operators to pledge to support residential and small business customers by signing the "Keep Americans Connected Pledge" [18], which was active from March 13, 2020 through June 30, 2020. More than 800 companies and associations signed the pledge to waive late fees incurred by residential or small business customers due to economic circumstances of the shelter-in-place orders, and not terminate residents or small businesses customers for non-payment due to the pandemic. In addition, companies supporting the pledge opened additional Wi-Fi hot spots to users, and in some cases, data limit caps were lifted. CISA declared telecommunications workers as essential in March of 2020 [19], allowing companies to provide human resources to support maintaining and hardening the network during the stay-at-home windows. During the stay-at-home periods when broadband became a necessary part of daily life, network operators kept customers connected and had the available human resources available to keep networks operational and operating at a high level of customer satisfaction [20].

The actions of the FCC and CISA to support telecommunications would not have been as efficient nor as effective without Presidential Policy Directive 21: *Critical Infrastructure Security and Resilience* (PPD-21) from 2013. PPD-21 [21] resulted in the Department of Homeland Security including the Communications Sector as one of the Critical Infrastructure Sectors. Under the policy, Sector members and policy makers were directed to protect essential services in order to "strengthen and maintain secure, functioning, and resilient critical infrastructure." The impact of a policy supporting national infrastructure provided a foundation for infrastructure owners to manage operations and risk during lockdowns with appropriate direction and resources to focus on continuity of services.

3.2 User Devices

As the shift to working and learning from home occurred, many users realized that their existing personally owned devices were ineffective or that they needed additional devices to meet requirements of full-time remote work or school. In some cases, devices lacked cameras for video conferencing, or those cameras were very low resolution. In other cases, the devices had very slow processors, insufficient memory and storage, or did not support newer Wi-Fi standards and so had slow LAN access speeds. Some employees, such as call center agents, shifted for the first time from call centers to working from home and needed a secure, managed personal computer to perform their duties. As a result, consumers purchased a significant number of devices to support this shift to remote work and learning.

From March through May 2020, this dramatic increase in consumer demand for tablets and laptops appeared to outpace supply [25]. Vendors reported recovery in fall 2020, with shipments increasing in the last quarter of 2020 compared to the first prior months [26]. While the demand remained high towards the end of 2020, it appears device manufacturers are starting to turn the corner amidst record sales [27].

It is also notable that in the shift to online learning, challenges emerged related to a lack of Internet connectivity that could not be corrected by devices. In some cases, a lack of connectivity was compounded by a lack of digital literacy and access to and training on the use of computers, with impact to lower-income households more pronounced [29]. Many companies have established or expanded programs to address connectivity issues [34] but the social and technical issues are complex, often vary from one community to the next, and will take significant collective effort to solve.

3.3 The Home Network

The shift to working and studying from home, as well as the purchase of many new devices intended for connection to the home local area network (LAN), placed a significant burden on the typical home LAN. One of the newer, more significant traffic demands on home networks has been real-time video conferencing. Collectively, the additional load has posed challenges with older home LAN equipment supplied by customers that only supports older and lower performing versions of Wi-Fi, such as 802.11n and its predecessors.

These challenges have led many home users to improve performance simply by upgrading their home gateway and/or Wi-Fi access points to the latest generation of Wi-Fi [35] [36]. Many homes have also experienced gaps in Wi-Fi coverage and have solved this[2] either by repositioning their Wi-Fi access point to a more central location in the home, by adding Wi-Fi extenders to the network (also referred to as Wi-Fi mesh networking), or by running Ethernet cables to distant but relatively fixed devices, such as a home office PC or printer.

In the past few years, new Wi-Fi mesh technology has become available that performs much better than earlier versions of Wi-Fi extenders [37]. Consumers have recently rushed to purchase and install this new technology [38][39] as a way to significantly improve both range and performance, making Wi-Fi mesh a mainstream technology. The latest generation devices tend to fall into two categories: Wi-Fi mesh network technology that uses Wi-Fi to backhaul traffic wirelessly to the home gateway, or higher performing Wi-Fi mesh access points that use Ethernet to backhaul the traffic over a wired connection. Consumers may choose a solution depending on factors such as the ability to install new wiring, price, the size of the home, types of devices, and mobility of users in home. Unfortunately, the very latest generation of Wi-Fi – version 6e, capable of using newer frequency bands, is not yet widely available. The new bands stand to increase Wi-Fi bandwidth dramatically in the near future.

3.4 First-Hop Networks

3.4.1 ISP Networks

ISPs, which provide access to the Internet to end users, showed significant increases in traffic in the first weeks of the shelter-in-place orders both in terms of volume of data transferred and peak usage.

Large cable operators reported downstream traffic growing 20% and upstream traffic growing 35% [14], while smaller cable operators reported downstream growing 27% and upstream growing 36% [7] during the shelter-in-place orders. Mobile operators reported data increasing by 9% at the beginning of the shelter-in-place orders, then trending up through July for a net increase of 28.4.% [40]. Over the same period, voice traffic growth increased by 12% and peaked at 24% on March 23, 2020. Wireline operators reported that mean traffic has increased 12% as July 2020, with the peak growth of 27% occurring on April 16, 2020.

The fixed wireless ISPs, as reported by Preseem, observed that during the first week of the shelter-in-place orders in California, Internet consumption went up by more than 40% during the peak business hours (10 am - 2 pm); and was up by 5-13% during other parts of the day. Preseem also observed was that the average Internet usage was up by more than 17% overall and 34% during business hours (9 am - 5 pm) [41].

As states began reopening in late spring of 2020, operators reported smaller changes in usage. By July downstream usage was up a net of 1.7% and 31% upstream [14], though overall traffic ratios remained highly asymmetric. Cable and wireline operators reported that their transit traffic did not grow by a measurable amount [7], and core network capacity was sufficient to meet demand [42]. It is worth noting that for the mobile wireless networks that data usage started to trend up in the late spring as the shelter-in-place restrictions were eased or lifted.

As we will explore in the subsections below, ISPs reacted to the sudden demand increase by rapidly adding extraordinary amounts of new capacity and pledging to Keep Americans Connected[30]. As part of the FCC's Keep Americans Connected initiative, ISPs pledged to: 1) not to terminate service because of inability to pay due to disruptions caused by the coronavirus pandemic, 2) waive late fees, and 3) open their Wi-Fi hotspots to any American who needed them. Many ISPs went above and beyond by providing 60 days of free broadband service to new households, suspending data usage limits, and upgrading service plans for existing customers among other things [43] [44] [45] [46] [47].

Some also added new quality of experience tests to validate the end user experience, such as the percent of advertised speed that was consistently delivered.

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[2] ISPs have and continue to educate their customers on how to optimize their Wi-Fi networks. See https://www.cox.com/residential/internet/guides/improving-wifi/extend-wifi-range.html, https://www.xfinity.com/support/articles/improve-your-wireless-home-network, https://www.verizon.com/support/residential/internet/equipment/network-extender, https://www.att.com/help/internet/optimize-your-connection/.

3.4.1.1 AT&T

AT&T is a provider of mobile phone service and broadband Internet service in the US. In the early weeks of the shelter-in-place orders, AT&T reported that its core network (business, home broadband, and wireless) usage peaked on March 29, 2020 at around 30% above the preshelter-in-place baseline. In the first week of April, AT&T reported that its core network traffic was up 24%, wireless voice minutes up 23%, consumer home voice calling minutes up 33%, and Wi-Fi calling minutes up 80% [48].

AT&T's data showed Wi-Fi calling nearly doubled during an average day. The data also showed that the number of minutes of audio and videoconferencing went up 500% [49].

Six months into the pandemic, AT&T reported the core network traffic remained up 20%, mobile voice minutes up 40%, and mobile data volume had slightly decreased. AT&T attributed the decrease in mobile data volume to the fact that most subscribers are connecting to the Internet using their home Wi-Fi throughout the day. As of early 2021, AT&T's network is carrying an average of 393 PB of data per day compared to a pre-pandemic daily average of 335 PB [50].

3.4.1.2 Charter Communications

Charter Communications, Inc. is a broadband connectivity company and cable operator serving customers through its Spectrum brand. Over an advanced communications network, the company offers a full range of state-of-the-art residential and business services including Spectrum Internet®, TV, Mobile and Voice. Charter has invested $40 billion over the last five years in new technology and network upgrades. This includes investments in its fiber backbone, and customer-facing projects like Charter's recent conversion to all-digital, which freed up capacity in its hybrid-fiber-coaxial network. These investments ensure that even in times of crisis it can deliver exactly what its customers need – reliable high-speed internet with enough capacity to support even the most high-bandwidth activities, such as HD video streaming and multi-player gaming on numerous devices. Charter monitors its network constantly so that it can add capacity in areas where it sees the potential for network congestion, or to provide additional support for critical services, such as first responders, hospitals and government agencies. Charter has tens of thousands of front-line employees on the ground monitoring and maintaining its physical network infrastructure and completing over 10,000 daily jobs to ensure its network continues to perform well.

In 2020, Charter reported that peak demand on its network increased nearly 20% on downstream traffic and 32% on upstream traffic. Charter reported that in many households Internet traffic doubled and even tripled from pre-pandemic level with peak demand continuing to be during primetime TV-viewing hours, 8-9 PM. Charter also reported seeing a shift in mobile phone traffic coming off cellular networks and moving to its in-home Wi-Fi networks. Through all of this, Charter's network continued to perform well on the downstream and upstream since it was built to exceed maximum capacity during peak evening usage, and even with the increased network activity in the daytime – especially in areas with larger COVID-19 closures – levels remained well below capacity and typical peak evening usage in most markets [51].

As the country has battled COVID-19, Charter connected nearly 450,000 students and teachers to reliable, high-speed broadband service for free for two months, kept nearly 700,000 customers connected when they faced economic hardship, gave small businesses a month of free service, and forgave $85 million in customers' overdue balances when they had a hard time paying bills due to COVID-related hardship. Moreover, Charter believes that no American should be kept from accessing the internet ecosystem because of an inability to afford service or equipment or due to fear or a lack of digital literacy. Charter has long been committed to helping to close these gaps. To make broadband more accessible for low-income learners and seniors, the company offers Spectrum Internet Assist, a high-speed, low-cost broadband service for qualified customers. To increase adoption and access to technology, the company offers philanthropic support to community organizations and has doubled its yearly commitment to the Spectrum Digital Education Grant program, which provides computers, digital education classes, and technology labs for thousands across the country [52].

3.4.1.3 Comcast

Comcast Cable[3] is a US-based provider of Internet, video, and phone to residential and business customers under the Xfinity brand. It also provides wireless, security, and automation services to residential and commercial customers.

Since the onset of the pandemic, Comcast's Internet traffic rapidly increased by as much as 60% in some markets. In-home Wi-Fi use increased 37% among Xfinity Mobile customers, who would typically have used LTE outside of the home. Comcast also observed decreased mobility as customers remained at home on their Wi-Fi network, leading to a 30% decline in LTE usage, 150% decline in data roaming, and more than 50% drop in international roaming. LTE has since returned to its March 2020 level, but data roaming and international roaming remains below normal. In contrast, voice usage minutes and SMS messages increased significantly and remain above pre-COVID levels.

