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Internet Engagement in the Remote Work Era: Insights from High-Frequency Household-Level Data

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Abstract

Widespread transitions to remote activities in the early 2020s led to a dramatic increase in residential internet usage. We document short-term and persistent trends in internet engagement during this period with the use of high-frequency household-level broadband data from a North American internet provider. In spring 2020, overall traffic surged, driven in part by expanded use of remote productivity applications. While demand for these applications remained elevated in subsequent years, the traditional drivers of residential broadband engagement– online video, web browsing, and social media– continued to dominate usage. We document trends in usage volumes, time spent online, and bitrates, and we explore how these patterns vary across demographic segments. Finally, we discuss the implications of these recent trends in internet engagement for ongoing policy debates– including broadband labeling, minimum speed standards, and efforts to narrow the digital divide.

Keywords Internet Access · Digital Divide · COVID-19 · Remote Work · Broadband Labels · Digitization

JEL Classification L86 · L96 · D12 · C23 · O33

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1 Introduction

The COVID-19 pandemic changed many aspects of daily life, including how and why people use the internet. Public health policies to limit the spread of COVID-19– such as social distancing and stay-at-home (SaH) orders– led to increased internet engagement, which tested the limits of global internet infrastructure, as more people went online than ever before. Emphasizing the internet's role during the pandemic, a Pew Research Center survey found that 90% of Americans believe the internet was essential or important to them during the pandemic and that 40% used technology in new ways.[1]

In this paper, we use a novel panel of household-level internet engagement, spanning a 28-month period from 2020 to 2022, to study short-term responses to SaH orders and long-run changes in internet usage during the COVID-19 pandemic. The goal of this research is to inform public policy that is related to the pandemic and telecommunications industry by documenting the state of residential broadband demand over this time period and highlighting notable changes from the pandemic. The panel is composed of five-minute observations that summarize the network demand of 7,017 North American households, with details on the usage of 2,039 individual applications and protocols (e.g., Facebook, Netflix, Zoom, HTTP). Each five-minute observation includes the number of bytes that were downloaded and uploaded by a subscriber for a specific application; the high-frequency level of observation also allows us to calculate the time that was spent online and bitrates by application.

The closure of local schools and businesses to in-person activity had a significant effect on residential internet activity. In the markets that we observe, SaH orders were implemented between March 15 and March 20, 2020. These orders put restrictions on public gatherings and closed broad categories of businesses. The single-day maximum of total internet usage was on Thursday March 26, 2020, just after SaH orders took effect. On that day, the average household generated 11.5 gigabytes (GB) of internet traffic, which was 53% greater than the 7.5 GB average on the same weekday three weeks prior. Consistent with other findings of a voluntary decline in mobility (McCrary and Sanga, 2021; Miller et al., 2022), we also document elevated internet usage one to two weeks prior to the SaH orders.

Daily upstream usage peaked on Thursday, April 2, 2020, when the average household generated 1.25 GB of upstream traffic– an 86% increase over the 0.67 GB three weeks prior. *Collaboration* applications had the largest increase in daily usage between the first and last weeks of March 2020; downstream and upstream usage in GB increased for *Collaboration* applications by 233% and 210%, respectively.

We incorporate regional census data that describe demographics to document differences in internet usage by socioeconomic group. Total internet usage is increasing in education attainment and decreasing in age. Application categories with strong demographic correlations include: *Collaboration*, the use of which is increasing in education attainment; and *Gaming*, *OTT Video*, and *Social Media*, which are decreasing with age. Many of the differences in categorical usage that are present throughout the sample grew when SaH orders were first implemented. In particular, households

[1] https://www.pewresearch.org/internet/2021/09/01/the-internet-and-the-pandemic/.

in census regions with the highest education attainment experienced significantly larger changes in overall internet usage– notably, in the *Collaboration* category– than was true for those households in regions with lower education attainment. Households in the top quartile of education attainment had a 63% higher usage growth rate over the period compared with households in the bottom quartile of education. Households in the top quartile of average age experienced a 43% higher growth rate over the period compared with households in the bottom quartile of average age.

Over the longer time horizon of January 2020 to April 2022, average downstream monthly usage grew from 247 GB to 340 GB, a 37% increase. The growth of monthly upstream usage was 71% (16 GB to 28 GB). After the initial demand surge in spring 2020, downstream and upstream monthly usage decreased briefly then grew at a slower, positive growth rate over the remaining months. The within-sample monthly peaks of both downstream and upstream monthly usage occurred in January 2022 (380 GB and 31 GB, respectively), which correlates closely to the peak in new COVID-19 cases during the Omicron variant wave. The average amount of time that people spent online grew by 23% between January 2020 (10.8 hours daily) and April 2022 (13.3 hours daily).

Increased *Collaboration* usage was persistent beyond the SaH orders in March 2020. Downstream *Collaboration* monthly usage increased by 310% (from 2.4 GB to 9.9 GB) between 2020 and 2022; upstream usage grew 285% (from 1.9 GB to 7.4 GB). However, even after this strong growth in monthly usage, *Collaboration* was not among the most-used downstream traffic categories in 2022. *OTT Video*, *Gaming*, *Social Media*, *Browsing*, and *Downloads* accounted for greater monthly downstream usage, on average. On the other hand, *Collaboration* applications are a plurality of monthly upstream usage, accounting for 7.4 GB (26%) in 2022. *Backup* (downstream growth of 153% and upstream growth of 184%) and *Enterprise* (downstream growth of 153% and upstream growth of 95%) applications also had notable monthly usage growth between 2020 and 2022. The growth of *Collaboration*, *Backup*, and *Enterprise* applications suggests that increased remote productivity at home persisted beyond the early days of the COVID-19 pandemic and could play a larger role in forecasting the future growth of residential broadband usage.

We discuss our results in the context of ongoing policy discussions, including relevance to standardized minimum broadband definitions, broadband labeling, and initiatives that are targeted at expanding access to broadband and reducing the "digital divide." As the importance of internet access became more salient during the early stages of the pandemic, several Federal Communications Commission (FCC) policy initiatives in the United States and Canadian Radio-television and Telecommunications Commission (CRTC) initiatives in Canada emerged that sought to reduce differences in access to internet across both geographic and socioeconomic lines. In particular, in the United States, the Emergency Broadband Benefit (replaced in 2022 by the Affordable Connectivity Program) earmarked $3.2 billion in federal funding to subsidize internet access for lower-income households; in Canada, the Universal Broadband Fund was a similar program that set aside funds for faster broadband deployment outlined in the 2019 Connectivity Strategy plan. Additionally, to address the rural-urban divide in connectivity, the FCC's Rural Broadband Accountability Plan updated guidelines through which broadband providers can receive incentives

for expanding the reach of their networks in areas with fewer economies of density than typical urban markets.

Our results have several notable policy implications for broadband minimum standards definitions. First, the largest usage growth rates occurred in application categories that are associated with remote productivity (*Collaboration*, *Backup*, *Enterprise*). These real-time applications have greater latency demands than do traditional internet drivers. Therefore, latency measures may be a key input into future broadband standards.

Second, despite larger growth rates in other categories, the traditional drivers of engagement– *OTT Video*, *Browsing*– remain by far the most-used internet applications in terms of both usage and time measures. This suggests that traditional broadband definition characteristics– download speed– continue to be highly relevant as the mix of internet traffic changes at a slow rate.

Third, though upstream traffic grew more rapidly than downstream traffic, the asymmetric nature of internet demand remains unchanged, with downstream usage 12.1 times the level of upstream usage in 2022. Therefore, large increases in the minimum upstream speeds that define minimum broadband connections may not yet be necessary.

On the topic of the digital divide, our data do not permit any analysis of broadband access. However, our demographic data do provide insight with respect to how internet engagement varies across socioeconomic groups. In particular, our results suggest that younger, more educated, and larger households have heavier monthly usage. However, older, more educated, and wealthier areas had the strongest increase in monthly usage under SaH orders. This heterogeneity in usage responses is suggestive of which types of households were most easily able to adapt to in-person closures by adopting work-from-home, remote schooling, and other methods of engaging with the digital economy. Not all professions are conducive to remote work; therefore, digital literacy and training for access to careers in professional services and other industries that are flexible to in-person or remote working arrangements are worth studying in future research.

Our analysis relates to other studies on mobility during the COVID-19 pandemic, and in particular broadband access and utilization. Related papers on this subject include Chiou and Tucker (2020), which finds that individuals in high-income areas and those with access to high-quality broadband were more likely to comply with SaH directives, and Bacher-Hicks et al. (2021), which finds that the intensity of web searches for remote school-related keywords was higher in high-income areas with high-quality broadband. Zeltzer et al. (2023) study the impact of increased access to telemedicine during the pandemic on the quality of care.

Other research has studied the effect of the pandemic on work-from-home adoption and its effect on productivity (Bloom et al., 2023; Aksoy et al., 2022). Barrero et al. (2021) seeks to measure the economic value of universal access to high-quality internet for work-from-home. Prior studies have also focused on measuring the digital divide (Wedlake et al., 2021; Hampton et al., 2020; Bronzino et al., 2021; Fernandez et al., 2018, 2019; Hollman et al., 2021; Strover, 2018).

Finally, our analysis relates to other studies on the demand for residential broadband, which have previously documented: correlations between internet behaviors

and demographic characteristics (Malone et al., 2023); the pricing decisions of broadband providers (Nevo et al., 2016; McManus et al., 2022, 2024); the importance of behavioral measures such as attention (Boik et al., 2019); and the implications of broadband plan characteristics for internet performance (Jordan, 2022; Clark and Wedeman, 2022).

2 Data

Our data describe subscriber-level network usage, plan choices, and demographics from January 1, 2020, through April 30, 2022. The sample was provided by a North American multiple-system operator (MSO), which delivers data, video, and voice services over a hybrid fiber-coaxial (HFC) network.

2.1 Sample Construction

The sample was constructed to be representative of the MSO's network by sampling a fixed set of *service groups*.[2] A service group is the first point of aggregation past the customer premise: "upstream" from the customer, in the direction of the MSO's core network. All subscribers that are connected to a service group– 200 to 400 homes in a typical North American service group– share a fixed amount of network capacity.[3] We observe 21 distinct service groups from across the MSO's network footprint.

We observe the behavior of 7,017 unique residential subscribers. Figure 1 shows that the count of subscribers observed over time is stable, averaging 3,209 per month. However, the set of observed subscribers adjusts over time. The panel is unbalanced because of the operator's priority of monitoring service group performance rather than the behavior of individual customers. The set of subscribers in a given month is a function of sample rebalancing to maintain a representative distribution of network utilization and business dynamics such as churn and customer acquisition. The average subscriber is observed for 13 of the months in the sample period; approximately 12% of households are observed in all 28 months of the sample period. Our analysis focuses on the full (unbalanced) set of household-months in the sample.[4]

2.2 Data Sources

Next, we describe the three distinct data sources in our sample.

[2] Past research with similar level of detail on network utilization has primarily observed the entire "footprint" of an operator's network in one or more markets (Malone et al., 2023; McManus et al., 2022).

[3] A service group's shared capacity is a function of the amount of spectrum and spectral efficiency used by the MSO. Service groups commonly have a one-to-one relationship with a fiber node, a device that manages sent and received data transmissions across fiber and coaxial cable. This combination of fiber and coaxial cable gives this type of access network the name *hybrid* fiber-coax (HFC). As HFC networks have evolved over time, fiber has been pushed closer to the customer premise, replacing coaxial cable.

[4] There are no statistically significant differences in demographic composition between the full and balanced set of households. All of the results that are shown are qualitatively similar when we limit the analysis to the subset of households that are observed across the entire sample.

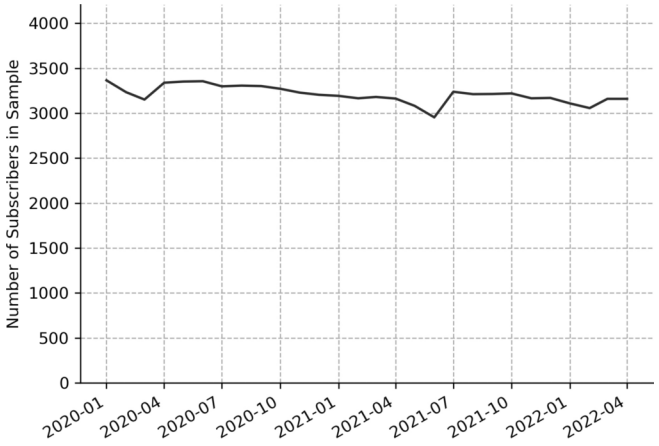


Fig. 1 Sample Size. Monthly count of unique subscribers. Includes all subscribers with positive usage in a given month

Table 1 Usage Categories

List of internet usage categories with example applications and protocols

Category	Example applications
AR/VR	Niantic, Oculus Rift
Backup	Amazon Drive, Dropbox, OneDrive
Browsing	Email, HTTP, QUIC, SSL
Collaboration	FaceTime, Microsoft Teams, Slack, Zoom
Downloads	Akamai, Apple Software Updates, CDNs, Microsoft Updates
ECommerce	Amazon, iTunes, Walmart
Enterprise	Adobe, GitHub, Office 365
Gaming	PlayStation Store downloads, Xbox Live
News	Apple News, BBC News, CNN, The Wall Street Journal
OTT Audio	Apple Music, SoundCloud, Spotify
OTT Video	Netflix, Peacock, YouTube
P2P/File Sharing	BitTorrent, FTP, Usenet
Remote Access	LogMeIn, TeamViewer, VPN applications
Smart Home	Amazon Alexa, Apple Siri, Nest
Social Media	Facebook, Instagram, LinkedIn, Snapchat

Subscriber network demand—Subscriber-level network utilization is recorded at a five-minute frequency by application or protocol. There are a total of 2,039 unique applications. Table 1 describes how applications and protocols are mapped to broader categories so as to make our analysis of usage patterns more tractable. This mapping was constructed by the authors.

