Stocker, Volker; Lehr, William; Smaragdakis, Georgios

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Chapter 2

COVID-19 and the Internet: Lessons Learned

Volker Stocker, William Lehr and Georgios Smaragdakis

Abstract

The COVID-19 pandemic has disrupted the 'real' world and substantially impacted the virtual world and thus the Internet ecosystem. It has caused a significant exogenous shock that offers a wealth of natural experiments and produced new data about broadband, clouds, and the Internet in times of crisis. In this chapter, we characterise and evaluate the evolving impact of the global COVID-19 crisis on traffic patterns and loads and the impact of those on Internet performance from multiple perspectives. While we place a particular focus on deriving insights into how we can better respond to crises and better plan for the post-COVID-19 'new normal', we analyse the impact on and the responses by different actors of the Internet ecosystem across different jurisdictions. With a focus on the USA and Europe, we examine the responses of both public and private actors, with the latter including content and cloud providers, content delivery networks, and Internet service providers (ISPs). This chapter makes two contributions: first, we derive lessons learned for a future post-COVID-19 world to inform non-networking spheres and policy-making; second, the insights gained assist the networking community in better planning for the future.

Keywords: COVID-19; Internet traffic; resilience; broadband; Internet Exchange Point; Content Delivery Network; clouds

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2.1. Introduction

The virus SARS-CoV-2 and the associated disease COVID-19, which the WHO declared a pandemic on 11 March 2020, turned the world upside down, resulting in countries across the globe issuing various forms of stay-at-home social distancing rules and closing in-person economic activity in an effort to stem the spread of the disease (European Centre for Disease Prevention and Control, 2022; WHO, 2022). Where possible, virtual encounters replaced physical ones, and social, educational, and commercial activity increasingly moved online during the course of the lockdown and ongoing pandemic (at least for those activities that could shift online).[1] This dramatic shift had profound effects on our social and economic lives. Some will result in long-lasting changes, while others may be temporary crisis responses. Some of the effects and responses were anticipated, some are surprises, and others are evolving in real-time.

COVID-19 has disrupted the 'real' world and has substantial implications for the virtual world and thus the Internet ecosystem. It caused a significant exogenous shock that offers a wealth of natural experiments and produced new data about broadband, clouds, and the Internet in times of crisis and enables testing of established and proposed hypotheses about the resilience and adaptability of the ecosystem. These unparalleled research opportunities for observing the interaction effects between the real and virtual worlds provide novel possibilities to evaluate how well today's communications networks, services, and applications have responded to the increased and changing traffic loads and assess the evolving responses by private actors such as ISPs and content and cloud providers as well as governments. The natural experiment(s) afforded will continue to be mined and analysed for network provisioning/management and policy insights in years to come.

In this chapter, we highlight emerging insights and explore the interaction effects between the real and virtual worlds. Our focus is on the USA and Europe and deriving lessons and insights into how we can better plan for the future post-COVID-19 'new normal'. Recognising the research potential of the ongoing crisis, we began collecting trade-press, blog posts, academic research, sundry white papers, and related materials that were publicly available and related to the performance and management of Internet infrastructure and services and user and policy responses as those evolved in real-time starting in the first quarter of 2020 when the extent, duration, and impact of the pandemic were uncertain. Our collection methods were not systematic but were informed by our long engagement in multidisciplinary research related to Internet technology, industry, and policy developments. The materials we collected numbered over 3,000 entries. Our initial review of these materials, presented here, focuses on identifying how

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[1]The ability to shift activities online depended both on the availability of appropriate infrastructure (e.g. access to broadband, home network environments, internet devices, and the requisite skills) and the nature of the activity. Some activities like restaurant meals, haircuts, and trash removal could not shift online; however, these were disrupted also. We will discuss this in Section 2.4.

the COVID-19 experience helps confirm what was known pre-COVID-19, what lessons are new, and what questions remain to be explored further.