In terms of downstream and upstream growth, Comcast observed an initial surge between March and May 2020, then a typical seasonal slowdown in late spring and summer, followed by a second surge in September and October 2020 as many schools resumed online classes. From late February to October 2020, Comcast notes that the average downstream peak grew by nearly 13% while upstream grew by 36%. In addition, it is notable that while upstream growth has outpaced downstream growth, a strongly asymmetric usage pattern remains typical for residential users.

Comcast engineers and technicians added fiber, other forms of connectivity, and performed software upgrades or optimization to support additional network capacity. Pre-pandemic, between February 1 - March 14, 2020, the company performed an average of 350 network improvements per week. Following the onset of the pandemic, between March 21 – September 5, 2020, the company performed an average of 771 network improvements per week, peaking at over 1,800 in a single week and running consistently at 1,000+ over 7 weeks. Thus, the normal volume of capacity augmentation work increased between 120% and 414% and was at 185% for nearly two consecutive months.

But the access network, while critical, was only one part of the network where capacity was rapidly added. As the pandemic developed, traffic across the Comcast fiber backbone grew by a third in the first 6 weeks after lockdown, reaching thresholds by April 2020 that hadn't been expected for a year. In response, between March and September 2020, over 500 improvements were made to the core network, adding over 146 Tbps in capacity and compressing a year of network growth into a seven-month period.

As a result of pre-COVID capacity investment and the network augmentation actions above, Comcast reported that customer network performance remained consistent during shelter-in-place orders. In addition to utilizing standard capacity metrics to ensure quality of performance, Comcast began running automated speed tests from cable modem gateway devices and now conducts roughly 700,000 speed tests across the network each day to provide additional assurances of a high quality of experience (QoE) for customers. National average speeds to customers (both downstream and upstream) have generally remained between 110% and 115% of advertised speeds since March 1, 2020, using this network performance measurement system that was audited by NetForecast [53] [54]. None of the Comcast local regions experienced any weeks below 105% of advertised speeds, and many remained consistently above 115%. Looking specifically at the gigabit service offering (1 Gbps/35 Mbps) the percent of advertised speed delivered is higher than at the time of the onset of the pandemic (115%).

3.4.1.4 Lumen Technologies

Lumen Technologies, formerly CenturyLink, is a US-based company offering an enterprise technology platform integrating network assets, cloud connectivity, security solutions, and voice and collaboration tools. As a networking company, it operates miles of fiber worldwide, and provides CDN, IP, voice, and edge compute services among others. Lumen is a critical infrastructure provider[4] and prepares regularly for situations like this pandemic. The network is designed to be resilient and support significant changes in traffic.

Lumen Technologies reported that web traffic rose 35% over the early course of the pandemic [55]. Broadband daily peak traffic increased by over 20% in mid-March. Customer upstream traffic increased at faster rates than downstream in 2020. After the initial increase, demand leveled off and has followed more typical seasonal patterns.

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[3] For more details on Comcast network performance during 2020 see https://corporate.comcast.com/press/releases/comcast-2020-network-performance-data

[4] See https://www.cisa.gov/communications-sector for more information on the communications sector and its role in critical infrastructure.

This overnight increase is in the low range of annual increases in subscriber bandwidth demand over the past few years. Daily broadband peak traffic for some video streaming services increased by 30%. Daily broadband subscriber combined upload and download volumes, in gigabytes, increased by about 40% when stay at home orders began, but have since leveled off. The ratio of broadband downstream to upstream monthly gigabytes decreased from 16:1 to under 14:1 as the use of teleconferencing increased.

Broadband diurnal traffic patterns also changed quickly. The weekday hourly traffic patterns now look like those on the weekend or on weekdays during the summer. Daily peak usage continued to occur in the evenings and traffic levels were sustained at higher levels during the day. Much of the demand increases in volume occurred off-peak, during the day, when excess capacity was available. To maintain high performance on the network, teams of Lumen engineers worked in real-time to optimize traffic flows globally by activating host circuits, upgrading capacity, revising data limits, strategically planning patch releases, utilizing overflow routing and rebalancing traffic as necessary.

Lumen continues to increase investment in performance monitoring and optimization tools to identify where faster access connection speeds may be offered. To meet increased traffic demands in April 2020, Lumen applied these tools to increase available connection bandwidth by 10 percent for over 360k customers.

Lumen installed high-speed connectivity to the hospital ship U.S. Naval Ship Mercy within 48 hours after it arrived at the port of Los Angeles in March 2020. The ship provided critical medical services to patients who had not contracted the COVID-19 virus. Lumen waived installation fees and the cost of 12 months of service for the 1 gigabit ethernet circuit connecting the ship to the Defense Information Systems Agency's shore-based infrastructure. Lumen also donated high-speed connectivity and waived fees for field hospitals in Seattle, Oregon and Argentina.

3.4.1.5 Sonic

Sonic, a small ISP in northern California that uses the AT&T network as well as its own fiber network, reported that their peak hour traffic was up by as much as 25% in March 2020 [56] when compared to 2019 patterns.

3.4.1.6 T-Mobile

T-Mobile is a US mobile wireless operator offering voice, text, and data services on nationwide 4G and 5G networks.

In the first weeks of the pandemic shelter-in-place orders, T-Mobile reported a 26% increase in texting, a 38% increase in mobile hot-spot usage, and a 45% increase in gaming traffic. T-Mobile also reported a decrease in mobility, with 86% of their New York City subscribers and 77% of San Francisco Bay Area subscribers connecting to cell sites in their primary location, with similar patterns observed across the country [57].

3.4.1.7 Verizon

Verizon is a US-based network operator that offers voice, data, and video services with both fiber-based Internet subscribers and mobile wireless subscribers.

Verizon reported during the March 24, 2020 week of the shelter-in-place orders in the US that mobile handoffs were down 27%, while call durations were up 33%. During the second week, Verizon reported that its network handled more than 218 terabytes of data [58].

At the beginning of April, Verizon reported that nationally mobile handoffs were down 29% from a typical day, with metro areas in the northeast reporting mobile handoffs down 37-53%. Data usage was increased with gaming up 102%, VPN data up 40%, video up 33%, and web traffic up 24%.

Verizon reported that at the end of April, usage started to decline from earlier peaks in the month.

3.4.2 Enterprise Networks

The sudden shift to work from home posed challenges for some enterprise networks using Virtual Private Network (VPN) [59] solutions. The primary issue appeared to be that during the initial pandemic period, centralized VPN capacity was completely insufficient. Enterprise network administrators were required to adapt tremendous changes to the core technical requirements for most company VPNs [60] [61] in order to meet the challenges.

Initially, many VPNs were deployed to support a small subset of a workforce working remotely. Many enterprises deployed VPNs in an era when most applications were hosted on premise behind the firewall, so that using a VPN was the only way to access many applications.

Over the past several years, many enterprise applications shifted to the public cloud, supporting access over the Internet, depending on access controls. In adapting to remote workforce support, Enterprise network administrators have been able to reduce demand on VPNs by removing IP address access control lists (ACLs) from public cloud services and implementing federated Single Sign On (SSO) technology and Multi-Factor Authentication (MFA). The changes enable enterprise users to have secure access to cloud-based enterprise applications without unnecessarily routing that traffic through a potentially constrained centralized VPN connection.

3.4.3 Campus Networks

Many campus networks use cloud-based learning platforms as well as VPN software that allows for remote access to campus resources from home networks. As campus populations shifted from on-campus learning to remote learning, traffic patterns reflected corresponding reductions in traffic volumes on campus. Below we outline statistics from one university network, The University of Chicago.

After shelter-in-place orders, the University of Chicago's campus network observed an increase in the VPN sessions as both students and faculty used VPN sessions to accessed campus resources through the VPN. In anticipation of the potentially increased demand for VPN services to access campus resources, campus IT staff significantly increased the number of VPN licenses on campus. In somewhat of a surprise, however, the number of VPN sessions did not increase as significantly as expected. In hindsight, the lack of a significant uptick in VPN sessions can be explained by the increasing reliance of educational institutions on software that is primarily hosted in the cloud, not on the campus itself. Examples of these cloud-hosted platforms that saw increased use include Zoom, Canvas (a learning management system), Panopto (software for producing and distributing asynchronous video lectures), GitHub, and Gradescope (cloud-based grading software). VPN sessions and traffic were primarily reserved to access certain on campus resources, such as the library and specific computing resources, but as VPNs are regularly used for these purposes in any case, the increase in VPN usage was not as significant as expected.

The network also saw a shift in traffic on its transit links with traffic on the Cogent link decreasing while traffic on the Lumen Technologies link increasing while the shelter-in-place order was in effect. Interestingly, the University of Chicago's traffic volumes for Internet2 and commodity Internet also changed.

3.5 Transit Networks

Overall, the Tier 1 transit providers' networks did well with no major disruptions due to sudden traffic growth. Noction, using its Tier 1 Network Performance Monitoring Service, looked at packet loss and latency for a select group of Tier 1 network providers (Cogent, GTT, Lumen, NTT, Telia, XO, Zayo, and Hurricane Electric) for the period of February 23 to March 23, 2020, to better understand the impact of the sudden traffic growth. Their data showed an increase in average packet loss and latency for the select group of providers in the early weeks of the shelter-in-place orders, but both metrics remained steady in the weeks that followed [62]. Two other large transit providers, AT&T and Telia, reported traffic growing 20-50%.

3.5.1 AT&T

AT&T reported that their core traffic grew by as much as 22% due to the shelter-in-place orders [63]. AT&T also reported that during the shelter-in-place orders their network was carrying an extra 71 PB of traffic per day for a total of 426 PB/day of traffic. It should also be noted that AT&T's network is carrying over seven times as much traffic as it was back in 2014 when it carried only 56 PB/day [49].

3.5.2 Telia

Telia is a Swedish multinational telecommunications company that runs an international IP backbone network which is ranked number 3 in the world by autonomous system connections.[5] The company reported that their peak utilization grew by roughly 35% during the shelter-in-place orders. It reported seeing a 20-50% increase in traffic with the large increases occurring during the morning hours and the peak traffic hours still occurring in the evening. Videoconferencing traffic grew by as much 450% with peak growth of videoconferencing occurring in the morning hours.

3.6 Network Interconnection Points

Interconnection arrangements that govern network connections between networks range from informal to formal, from paid transit to settlement free interconnection and paid interconnection, flexible to adapt to the dynamic and diverse nature of the Internet and different networks around the world. It appears that network operators worked cooperatively and quickly to cut through any red tape and add new capacity as quickly as possible in response to dramatic increases in traffic, as discussed below. Most Internet exchanges experienced traffic growth of 20-30%, while the Kenyan Exchange point experienced traffic growth in excess of 200%.

3.6.1 Internet Exchange Points (IXPs)

As reported by Packet Clearing House (PCH) Internet exchange traffic in the US grew 25%[63]. Internet exchanges in Europe reported similar growth with the AMX-IX in Amsterdam and the INEX in Dublin reporting 12% and 20% growth, respectively. The LINX in London hit a maximum peak of 5 Tbps on March 26, 2020. Internet exchange grew elsewhere as described below.

3.6.1.1 Belgian Internet Exchange (BNIX)

The Belgian Internet Exchange (BNIX), managed by Belnet, reported a traffic increase of about 30% during the first weeks of the shelter-in-place orders [64]. Traffic jumped from a daily average of ~300 Gbps to close to 350 Gbps.