The subscriber-level usage records are collected and labeled based on information that is contained in packet headers. This aggregation occurs in the operator's core

network– not at the customer premise.[5] Because network statistics are recorded at a cable modem level of observation, individual devices within the home are not identifiable. Therefore, multiple active applications observed within the same five-minute interval could be multiple individuals using the internet simultaneously or a single individual multitasking.

Traffic that is sent and received with the use of cellular networks– including mobile hotspot activity– is not observable in the sample. The effects of not being able to observe cellular traffic are mostly limited to smartphones. An industry report claims that the majority of at-home smartphone usage occurs while users are connected to Wi-Fi—up to 76% for Xfinity Mobile customers (Mills and Armstrong, 2019).

Plan choices—Subscriber plan choices are recorded at a daily frequency. Observable plan details include advertised download and upload speeds, but not pricing. The MSO completed its rollout of 1 gigabit per second (Gbps) service in early 2020. Figure 2 summarizes the sample's average download and upload speeds. The average download speed increased by 61% between January 2020 and April 2022 (264 Mbps versus 426 Mbps); average upload speeds grew by 315%, from 13 Mbps to 54 Mbps, respectively.

Demographics—Demographic data are available for each subscriber at the granularity of a postal code extension– ZIP+4 in the United States or Local Delivery Unit

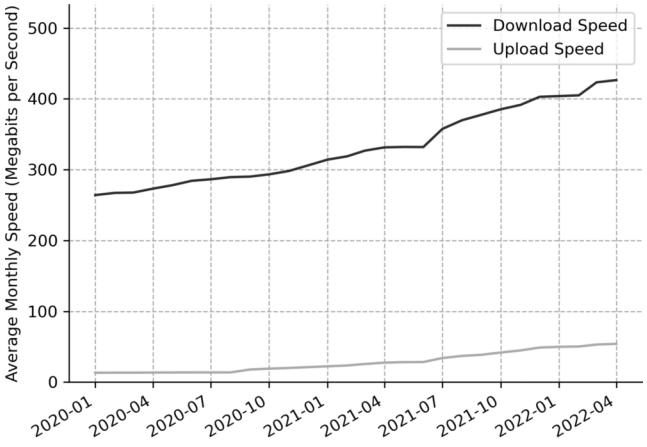


Fig. 2 Connection Speeds. Average download and upload plan speeds are computed at the year-month level across all subscribers observed in a given month

[5] Network traffic is attributed to individual subscribers with the use of a key that maps a cable modem's Media Access Control (MAC) address to a (de-identified) subscriber identifier. Cable modems are the customer equipment that HFC network operators distribute to provide internet service, where the input on the device is coaxial cable and the outputs are Ethernet ports for home networking. Some devices also include Wi-Fi functionality. Therefore, any device that connects to the internet through the cable modem is included in this sample, whether this is a wired Ethernet connection or a wireless Wi-Fi connection. This includes both subscriber-owned and operator-provided Wi-Fi routers.

in Canada. We use age, income, household size, and education attainment to describe the mix of observed households.[6]

Table 2 provides summary statistics on age, education, household size, and income for the 1,526 postal code extensions in our sample. The “average resident"in our sample is 40 years old, has 15 years of education, a household income of $86,034, and comes from a household with 2.05 members. To show how representative the postal code extensions in our sample are of the states or provinces in which they lie, we compute composite averages of each demographic variable with the use of state-level Census data, where the state-level averages are weighted according to the share of postal code extensions in each state in our sample. The composite average statistics (age: 39.9, income: $71,938, education: 14.00, household size: 2.55) are comparable to the sample averages.

2.3 Measuring Network Utilization

The subscriber-level usage data provides several outcomes that can be used to measure network demand and consumer behavior.

The most common way to describe network utilization is in volumetric terms– bytes, or for larger volumes, gigabytes (GB). Volumetric measures are used because sending and receiving large quantities of data historically have generated larger costs for MSOs because of greater demand on the network’s fixed capacity. As such, usage-based billing– internet access price schedules that include data allowances and overages– focuses on the volume of usage that is generated by a subscriber during a billing period. We observe usage volumes in both the downstream (downloaded content) and upstream (uploaded content) directions.

Network utilization can also be described by how much time is spent engaging with different types of applications. Given the opportunity cost of time, the amount of time that consumers engage with different applications is suggestive of the value that internet connectivity creates. Additionally, because different applications generate different volumes of usage– e.g., email versus video streaming– time use may be a better measure of consumer behavior.

Table 2 Distribution of Demographic Variables

	Min.	25 th Pct.	Median	Mean	75 th Pct.	Max.
Age	22.20	36.10	38.20	40.05	43.40	75.90
Income	$10,478	$45,163	$56,981	$66,114	$81,040	$1,691,116
Education	12.51	14.50	14.97	15.03	15.73	16.87
Household Size	1.10	1.50	1.90	2.05	2.50	8.00

Summary statistics across the 1,526 postal code extensions observed in the sample. Age and education are both measured in years. Income is measured in 2022 US dollars

[6] The exact sizes of ZIP+4 and Local Delivery Unit areas vary, but both are designed to represent small geographic segments– typically smaller than a city block in urban areas and, in some cases, encompassing only a few distinct addresses. We hereafter refer to these segments collectively as *postal code extensions*, and report income in 2022 US dollars using the average annual exchange rates published by the Bank of Canada.

We note several caveats and limitations of our network utilization measurements. First, although our volumetric measures are precise, our application-specific time measures are estimates derived from the count of five-minute intervals in which a consumer generates positive usage. Since activity may not span the entire five-minute window, these time estimates should be interpreted as upper bounds. This issue is most relevant for short-lived applications– e.g., uploading a small file to Dropbox, which may take only seconds-and less relevant for longer-duration activities, such as streaming a movie on Netflix. Additionally, these passive measures do not guarantee the presence or attention of the subscriber who initiated the activity.

The link between these two perspectives– time and volume– is a bitrate, expressed as data volume per unit of time.[7] An application with a greater bitrate will generate more data and be more demanding on the network by utilizing more of its shared capacity. However, applications can also have latency[8] or reliability needs, both of which are more difficult to measure than bitrates. How an application is developed and the nature of the activity itself determine the optimal mix of bitrate, latency, and reliability. For example, downloading a new video game from a digital marketplace (e.g., the PlayStation Store) benefits the most from a faster speed tier—because of the large payload, there is little need for low latency, and it can be more resilient in the event of a network dropout. However, subscribers who engage in video calls may not benefit from faster speeds beyond what the call's video and audio encoders need, but might prefer lower latency and greater reliability because it is a real-time application.

2.4 Summary Statistics

Average daily downstream usage across the entire 28-month sample was 9.41 GB. The distribution across subscribers is heavily right-skewed, with a 25 th percentile of 3.01 GB, median of 7.10 GB, and 95 th percentile of 26.15 GB. These aggregate statistics– along with category-specific summaries– are reported in Table 3. On average, the top downstream applications by volume are *OTT Video* (5.08 GB), *Gaming* (1.03 GB), *Social Media* (0.84 GB), and *Browsing* (0.77 GB). Each category's usage is right-skewed.

Average daily upstream usage was 0.73 GB during the sample period, an order of magnitude smaller than the downstream average. The distribution of daily upstream usage– which is described in Table 4– is more right-skewed than is downstream usage. The 95 th percentile daily upstream value (2.20 GB) is 5.8 times greater than the median (0.38 GB). The same ratio is 3.7 for daily downstream usage.

The largest-volume upstream categories are different from the top downstream applications. *Collaboration*, *P2P/File Sharing*, and *Backup* are the top three daily upstream categories, none of which are top three downstream categories. The top downstream applications are ranked sixth through eighth as upstream drivers. In con-

[7] Since our time estimates are upper bounds, our bitrate calculations should be interpreted as lower bounds.

[8] When discussing the latency demands of different types of applications, a related but equally important, concept is *jitter*. Jitter describes the variability of latency. For example, low jitter values means that a given latency measurement is consistent. Often, the consistency in latency is just as relevant to application performance as is the overall latency measurement itself.

Table 3 Distribution of Downstream Usage

Category	Mean	Std. dev.	p5	p25	p50	p75	p95	N
OTT Video	5.08	5.30	0.05	1.28	3.60	7.09	15.09	7,017
Gaming	1.03	2.73	0.00	0.00	0.01	0.73	5.68	7,017
Social Media	0.84	1.66	0.00	0.08	0.40	1.01	2.70	7,017
Browsing	0.77	1.32	0.01	0.16	0.43	0.93	2.52	7,017
Other	0.44	0.90	0.01	0.08	0.21	0.48	1.52	7,017
Downloads	0.38	0.59	0.00	0.09	0.21	0.44	1.33	7,017
Collaboration	0.25	0.45	0.00	0.02	0.10	0.30	0.93	7,017
ECommerce	0.21	0.30	0.00	0.06	0.14	0.27	0.61	7,017
P2P/File Sharing	0.13	1.06	0.00	0.00	0.00	0.01	0.37	7,017
OTT Audio	0.08	0.16	0.00	0.00	0.02	0.10	0.34	7,017
Remote Access	0.08	0.52	0.00	0.00	0.00	0.00	0.27	7,017
Backup	0.06	0.23	0.00	0.00	0.01	0.05	0.25	7,017
Enterprise	0.05	0.24	0.00	0.00	0.01	0.03	0.17	7,017
News	0.01	0.10	0.00	0.00	0.00	0.01	0.03	7,017
AR/VR	0.00	0.03	0.00	0.00	0.00	0.00	0.00	7,017
Smart Home	0.00	0.02	0.00	0.00	0.00	0.00	0.00	7,017
Total	9.41	9.04	0.22	3.01	7.10	13.08	26.15	7,017

Distribution across subscribers of average daily downstream usage by application category and overall, measured in gigabytes

Table 4 Distribution of Upstream Usage

Category	Mean	Std. dev.	p5	p25	p50	p75	p95	N
Collaboration	0.17	0.40	0.00	0.01	0.05	0.18	0.64	7,017
P2P/File Sharing	0.10	1.11	0.00	0.00	0.00	0.00	0.13	7,017
Backup	0.09	0.25	0.00	0.00	0.02	0.09	0.38	7,017
Other	0.09	0.36	0.00	0.01	0.02	0.07	0.31	7,017
Browsing	0.08	0.40	0.00	0.01	0.03	0.07	0.25	7,017
OTT Video	0.07	0.16	0.00	0.02	0.04	0.08	0.20	7,017
Social Media	0.04	0.16	0.00	0.00	0.02	0.04	0.12	7,017
Gaming	0.03	0.16	0.00	0.00	0.00	0.01	0.11	7,017
Enterprise	0.02	0.07	0.00	0.00	0.00	0.01	0.07	7,017
Remote Access	0.02	0.17	0.00	0.00	0.00	0.00	0.05	7,017
Smart Home	0.01	0.25	0.00	0.00	0.00	0.00	0.00	7,017
ECommerce	0.01	0.02	0.00	0.00	0.01	0.01	0.03	7,017
Downloads	0.01	0.02	0.00	0.00	0.00	0.01	0.02	7,017
OTT Audio	0.00	0.00	0.00	0.00	0.00	0.00	0.01	7,017
News	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7,017
AR/VR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7,017
Total	0.73	1.60	0.01	0.14	0.38	0.81	2.20	7,017

Distribution across subscribers of average daily upstream usage by application category and overall, measured in gigabytes

trast to downstream usage, which is dominated by the single category of *OTT Video* (54% of the overall downstream average), upstream usage is spread across multiple categories. The largest category– *Collaboration*– accounts for 23% of the overall upstream average.

Estimated time that is spent online by category is reported in Table 5. The average household is connected to the internet for 11.8 hours per day.[9] The distribution of time intensity has less variability than the usage distributions above. The coefficient of variation of time intensity is 0.25, compared to 2.19 and 0.96 for daily upstream and downstream gigabytes, respectively. The 95 th percentile subscriber spent 21.4 hours online, 1.76 times that of the median subscriber.