The remainder of this chapter is structured as follows. In Section 2.2, we provide an overview of the effects of COVID-19 on Internet traffic and explore how well the Internet has coped with the new demands and where specific weaknesses were revealed. Section 2.3 highlights the responses by policy-makers and by industry. Section 2.4 discusses the impact of COVID-19 in light of those responses for the Internet ecosystem and the lessons we take from our evaluation. Section 2.5 briefly sums up and concludes.

2.2. The Effect of COVID-19 on Internet Traffic

The pandemic and the measures to contain the spread of the virus have fundamentally changed social and commercial activity. Unsurprisingly, it has caused sudden and unexpected increases and shifting patterns in Internet traffic and substantially changed usage patterns (Feldmann et al., 2020, 2021; Koeze & Popper, 2020; Labovitz, 2020a; OECD, 2020a, 2020b). One of the most significant changes relates to the location of Internet access as many individuals had to rely on their residential broadband connections to maintain their social and economic activity, for example, working, educating, and consuming entertainment from home. Moreover, many citizens changed locations, leaving city centers and (temporarily) moving to more rural or remote areas. The change of access point has emphasised the important role of residential broadband access and in-home networks (e.g. local home WiFi networks). Where these networks are not well-provisioned, rely on outdated hardware and software, or are not configured correctly, they can present performance bottlenecks that limit access to online services and a good-quality user experience. Additionally, the shift to at-home use led to a geographical dispersion of the access points from 'aggregation points' such as enterprise networks or university campus networks. Moreover, reduced mobility implied that even when mobile devices were used, they were often connected via local home WiFi networks, thus relieving mobile network traffic (Comcast, 2020; Feldmann et al., 2020; Lutu et al., 2020; Schlosser et al., 2020; The Economist, 2020; see also Apple, 2021[2]; Ritchie et al., 2022). Thus, the traffic that ISPs needed to carry shifted from originating at business locations to residential locations, with the attendant shift in the utilisation of the 'first-hop' access network facilities used to provision such activity. For example, the typical away-from-home access connection (e.g. office building, school, etc.) aggregates access traffic for many users (employees, students, etc.) before connecting it to wider-area networks off-site (whether those be the public Internet or private networks) via business-grade connections which are typically provisioned and tariffed differently from mass-market (residential) fixed or mobile broadband connections.

In addition, the change of access location has often been accompanied by a change in the access environment – for example, a workplace (or school) network environment optimised and specifically secured was replaced by local access from

[2]Apple stopped providing COVID-19 mobility trends reports in April 2022.

home and remote access via virtual private networks (VPNs) (Feldmann et al., 2021; World Bank, 2020). Because bricks and mortar retailing (see Whalley & Curwen, 2023, this volume) and other places like cinemas had to close during lockdown measures, offline entertainment and commercial activities like retail shopping, restaurants, gyms, and other offline activities migrated to the virtual sphere. The result of these shifts was higher traffic demands by residential broadband access users and shifts in usage and traffic patterns (e.g. Baumgartner, 2020; Cloudflare, 2021; Feldmann et al., 2020, 2021; Filipovic & Cervall, 2020; OpenVault, 2020a, 2020b, 2020c, 2020d; The Economist, 2020).

The changes noted above would not have been possible with the pre-2000 Internet where most users accessed the Internet over low-speed, intermittent dial-up modem connections. In such a world, the opportunity to shift economic activity online would have been much more severely constrained. The basic networking infrastructure for enabling connectivity, the devices, the applications, the software, and the digital services used by businesses and consumers were much less capable and ubiquitously in use than they were in the years immediately preceding the onset of the pandemic. Over the past decade, significant changes have occurred in the Internet ecosystem, with perhaps the most important change being the shift to generally available broadband Internet access services offering data rates measured in the 10s to 100s of Megabits per second or faster[3] and the wide availability of end-user devices and supporting applications and software capable of real-time video-conferencing and other interactive, multimedia applications.