3.6.1.2 Canadian Internet Exchanges (VANIX, MBIX, TORIX, YYCIX)

The four leading IXPs in Canada (Vancouver, Manitoba, Toronto, and Calgary), shared the impact of the shelter-in-place orders on traffic across the IXPs. The IXPs reported seeing a 20-30% increase in traffic during the workday and a 12% increase in the evenings [65].

3.6.1.3 Kenya Internet Exchange Point (KIXP)

The Kenya Internet Exchange Point, used by 68 companies in the region, saw a greater than 200% increase in traffic [66]. Before the shelter-in-place orders, traffic on the KIXP was around 7.5 Gbps and jumped to 22 Gbps in early March with spikes as high as 57 Gbps. The massive spike was attributed to increased video streaming and videoconferencing.

3.6.2 Direct Interconnection

Network operators use a combination of intermediary Internet transit, public Internet exchanges, and direct network-to-network interconnection to provide Internet connectivity. Network operators often choose direct interconnections for a variety of economic and performance reasons.

3.6.2.1 Comcast's Interconnections

The interconnections between the Comcast Internet access network and other networks also experienced extraordinary growth during this time. In 2019, settlement free interconnection capacity, representing a portion of Comcast's interconnection, grew by 15%. But as the pandemic emerged between January and August 2020, there was

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[5] See https://asrank.caida.org/asns

an overall 37% increase in capacity from the 2019 level. Looking at all interconnection traffic types between March and October 2020, individual interconnect partner traffic growth varied widely, with one partner growing 115%, and others by 245% and 3,900%. During this time hundreds of additional 100G links were added, with most augmentation occurring in March to May 2020.

3.6.2.2 Interconnection Measurement Project (IMP)

Similarly, the Interconnection Measurement Project (IMP) collects, aggregates, and analyzes data from a set of US ISPs and their neighboring partners for a set of private interconnection links. In another paper presented at the IAB workshop, IMP researchers reported that ISPs did experience a significant increase in utilization on their direct interconnection links [67]. The overall diurnal patterns did not change, but the overall volume of traffic did increase on the links with some showing an increase in upstream utilization by two or three orders of magnitude. Researchers attribute the growth in the upstream traffic to users working from home and connecting to services that would cause more traffic to transverse the peer link in the upstream direction. Much of the traffic growth is attributable to video streaming and video conferencing. As a percentage of the overall traffic video conferencing grew from 1% of the traffic to 4%, while video streaming's share of the overall traffic declined from 67% to 63% while still growing overall.

The IMP researchers also studied the interconnect capacity for two ISPs in the IMP and observed that both aggressively added two times the normal capacity rate at their interconnects to help bring the utilization rates to pre-COVID-19 levels.

3.6.2.3 MIT Computer Science and Artificial Intelligence Laboratory (CSAIL)

At the September 2020 Internet Architecture Board (IAB) COVID-19 Impacts Workshop 2020, researchers at MIT CSAIL provided an update on a longitudinal study they have been performing on the measurement of congestion on ISP interconnection links. In their update, they looked at the change in latency using the Time Series Latency Probes (TSLP) [68] on links or link aggregation groups (LAGs) for AT&T, Comcast, Cox, and Verizon connecting to their peers. The TLSP system uses a method that involves sending pairs of packets with carefully crafted time-to-lives (TTLs) to each interconnection link. One of the packets triggers a TTL expired from the router on the near side of the link and the other from the router on the far side of the link. Probe packets experience increased delay as they sit in the queue if the link is experiencing congestion. Using this technique, it is possible to infer from congestion on a hop-by-hop basis by looking at the change in delay. Using this method, the researchers noted observed increased overall congestion in both early 2017 and 2018. For the period of spring 2020 they did not observe a consistent pattern of increasing latency for the LAGs from Comcast, Cox, AT&T, or Verizon [69].

3.7 Content Delivery Networks

A number of the gaming platforms, such as Microsoft and Sony, routinely push out very large software updates. A software update for a modern game can generate traffic roughly equivalent to 30,000 web pages. In regions where demand was creating bottlenecks, Akamai worked with its customers to reduce gaming downloads at peak times and shifting the downloads to finish during off-peak times [70].

As COVID-19 took hold in Seattle, Washington in early March, Cloudflare noted that its traffic to the city was up 40% during the week of March 5-12 as compared to January 2-7. In Italy, which was also hard hit early on during the pandemic, Cloudflare stated that traffic grew by more than 30% when comparing the weeks in January and March. In looking at the domains being accessed by Italian users during that week in March, it found that online chat systems were up 1.3-3x the normal usage, video streaming roughly doubled, online gaming was up about 20%, and news and information websites increased 30-60%. In South Korea, Cloudflare found that traffic increased by only about 5% comparing the weeks in January and March [71].

Fastly also looked at traffic changes on its network during February and March. In Japan, France, and Spain, Fastly reported traffic changes between 30-40%, while in the United Kingdom, it was up nearly 80% and nearly 100% in Italy. In the United States, Fastly reported that traffic grew almost 38% in Michigan, nearly 45% in New York and New Jersey, and over 46% in California [72].

3.8 Cloud Providers & Backend Infrastructure

With the move to working from home and employees using VPNs, it was observed by RIPE[6] that traffic on open public and ISPs DNS resolvers went down as employees shifted to using their employer's DNS. RIPE observed that before the shelter-in-place orders, that for one of the largest consumer ISPs in the US, users of the ISP's DNS service dips about 5% on weekdays compared to weekends while the use of Google's DNS service is 3-4% higher on weekdays compared to weekends. Once the shelter-in-place orders began, both services trended towards the weekend usage level indicating that many employees were either using a split-VPN or not using VPN at all while working from home [73] [74].

3.9 End User Application Providers

Application providers reported increased usage during the shelter-in-place orders for several types of applications [75]. Verizon reported traffic trends showing gaming up 102% [76], video streaming up between 33-58% [76][77], and VPN usage up 52% [76]. Nokia [77] reported that videoconferencing was up 350% and, on some networks, as high as 700%. Social media use jumped by 50% to 1000% in some countries [78][79], and social messaging went up between 6-27% [77].

3.9.1 Video Conferencing

Video conferencing was one category of applications that experienced tremendous growth in popularity. Cisco reported that the use of its video conferencing application, WebEx, peaked at 24x higher in volume [80], with the meeting minutes growing from 6.7 billion in February to 21.8 billion in April, the number of meetings growing from 37 million to 96 million, and the number of participants growing from 161 million to 509 million [81].

Likewise, another video conferencing application, Zoom, also experienced tremendous growth. In response to the crisis, Zoom introduced a limited free hosting service [82] [83], adding hundreds of thousands of paying users over the course of the year [84]. In June 2020, Zoom said that daily meeting participants had grown from 10 million in December 2019 to 300 million [85]. It was also observed that Zoom switched to a multi-CDN strategy as part of scaling up to meet the demand [10].

In addition to dealing with the tremendous growth in the use of its product, Zoom was responding to criticism about the weak security in its product. Concerns were raised by many, including the FBI [86] and the New York attorney general's office, that "Zoom's existing security practices might not be sufficient to adapt to the recent and sudden surge in both the volume and sensitivity of data being passed through its network" [87]. In response to these concerns Zoom worked quickly to address the complaints [88].

3.9.2 Video Streaming

The video streaming providers reported seeing limited issues in most markets [89]. For the most part, the increased usage of video streaming was within the existing capacities of video streaming platforms [89]. The video streaming providers reported seeing a shift in usage patterns similar to what the network operators reported with shelter-in-place, where they saw peak utilization in the mid-day and a greater distribution of the demand across the day. Google reported that its YouTube service was seeing twice as much traffic at 85% of the actual peak compared to preshelter-in-place [89], while Netflix reported the biggest change was in the mid-day with the evening traffic being very similar to before shelter-in-place orders were implemented.

Concerns were raised early on by European regulators about a sudden increase in video streaming potentially overwhelming some of the European networks. In response to the concerns raised by European regulators, Netflix [90], Amazon Prime, Apple [91], YouTube [92], Facebook [93] and others all agreed to scale back bit rates in Europe for at least 30 days as a precautionary measure. Later in May 2020, operators began work to restore streaming quality

[6] RIPE is the Regional Internet Registry (RIR) for Europe, the Middle East and parts of Central Asia.

[94]. A recent December 2020 update of the Netflix ISP Speed Index[7] shows many US ISPs have performed consistently well over the last six months of 2020, with a group of seven top ISPs measured at 3.8 Mbps of prime time Netflix performance. Finally, looking at average performance by country, many countries were 5% - 10% lower than those in the US - including as France, Greece, Hungary, Italy, Japan and Taiwan.

3.9.3 Social Media

Facebook, a large global social media company, reported on Internet traffic growth and Internet performance as seen from Facebook's edge network [95]. Facebook's global network, which serves over 2.5 billion monthly active users, is comprised of a series of PoPs and off-net cache servers with interconnections spread across six continents with major ISPs in all regions. Because Facebook sees users from a significant portion of the Internet, its network serves traffic in excess of 100 Tbps at peak As a whole, Facebook observed a 38.7% increase in egress traffic on its network with traffic growing 1.41x as much for broadband and 1.24x for mobile.

Facebook's report focused on four product categories: messaging, livestreaming, video, and photo. Of the four product categories, the livestreaming products witnessed an exponential surge in popularity (200-300% growth) while contributing little to overall traffic.

Facebook reported that North America and Europe did not show any signs of degradation in video quality, while networks in India, Sub-Saharan Africa, and South America did witness signs of network stress. Facebook used a number of indicators to assess video quality including the discrepancy between video traffic growth and video engagement growth, video Quality of Experience (QoE) using a metric called bad session rate (BSR), overflow to transit and public peering, and round-trip times. Facebook observed that in countries with a low video QoE, there was a significant gap between video traffic growth and video engagement growth with India being a good example of low video QoE with video traffic growing 10% while video engagement grew 60%. Facebook observed a 5-25% growth in indirect traffic flowing through transit and public peering during the second half of March and observed a correlation between this growth and low video QoE. Facebook also observed a strong correlation between an increase in round trip times and low video QoE, as it asserts that an increase in round trip time is a good indicator of path congestion.

Facebook saw that degraded video quality always coincided with an increase in network metrics like round trip times and the amount of traffic overflowing to indirect links. And finally, Facebook also noted that it cannot pinpoint the exact causes of network stress as it could be caused by a variety of factors including congestion of direct CDN peering links, overutilization of CDN servers, and congestion of ISP access networks, particularly mobile carriers in emerging markets, but that measures taken by operators did allow networks to recover to their pre-COVID-19 performance levels relatively quickly.

3.9.4 Internet Measurements

Internet measurement platforms collect performance data, usually without knowledge of the advertised rate of the ISP connection. These platforms rely either on tests running from a test probe on the home network or from user-prompted software clients that can be device native or web browser clients. If one of these platforms recorded an increase or decrease in speed, unless the ISP has told the client the advertised speed, the platforms do not know if a decrease meant that an ISP was still providing more than the advertised speed, just slightly less than before, or whether speeds are now below those advertised. SamKnows and Ookla are two Internet measurement companies.