Browsing (7.0 hours), *OTT Video* (5.9 hours), *Social Media* (3.6 hours), and *ECommerce* (2.2 hours) are the top four categories by average daily time engagement. Though three of these applications are in the top four applications of daily downstream usage, the level differences between them are notably smaller when we measure time use. For example, in Table 3, *OTT Video*'s daily downstream usage is 560% times larger than *Browsing* (5.08 GB versus 0.77 GB); however, in Table 5, *Browsing*'s average daily time is only 17% more than *OTT Video*'s (7.0 hours versus 5.9 hours). From the perspective of application volume, one could conclude that *OTT Video* is the runaway most popular online activity; but a complementary view of time engagement suggests that, though video is one of the top applications, social media, shopping, and browsing are also very commonplace online activities.

Table 5 Distribution of Time Spent Online

Category	Mean	Std. dev.	p5	p25	p50	p75	p95	N
Browsing	7.0	5.1	0.4	3.1	5.9	9.7	17.6	7,017
OTT Video	5.9	3.9	0.2	2.9	5.6	8.4	13.2	7,017
Other	4.9	3.7	0.3	2.2	4.1	6.9	12.3	7,017
Social Media	3.6	2.9	0.1	1.2	3.1	5.2	9.0	7,017
ECommerce	2.2	2.0	0.1	0.8	1.7	3.0	5.8	7,017
Collaboration	1.8	2.0	0.0	0.3	1.1	2.7	5.9	7,017
Backup	1.0	1.3	0.0	0.1	0.6	1.4	3.4	7,017
Downloads	1.0	0.9	0.0	0.4	0.8	1.3	2.6	7,017
Gaming	1.0	1.9	0.0	0.0	0.2	1.1	4.8	7,017
Enterprise	0.9	1.2	0.0	0.2	0.6	1.1	2.9	7,017
OTT Audio	0.7	1.4	0.0	0.0	0.2	0.8	2.6	7,017
P2P/File Sharing	0.4	1.4	0.0	0.0	0.0	0.2	1.3	7,017
News	0.3	0.5	0.0	0.0	0.1	0.4	1.2	7,017
Remote Access	0.3	1.1	0.0	0.0	0.0	0.0	1.6	7,017
Smart Home	0.2	1.2	0.0	0.0	0.1	0.1	0.4	7,017
AR/VR	0.1	1.0	0.0	0.0	0.0	0.0	0.0	7,017
Overall	11.8	5.9	0.9	7.7	12.1	16.2	21.4	7,017

Distribution across subscribers of average daily time spent by application category and overall, measured in hours. The category-specific means do not sum to the overall mean because multiple categories can be used in the same five-minute observation interval

[9] We note that some traffic may be from background or network management traffic; therefore, not all of this activity is created by active human engagement.

Table 6 Distribution of Active Downstream Bitrates

Category	Mean	Std. dev.	p5	p25	p50	p75	p95	N
OTT Video	1,632	1,079	265	824	1,416	2,227	3,691	6,939
Gaming	1,620	3,652	9	32	216	1,806	7,279	6,657
Downloads	799	871	134	371	589	937	2,080	6,944
P2P/File Sharing	551	1,778	6	25	100	330	2,331	6,429
Social Media	376	428	28	135	296	483	897	6,923
OTT Audio	296	546	19	72	167	325	945	6,755
Collaboration	270	299	19	98	196	347	755	6,888
ECommerce	235	266	52	124	189	277	528	6,933
Browsing	232	395	39	89	152	263	653	6,977
Remote Access	200	671	2	5	22	133	931	5,239
Other	162	243	32	67	109	183	425	6,984
AR/VR	145	815	5	17	17	34	483	2,035
Backup	140	293	10	35	66	133	517	6,789
Enterprise	88	227	6	18	39	82	279	6,922
News	66	165	8	17	34	67	195	6,775
Smart Home	5	31	0	1	1	4	13	6,038

Distribution of downstream subscriber-average bitrates by category, conditional on positive usage within the category. The *N* column provides the number of subscribers who generated traffic in a given category

Table 7 Distribution of Active Upstream Bitrates

Category	Mean	Std. dev.	p5	p25	p50	p75	p95	N
Collaboration	191	261	1	38	109	239	662	6,888
Backup	155	264	4	33	90	189	487	6,789
P2P/File Sharing	93	440	0	0	2	14	438	6,429
Remote Access	40	301	0	2	5	25	129	5,239
Enterprise	34	71	1	5	15	36	122	6,922
Gaming	27	68	0	2	9	30	98	6,657
Other	26	69	2	6	12	25	85	6,984
Browsing	21	78	3	6	10	18	60	6,977
OTT Video	21	31	4	10	15	24	50	6,939
Social Media	19	50	2	7	12	19	50	6,923
Downloads	11	29	1	3	6	11	32	6,944
ECommerce	7	12	2	4	6	8	15	6,933
Smart Home	7	32	0	3	5	6	9	6,038
OTT Audio	4	14	0	1	3	5	10	6,755
AR/VR	1	5	0	0	0	1	5	2,035
News	1	2	0	0	1	1	4	6,775

Distribution of upstream subscriber-average bitrates by category, conditional on positive usage within the category. The *N* column provides the number of subscribers who generated traffic in a given category

In Tables 6 and 7, we describe application-specific bitrates. These statistics can be calculated only for the set of subscribers who use the applications in a given category; this is why the number of observations varies by row. For each "active" subscriber, an average bitrate is calculated; then the distribution across subscribers is shown to permit comparison across applications and variability across subscribers.

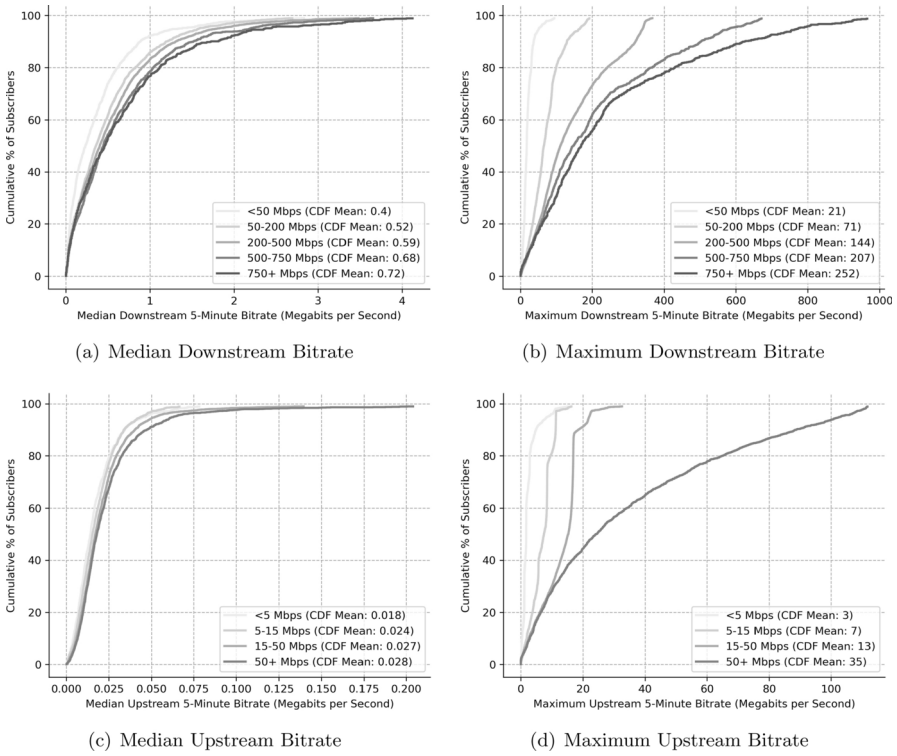
Application bitrates can vary across subscribers for several reasons. First, some applications scale content delivery speed with plan speeds, so those on faster speed tiers (all else constant) will have higher bitrates. *Downloads* are an example of this behavior. Second, some subscribers prefer richer or more immersive experiences in certain types of applications. For example, some subscribers may prefer to use collaboration software with video enabled or watch 4 K video resolution instead of standard definition. Third, bitrates may vary because of the set of internet-connected devices in different subscriber homes. Whereas newer-model smart TVs and media devices may be capable of streaming higher-quality video, older models may be limited to lower-quality streams. Fourth, subscribers may use the same applications to engage with files of different sizes: for example, using backup software to capture Office documents versus routinely using the same software to upload video files to the cloud.

The top bitrate applications, ranked by average subscriber bitrate, are: *OTT Video* (1.6 Mbps); *Gaming* (1.6 Mbps); *Downloads* (799 Kbps); and *P2P/File Sharing* (551 Kbps). *Gaming* traffic has the heaviest 95 th percentile subscriber at 7.3 Mbps. *OTT Video* and *Downloads*, though, produce higher bitrates more consistently. These two categories are the only ones with 5 th percentiles over 100 Kbps and median bitrates over 500 Kbps. They also experience broader use than do other categories, with engagement from over 98% of the subscribers in the panel. In terms of coefficients of variation, *Smart Home* (6.2), *AR/VR* (5.6), *Remote Access* (3.4), *P2P/File Sharing* (3.23), and *Enterprise* (2.6) have the most variability across subscribers. *OTT Video* (0.7), *Downloads* (1.1), *Collaboration* (1.1), *ECommerce* (1.1), and *Social Media* (1.1) have the least variability.

Collaboration (191 Kbps), *Backup* (155 Kbps), *P2P/File Sharing* (93 Kbps), *Remote Access* (40 Kbps), and *Enterprise* (34 Kbps) are the top five upstream applications by bitrate. *P2P/File Sharing* is the only application that intersects with the top five downstream applications. None of the statistics that are included in Table 7 are above 1 Mbps, which is another contrast to the downstream bitrates. Using the coefficient of variation again to measure variability, *Remote Access* (7.5), *AR/VR* (5.0), *P2P/File Sharing* (4.7), *Smart Home* (4.6), and *Browsing* (3.7) have the most and *Collaboration* (1.4), *OTT Video* (1.5), *Backup* (1.7), *ECommerce* (1.7), and *News* (2.0) have the least.

If we compare average downstream and upstream bitrates in Tables 6 and 7, *Smart Home*, *Backup*, *Collaboration*, and *Remote Access* have the most symmetric directional bitrates. *AR/VR*, *OTT Video*, *OTT Audio*, *Downloads*, and *News* have the largest relative differences in bitrates. For many applications with notably greater downstream bitrates than upstream– especially *OTT Video* applications– upstream usage is light because its primary purpose is to send acknowledgement information that confirms successful data delivery.

Up to this point, we have described the bitrates of individual applications. However, it is often the case that some combination of applications is active at the same time. In Fig. 3, we report CDFs of median and maximum five-minute bitrates by speed tier. In these figures, the calculated bitrates include *all* application traffic within a single five-minute observation. Differences in realized speeds across speed tiers



(a) Median Downstream Bitrate (b) Maximum Downstream Bitrate

(c) Median Upstream Bitrate (d) Maximum Upstream Bitrate

Fig. 3 Active Bitrates by Plan Speed. These figures report bitrate distributions for downstream and upstream traffic. Each subscriber's entire panel is used to record their median and maximum five-minute average bitrates. The CDFs in the figures are the distributions of these median and maximum bitrate values across subscribers. Subscribers that selected into multiple speed bins during the panel are included in each bin's distribution

may be because of network management or selection. For example, tier choice may be correlated with preference for engaging in activities that benefit from faster speeds.

Median downstream bitrates are one to two orders of magnitude smaller than maximum bitrates. Within each range of downstream tiers, the average median value– the average of the CDF– is below 1 Mbps. Average median bitrates do increase from slower to faster tier groups (0.72 Mbps for 750+ Mbps tiers versus 0.40 Mbps for tiers below 50 Mbps).

Despite what the light median bitrates might suggest, the maximum bitrates show that advertised bandwidth limits do meaningfully affect realized bandwidth. With the use of subscribers on tiers below 50 Mbps and above 750 Mbps as points of reference, the average maximum bitrates are 21 Mbps and 252 Mbps, respectively: a 1,100% difference. In general, the top percentiles of each CDF provide evidence that some subscribers can saturate their entire plan speed. For example, roughly 5% of

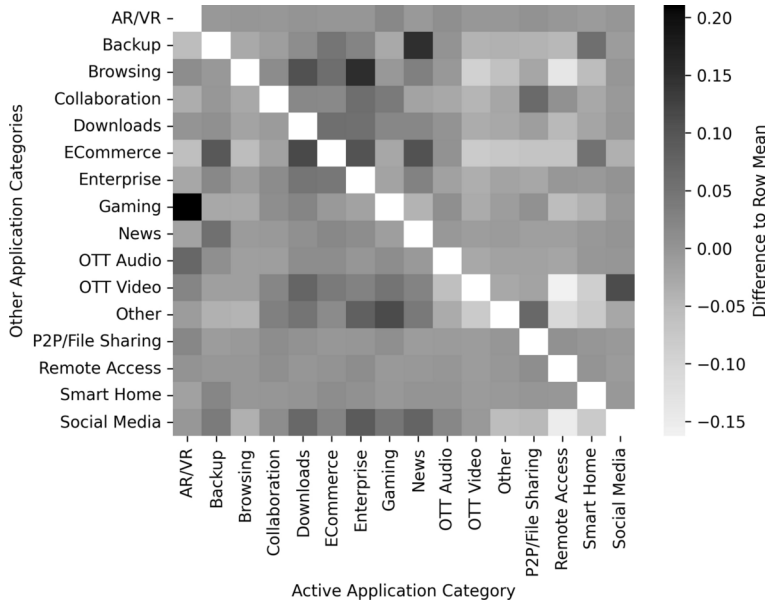


Fig. 4 Rates of Category Concurrency, 2020-2022. This heatmap reports the rates of a categories being active concurrently. Each column conditions on activity in the category listed beneath the horizontal axis. The cell in a particular row reports the percentage of observations for which that row's category is also active. For example, the bottom left corner of the heatmap is the percentage of five-minute observations in which *AR/VR* is active that *Social Media* is also active. This heatmap was created at a monthly level and averaged across the entire sample to produce the version shown in the figure

subscribers on tiers above 750 Mbps have averaged over 800 Mbps for at least five minutes.[10]

Many of the same patterns in downstream bitrates hold for the upstream bitrates that are described in Fig. 3. Median bitrates are again much lower than the maximums, but there are fewer differences among the groups. This is partly because of the smaller differences across tiers in offered upstream speeds relative to downstream speeds. Subscribers on the fastest upstream tiers (above 50 Mbps) have a median bitrate that is 64% greater than subscribers on tiers below 5 Mbps (0.028 versus 0.018 Mbps). Maximum bitrates between these two groups differ by a factor of about 12 (35 Mbps versus 3 Mbps).