These evolutionary ecosystem changes set the stage for a shift from face-to-face physical interactions to virtual interactions for those with the right equipment, skills, networking infrastructure, *and* jobs. E-commerce also flourished, with growing shares of global commercial activity having moved online. A key demand driver for much of this investment was the growth in demand for over-the-top (OTT) video entertainment, and concurrently, growing demand for everywhere accessibility that fuelled simultaneous growth in streaming media (video and music services like YouTube, Netflix, and Spotify launched in 2005, 2007, and 2011, respectively) as well as real mobile broadband (e.g. smartphones after 2007 iPhone release and 4G LTE after 2010).

Accommodating these changes required significant investment and adjustments by network and service providers across the Internet ecosystem.[4] In addition to the

[3]In the United States, broadband use at home exceeded 50% for the first time in the third quarter of 2007, and as of later 2020, has plateaued at 77% (Pew Research Center, 2021). Today's broadband access services are based on a wide range of wired and wireless access technologies and continue to evolve, technologically and in terms of their capabilities (see, e.g., Stocker, 2020, ch. 3).

[4]This includes the shift to software-based systems to control and manage networks. This softwarization of networks has proceeded across datacenters and core networks and includes the rise of Software Defined Networking, Network Function Virtualization, and the emergence of cloud platforms and application providers. A full discussion of these developments is beyond the scope of this chapter.

investment in more capable broadband last-mile infrastructure, the need to deliver the surge in video traffic propelled the rise of Content Delivery Networks (CDNs) that increasingly sought to deploy (highly) distributed serving infrastructures to cache content closer to end-users. Distributed cloud and serving infrastructures have brought networked computing resources closer to end-users. In addition, they reflect a cloudification process by which a growing share of traffic is delivered via cloud-based systems. On top of that, the rise and rapid growth of geographically distributed interconnection facilities expanded options for where networks can meet, directly interconnect, and exchange traffic (e.g. via so-called Internet Exchange Points (IXPs)). Consequently, these developments have contributed to significant changes in the topology of the Internet. The Internet has become flatter with fewer hops between communicating endpoints – for example, between end-users (human-to-human), smart devices (machine-to-machine), or an end-user and the server where the content is stored or data is processed (human-to-machine).[5] Due to these pre-COVID-19 developments, the Internet was already well-positioned to handle the COVID-19 pandemic's sudden and forced shift from physical to virtual economic and social activity in many advanced, broadband-capable markets as a consequence of having been investing heavily in prior years to address the double-digit annual growth rates in traffic that have characterised the Internet for the past decades.

2.2.1. Impact on Application Usage

The first question to ask is how the demands for different applications have changed compared to pre-pandemic levels. In other words, how much strain has the shift towards more virtual activities put on the providers of those applications that have been used during the pandemic, especially those that have acted as virtual substitutes for previously physical activities. Exploring this strain is crucial. We have already mentioned that real-world changes have caused adaptations and changes in the virtual world which, in turn, translate into changing demands for application usage and also for network traffic. Let us consider how real-world changes in developed countries have manifested themselves in the virtual world. In doing so, we first take a look at changes in Internet usage by application category as reported in numerous reports and studies as well as blog and news articles. The data is rich since over the course of the pandemic, especially during the first wave and the concomitant restrictions to contain the spread of the virus, a wide range of actors like ISPs (e.g. Comcast, 2020, 2021; Verizon, 2020), vendors like Sandvine (2020) or Nokia (Labovitz, 2020a), advisory groups like BITAG (2021), and also academics (e.g. Arkko et al., 2021) have published data and insights into the changing usage patterns. We analysed these sources and collected some of the reported changes in Table 2.1.

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[5]'Fewer hops' in this context means that data packets need to traverse fewer network borders, typically interconnection points, between communicating endpoints. Broadly speaking, delivery chains are shortened so that fewer players are involved in delivering a service. For overviews and further discussion of these changes, see Labovitz et al. (2009), Clark et al. (2016), and Stocker et al. (2017, 2021).