SamKnows tests use controlled test probes and the tests will only run when there is no competing cross traffic on the home LAN so as to develop a more accurate view of capacity. If cross traffic was ignored, a throughput test could run while the network was being used heavily and the result would not show the capacity of the connection but only the unused portion of the connection. SamKnows [96] reported that during March 2020 a majority of wireline download speed tests recorded a very slight decline in speed of about 1% with the largest drop of any ISP being 3.9%. When looking at recent FCC Measuring Broadband America (MBA) reports, which uses SamKnows probes and collects the advertised rates from the ISP for the annual measurement period, most ISPs deliver more than 100% of advertised

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[7] See https://ispspeedindex.netflix.net for the index and https://about.netflix.com/en/news/new-and-improved-isp-speed-index for more information in the updated methodology

speeds. As a result, this suggests ISPs continued to over-deliver but at temporarily lower levels of over-delivery (as demonstrated for example in the independently assessed Comcast data).

Ookla's tests may run on an automated basis from embedded LAN gear (e.g., software on a home gateway) or may be prompted by end-user action via a speed testing client (native or web-browser based). Given that these tests do not check for cross traffic before running, and that clients are likely connected over Wi-Fi (which tends to be a key performance bottleneck), it seems likely that their observed declines will be a bit greater than for SamKnows. Indeed, Ookla reported about a 7% decrease in download speed for wireline networks and a 9% decrease in download speed for mobile networks [97] in March 2020, with download speeds returning to normal later in Q2 2020. Unlike SamKnows, Ookla cannot demonstrate the percent of advertised speed being delivered to an end user but given their huge volume of tests it is interesting on a relative basis over time.

The Internet Health Report (IHR) reported on measured round-trip time (RTT) as a proxy for network delays, using March 19, 2020 as a lock-down start date [98], and observing from networks to nearby destinations on the Internet using data from the RIPE Network Coordinating Center's (NCC) Atlas measurement platform network of over 10,000 measurement probes. No measurable change in RTT was observed during the shelter-in-place orders by the IHR for major US ISPs, while the IHR did observe some delays for French ISPs during the shelter-in-place orders. A study performed by Internet researchers looked at the last-mile latency using traceroute data from RIPE Atlas probes on 646 different networks globally and noted prior to the pandemic only 7% of the networks experienced persistent last-mile network delays but recorded 55% more (from 45 to 70 ASes) after the pandemic outbreak [99].

Internet researchers [100] seeking to characterize ISP responses during the stay-at-home window analyzed the FCC's ongoing nationwide performance study of broadband service in the US [101], and the data collected by the distributed measurement devices known as Whiteboxes [102] placed in volunteer's homes and operated by SamKnows. Researchers analyzed the seven-day moving average of round-trip latencies between the Whiteboxes and the top 10 most targeted servers across the US to represent the overall performance. They observed an increase in the seven-day moving average round-trip latency by as much as 10%, corresponding to a 30x the standard deviation among all the Whiteboxes, while noting that they have observed similar deviations and increases in latency in the past and attribute some of it to seasonality. The researchers concluded some performance effects are visible during the COVID-19 lockdown, but that the event and its effect on network performance are not significantly different from other performance aberrations demonstrated in past FCC MBA reports.

There were large increases in the volume of consumer Internet tests performed on wireline networks during the initial months of the pandemic. Ookla shared that it saw 84% more U.S. wireline tests in April 2020 (29.5 million) compared to February 2020 (16 million) on their Speedtest platform while the number of mobile network tests remained relatively flat. Based on analysis by Ookla of Speedtest Intelligence® median download speeds for July 2019–July 2020, the U.S. median download speed decreased by 3.3% across wireline networks for the same months (on a relative basis - not reflective of over or under advertised rates), but the picture is a bit different when looking at ISPs separately.

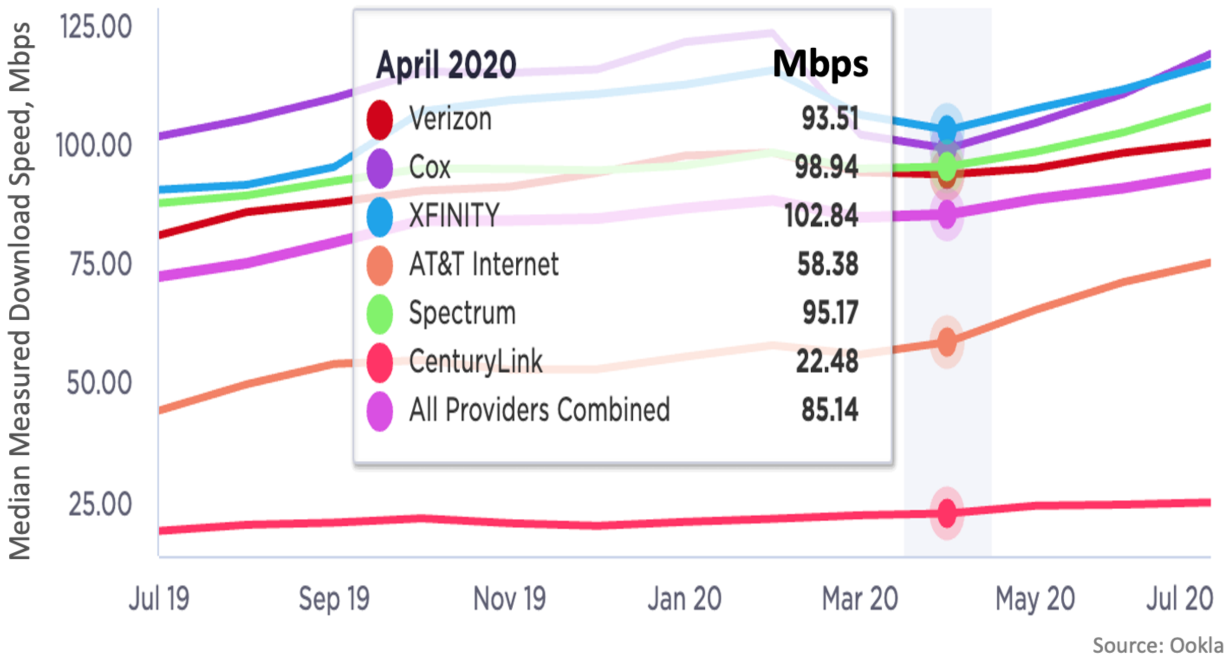

Figure 2. Ookla Speedtest Results. Source: Ookla

As Figure 2 illustrates, some of the ISPs experienced a speed decrease in April. It is worth noting that the median speeds still remained above the advertised speeds, and performance returned to pre-pandemic peaks by July. It should also be noted that the median download speeds are a reflection of the subscriber's choice in service plans.

3.9.5 Online Payment

While not particularly bandwidth-intensive, it is notable that the usage of online payment platforms has also increased. The stay-at-home orders required reduced contact between merchants and customers, resulting in increases in e-commerce, mobile banking, and a greater use of cashless payment options [103]. As PayPal CEO Dan Schulman related on a 3rd Quarter 2020 earnings call [104] [105], payment volume grew a record 36% during the quarter, and PayPal transactions totaled a record of over $4 billion, up 30% from that same time period in 2019. PayPal added 15.2 million new end users in the 3rd quarter, its second highest after adding 21.3 million in the 2nd quarter. PayPal also added over 1.5 million new merchants, more than twice the pre-COVID rate. While merchants were migrating to cashless applications prior to the stay-at-home orders, PayPal leadership believes this marks a permanent shift in consumer behavior.

4 Observations

As noted earlier in this report, the shift-to-home caused a massive increase in Internet usage in a short period of time. In some cases, this represented a full year's worth of growth in a matter of a few weeks, posing interesting capacity management challenges across the Internet ecosystem. A wide array of different types of network operators sprang into action to rapidly add capacity, as did application platforms and others that experienced incredible growth (e.g., video conferencing). Network and application performance metrics clearly show the onset of this shift, which generally begins to normalize as the Internet ecosystem reacted.

This also ended up exposing performance limitations with legacy user devices and older home networks, which are also being replaced and upgraded broadly by consumers in response. Because of the adaptive nature of application protocols on the Internet today, applications have been able to adapt quite well to temporary changes in things like latency or capacity - one of the things that has enabled this sudden behavioral shift to be so successful.

There is much technical learning that is occurring, which will continue to lead to operational and protocol adaptations and will just as surely lead to the development of new applications, protocols, devices, and other exciting changes. As an example, the learnings from disaster planning and security evaluations rapidly implemented into practice during periods of extreme organizational stress may result in private and public sector recommendations published to improve response times during future events.

Put simply, the Internet did not collapse as some were concerned it would [106][107]. Rather, it has been a success story that has enabled the United States to transition to working and learning from home. If it had collapsed there would have been numerous reports of Internet users having trouble getting online, slow page loads, aborted or failed video conferencing sessions, streaming video quality issues, and other issues. Nor did we find any data that supports that there were widespread issues.

4.1 Shift in Usage Patterns

Internet usage growth was not uniform across the United States as shown in Figure 3 with some areas experiencing larger growth or growth later in the spring.

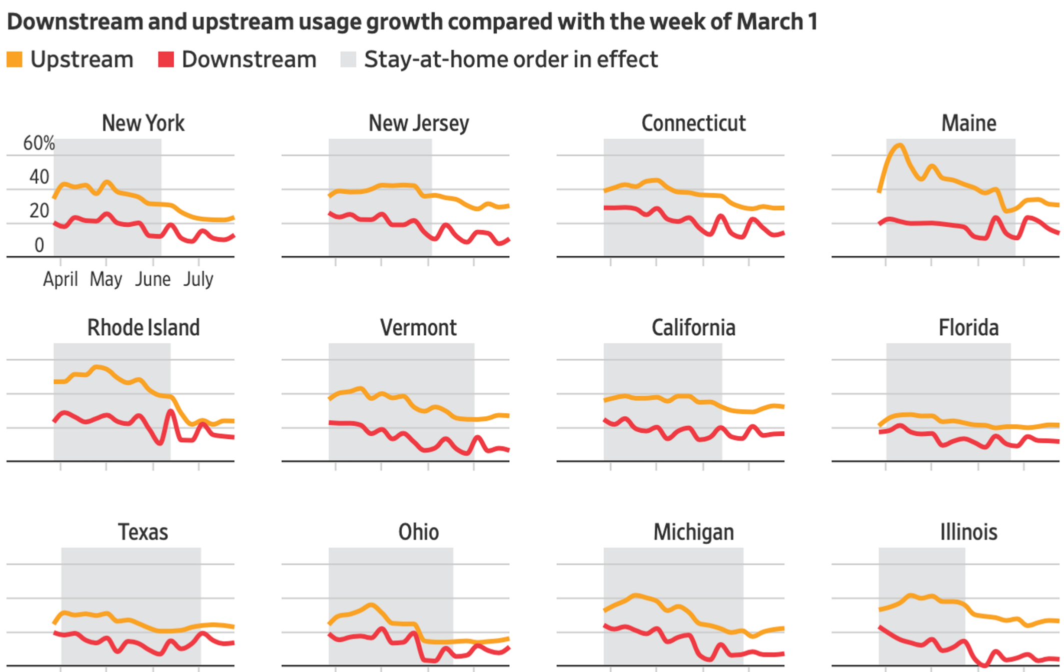

Figure 3. Downstream and Upstream Growth Since March 1 Source: Wall Street Journal [108]

Growth also did not occur uniformly across the day. Looking at diurnal traffic patterns such as the one shown in Figure 4, we can begin to see how changes in subscriber behavior impacted network traffic. CommScope [109] looked at the upstream and downstream traffic across thousands of aggregation points in ISP networks and observed that broadband usage for both upstream and downstream started earlier in the day and went later into the evening. For the downstream the busy hour was still in the evening and grew 12-25% and the mid-day traffic grew 25-50%. The big and more important change is the shape of the upstream, where the busy hours now start in the morning and run until about midnight.