[10] We add several caveats to the interpretation of these results. First, bitrate averages here are taken over five-minute intervals and, therefore, average over any "bursting"by an application during shorter intervals. For example, speed tests do not typically last five minutes but will commonly saturate a connection when active. Second, many household devices connect to the internet using Wi-Fi, not wired connections. A wired Ethernet connection will produce the best speed performance; but, for many types of devices, wired connections are rare– e.g., smartphones or tablets. The speed of Wi-Fi connections depends on the antennas that are included in the device, which can generally be upgraded only through the purchase of a new device, the Wi-Fi generation that is supported by the router (e.g., Wi-Fi 5 versus Wi-Fi 6), and how optimally networking equipment is installed in the home. Each of the above factors could result in a specific device's (e.g., a laptop) maximum attainable bitrate falling below an advertised plan speed– independent of the MSO's network quality. For this reason, the FCC's Measuring Broadband America report uses only wired performance.

We conclude this section with a discussion of application concurrency, which provides additional context to the aggregate bitrate distributions that were shown above. Since applications have widely variable bitrates, which applications are used concurrently influences overall bitrate realizations. In the heatmap that is depicted in Fig. 4, we condition on activity within a particular category (horizontal axis) and ask what share of the time other usage categories are active within the same five-minute intervals (vertical axis). Each cell is normalized using the row-wise mean: the average overall probability that the application category is active. Red cells show applications that are more common when compared to these means; blue cells indicate combinations that are less common. The row-wise averages are shown in Fig. 5.

Several intuitive patterns in concurrent usage emerge. For example, when *AR/VR* is active, *Gaming* (a common application of AR/VR technology) is often used concurrently; *Browsing* is common when households are using *Enterprise* applications (e.g., work-related internet usage); households are less likely to watch video and listen to music at the same time; when households are using *Social Media*, they are more likely to be watching *OTT Video*; because *Remote Access* includes VPN applications, which redirect traffic, common applications– such as *OTT Video*, *Browsing*, and *Social Media*– are less likely to co-occur because they cannot be classified.

In levels, *Browsing* and *Other* are the only categories that were active more than 50% of the time. *OTT Video* is close at 49%. *Collaboration* applications are active about 20% of the time, and activities such as *OTT Audio*, *Gaming*, *Enterprise*, *Backup*, and *Downloads* are active closer to 10–15% of the time. The rankings of these applications closely match other rankings of daily time spent and downstream usage.

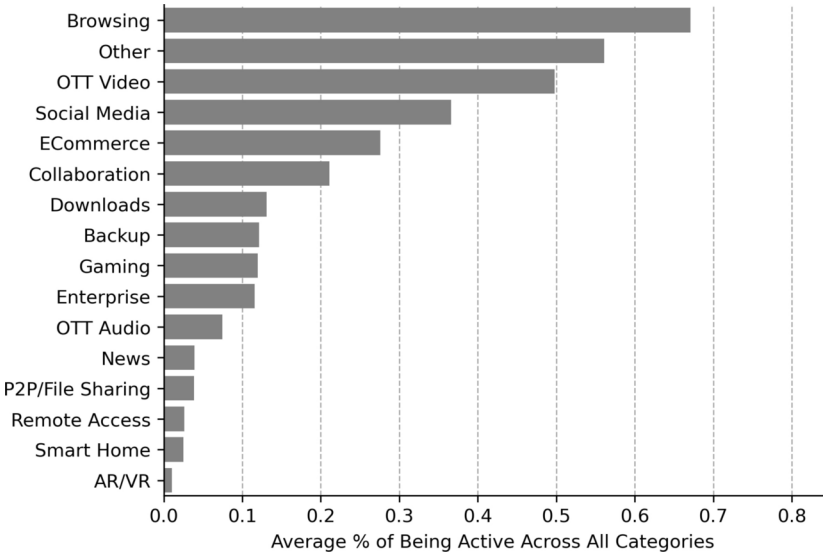


Fig. 5 Average Rates of Category Concurrency (All Categories), 2020-2022. This barplot reports the row-wise averages of Fig. 4 to highlight which applications are active most frequently

2.5 Demographic Heterogeneity

Previous research has documented correlations between internet behaviors and demographic characteristics (Malone et al., 2023). Though we are not able to match our usage records to subscriber-level demographic information, we do observe demographics at the postal code extension level.

Table 8 Distribution of Daily Usage by Demographic Segment

	Age quartile				Education quartile			
Category	1	2	3	4	1	2	3	4
AR/VR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Backup	0.16	0.21	0.19	0.16	0.14	0.14	0.21	0.22
Browsing	1.06	0.93	1.00	0.83	0.94	0.95	0.98	0.96
Collaboration	0.58	0.47	0.43	0.39	0.35	0.42	0.46	0.63
Downloads	0.49	0.41	0.47	0.38	0.45	0.45	0.44	0.41
ECommerce	0.28	0.25	0.28	0.22	0.25	0.22	0.26	0.28
Enterprise	0.08	0.10	0.07	0.06	0.06	0.05	0.09	0.11
Gaming	1.40	1.09	1.40	0.84	1.44	1.02	1.25	1.03
News	0.01	0.01	0.02	0.01	0.01	0.01	0.02	0.01
Other	0.66	0.60	0.55	0.58	0.55	0.56	0.59	0.69
OTT Audio	0.10	0.10	0.10	0.08	0.08	0.08	0.11	0.11
OTT Video	7.05	5.65	5.90	4.65	6.02	5.21	5.74	6.30
P2P/File Sharing	0.24	0.34	0.20	0.25	0.22	0.20	0.31	0.28
Remote Access	0.10	0.14	0.09	0.10	0.08	0.08	0.11	0.15
Smart Home	0.03	0.00	0.01	0.01	0.01	0.01	0.03	0.00
Social Media	1.12	1.05	1.00	0.77	0.95	0.85	1.10	1.04
Total	13.36	11.34	11.69	9.31	11.55	10.24	11.69	12.23
	Household size quartile				Income quartile			
Category	1	2	3	4	1	2	3	4
AR/VR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Backup	0.19	0.19	0.15	0.17	0.16	0.15	0.20	0.19
Browsing	0.80	0.92	0.96	1.13	0.78	0.96	1.04	1.04
Collaboration	0.40	0.45	0.55	0.46	0.35	0.59	0.45	0.48
Downloads	0.35	0.42	0.45	0.54	0.37	0.43	0.46	0.49
ECommerce	0.24	0.24	0.27	0.28	0.21	0.26	0.27	0.29
Enterprise	0.08	0.08	0.07	0.07	0.06	0.08	0.08	0.08
Gaming	1.04	0.91	1.43	1.36	1.06	1.27	1.25	1.15
News	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02
Other	0.59	0.59	0.58	0.63	0.59	0.65	0.55	0.59
OTT Audio	0.09	0.10	0.09	0.10	0.08	0.09	0.11	0.10
OTT Video	5.16	5.63	6.33	6.15	5.07	6.69	6.07	5.43
P2P/File Sharing	0.29	0.32	0.20	0.21	0.31	0.16	0.34	0.21
Remote Access	0.14	0.11	0.07	0.10	0.12	0.09	0.11	0.10
Smart Home	0.00	0.00	0.01	0.04	0.00	0.00	0.02	0.03
Social Media	0.94	0.93	1.08	1.00	0.93	1.12	0.97	0.93
Total	10.34	10.88	12.24	12.24	10.11	12.56	11.93	11.12

Average subscriber-level daily usage (measured in GB) across quartiles of the age, education, household size, and income demographic variables

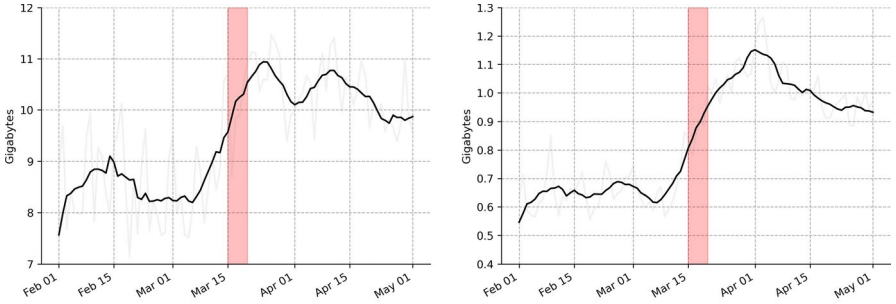
Table 8 describes mean usage by traffic category across quartiles of four demographic variables. Despite the aggregate level of demographic observation, several intuitive patterns emerge. First, total internet usage is increasing in household size. Subscribers from postal code extensions in the fourth quartile of household size have an 18% higher average daily level than do subscribers from postal code extensions in the first quartile of household size. Internet usage is decreasing in age; subscribers from fourth quartile age postal codes generate 30% less internet traffic than do subscribers from first quartile postal codes.

Decomposing total internet usage into categories, we see that larger categories– such as *OTT Video* and *Browsing*– tend to mirror the directional trends of overall usage. For other categories– particularly those associated with remote work and other aspects of engagement with the digital economy– we see additional meaningful differences by demographic segment. The use of *Collaboration* and *Enterprise* software increases substantially with education level. The most educated areas generate over 80% more *Collaboration* and *Enterprise* traffic than the least educated areas. Additionally, *ECommerce* traffic increases monotonically by income quartile, with the highest-income quartile generating 38% more traffic than the lowest-income quartile. These four demographic variables are certainly correlated.

Though usage levels differ meaningfully across demographic segments, we do not observe systematic differences in take-up of high-speed internet tiers by the same segments. The average download speed chosen by each of the 16 segments in Table 8 ranges from 311 Mbps to 373 Mbps, and the average upload speed ranges from 28 Mbps to 34 Mbps. It does not appear that plan characteristics offered by this MSO vary systematically with regional demographic characteristics.

3 The Effect of Stay-at-Home Orders

In this section, we study the short-run effect of school and business closures on internet engagement. For each of the markets we observe in the MSO's footprint, states of emergency were declared between March 15, 2020 and March 20, 2020.



(a) Downstream (b) Upstream

Fig. 6 Spring 2020 Internet Utilization. Average downstream and upstream internet traffic by day (gray) with seven-day moving average (black). Local SaH orders went into effect during the red shaded time interval

These local policy changes canceled classes in pre-K, primary, and secondary schools; placed limits on the sizes of gatherings; and closed many non-essential businesses.

Figure 6 shows the time series of daily internet traffic from February through April of 2020. Through the first week of March, downstream and upstream traffic levels were relatively flat after accounting for intraweek fluctuations, averaging 8.5 GB and 0.65 GB per day, respectively. Beginning in the second week of March, downstream network usage steadily increased in the days that led into SaH order declarations. Downstream traffic reached a single-day peak of 11.5 GB per household on Thursday March 26, a 53% increase over the 7.5 GB average on the same weekday three weeks prior.