Table 2.1. (Examples of) Changes in Internet Usage by Application Category.

Application Category		What?	Change (Time Period; Location/Network)	Source
Entertainment		Downloads (Network Usage)	+20–80% (16 May 2020 vs. 1 Mar. 2020; Comcast)	Comcast (2020)
	Online Gaming	Data Usage/Traffic	+82% (21 May 2020 vs. Typical Pre-pandemic Day; Verizon)	Verizon (2020)
			+71% (22 Apr. 2020 vs. Typical Pre-pandemic Day [Peaks]; Verizon)	
			+115% (9 Apr. 2020 vs. Typical Pre-pandemic Day; Verizon)	
			+75% (16 Mar. 2020 vs. 9 Mar. 2020; Verizon)	
	Video Streaming	Consumption (Network Usage; Streaming & Web Video)	+20–40% (16 May 2020 vs. 1 Mar. 2020; Comcast)	Comcast (2020)
		Data Usage/Traffic	+36% (14 May 2020 vs. Typical Pre-pandemic Day; Verizon)	Verizon (2020)
			+26% (22 Apr. 2020 vs. Typical Pre-pandemic Day [Peaks]; Verizon)	
			+36% (9 Apr. 2020 vs. Typical Pre-pandemic Day; Verizon)	
			+12% (16 Mar. 2020 vs. 9 Mar. 2020; Verizon)	
		Traffic Share (Absolute)	Overall Traffic Share of Video Streaming: 57.64% (Apr. 2020; Global)	Sandvine (2020)
			Netflix: 11.42% of Global Internet Traffic (Apr. 2020; Global)	
			YouTube: 15.94% of Global Internet Traffic (Apr. 2020; Global)	

	Social Media	Facebook/Instagram/ WhatsApp Usage	>+50% Total Messaging (In Many Countries 'hit hardest'; ca. 24 Mar. 2020 vs. Previous Month)	Schultz and Parikh (2020)
			Up to +70% More Time Spent on Apps (ca. 24 Mar. 2020 vs. Pre-pandemic Levels; Italy)	
			>+1,000% Group Call Time (Within One Month; Data: ca. 24 Mar. 2020; Italy)	
			+100% Live Views on Instagram and Facebook (Within One Week; Data: ca. 24 Mar. 2020; Italy)	
Remote Work/ Learning	VPN	Network Usage/Traffic	+30–40% (16 May 2020 vs. 1 Mar. 2020, Weekdays; Comcast)	Comcast (2020)
		Data Usage/Traffic	+72% (21 May 2020 vs. Typical Pre-pandemic Day; Verizon)	Verizon (2020)
			+81% (14 May 2020 vs. Typical Pre-pandemic Day; Verizon)	
			+49% (9 Apr. 2020 vs. Typical Pre-pandemic Day; Verizon)	
			+34% (16 Mar. 2020 vs. 9 Mar. 2020; Verizon)	
		Traffic	>+200% (Mar. 2020 vs. Mar. 2019, During Workdays & Working Hours; Different Vantage Points)[a]	Feldmann et al. (2020)
	Online Collaboration Tools	Data Usage/Traffic (Aggregate over all Tools)	+1,200% (14 May 2020 vs. Typical Pre-pandemic Day; Verizon)	Verizon (2020)
		Network Usage/Traffic (Voice over IP & Video Conferencing)	+210–285% (16 May 2020 vs. 1 Mar. 2020, Weekdays; Comcast)	Comcast (2020)
		Traffic (Web Conferencing and Telephony)	>+200% (Mar. 2020 vs. Mar. 2019, During Workdays & Working Hours; Different Vantage Points)[a]	Feldmann et al. (2020)

(*Continued*)

Table 2.1. (*Continued*)