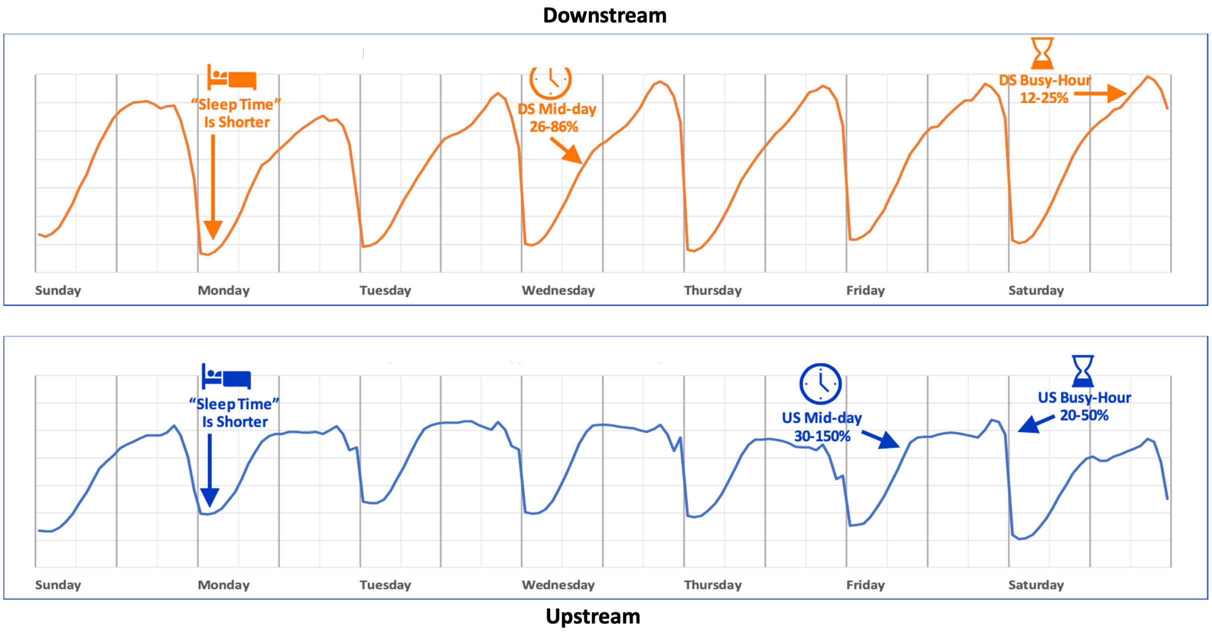

Figure 4. Typical traffic pattern last two weeks in March Source: CommScope [109]

Looking a little closer at the upstream for one US ISP, as shown in Figure 5 below, [110] we can see that the upstream busy hours started around 10 AM and went until around 10 PM each day, with the upstream peak hour shifting from 9 PM to 2 PM. The shift and growth in the upstream is likely due to the shift to working from home and remote learning using upstream bandwidth applications like video conferencing.

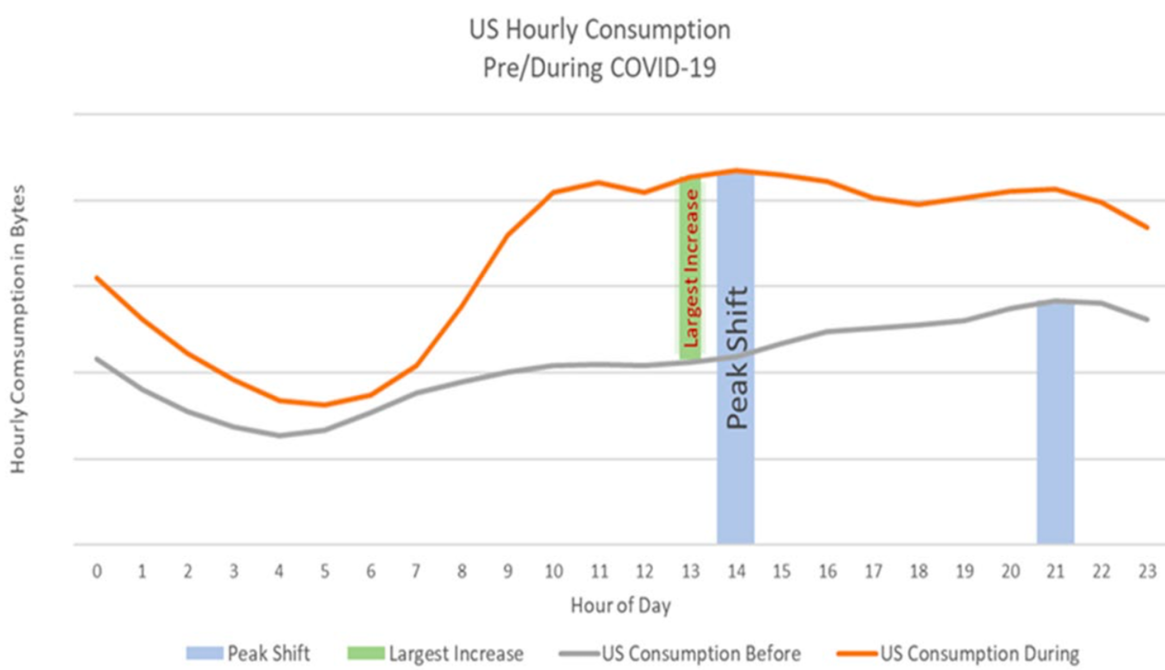

Figure 5. Change in upstream traffic Source: Comcast [110]

Figure 6 provides more insight into the applications that contributed to the change in the upstream bandwidth growth. As can be seen in the figure, two of the top applications that contributed to growth in the upstream usage were Apple’s FaceTime and Zoom.

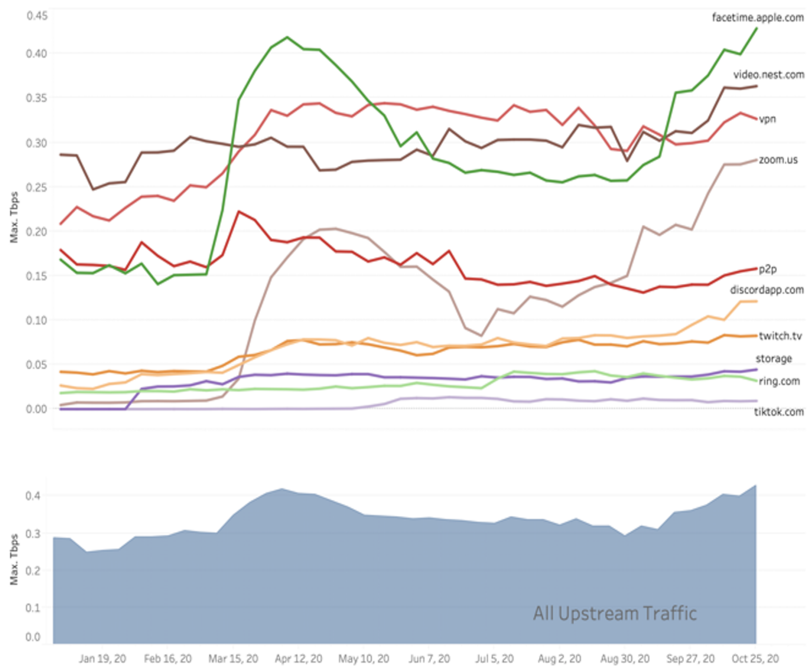

Figure 6. Change in weekly average upstream consumer traffic for top applications over the course of the pandemic Source: Nokia Deepfield

For some operators, the shift in usage resulted not only in a shift in the busy hour(s) but also a shift in traffic from their business customer networks to the residential customer networks.

Even though this dramatic growth is interesting and makes for good press, it doesn’t say much about how well networks, cloud platforms, applications or other parts of the Internet ecosystem performed. To understand this, you need to look at how the changes in subscriber behavior impacted the performance of the networks and the applications driving the usage.

4.2 Downstream to Upstream Traffic Ratio

With the increase in upstream bandwidth usage, the downstream-to-upstream traffic ratio declined from 20:1 to 16:1 and was still ahead of where it was in 2019 according to a CommScope technical report [111]. OpenVault reported that even after the stay-at-home orders the ratio of downstream-to-upstream traffic was still asymmetrical with the average daily consumption during 9 am to 5 pm of 6.35 GB and the average upstream usage of 0.39 GB. This is consistent with the traffic growth reported by the NCTA, ACA, and many of the ISPs. In absolute numbers, the volume of downstream traffic grew at a greater rate than the upstream traffic due to fact that on average video streaming uses anywhere from 2 to 10x more downstream bandwidth than the average upstream bandwidth used by video conferencing. Even with the growth in the use of upstream intensive applications such as video conferencing, the downstream-to-upstream traffic ratio is still highly asymmetrical and illustrates that asymmetrical broadband fulfils the requirements for most residential broadband users.

4.3 Video Streaming & Video Conferencing

As was reported and as can be seen in Figure 7, the applications driving the increased usage were video based: both video streaming and video conferencing. Part of the growth in video streaming traffic can be attributed to users shifting from devices with small screens to devices with larger screens [112].

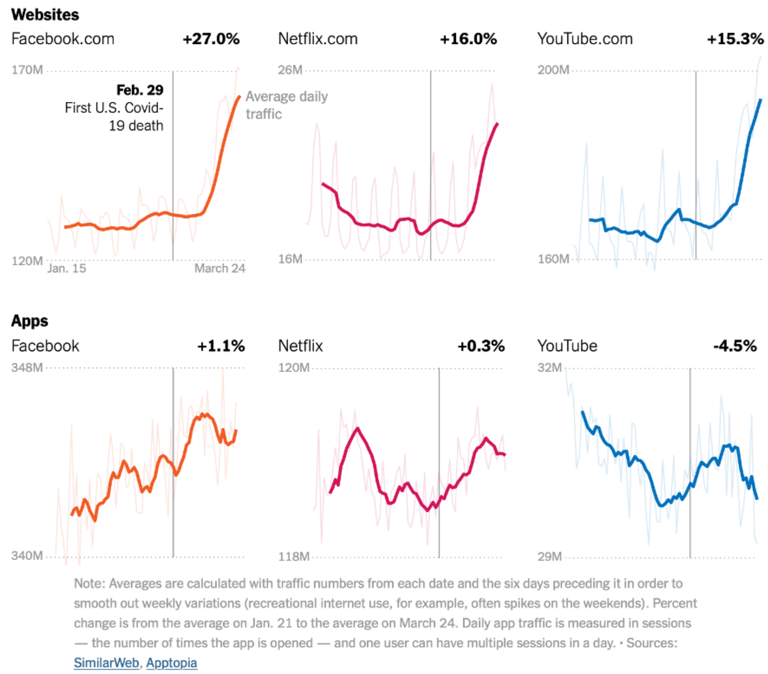

Figure 7. Shift to larger screens. Source: New York Times [112]