Upstream internet traffic, which, as described in Sect. 2, is partially driven by engagement with real-time collaboration applications, grew at an even stronger rate during the SaH order declaration period. The single-day peak over the three-month period shown in Fig. 6 is 1.25 gigabytes per day on Thursday, April 2, an 86% increase over the 0.67-gigabyte average three weeks prior. Both downstream and upstream traffic decreased slightly toward the end of April but remained at significantly elevated levels compared to their pre-SaH levels.[11]

Table 9 Change in Internet Usage Following Stay-at-Home Orders

	Downstream			Upstream		
Category	Pre	Post	% Diff	Pre	Post	% Diff
OTT Video	4.84	5.44	12.54	0.07	0.08	24.71
Gaming	0.87	1.23	41.05	0.02	0.03	33.31
Browsing	0.70	0.96	36.23	0.07	0.11	58.23
Social Media	0.59	0.84	41.88	0.04	0.06	63.42
Downloads	0.31	0.37	18.36	0.00	0.00	9.69
ECommerce	0.27	0.32	19.27	0.01	0.02	90.70
Other	0.23	0.33	43.28	0.05	0.09	70.94
P2P/File Sharing	0.13	0.27	98.34	0.13	0.22	68.23
Collaboration	0.08	0.28	233.12	0.06	0.18	209.65
OTT Audio	0.07	0.10	43.29	0.00	0.00	36.47
Remote Access	0.06	0.11	81.53	0.08	0.09	6.84
Enterprise	0.05	0.04	−6.16	0.01	0.03	174.52
Backup	0.03	0.05	60.29	0.06	0.09	57.71
News	0.01	0.02	82.65	0.00	0.00	70.43
AR/VR	0.00	0.00	−28.99	0.00	0.00	33.27
Smart Home	0.00	0.00	6.02	0.02	0.02	−6.69
Total	8.26	10.37	25.5	0.63	1.04	64.6

Average daily usage in the first week of March 2020 ("Pre") and the last week of March 2020 ("Post"). Mean differences are statistically significant ($p < 0.05$) except for *Enterprise*, *AR/VR* (downstream); and *ECommerce*, *Downloads*, *Enterprise*, *P2P/File Sharing*, *Remote Access*, *AR/VR* (upstream)

[11] One alternative explanation for the increase in usage between February and March 2020 is seasonality. To determine whether the observed increase in internet usage during March 2020 is consistent with seasonal trends in prior years, we obtained aggregate statistics describing total monthly usage volume on the MSO's network from 2015 to 2022. On average, usage increased by 12% between February and March during the years 2015-2019, with a maximum increase of 16%. In 2020, monthly usage increased by 27%

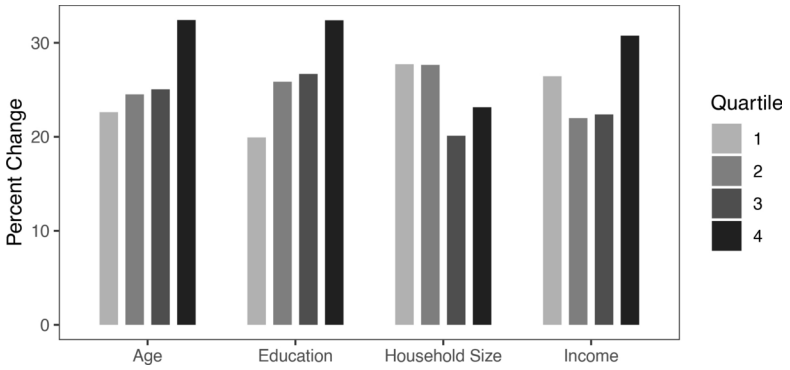


Fig. 7 Heterogeneity in Stay-at-Home Order Usage Responses. Percent change in total internet usage between February and April 2020, by quartile of household age, education, size, and income

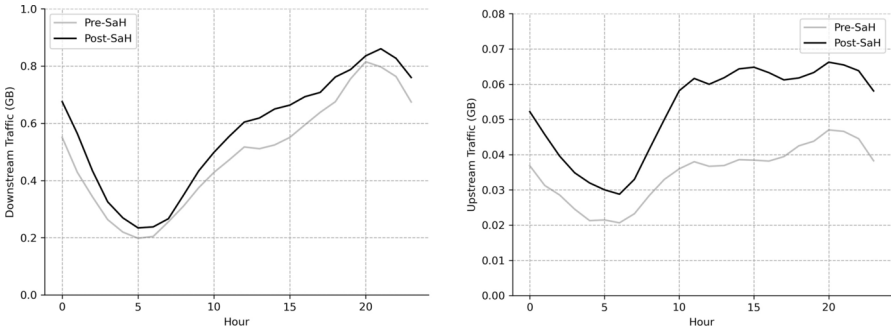
Next, we decompose these changes in aggregate internet traffic around the SaH orders into categories. Table 9 shows levels of internet traffic by category during the first and last weeks of March 2020. The largest category by volume is *OTT Video*, which accounted for about 70% of downstream internet traffic during the pre-SaH period and increased by 0.6 GB (12%) between the first and last weeks of March. The two categories with the largest percent increase in daily downstream usage were *Collaboration* (233% increase) and *P2P/File Sharing* (98% increase). *News* (83%) and *Remote Access* (82%) also had strong growth in daily downstream usage.

Because SaH orders forced businesses and individuals to interact remotely, *Collaboration*'s 210% growth in daily upstream growth is intuitive; *Collaboration* applications had the strongest upstream growth of all categories. Skype, Zoom, and Microsoft Teams were the top collaboration applications by volume. Other traffic categories with strong upstream growth included *Enterprise* (176%), *ECommerce* (91%), *News* (70%), *P2P/File Sharing* (68%), *Social Media* (63%), *Browsing* (58%), and *Backup* (58%). This set of categories includes applications that are correlated with behaviors that were affected by SaH: remote productivity; entertainment at home; and shopping at home.

In Fig. 7, we document differences in usage responses by demographic segment. Usage following SaH orders increased for all demographic segments, with the magnitude of the increase monotonically increasing in age and education. Overall, older, more educated, and wealthier demographics are correlated with the largest percent changes in daily usage. These differences are suggestive of which demographic segments were most able to continue work and other aspects of daily life remotely after widespread business closures.

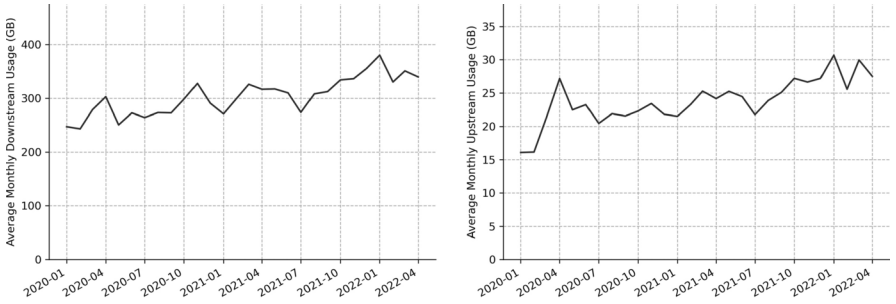
School and business closures affected intraday mobility, and these behavioral changes are reflected in the distribution of internet consumption over the day. Figure 8 shows average internet traffic levels by hour both before and after the SaH orders. In addition to an increase in the overall level of usage after the SaH orders, the larg-

between February and March. In 2021 and 2022, the usage changes during the same period were 11% and 9%, respectively.



(a) Downstream (b) Upstream

Fig. 8 Changes in Intraday Internet Traffic. Average downstream and upstream traffic by hour of the day. Pre-SaH contains observations from the last week of February 2020. Post-SaH contains observations from the first week of April 2020



(a) Downstream (b) Upstream

Fig. 9 Monthly Usage Growth. Monthly downstream and upstream usage, reported as an average across all subscribers in a given month, measured in GB

est increases in both downstream and upstream traffic were during typical workday hours. Though the downstream traffic peak shifts one hour later in the evening, its diurnal pattern was mostly unchanged after the SaH orders. On the other hand, the upstream intraday distribution changed from increasing over the day into the evening to being approximately flat after noon until 9 PM.

4 Persistent Changes in Internet Behavior

In this section, we study how subscriber behavior changed between 2020 and 2022, so as to uncover the long-term impact that the COVID-19 pandemic may have had on residential internet traffic. To hold fixed seasonal patterns in behavior, we use the first two months of 2020 as a pre-pandemic baseline and take the same two months in 2022 as a more recent point of comparison.

4.1 Network Utilization

We first describe changes in the aggregate level of network utilization. Average downstream monthly usage, which is shown in panel (a) of Fig. 9, grew from 247 GB in January 2020 to 340 GB in April 2022: a 37% increase. There was a sharp increase in average downstream usage in spring 2020, during the early days of the pandemic, and increases of a similar magnitude can also be seen in late 2020 and early 2021. Peak downstream monthly usage occurred in January 2022 at 380 GB.

The increase in monthly upstream usage over this period of time is stronger than the growth in downstream usage. Monthly upstream usage increased from 16 GB in January 2020 to 28 GB in April 2022, an increase of 71% (almost two times greater than downstream monthly usage growth). The most notable increase is a spike in spring 2020, which accounted for almost the entirety of the in-sample growth in traffic. After spring 2020, monthly upstream usage levels subsided and then grew more slowly; they peaked in January 2022 at 31 GB.

Despite historic growth in monthly upstream demand, the asymmetric nature of internet demand was unchanged during the sample period. While upstream growth is stronger, the in-sample change in usage volume was only 12 GB per month, whereas monthly downstream usage increased by 93 GB over these two years. In 2020, average monthly downstream usage was 15.4 times upstream usage; this ratio decreased to 12.1 in 2022.

In Table 10, we show category-specific changes in network utilization. *OTT Video* was the highest-volume downstream category in both 2020 and 2022; however, *Col-*

Table 10 Changes in Usage Levels by Category

	Downstream			Upstream		
Category	2020	2022	% Change	2020	2022	% Change
AR/VR	0.0	0.1	277%	0.0	0.0	176%
Backup	1.2	3.0	153%	1.4	3.9	184%
Browsing	18.1	24.3	34%	1.8	2.8	53%
Collaboration	2.4	9.9	310%	1.9	7.4	285%
Downloads	8.2	16.1	96%	0.1	0.2	79%
ECommerce	7.2	6.1	−15%	0.2	0.4	133%
Enterprise	0.9	2.3	153%	0.4	0.7	95%
Gaming	23.6	35.3	49%	0.5	1.2	158%
News	0.3	0.3	1%	0.0	0.0	38%
OTT Audio	1.9	3.1	57%	0.0	0.1	54%
OTT Video	152.0	199.3	31%	1.9	2.8	48%
Other	5.8	18.0	209%	1.2	3.6	190%
P2P/File Sharing	5.0	3.7	−26%	4.3	3.3	−24%
Remote Access	2.2	2.7	20%	0.5	0.4	−4%
Smart Home	0.0	0.0	−1%	0.7	0.3	−56%
Social Media	16.3	31.3	92%	1.2	1.0	−19%
Total	245.3	355.5	45%	16.1	28.1	75%

Unconditional averages of monthly usage by application category. Values are calculated over the *subscriber-month* observations in January and February of 2020 and 2022, respectively. Since unconditional averages are reported, the columns do sum to the values that are reported in the *Total* row

laboration, *Backup*, *Enterprise*, *Downloads*, and *Social Media* categories all had notable growth over these two years. They grew by 310%, 153%, 153%, 96%, and 92%, respectively. These categories– especially *Collaboration*, *Backup*, and *Enterprise*– are commonly associated with remote productivity: e.g., work from home and remote schooling. Despite such strong growth for these categories, the average volume of *OTT Video* usage remained an order of magnitude larger. Even after growing by 310%, *Collaboration* applications still comprised only 2.8% of downstream monthly usage in 2022.

Collaboration's 285% growth is the strongest contributor to aggregate upstream growth over these two years. In 2020, *Collaboration* applications were the number two driver of upstream usage; *Collaboration* was tied with *OTT Video* and behind only *P2P/File Sharing*. In 2022, *Collaboration* applications were the plurality of monthly upstream usage at 26%, followed by *Backup* (14%) and *P2P/File Sharing* (12%). In addition to *Collaboration*, some categories with strong downstream growth also had strong upstream usage growth such as *Backup* (184%), *Downloads* (79%), and *Enterprise* (95%). Categories with notably stronger upstream growth compared to their downstream growth included *Gaming* (158% versus 49%) and *ECommerce* (133% versus −15%).

4.2 Time Allocation

The amount of time that subscribers were active online per day grew by 23% between January 2020 and April 2022: from 10.8 hours daily to 13.3 hours daily, respectively. The time series of this statistic is shown in Fig. 10. The sharp increase in daily time online in spring 2020 is the most notable change in the time series and correlates closely with similar growth in downstream and upstream monthly usage that was discussed above. Peak daily activity occurred in April 2020 and then again in January 2022, when average time online reached 14 hours. The elevated levels of internet engagement in January 2022– time online, downstream usage, and upstream usage

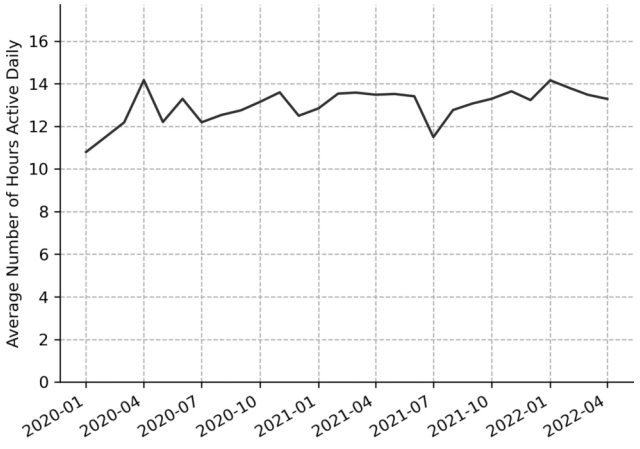


Fig. 10 Monthly Time Online. Monthly time spent online, reported as an average across all subscribers observed in a given month, measured in hours

all peaked that month– coincided with a surge in cases of the Omicron COVID-19 variant in North America.[12]. Since the spring 2020, time active online was flat, with typical levels hovering around 13 hours daily. The smaller growth in the amount of time spent online suggests that usage growth in recent years may have been driven in large part by bitrate changes– a topic that will be covered in more detail later in this section– either through increased concurrency or increasing application bitrates.