Application Category		What?	Change (Time Period; Location/Network)	Source
Other	Telehealth	Utilization	38 Times Higher Utilisation Compared to Pre-pandemic Levels (Feb. 2021; Global)	Bestsennyy et al. (2021)
			78 Times Higher Utilisation Compared to Pre-pandemic Levels (Apr. 2020; Global)	
	E-Commerce	COVID-19 Related Additional Growth in Revenues	+22% (2020–2021; Global [Forecast])	Statista (2021)
			+19% (2019–2020; Global)	
		Change in the Share of Online Retail Sales of Total Retail Sales (per Country)	+47.5% (2019–2020) versus +6.0% (2018–2019) in the UK	Own calculation based on UNCTAD (2021)
			+27.3% (2019–2020) versus +11.1% (2018–2019) in the USA	
		Change in Gross Merchandise Value (GMV) per E-Commerce Company	+38.0% (2019–2020) versus +21.0% (2018–2019) for Amazon	UNCTAD (2021)
			+17.0% (2019–2020) versus –4.8% (2018–2019) for eBay	
			+95.6% (2019–2020) versus +48.7% (2018–2019) for Shopify	
			–37.1% (2019–2020) versus +29.3% (2018–2019) for Airbnb	
			–63.3% (2019–2020) versus +4.0% (2018–2019) for Booking Holdings	

[a] The authors utilise data from a set of vantage points: one large European ISP which operates a Tier-1 network, three IXPs (a major IXP in Central Europe; an IXP in Southern Europe; an IXP at the US East Coast), and one metropolitan educational network (REDImadrid).

Table 2.1 gives a good idea of the nature and magnitude of the changes in the usage of different applications during the crisis. Whereas the applications and the usage changes presented are inherently selective, reflecting observations from different vantage points in the USA and Europe, they are broadly representative. A glance at the table yields three important insights.

First, the demands for different applications have indeed changed through the pandemic, often dramatically. However, the changes varied strongly across applications and across providers. As Table 2.1 shows for different application categories, the demands for VPN services, social media, Telehealth, online gaming, video streaming, and online collaboration tools increased sharply, and even skyrocketed in some cases (see also Arkko et al., 2021; Feldmann et al., 2020, 2021; Jennings & Kozanian, 2020).[6] In this context, it needs to be noted that applications with stringent latency requirements such as online gaming or video conferencing (as used for online collaboration in remote work or learning contexts or in Telehealth) have experienced dramatic growth rates. Video conferencing relies on bidirectional, real-time communications. Thus, these applications emphasise the role of upstream data rates and high and stable quality of service levels (especially regarding latency and jitter which are important to enable real-time interactivity of the sort required for video conferencing, gaming, and business 'groupware' applications). Specific services (such as corporate websites or databases used by employees) or VPNs that relied on centralised server architectures rather than on hosted-cloud solutions experienced significant congestion, especially on the up-links connecting end-users to centralised servers. In contrast, applications or VPNs that were provisioned using cloud services were better able to manage the demand shocks. Hosted-cloud solutions performed better since they were able to distribute the load and provide easier scalability options. For example, business applications like Office360 and Zoom's video conferencing which are native cloud applications were better able to scale quickly and resiliently to meet localised COVID-19 traffic surges (Feldmann et al., 2020, 2021; see also Sections 2.3 and 2.4).

Second, when taking a look at application categories as aggregates, Table 2.1 shows that shifts in the pre-pandemic application mix have emerged. For example, with employees working from home and children home from school, applications like video conferencing and group-sharing applications like Google Docs and Slack and video streaming and gaming applications saw significant jumps in

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[6]Outperforming their competitors in terms of growth, Zoom's daily meeting participants increased from 10 million in December 2019 to more than 300 million in April 2020 (Zoom, 2020). The usage growth in different collaboration tools between 17 February and 12 April 2020 has been reported in a report on global remote work productivity by Aternity. The report finds that Zoom usage has increased by 552%, GoToMeeting by 442%, Microsoft Teams by 439%, WebEx by 296%, Slack by 215%, and Skype for Business by 166% (Aternity, 2020, Fig. 4 at p. 6). See also BITAG (2021, p. 11) and Koeze and Popper (2020).