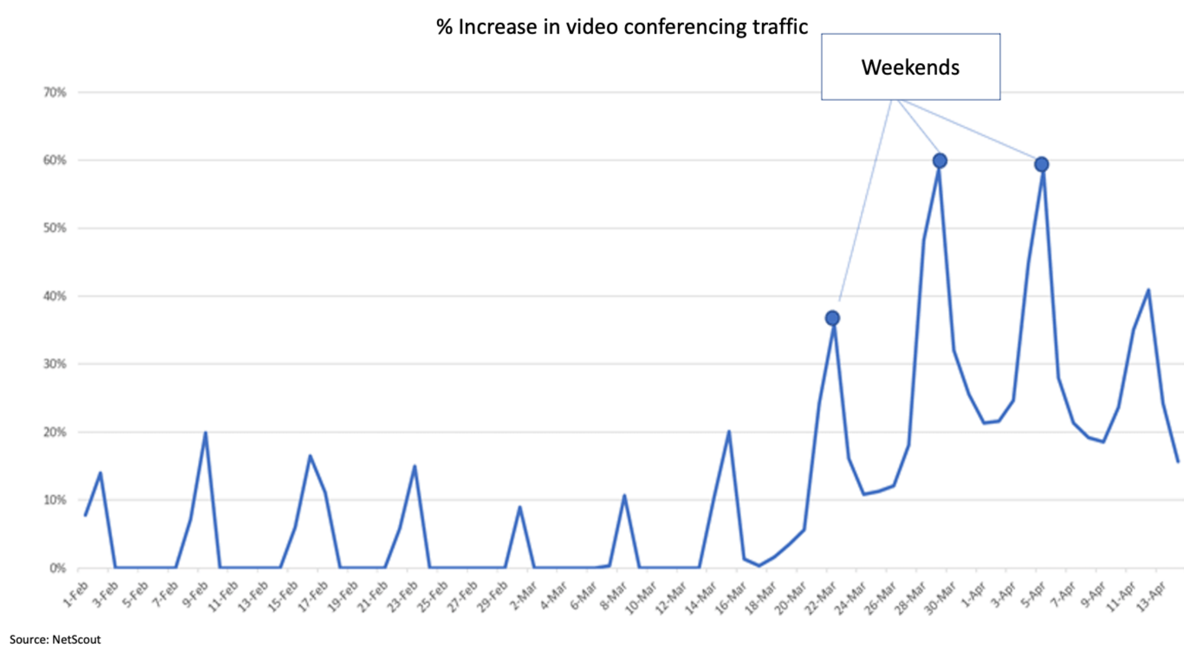

Figure 8. Application growth. Source: NetScout [15]

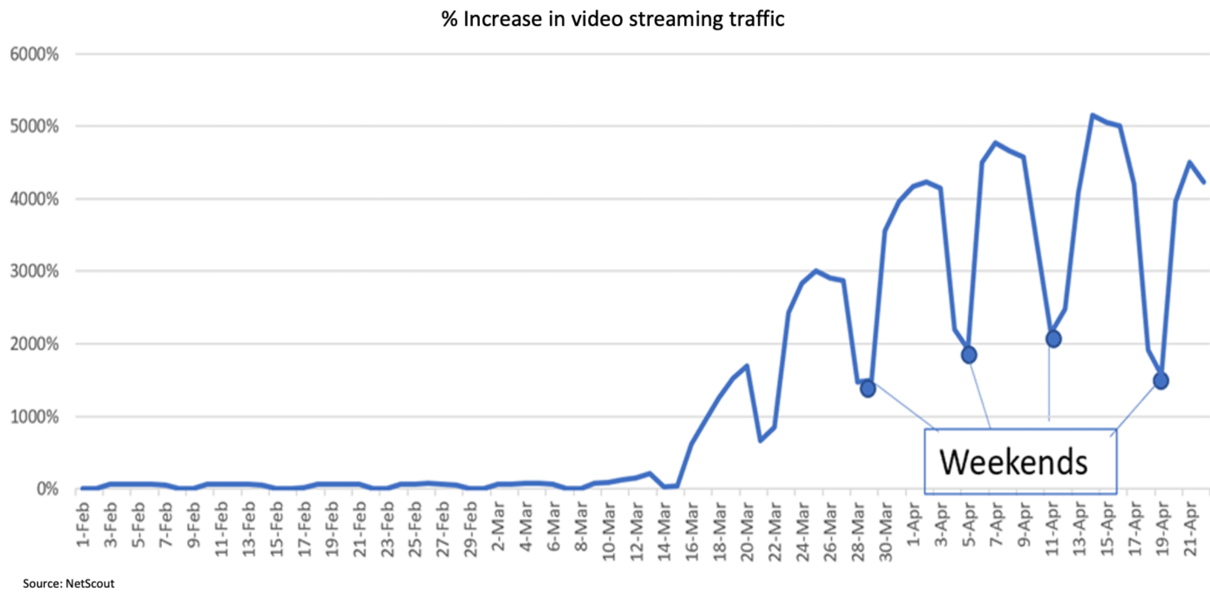

Figure 9. Application growth. Source: NetScout [15]

Video streaming and video conferencing were two applications that experienced a significant growth in popularity and that measurably contributed to the overall bandwidth growth. Figures 8 and 9 give an idea of how they each contributed to the bandwidth growth. Other applications like VoIP and messaging also grew in popularity but have low bandwidth requirements and therefore did not contribute significantly to the overall bandwidth growth. Video streaming typically requires 3 to 5 Mbps for high-definition video[113][114], and video conferencing typically requires anywhere from 500 Kbps to 2 Mbps for both upstream and downstream[115][116]. Knowing this we can infer that upstream growth is due to the increased usage of video conferencing and the downstream growth is primarily driven by video streaming.

4.4 Round Trip Times and Latency

Path congestion typically goes hand-in-hand with increased round trip times (RTT) or latency. Studies have shown that latency is one of the key metrics for user quality of experience (QoE) when using the Internet. This is true for web page load times [117] as well for video [118]. Overall video QoE is impacted less by temporary changes in throughput, and this can be attributed to the fact that modern video applications all use a form of adaptive streaming to account for variations in network conditions along the end-to-end path. Most use either the Dynamic Adaptive Streaming over HTTPS (DASH) or HTTP Live Streaming (HLS) protocols in conjunction with a proprietary application layer Adaptive Bitrate (ABR) algorithm and a video encoder, such as H.264, that supports video compression, in order to dynamically adjust the bitrate of the video stream. The actual bitrate transmitted and/or received is a function of the device capabilities (screen resolution, etc.), network conditions, and user activity. This is particularly true for video conferencing when the video may not be full screen, when there may not be a lot of activity on the screen, or when the user is on mute.

To better understand if networks experienced a measurable change in latency, we looked at the aggregated average RTT times from RIPE Atlas test probes for the larger North American wireline and wireless operators.

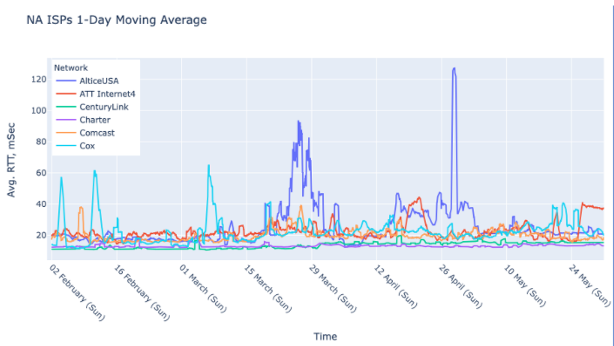

Figure 10. RIPE Atlas wireline ISPs round-trip-time. Source: BITAG and RIPE Atlas[8]

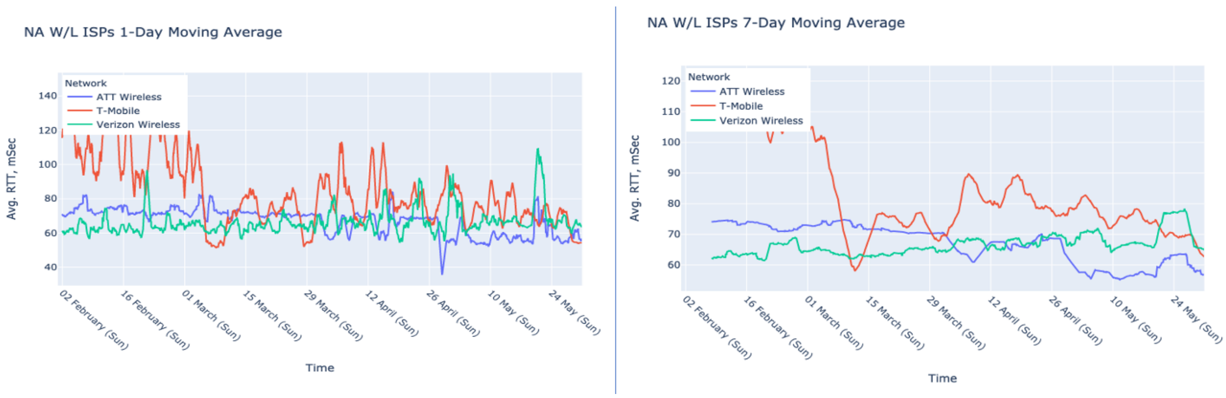

Figure 11. RIPE Atlas wireless ISPs round-trip-time. Source: BITAG and RIPE Atlas

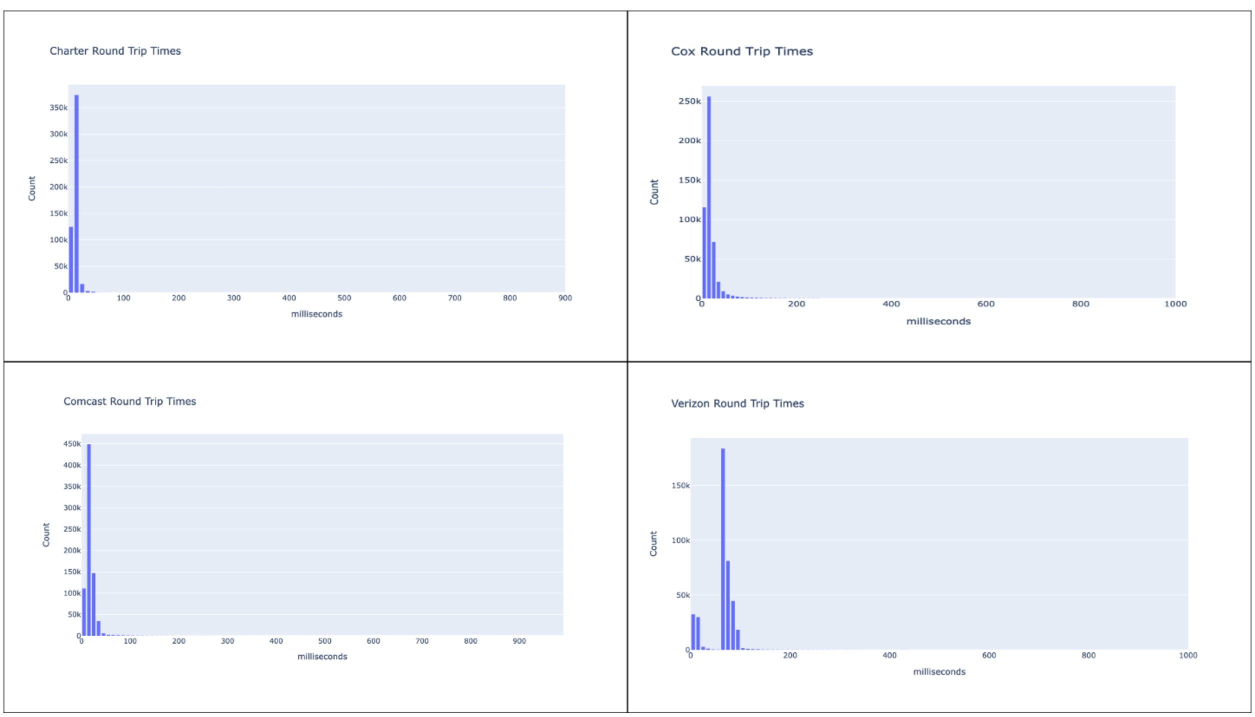

Figure 12. RIPE Atlas RTT distributions. Source: BITAG and RIPE Atlas

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[8] BITAG aggregated Ping and Traceroute measurements from the RIPE Atlas (https://atlas.ripe.net).