In Table 11, we describe the amount of time that was allocated to various categories of applications in two ways. First, we calculate the average number of hours active per day, estimated by the change in the number of five-minute observations by category per subscriber. If a five-minute observation has two categories of applications active (e.g., *OTT Video* and *Social Media*), the observation will count toward each category's totals; therefore, the sum of each column is larger than the levels that are shown in Fig. 10. Second, we compute the share of total time that each category is active. Specifically, each category's share is equal to its value from the left side of the table (i.e., average daily hours) divided by the total level shown in Fig. 10.

News (266%), *AR/VR* (147%), *Backup* (133%), and *Collaboration* (129%) had the strongest growth in daily hours between 2020 and 2022. Growth in *Backup* and *Collaboration* time allocation suggests an increase in remote productivity at home; this is a pattern that is also present in downstream and upstream monthly usage changes. However, as with monthly downstream usage, these categories were smaller drivers of overall demand. For example, the percentage of time *Backup* applications were active doubled; however, the category was active for only 12% of the time in 2022.

Table 11 Changes in Time Allocation byCategory

	Average daily hours			Share of time active		
Category	2020	2022	% Change	2020	2022	% Change
AR/VR	0.0	0.1	147%	0.0	0.01	106%
Backup	0.7	1.6	133%	0.06	0.12	94%
Browsing	6.5	7.7	17%	0.57	0.55	−2%
Collaboration	0.8	1.8	129%	0.07	0.13	90%
Downloads	0.8	1.1	30%	0.07	0.08	8%
ECommerce	1.6	3.1	86%	0.14	0.22	54%
Enterprise	0.7	1.1	61%	0.06	0.08	34%
Gaming	0.8	1.2	38%	0.07	0.08	15%
News	0.1	0.4	266%	0.01	0.03	205%
OTT Audio	0.6	0.8	51%	0.05	0.06	25%
OTT Video	5.3	7.7	44%	0.46	0.56	20%
Other	3.4	7.2	116%	0.29	0.52	80%
P2P/File Sharing	0.4	0.4	15%	0.03	0.03	−4%
Remote Access	0.2	0.4	99%	0.02	0.03	65%
Smart Home	0.2	0.3	51%	0.02	0.02	26%
Social Media	3.1	4.1	32%	0.27	0.30	10%

Daily time spent online by category. The share of time that a category is active is calculated by taking the values from the left side of the table and dividing by the monthly averages that are shown in Fig. 10. Shares do not sum to 1 due to concurrent usage

[12] https://www.nytimes.com/2022/01/22/us/omicron-cases-us-deaths.html.

Collaboration's relative frequency increased by 90%, but it was active only 13% of the time in 2022. As with *Backup* and *Collaboration*, *Remote Access* (99%) and *Enterprise* (61%) also had strong growth. All four categories are correlated with remote productivity, though the latter two were active less frequently than were *Backup* and *Collaboration*.

Browsing and *OTT Video* are the only categories that were active over 50% of the time in 2022. Both categories were also the top two drivers of time online in 2020 and 2022. Despite already heavy usage in 2020– *Browsing* averaged 6.5 hours in 2020 and *OTT Video* averaged 5.3 hours– these two categories still grew substantially over the two-year period: *Browsing* grew by 17% to 7.7 hours daily, and *OTT Video* grew 44% to 7.2 hours daily. *Social Media* had the third greatest average of daily time active in both 2020 (3.1 hours) and 2022 (4.1 hours). *ECommerce* (3.1 hours) and *Collaboration* (1.8 hours) round out the top five categories.

In Fig. 11, we summarize each category's 2022 network demand by both volume and time measures to reconcile the results of the last two subsections. As was discussed in Sect. 2, using time to compare application engagement complements a usage-based ranking. Each dot in the figure represents a category's share of time active (on the horizontal axis) and its share of monthly downstream usage (on the vertical axis). The diagonal line represents an exact match in proportion between time and usage. It follows that categories below the diagonal line have time shares that were greater than their usage shares, with the reverse being true for categories above the line.

Browsing, *Social Media*, and *ECommerce* all have time shares that are notably larger than what their downstream usage shares suggest. Each of these categories was active more than 20% of the time but accounted for less than 10% of downstream

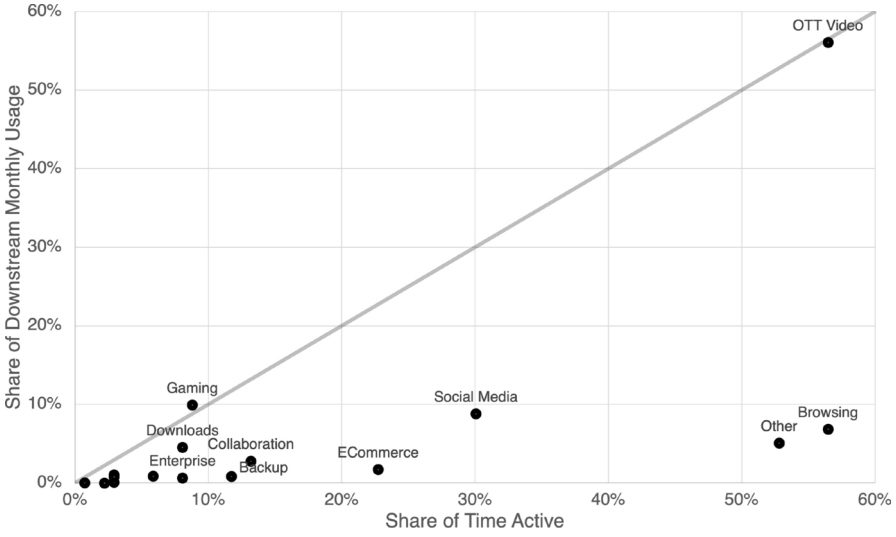


Fig. 11 Comparison of Time and Usage Shares. This figure compares the share of time active and overall downstream monthly usage by category using category averages for January and February 2022 from Tables 10 and 11

monthly usage apiece. *OTT Video* is the only category with a large time and usage share, as is indicated by its location on the diagonal line in the top right corner of the figure. *Gaming*, similar to *OTT Video*, also has balanced shares between time and downstream usage around 10%, respectively. *Collaboration*, *Backup*, *Enterprise*, and *Downloads* constitute a small cluster of categories with time shares that are greater than their usage counterparts, but still relatively small by both measures. Figure 11 also shows that by comparing time and usage, the gap between *OTT Video* (the top online category), and *Browsing* is smaller than a usage-only view suggests: subscribers spend just as much time browsing the internet as they do streaming video, but *OTT Video* bitrates are an order of magnitude larger than *Browsing* bitrates, which creates a large difference by volume between them.

Another way to summarize network engagement across both time and volume measures is to study the reach of each category: the extensive margin. In Table 12, we report the relative popularity of each category in 2020 and 2022 by calculating the share of subscribers with at least 25 megabytes of usage. Several categories are used by most subscribers online in 2022: *Backup*, *Browsing*, *Collaboration*, *Downloads*, *ECommerce*, *Enterprise*, *OTT Video*, and *Social Media* had shares that were greater than 90% in 2022. Of these eight categories, *Browsing*, *Downloads*, *ECommerce*, *OTT Video*, and *Social Media* also had shares greater than 90% in 2020, which suggests that during the pandemic remote productivity activity online became increasingly commonplace in our sample. By contrast, *AR/VR* (3%) and *Smart Home* (11%) are by far the least popular categories in this sample. Most categories had shares that remained constant, or even dropped, over the two years. However, *AR/VR* experienced 180% growth from 1% to 3% of the sample. *Remote Access* (48% growth) and *News* (31% growth) also had notable increases in their popularity.

Table 12 Changes in Category Reach

Category	2020	2022	% Change
AR/VR	0.01	0.03	180%
Backup	0.88	0.92	4%
Browsing	0.99	0.98	−1%
Collaboration	0.78	0.91	16%
Downloads	0.97	0.98	0%
ECommerce	0.97	0.97	0%
Enterprise	0.88	0.93	5%
Gaming	0.63	0.63	0%
News	0.55	0.72	31%
OTT Audio	0.73	0.77	6%
OTT Video	0.99	0.98	−1%
Other	0.98	0.99	1%
P2P/File Sharing	0.49	0.39	−20%
Remote Access	0.18	0.27	48%
Smart Home	0.13	0.11	−15%
Social Media	0.95	0.95	0%

This table reports the share of subscribers that have positive usage by application category. A subscriber is considered a "user" of an application category if they recorded greater than 25 MBs of usage in the category during the first two months of the indicated year

Table 13 Changes in Bitrate by Category

	Downstream			Upstream		
Category	2020	2022	% Change	2020	2022	% Change
AR/VR	48	73	52%	1	2	12%
Backup	127	138	9%	148	180	22%
Browsing	202	231	14%	21	27	31%
Collaboration	227	407	79%	180	302	68%
Downloads	713	1,075	51%	9	12	38%
ECommerce	318	146	−54%	8	10	25%
Enterprise	96	151	57%	39	47	21%
Gaming	2,046	2,213	8%	41	77	87%
News	191	53	−72%	4	1	−62%
OTT Audio	257	268	4%	5	5	2%
OTT Video	2,088	1,896	−9%	26	26	3%
Other	126	181	43%	27	36	34%
P2P/File Sharing	1,044	670	−36%	887	586	−34%
Remote Access	876	530	−40%	185	90	−52%
Smart Home	13	9	−35%	272	79	−71%
Social Media	378	551	46%	29	18	−38%

Bitrates in Kbps are calculated by taking the time estimates that were reported in Table 11 and the monthly usage estimates in Table 10 and using the relationship $Time \times Bitrate = Usage$

4.3 Downstream and Upstream Bitrates

In general, growth in application bitrates was slower than was growth in monthly usage and time online. For example, in Table 13, no bitrates exceed 100% growth despite this being a threshold of growth that is common in the usage and time tables. *Collaboration* (79%), *Enterprise* (57%), *AR/VR* (52%), *Downloads* (51%), and *Social Media* (46%) had the strongest growth in downstream bitrates. *Gaming* (2.2 Mbps), *OTT Video* (1.9 Mbps), and *Downloads* (1.0 Mbps) are the only categories in 2022 with downstream bitrates over 1 Mbps. Categories that are associated with remote productivity have notably lighter bitrates. *Collaboration*'s 407 Kbps bitrate is 21% of *OTT Video*'s bitrate; *Enterprise* (151 Kbps) is 8.0%; and *Backup* (138 Kbps) is 7.3%.

Collaboration and *Gaming* are the only categories with over 50% growth in upstream bitrates. *Collaboration* grew from 180 Kbps in 2020 to 302 Kbps in 2022 (68% growth). *Gaming* went from 41 Kbps in 2020 to 77 Kbps in 2022 (87% growth). *Backup* (180 Kbps) and *P2P/File Sharing* (586 Kbps) also have upstream bitrates that were greater than 100 Kbps in 2022, but had lower growth at 22% and −34%, respectively. Other categories with strong upstream bitrate growth are *Downloads* (38%), *Browsing* (31%), *ECommerce* (25%), *Enterprise* (21%), and *AR/VR* (12%). For most categories besides *Collaboration*, *Backup*, and *P2P/File Sharing*, upstream bitrates are small, and growth over these two years had little effect on their network demands. For example, *Downloads*' 38% growth is only an additional 2.5 Kbps, on average; *Gaming*'s 87% growth was an additional 36 Kbps.

4.4 Explaining Growth in Network Usage

As was discussed in Sect. 2, the growth in monthly usage (gigabytes) is a function of how subscribers spend time online and the network demands of their activities (bitrates). Over the last few subsections, high-level summaries of how each of these three measures of network demand changed over the 2020-2022 time period have been discussed. In this section, we present complementary views on network demand to study whether time or bitrate growth was a greater driver of monthly usage growth. Bitrate changes, in particular, can be quite illustrative of how the internet is evolving. Larger bitrates are indicative of changes in: application demands (e.g., *OTT Video* providers using a higher/lower bitrate for a given resolution); how subscribers are interacting with applications (e.g., greater likelihood of turning on video on when using *Collaboration* applications); or greater levels of multitasking/concurrency in the home. Time, on the other hand, suggests changing opportunity cost and marginal benefit of an application to subscribers.