usage, resulting in these accounting for a larger share of the application mix (see also Sandvine, 2020, p. 6). Although this is rather unsurprising, it has profound implications for the traffic experienced by networks over time and at different locations. The shifts in application mix varied by geographic location and over time for multiple reasons, including demographic and employment differences (across residential communities), differences in the progress of the pandemic and responses to it, or seasonal effects. These differences complicate the challenge of traffic analyses and of assessing the reasons behind the variable performance, to the extent such variances were observed. They demonstrate the need for differentiated assessments and evaluations of (i) the impact of the pandemic and (ii) the providers' and networks' resilience and ability to absorb and adapt to the changing demands.

Third, demand shocks have posed challenges for application providers, content and cloud providers, and networks and communications service providers. The example of Zoom has shown that the demand shifts experienced by single application providers significantly exceeded the changes in terms of application categories or aggregate Internet traffic. As a consequence, the need to rapidly scale capacities and business operations capacities and adapt resource management strategies to handle localised hotspots (associated with particular applications at particular locations and times) while maintaining high levels of customer experience varies strongly across applications and service providers, and those differed with respect to their capabilities to accommodate the (unexpected) shifts in demand based on multiple factors, including their level of pre-pandemic investment, network architecture, and traffic management practices (e.g. how hot or close to peak capacity they typically ran their networks). Similarly, although aggregate web traffic increased, certain websites experienced traffic increases that were orders of magnitude larger (e.g. Berthene, 2020; Burke, 2020; Hendry, 2020; Koeze & Popper, 2020). The latter included sites providing such content as COVID-response-related material, including unemployment subsidy applications and COVID-19 testing information. This insight emphasises the relevance to perform differentiated analyses and consider the context- and locality-specific nature of the challenges by different actors of the ecosystem.

2.2.2. Impact on Internet Traffic

Changing end-user and edge provider (e.g. application and content provider) usage patterns translate into changes in network traffic. They also imply changing requirements regarding network capacity and performance (e.g. in terms of reliability and latency, jitter, and packet loss rates). As we described above, the shift towards more virtual activities changed the locations from where, the timing for when, the selection of applications, and the modalities (e.g. type of device) online applications and services were used.[7] These shifts resulted in commensurate shifts

[7]As noted earlier, the ability to shift online depends on the level of economic development, and even among developed economies, differences in work patterns, broadband network development, and the phasing of COVID's progress and responses resulted in significant heterogeneity in traffic patterns.

in network traffic, imposing strains on the ISP networks and ancillary service providers that connect end-users and application/content service providers.

Against the background of the sudden demand shifts caused unexpectedly by the pandemic, it is hardly surprising that in the early stages of the lockdown measures, concerns arose that the Internet might collapse from the need to rapidly adjust to shifting so much activity online in response to COVID-19-related mandates (e.g. Fleming, 2020; Watson, 2020). Although ISPs had grown accustomed to aggregate traffic growth on the order of 30% per year, in March 2020, many ISPs and other providers experienced such levels of growth over a few weeks (e.g. Feldmann et al., 2020). As collective experience has demonstrated, the Internet has not collapsed but instead coped rather well with the unexpected increases and shifts in traffic. Already by mid-2020, the Internet had weathered the storm of the first wave and had proven its critical role in enabling online activity to substitute for offline activities, and in so doing, contributed significantly to mitigating the substantial negative social and economic effects of the pandemic that otherwise would have occurred had the pandemic struck in a world with less-advanced Internet capabilities (e.g. Belson, 2020a; Heaven, 2020; Stocker & Whalley, 2021; Timberg, 2020). Digital infrastructures, in particular the Internet, provided a lifeline for many and contributed significantly to social and economic resilience during the crisis (e.g. Briglauer & Stocker, 2020;[8] Cloudflare, 2021; Feldmann et al., 2020, 2021; Rexford, 2021). With the trend towards telecommuting and more flexible work/schooling options (with mixed onsite and remote work/education) becoming increasingly prevalent, especially as the pandemic continues to cause restrictions that require the adoption of such options, COVID-19 has provided a significant step-change boost in support for and efforts to improve the robustness and capabilities of our broadband networks. In 2022, the question now is where the future post-COVID new normal will be and how will employers and schools adjust when onsite and in-person operations become increasingly acceptable.