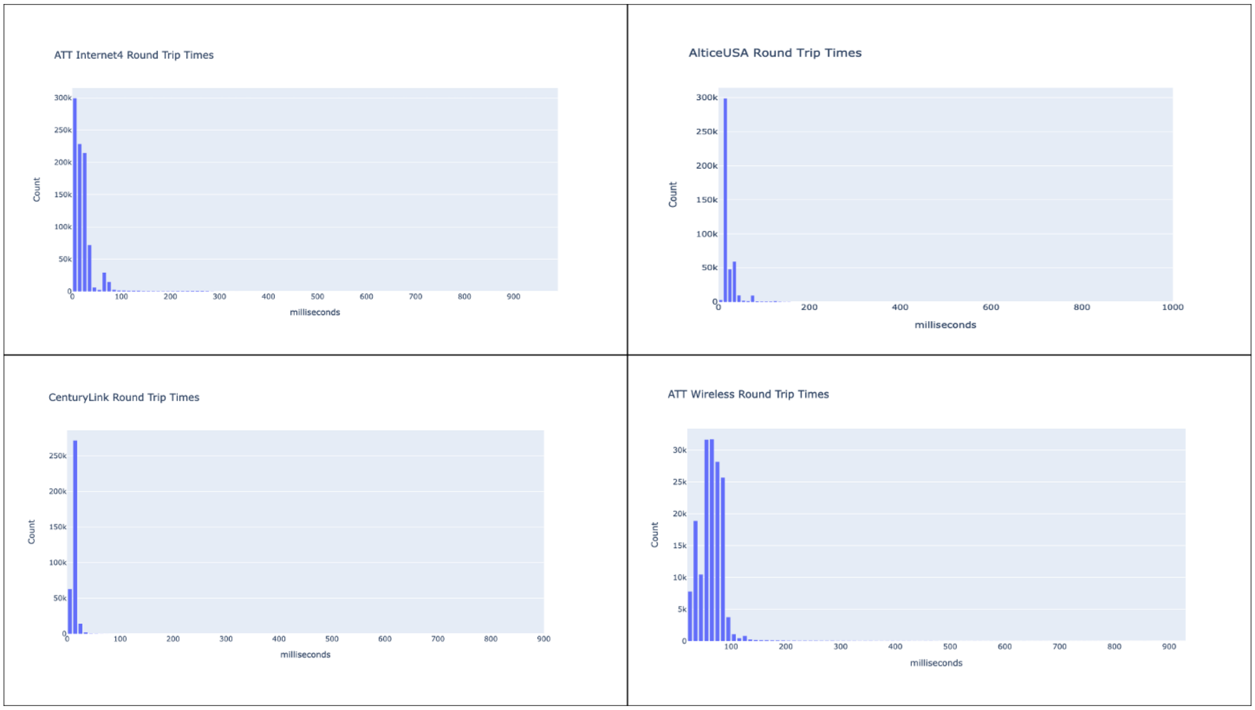

Figure 13. RIPE Atlas RTT distributions. Source: BITAG and RIPE Atlas

Figures 10, 11, 12, and 13 above show the aggregated average RTTs and their distributions from RIPE Atlas test probes on first-hop access networks to a set of nearby destinations (DNS root-servers) to better understand if the growth in Internet usage resulted in an increase in RTT as an indicator of congestion. As shown in the figures above, we can see that the average RTT did not measurably change from before the shelter-in-place orders and when they went into effect for most of the networks. Overall, the latency measured on the first-hop access networks measured was less than 50 ms and well below the 300 ms round-trip latency threshold for video conferencing.

We also looked at CDN connection time data gathered by SamKnows with their Whiteboxes as part of the Measuring Broadband America program on ISP networks to the Akamai, Cloudflare, and Google CDNs. Public and private CDNs account for 90% of the consumer internet traffic [119] with most CDNs being within one hop of ISP networks. The CDN connection time is the total time it took the Whitebox to establish a connection to the CDN. Given that most CDNs are within one hop of ISP networks, the CDN connection time provides us another indicator of the change in latency in the first hop access networks.

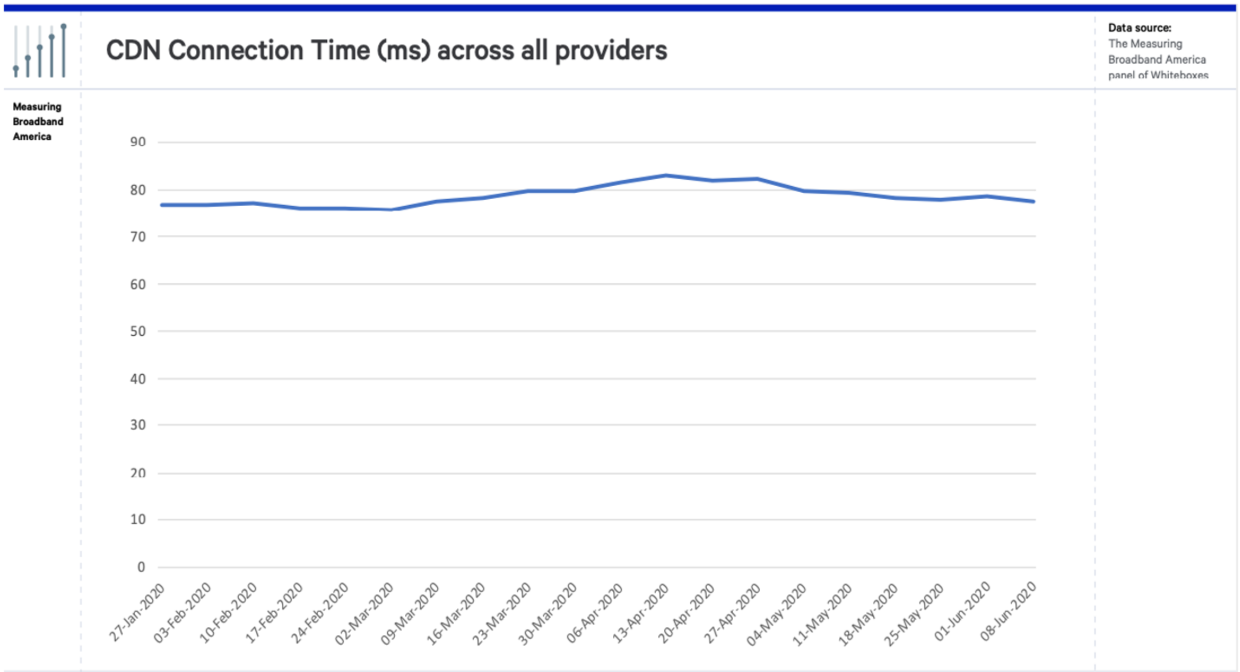

Figure 14. CDN Connection Time (ms) across all providers. Source: SamKnows

Figure 14 shows the aggregated median CDN connection time for Akamai, Cloudflare, and Google. The figure shows that the median connection time had about a 6% increase starting in March 2020. Figure 15 shows the CDN connection times on a per CDN basis and on an hourly basis for each CDN.

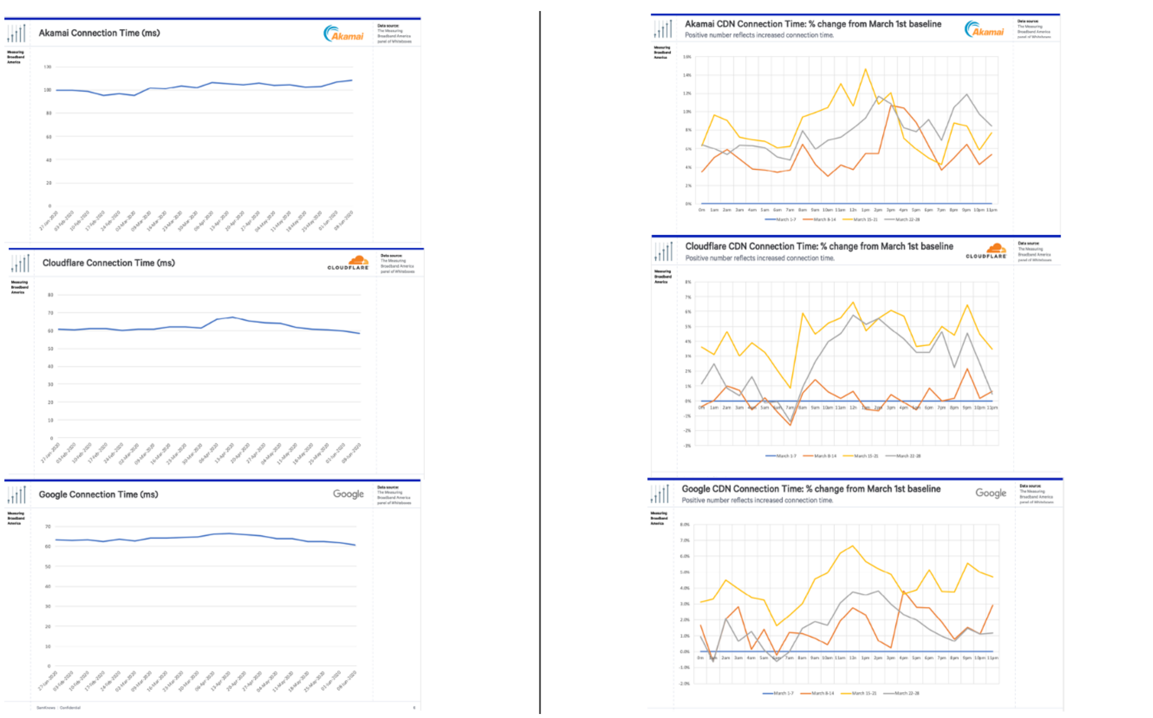

Figure 15. CDN Connection Time (ms) for Akamai, Cloudflare, and Google. Source: SamKnows

We can see that with each of the CDN providers that the CDN connection time increased between 1% and 14% with the largest increases occurring between 8 am and 10 pm.