To decompose the relative contributions of time and bitrates to category-specific usage growth, we use 2020 application bitrates (see Table 13) and 2022 time estimates (see Table 11) to calculate what 2022 usage (gigabytes) would have been if only time grew over the two years and bitrates were constant. Table 14 reports actual usage, estimated usage from the constant-bitrate calculation, and the difference in gigabytes between these two values. A negative usage difference suggests that posi-

Table 14 Differences in Implied and Actual Usage Growth

	Downstream			Upstream		
Category	Actual 2022	Estimated 2022	Difference	Actual 2022	Estimated 2022	Difference
AR/VR	0.1	0.1	−0.0	0.0	0.0	−0.0
Backup	3.0	2.8	−0.2	3.9	3.2	−0.7
Browsing	24.3	21.2	−3.0	2.8	2.2	−0.7
Collaboration	9.9	5.5	−4.4	7.4	4.4	−3.0
Downloads	16.1	10.7	−5.4	0.2	0.1	−0.0
ECommerce	6.1	13.3	7.2	0.4	0.3	−0.1
Enterprise	2.3	1.5	−0.8	0.7	0.6	−0.1
Gaming	35.3	32.6	−2.7	1.2	0.7	−0.6
News	0.3	1.0	0.8	0.0	0.0	0.0
OTT Audio	3.1	2.9	−0.1	0.1	0.1	−0.0
OTT Video	199.3	219.5	20.2	2.8	2.7	−0.1
Other	18.0	12.5	−5.4	3.6	2.7	−0.9
P2P/File Sharing	3.7	5.8	2.1	3.3	4.9	1.7
Remote Access	2.7	4.4	1.7	0.4	0.9	0.5
Smart Home	0.0	0.1	0.0	0.3	1.1	0.8
Social Media	31.3	21.5	−9.8	1.0	1.6	0.6

This table reports estimated monthly usage in 2022 if bitrates were constant between 2020 and 2022. Reported estimates of time active in Table 11 for 2022 are combined with the estimated bitrates in Table 13 for 2020 to estimate what usage would be in 2022 if changes in time explained all growth. Positive differences correspond to bitrate decreases between 2022 and 2020

tive bitrate growth played a role in actual 2022 usage, and a positive difference suggests the opposite.

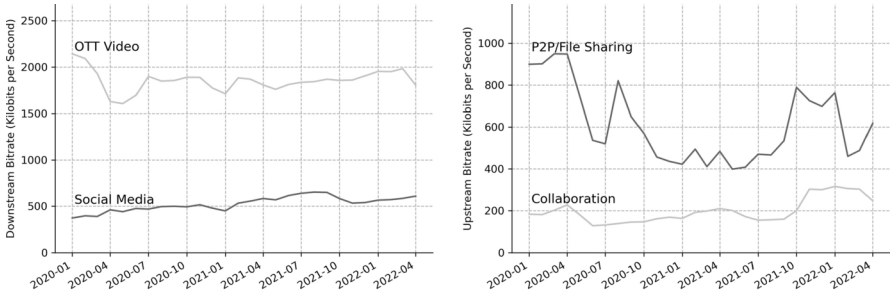
Of the downstream categories that are listed in Table 14, *OTT Video* has the largest positive difference between estimated and observed 2022 usage at 20.2 GB, and *Social Media* has the largest negative difference at −9.8 GB. Of the upstream categories that are listed in the table, *Collaboration* has the largest negative difference between 2022 estimated and observed usage (−3.0 GB), which suggests strong bitrate growth over these two years. *P2P/File Sharing* has a positive difference of 1.7 GB, the largest positive difference of the upstream categories.

Many categories in Table 14 do not have large differences between their observed and estimated 2022 totals. Part of this is explained by some of these categories being small drivers of overall demand (e.g., *News*), whereas others can be explained by time driving almost all growth observed (e.g., *OTT Audio*). Therefore, if we examine at the differences in usage proportionally, we can identify other notable differences more easily.

In the downstream direction, *Collaboration*'s estimated 5.5 GB downstream usage is 44% below actual downstream usage (the largest negative proportional difference); and *News*, at 262%, had the largest positive proportional difference. The minimum and maximum proportional differences for upstream demand are *Gaming*'s estimated upstream usage (46% smaller than the actual level) and *Smart Home*'s estimated usage (243% greater).

On the upstream side, *Collaboration* falls just behind *Gaming*, with estimated usage 41% below the actual level. The role that *Collaboration*'s bitrate growth had over these two years is evident in both levels and proportions.

In Fig. 12, we highlight the time series of category-specific bitrates for the categories with the maximum and minimum differences in estimated versus actual usage. *OTT Video*'s bitrate dropped sharply in the early days of the pandemic before increasing in the summer of 2020. This sharp drop was caused by many of the largest *OTT Video* providers reducing their downstream bitrates in the early days of the pandemic, when the ability



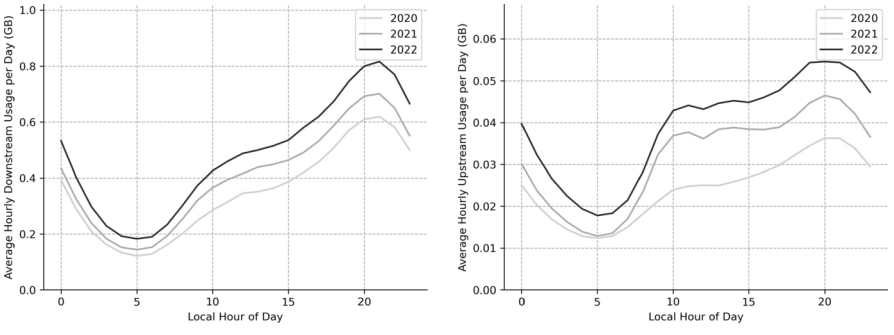
(a) Downstream (b) Upstream

Fig. 12 Bitrate Time Series of Select Categories, January 2020-April 2022. This figure presents average bitrates in the downstream and upstream directions for the categories in Table 14 with the largest and smallest estimated deviations. Each month's bitrate is calculated using the total amount of time spent on that category and the corresponding monthly usage observed

of broadband networks to accommodate the increased network demand was uncertain.[13] Much of the bitrate growth that drove usage changes in both *Social Media*, on the downstream side, and *Collaboration*, on the upstream side, was the emergence of more video-based content and interaction.

For example, within the social media category, Instagram has added features such as Reels, while TikTok is entirely video based, which has made the network demand for these applications more comparable to *OTT Video* platforms than has been true for other websites. The reasons for the decrease in *P2P/File Sharing*'s bitrates over time are less clear. Possible explanations include: differences in how applications such as BitTorrent share resources across users; the types of content being shared; or the amount of time that users spent actively uploading data.

In total, the most notable change in monthly subscriber demand between 2020 and 2022 was the growth in remote productivity applications, which is intuitive given the pressures that the COVID-19 pandemic placed on school and work arrangements during this period. Categories such as *Collaboration*, *Backup*, and *Enterprise* consistently had strong growth by any measure: monthly usage volume; time active; and bitrates. In 2022, each of these categories was used by over 90% of the subscribers in the sample, whereas in 2020, none of them were above 90%. Interestingly, the growth of these categories did not fundamentally change which categories generate the most volume or on which categories subscribers spend the most time. *Browsing*, *OTT Video*, and *Social Media* remain the most common online activities in 2022. Except for certain types of *Social Media* traffic (e.g., broadcasting on Twitch), the growth of *Collaboration*, in particular, suggests that the need for residential broadband connections is more than just faster plan speeds. The real-time nature of video collaboration means consistent (lower jitter) and lower latency connections that are reliable is just as important.



(a) Downstream (b) Upstream

Fig. 13 Trends in Intraday Network Usage. Hourly usage is reported as the average across all subscribers and traffic categories. Data from the first quarter of each year is used, so as to control for seasonality

[13] https://www.forbes.com/sites/johnarcher/2020/03/19/netflix-to-reduce-picture-quality-during-coronavirus-pandemic/?sh=13ed005c3711.

4.5 Intraday Behavioral Patterns

We next study the persistence of the changes in the intraday internet activity that was documented in Sect. 3. Internet traffic typically has a stable diurnal pattern with a peak in the evening and a trough in the early morning hours. Changes in the historically predictable timing of peak network demand could have implications for long-term network planning and engineering.

In Fig. 13, we show average hourly usage during the first two months of 2020, 2021, and 2022. The hourly downstream usage pattern over the day was similar across all three years. Usage increased during all hours of the day between 5 a.m. and 9 p.m. Peak hour usage increased by 0.2 GB (33%)– from 0.6 to 0.8 GB– between 2020 and 2022.

Hourly upstream usage, on the other hand, changed over these two years. In 2020, hourly upstream usage followed a similar pattern to that of hourly downstream usage. However, in 2021, there was a flatter profile over the day: there was a sharp rise between 5 a.m. and 10 a.m.; a plateau in usage between 10 a.m. and 5 p.m.; and then another notable increase in hourly usage up to the evening peak. This new profile of hourly usage was consistent in both 2021 and 2022– other than 2022 having heavier average usage for every hour of the day. From a network engineering perspective, which focuses solely on a network's peak demand, if the evening peak remains larger than the daytime plateau, the fundamentals of network capacity plan remain unchanged.

In Table 15, we present daily downstream and upstream usage shares by time of day from the first quarters of 2020 and 2022. Hours of the day are divided into five time intervals, with each column in the table summing to 1.

In general, the shares that are reported in Table 15 are consistent over the two-year period. Therefore, despite the increases in hourly usage and the changes in the profile of hourly upstream usage, the proportion of traffic that occurred between certain hours is mostly the same. For the same year, upstream usage shares were larger than downstream usage shares in morning hours, whereas downstream usage gained a larger share in evening hours. This evidence is consistent with upstream traffic that was associated with work-related application categories such as *Collaboration*, *Remote Access*, and *Downloads*, which rely heavily on broadband during morning hours. Downstream usage mainly involved activities such as *OTT Video* and *Social Media*– most of which are performed in the evening.

Table 15 Trends in Intraday Time Allocation

	Downstream usage shares			Upstream usage shares		
Time of Day	Q1 2020	Q1 2021	Q1 2022	Q1 2020	Q1 2021	Q1 2022
Morning (7am-10am)	0.11	0.12	0.12	0.13	0.14	0.14
Midday (11am-1pm)	0.12	0.13	0.13	0.13	0.15	0.14
Afternoon (2pm-5pm)	0.19	0.2	0.2	0.19	0.2	0.2
Evening (6pm-11pm)	0.41	0.39	0.39	0.35	0.34	0.34
Night (12am-6am)	0.17	0.17	0.18	0.2	0.17	0.19

Share of total time online during five mutually exclusive and collectively exhaustive intervals

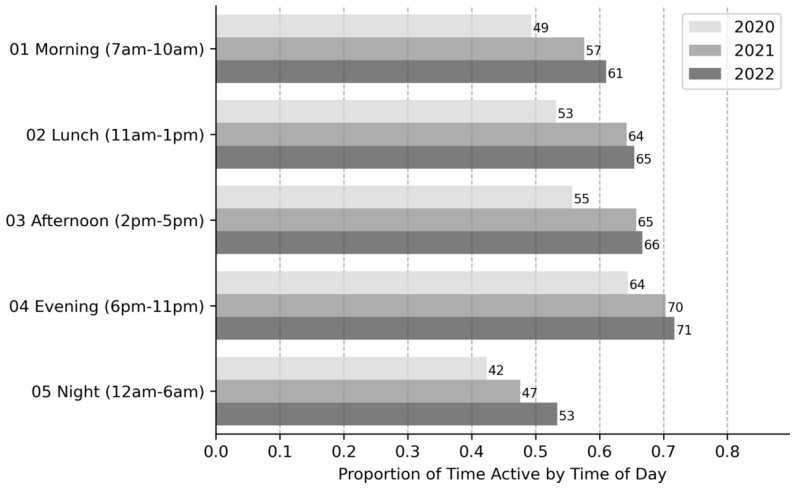


Fig. 14 Proportion of Time Active by Time of Day. This table reports the average proportion of time active by subscribers by time of day

In Fig. 14, the same five time intervals from Table 15 are used to report the average proportion of time that users were active. Within each time bin, user connections are more active in each subsequent year, with most of this growth coming between 2020 and 2021. The largest growth occurs during typical work hours– particularly in the morning and midday hours. Evening hours had the smallest increase in activity between 2020 and 2022.

5 Policy Discussion

The COVID-19 pandemic increased the salience of public policy discussions that are centered on broadband access, which prompted multiple policy initiatives that are intended to expand broadband coverage and quality. In this section, we provide a brief overview of recent policy issues in the United States and Canada; we then discuss the implications of our empirical findings for these ongoing discussions.

Several recent policy initiatives establish subsidies to incentivize investment in broadband networks and lower service costs. In the United States, the Emergency Broadband Benefit earmarked $3.2 billion in federal funding to subsidize internet access for lower-income households. Funding was expanded to $14 billion in 2022 via the Affordable Connectivity Program.[14] Additionally, to address the rural-urban divide in connectivity, the Rural Broadband Accountability Plan outlined new guidelines that incentivize broadband providers to expand the reach of their networks in areas with fewer economies of density than are present in typical urban markets.

In Canada, prior to the onset of the COVID-19 pandemic, the 2019 Connectivity Strategy plan established the goal of 100% coverage of high-speed internet. This plan was re-emphasized early in the pandemic and allocated additional resources in

[14] https://www.fcc.gov/affordable-connectivity-program.