The increase in CDN connection time is consistent with the observed change in the ATLAS RTT times and would indicate that most of the increase in CDN connection time can be attributed to increased latency in the ISP networks. Even though there was an increase in latency in the ISP networks, on some more than others, the overall latency was still below the required threshold (end-to-end latency to be less than 150 ms or an RTT of less than 300 ms) for latency sensitive applications like video streaming and video conferencing. The data suggests that the growth in Internet usage did not have a measurable impact on applications including the video quality of video streaming and video conferencing applications.

Internet researchers presented a peer-reviewed paper [100] at the Passive and Active Measurement Conference (PAM) 2021 that also looked at impacts of the traffic shifts to latency using data from the Internet Connection Measurement Project and the FCC Measuring Broadband America project. The researchers observed many of the same impacts, in particular the increase in latency for some of the ISPs during March and April in 2020, further corroborating observations we observed in the RIPE Atlas and Ookla data.

4.5 Home Devices and Local Area Networks

The unique application and traffic demands have strained the performance of some home devices and home networks. Users can often improve performance by upgrading their devices, especially in home wired and wireless network. The performance gap between Wi-Fi and Ethernet on the home LAN demonstrates an unmet capacity need in Wi-Fi. Now that the FCC has made additional unlicensed spectrum available (e.g., 5.9 GHz) [120] this should help eventually close that gap, as will purchase and use of Wi-Fi 6 devices and home network gear [121]. Additionally, features such as Active Queue Management[9] (AQM) can be used to reduce latency caused by network congestions.

4.6 Overflow to Transit and Public Peering

Looking at the change in traffic volumes on transit and public peering links compared to direct interconnects provides another vantage point to understand how well the networks are performing. Facebook concluded that it saw no video quality issues on its edge-network, as it did not observe any increase in metrics such as latency nor any increase in traffic overflowing to indirect links [95]. This is consistent with the data from the IMP, MIT CSAIL, NCTA, and ACA as traffic increased significantly on the direct interconnections while not measurably increasing on the transit links.

Contributing to this is the fact that CDNs account for 90% of consumer Internet traffic, thereby reducing the length of the end-to-end path for this traffic as it must transit the first hop network to or from a CDN. This was true even before the shelter-in-place orders were in effect as we observed that transit utilization did not change nearly as much as the access network utilization, indicative that most of the traffic for the first-hop networks still goes through either CDNs or other direct interconnects. The same was true for video streaming as Nokia Deepfield observed changes in the traffic distribution of Netflix video streaming. The percentage ratio of on-net caches and off-net over peering routers changed from 63:37 (on-net:off-net traffic) before the shelter-in-place orders to 46:54 after the shelter-in-place orders. In other words, more than 50% of all Netflix traffic during the shelter-in-place orders in the observed network was delivered as off-net traffic compared to 37% in preshelter-in-place orders.

4.7 Taming Traffic Increases

As part of managing the changes in traffic, it was observed that there was a greater level of cooperation and collaboration between members of the Internet ecosystem. A good example of this is when a software update for modern video game is pushed out.

And finally, as noted by the FCC [122] and others, there is a generally a clear difference in throughput between Ethernet and Wi-Fi on the home LAN. Common Ethernet devices operate at 100 Mbps or 1 Gbps, with even higher speed 2.5, 5, and 10Gbps devices emerging. Ethernet devices are not affected by concurrent use because they do not

[9] Active Queue Management (sometimes referred to as Smart Queue Management or Queue Discipline) can significantly improve user experience and the performance of certain applications during times of network congestion. This feature can sometimes be enabled by the user by turning on Quality of Service (QoS) features. For further discussion see: https://www.bufferbloat.net/projects/bloat/wiki/What_can_I_do_about_Bufferbloat/

rely on shared media apart from upstream aggregation links. As long as Ethernet speeds are greater than broadband connections, it's not a bottleneck.

Wi-Fi, on the other hand, shares a limited inventory of spectrum bands and is potentially affected by interference with other users within the home, the apartment building, and the neighborhood. Wi-Fi throughput also declines with distance, such that devices close to their Wi-Fi access points can operate as much as five times faster than those farther away.

Under ideal conditions, Wi-Fi networks provide enough bandwidth that they don't bottleneck broadband connections. This applies to networks using the 802.11.ax standard on 5.9 or 6 GHz spectrum bands; devices with clear and short paths to their access points; an absence of interference from other Wi-Fi networks; and sufficient processing power to fill the wireless pipe.

In the optimal scenario, Wi-Fi devices can achieve throughput in excess of 1 Gbps, but in many other scenarios Wi-Fi speeds can decline to less than 100 Mbps. Wi-Fi networks are also less consistent than Ethernet with respect to variations in throughput over time and more prone to packet loss.

5 Conclusion

The Internet in the United States has performed and continues to perform well during the pandemic, in the face of extraordinary and unprecedented changes in demand and use. This strong performance covers all of the connected parts of the Internet, from user applications to content distribution infrastructure, all types of Internet access networks, and everything in between. This is likely due to a combination of the nature of the design of the Internet itself, open and interoperable standards, competent technical and operational execution, and significant long-term investments across the entire Internet ecosystem [2]. Infrastructure operators and network operators also responded rapidly to the sudden increase in application and network usage by quickly adding everything from server capacity to interconnection capacity, and last mile access network capacity at rates far beyond pre-pandemic levels.

While all of these things are extraordinarily positive, it also is clear how important reliable, high speed Internet access, digital literacy, and access to computers are for society. Rural and low-income households have struggled with these issues [123] [124]. ISPs quickly undertook efforts to help connect people at no or low cost and provided devices and training. Schools and local governments also launched similar programs to ensure students and their families had Internet access, devices and training. Application providers made platforms such as video conferencing freely available for people during this critical time. Finally, it is apparent that performance issues inside of home networks related to inadequate customer supplied user devices and Wi-Fi have become real problems. Post-pandemic commitment to solving these problems will be required to support converting the short-term gains into lasting impact.

The pandemic of 2020 and the associated shelter-in-place orders triggering many people to shift working from home and/or learning from home as well as the reliance on broadband for many forms of contactless social interactions (e.g., video conferencing, shopping, take-out, entertainment, etc.) further illustrated that reliable broadband has become an essential service for many Americans [3]. The overall strong performance of US networks as compared to other impacted regions during these times illustrates the value of private investment [125] in broadband networks.

6 Recommendations

In closing, BITAG offers these recommendations based on observations of responses of the Internet ecosystem to the technical challenges of shifts in user network access. The recommendations cover key technical adjustments that could be implemented across all parts of the Internet ecosystem. While some recommendations may be implemented independently, the sum total may offer benefits to the whole.

- End users experiencing performance issues, particularly with video conferencing applications should consider (a) upgrading their device, (b) switching from Wi-Fi to Ethernet if possible, (c) re-positioning their Wi-Fi access point and consulting with online resources, including from ISPs, containing helpful guidance on these issues to improve network performance, (d) upgrading their home gateway device and/or Wi-Fi network and possibly as by adding Wi-Fi mesh networking to extend coverage and improve performance and (e) upgrading the speed of their Internet service .

- End users should replace older Wi-Fi routers and access points, such as those using the 802.11b standard, and upgrade to equipment that uses Wi-Fi 6e.
- Home network equipment vendors and ISPs that issue their own CPE should add Wi-Fi 6 to the next update of their devices (if they have not already done so) and when possible add support for Wi-Fi 6e to provide access to the 6 GHz spectrum released by the FCC in November 2020.[10]
- Home network equipment vendors and ISPs that manage CPE should consider supporting and enabling features like Active Queue Management (AQM) in newly shipping equipment and in software updates to deployed devices.
- Enterprise network operators should consider enabling cloud-based applications to use federated Single Sign On (SSO) authentication to allow their users to access applications securely over the Internet without having to route all traffic through an enterprise VPN.
- Network operators should continue to build out network infrastructure with long enough outlooks to factor in headroom that facilitates quick reaction to sudden traffic and usage changes.
- The Internet ecosystem should continue to explore, develop and refine measurement tools that help providers to assess the quality of experience delivered to customers.
- Operators should continue to make use of open standards and open technology as a means to develop cost effective solutions for providing network services.
- Stakeholders should continue with open communications and collaboration for the continued success of the Internet.

[10] See the following for efforts by ISPs: https://corporate.comcast.com/press/releases/comcast-launches-internet-device-multi-gigabit-speeds-wifi-6,https://www.business.att.com/learn/what-is-wifi-6.html, https://www.verizon.com/about/news/verizon-fios-internet-customers-new-router, https://corporate.charter.com/newsroom/Charter-Becomes-First-US-Broadband-Provider-To-Launch-Next-Generation-Router-Delivering-Faster-WiFi-Speeds, https://www.cox.com/residential/internet/panoramic-whole-house-wifi.html

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8 Acronyms

Acronym	Meaning
100G	100 Gigabit Ethernet
ABR	Adaptive Bitrate
ACA	America's Communications Association
ACL	Access Control List
AQM	Active Queue Management
ASes	Independent networks (Autonomous Systems)
BITAG	Broadband Internet Technical Advisory Group
BNIX	Belgian Internet Exchange
CDN	Content Delivery Network
CISA	Cyber & Infrastructure Security Agency
COVID-19	COVID-19 Coronavirus Disease 2019
CPE	Customer-premises Equipment or Customer-provided Equipment
DASH	Dynamic Adaptive Streaming over HTTPS
DNS	Domain Name System
DS:US	Downstream to Upstream ratio
FCC	Federal Communications Commission

GB	Gigabyte
Gbps	Gigabit per second
HLS	HTTP Live Streaming
HTTP	Hypertext Transfer Protocol
HTTPS	Secure Hypertext Transfer Protocol
IHR	Internet Health Report
IMP	Interconnection Measurement Project
IP	Internet Protocol
ISP	Internet Service Provider
IXP	Internet Exchange Point
KIXP	Kenya Internet Exchange Point
LAN	Local Area Network
LTE	Long-Term Evolution
MIT	Massachusetts Institute of Technology
MIT CSAIL	MIT's Computer Science and Artificial Intelligence Laboratory
NCC	Network Coordinating Center
NCTA	The Internet and Television Association
PB	Petabyte
PCH	Packet Clearing House
PoP	Point of Presence
QoE	Quality of Experience
RIPE	Regional Internet Registry
RTT	Round Trip Times
SARS-COV-2	Severe Acute Respiratory Syndrome Coronavirus 2
SMB	Small to Midsize Business
SMB Wi-Fi	Small to Midsize Business Wi-Fi
SSO	Single Sign On
TSLP	Time Series Latency Probes
TTL	Time to Live
UK	United Kingdom
US	United States of America
VoIP	Voice over Internet Protocol
VPN	Virtual Private Network
WHO	World Health Organization

9 Document Contributors and Reviewers

- David Belson, Fastly
- Richard Bennett
- Amie Elcan, Lumen Technologies
- Nick Feamster, University of Chicago
- Craig Labovitz, Nokia Deepfield
- Kate Landow, Dish
- Matt Larsen, Vistabeam
- Jason Livingood, Comcast
- Alex Pavlovic, Nokia Deepfield
- Alex Salter, SamKnows
- Doug Sicker, BITAG
- Kevin Schneider, Adtran
- Barbara Stark, AT&T
- Doug Suttles, Ookla
- Matt Tooley, NCTA
- Greg White, CableLabs
- David Winner, Charter Communications
- Bill Woodcock, Packet Clearinghouse