2020 with the creation of the $3.2 billion Universal Broadband Fund.[15] These actions to promote better access and broader deployment of broadband networks were seen as efforts to bridge the “digital divide". This term predates the pandemic and refers to the unequal distribution of access to the internet, internet-connected devices, and digital literacy.

The sharp growth in residential internet use has also raised questions with respect to the appropriate modern (minimum standards) definition of broadband– particularly as it relates to qualifying for federal subsidies. The broadband definition used by the FCC during the sample period– which was written in 2015– set minimum download speeds at 25 Mbps and upload speeds at 3 Mbps. These minimum levels were increased to 100 Mbps for downloads and 20 Mbps for uploads, with long-term goals of 1 Gbps for downloads and 500 Mbps for uploads (Federal Communications Commission, 2024). In Canada, recent policy initiatives have continued to use the definition of 50 Mbps for downloads and 10 Mbps set by the CRTC in 2016. Despite calls to increase broadband speed standards, some have questioned the need for large-scale speed increases, citing few practical use cases for the fastest speeds currently available.[16]

In a related issue to defining broadband standards, the FCC recently released an order that requires internet service providers to provide “labels” on their plans so as better to: inform consumers; promote competition; and provide transparency with respect to pricing, features, and network performance. The order stipulates that these labels will contain pricing information, including: recurring and one-time fees; penalties; usage allowances; and discounts. Additionally, operators will be required to provide “typical” realized download speeds, upload speeds, and latency for each offering (Federal Communications Commission, 2022).

This paper’s analysis of current residential internet demand trends provides several insights that are relevant to the policy issues described above. One consistent theme in this paper’s results is the strong growth of application categories correlated with remote productivity. *Collaboration*, *Backup*, and *Enterprise* applications recorded comparatively large increases in both usage and time spent between 2020 and 2022. While these categories still account for a modest share of total usage and time online, they have quickly become ubiquitous, with positive usage records (penetration) across over 90% of household-months in the 2022 sample.

Considering the network demands of these fast-growing categories is relevant for defining “future-proof” broadband standards. Compared to the most common categories online in 2022 (*OTT Video*, *Browsing*, and *Social Media*), *Collaboration* applications typically involve real-time experiences in which users must send and receive audio and video feeds simultaneously. Real-time applications have greater latency, jitter, and reliability demands of the network.

For example, poor latency performance– larger latency measurements– can cause video and audio to stutter, and dropouts in a connection can lead to failed calls. In the case of *OTT Video*, local caches on client devices help minimize latency and reli-

[15] https://ised-isde.canada.ca/site/high-speed-internet-canada/en/universal-broadband-fund.

[16] See, e.g., https://www.wsj.com/graphics/faster-internet-not-worth-it/.

ability issues because content is being downloaded before the user views it; however, such methods are not relevant for real-time applications.

Historically, broadband has primarily been defined with respect to download and upload speeds. However, increased use of real-time communication– especially given the high value of their applications when used for remote work or school purposes– suggests that latency may be an appropriate addition to future broadband policy discussions on broadband definitions and access network technologies. The FCC's inclusion of "typical latency performance" on its broadband labels is a step in this direction.

Despite strong growth in remote productivity applications, many of the largest drivers of residential subscriber demand remain unchanged. *Browsing*, *OTT Video*, and *Social Media* are the top application categories by both usage and time measures. In particular, *OTT Video* comprised 62% of monthly downstream usage in 2020 and 56% of monthly downstream usage in 2022. *Browsing* and *Social Media* also remained top downstream drivers, with monthly engagement from 95% of subscribers in our sample. Conditional on being online, subscribers are either browsing the web or watching *OTT Video* over half of the time that they are online; and *Social Media* is active 30% of the time. Remote productivity's strong growth came from a relatively small pre-pandemic baseline and has not yet unseated the traditional drivers of network demand. Therefore, current network demands continue to be driven by the same applications as before the pandemic.

The asymmetry of downstream and upstream bandwidth utilization is another key aspect of network demand that remains unchanged in this sample. In 2020, the ratio of downstream monthly usage to upstream monthly usage was 15.4; in 2022, this ratio decreased to 12.1. This asymmetry in traffic partially explains why internet plans have historically offered faster downstream speeds than upstream. The FCC's modification of the 2015 broadband minimum definition– 25 Mbps downstream by 3 Mbps upstream– to the 2024 standard– 100 Mbps by 20 Mbps– reflects a decreased downstream to upstream ratio consistent with the findings above.

Asymmetry in downstream and upstream network use is also observable in estimated bitrates. The average subscriber's median downstream bitrate in the sample is 0.58 Mbps.[17] The average median upstream bitrate is 0.02 Mbps: 29 times smaller. Compared to monthly usage totals, bitrates are a better reflection of plan speeds because they capture the instantaneous demand on a network's capacity. As was shown in Sect. 2, there tends to be a large difference between a subscriber's median and maximum bitrates. For reference, the average subscriber's maximum five-minute bitrate in this sample across all tiers is 86 Mbps downstream and 11 Mbps upstream. Therefore, our sample does not provide evidence that symmetric downstream-upstream speeds are a key priority for *minimum* broadband definitions.

Application-specific bitrates also show little need for symmetric high-speed broadband plans. Take for example the *Collaboration* applications Zoom and Apple FaceTime. In April 2022, Zoom's median five-minute downstream bitrate, across all subscribers, was 42 Kbps. Its median upstream bitrate was 51 Kbps. FaceTime's

[17] Calculated as the mean of subscriber-specific median bitrates.

median bitrates was notably higher: 547 Kbps; its upstream median bitrate, however, was only47 Kbps.

By comparison, 99 th percentile bitrates of these applications do suggest that the current minimum upstream speed of 3 Mbps in the FCC definition is limiting in some circumstances. For Zoom, downstream and upstream 99 th percentile bitrates were 2.8 Mbps and 2.1 Mbps, respectively. For FaceTime, 99 th percentile bitrates were 4.1 Mbps for both downstream and upstream traffic. Some MSOs have already begun to increase the upstream speeds on their low cost tiers. In the United States, Comcast's Xfinity Internet Essentials program now offers a starting tier of 75 Mbps by 10 Mbps (up from 50 Mbps by 10 Mbps during the sample period).[18] In Canada, the speeds of low-cost plans were increased in 2022 to match the minimum broadband definition of 50 Mbps by 10 Mbps in the Connecting Families 2.0 initiative, up from the original guidance of "at least 10 Mbps" in the original order from 2018.[19]

Finally, the demographic information in our sample provides insights into policy that is targeted at reducing the digital divide. While we cannot address the gap in internet *access*, our results do illustrate the differences in level and composition of internet *utilization* across socioeconomic groups and how these differences have changed since the start of the pandemic. Overall, our results suggest that younger, more educated, and larger households have larger monthly usage. During the SaH orders of spring 2020, older, more educated, and wealthier areas had the strongest increase in monthly usage. This heterogeneity in usage responses is suggestive of which types of households were most easily able to adapt to in-person closures by adopting work-from-home, remote schooling, and other methods of engaging with the digital economy.

6 Conclusion

This paper provides an empirical description of residential internet demand during the COVID-19 pandemic. We document both short- and long-run changes in internet engagement, including both the adoption and intensity of use of application categories that support remote work and schooling. Though the dominant historical drivers of network engagement– *OTT Video*– remained unchanged, remote productivity applications experienced the highest levels of growth. Increased use of real-time applications suggests that latency measures may be appropriate inclusions in future broadband standards.

Though we cannot disentangle the mechanisms that explain the heterogeneous patterns in online behaviors across socioeconomic segments, our results suggest that not all households share the same ease of participation in the digital economy. Future efforts to bridge the digital divide may be best directed not only toward expanding access to internet connectivity, but also in promoting digital literacy and training to increase participation in the digital economy as a whole.

[18] https://www.xfinity.com/support/articles/comcast-broadband-opportunity-program.

[19] https://ised-isde.canada.ca/site/connecting-families/en.

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Declarations

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References

Aksoy, C. G., Barrero, J. M., Bloom, N., Davis, S. J., Dolls, M., & Zarate, P. (2022). Working from Home Around the World. Working Paper 30446, National Bureau of Economic Research.

Bacher-Hicks, A., Goodman, J., & Mulhern, C. (2021). Inequality in household adaptation to schooling shocks: Covid-induced online learning engagement in real time. *Journal of Public Economics,193*,

Barrero, J. M., Bloom, N., & Davis, S. J. (2021). *Internet Access and its Implications for Productivity, Inequality, and Resilience*. Technical Report 2021-88.

Bloom, N., Bunn, P., Mizen, P., Smietanka, P.,& Thwaites, G. (2023). The Impact of COVID-19 on Productivity. *The Review of Economics and Statistics*: 1–45.

Boik, A., Greenstein, S., & Prince, J. (2019). The persistence of broadband user behavior: Implications for universal service and competition policy. *Telecommunications Policy,43*(8)

Bronzino, F., Feamster, N., Liu, S., Saxon, J.,& Schmitt, P. (2021). Mapping the Digital Divide: Before, During, and After COVID-19. In TPRC48: The 48th Research Conference on Communication, Information and Internet Policy,.

Chiou, L., & Tucker, C. (2020). Social Distancing, Internet Access and Inequality. Working Paper 26982, National Bureau of Economic Research.

Clark, D. D., & Wedeman, S. (2022). Understanding the Metrics of Internet Broadband Access: How Much Is Enough? Working Paper 4178804, SSRN.

Federal Communications Commission (2022). Empowering Broadband Consumers Through Transparency. Technical Report FCC-22-86, Federal Communications Commission, https://www.fcc.gov/document/fcc-requires-broadband-providers-display-labels-help-consumers.

Federal Communications Commission (2024). FCC Increases Broadband Speed Benchmark. Press Release, https://docs.fcc.gov/public/attachments/DOC-401205A1.pdf, dOC-401205A1.

Fernandez, L., Reisdorf, B., Dutton, W. H.,& Hampton, K. (2018). Urban Myths of the Digital Divide: An Exploration of Connectivity, Breadth Of Use, and Interest Across Detroit Neighborhoods. In TPRC 46: The 46th Research Conference on Communication, Information and Internet Policy,.

Fernandez, L., Shillair, R., & Reisdorf, B. (2019). Building Our Own Bridges: How a Distressed Urban Neighborhood Bridges the Digital Divide. In Quello Center Working Paper, TPRC47: The 47th Research Conference on Communication, Information and Internet Policy,.

Hampton, K., Fernandez, L., Robertson, C., & Bauer, J. M. (2020). Repercussions of Poor Broadband Connectivity for Students in Rural and Small Town Michigan. In TPRC48: The 48th Research Conference on Communication, Information and Internet Policy,.

Hollman, A. K., Obermier, T. R., & Burger, P. R. (2021). Rural Measures: A Quantitative Study of The Rural Digital Divide. *Journal of Information Policy,11*, 176–201.

Jordan, S. (2022). Broadband Labels: Performance and Network Management. Working Paper 4175616, SSRN.

Malone, J. B., Nevo, A., Nolan, Z., & Williams, J. W. (2023). Is OTT Video a Substitute for TV? Policy Insights from Cord-Cutting. *The Review of Economics and Statistics,105*(6), 1615–1623.

McCrary, J. & Sarath S. (2021). The Impact of the Coronavirus Lockdown on Domestic Violence. *American Law and Economics Review*, 23.

McManus, B., Nevo, A., Nolan, Z., & Williams, J. W. (2022). The Steering Incentives of Gatekeepers in the Telecommunications Industry. Working Paper 30399, National Bureau of Economic Research.

McManus, B., Nevo, A., Nolan, Z., & Williams, J. W. (2024). Does Pricing of Internet Usage Steer Consumers or Meter Usage? Evidence from a Pricing Experiment., working paper.

Miller, A., Segal, C., & Spencer, M. (2022). Effects of COVID-19 shutdowns on domestic violence in US cities. *Journal of Urban Economics,131*,

Mills, C. & Fiona, A. (2019). United States of America: Special Report: State of MVNOs. Technical report, Tutela, https://www.tutela.com/blog/usa-state-of-mvnos-19.

Nevo, A., Turner, J. L., & Williams, J. W. (2016). Usage-Based Pricing and Demand for Residential Broadband. *Econometrica,84*(2), 411–443.

Strover, S. (2018). Urban Poverty and the Internet: Libraries, Information Needs, Technology and Local Policy. In TPRC 46: The 46th Research Conference on Communication, Information and Internet Policy,.

Wedlake, S., Iribe Ramirez, Y., Carson, K., Jowaisas, C., Keyes, D., & Houghton, M. (2021). Creating a Digital Bridge: Lessons and Policy Implications from a Technology Access and Distribution Program for Low-income Job Seekers. In TPRC49: The 49th Research Conference on Communication, Information and Internet Policy,.

Zeltzer, D., Einav, L., Rashba, J., & Balicer, R. D. (2023). The Impact of Increased Access to Telemedicine. *Journal of the European Economic Association*.

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