A series of studies and reports have investigated the stability, resilience, and adaptability of the Internet during the pandemic. Whereas many of these reports and studies had been motivated by the initial impact of the first wave and lockdowns across different countries and the sudden changes these have caused, some also covered the effects of subsequent waves and lockdown measures. Appendix 2.1 provides an overview of some of these studies and reports.

2.2.2.1. Internet Traffic and Network Performance – A Tale of Aggregates, Peaks, and Troughs. To understand the pandemic's impact on Internet traffic and network performance, it is important to understand the extent to which peak traffic and network utilisations change. As mentioned above and as shown in several studies, overall Internet traffic increased by 25–30% within a few couple of weeks and thus by as much as it would normally increase within an entire year

[8] Briglauer and Stocker (2020) contains a brief and early discussion of the role of broadband in times of crisis. In this chapter, we update and expand on several aspects of the discussion presented there.

(FCC, 2020b; Feldmann et al., 2020; Leighton, 2020b).[9] This level of aggregate increase in demand in a few short weeks represents a significant demand shock that would stress many industries, and so for those not familiar with how networks are provisioned, it is hardly surprising that some feared the increased traffic might result in serious disruptions and degradation in Internet performance (Fleming, 2020; Timberg, 2020). However, the Internet has lived with double-digit annual aggregate (and per-average-user) traffic growth for several decades (e.g. Cisco, 2020) so the challenge for well-provisioned ISPs was to accommodate a year's worth of growth in a few weeks – difficult, but not infeasible. Similar levels of traffic growth as were experienced by access provider ISPs were experienced by transit providers, cloud and content providers, and at IXPs (e.g. BITAG, 2021; Davidson, 2020; OECD, 2020a).

In provisioning networks, capacity is added in lumpy increments in advance of projected demand growth. The reference point for upgrade decisions is oriented at traffic peaks and peak utilisation levels since this indicates network congestion. To address the unexpected COVID-19-related traffic spikes and to maintain high customer experience levels, ISPs needed to pull forward their annual capital spending and provisioning work by a number of months to allow them to accommodate the growth in traffic peaks (e.g. Liu et al., 2021).

Whereas changes in peak traffic and peak utilisation are critical in assessing the impact on Internet performance, it is worthwhile to note that (i) decisions on capacity upgrades are based on expected growth in traffic peaks since these critically determine the stability and performance of network operations during peak demands and thus customer experience; and (ii) that providing for excess capacity during the peak to accommodate normal fluctuations in traffic is a standard operating procedure. However, the amount of excess peak capacity that is provisioned must be balanced with economic considerations. That is, too much excess capacity for unexpected peaks results in over-provisioning, excessively low average utilisation, and equivalently, high average costs and is – at least in normal times when average yearly growth rates are rather predictable at about 25 to 30% – economically inefficient.

The fact that aggregate traffic growth alone does not give insights into the (potential) impact of the pandemic on network performance can be illustrated by a simple example. Suppose all traffic growth would have been in off-peak hours, that is, in pre-COVID-19 traffic troughs when network utilisation was very low anyway. In such a case, large traffic growths may not even require additional capacity investment. So, the questions to ask are when did the major increase in traffic occur and how have traffic peaks changed?

[9] Tom Leighton, CEO of Akamai, one of the world's largest CDN provider, was quoted to have said: "From our vantage point, we can see that global Internet traffic increased by about 30% during the past month. That's about 10× normal, and it means we've seen an entire year's worth of growth in Internet traffic in just the past few weeks" (McKeay, 2020).

In fact, much of the traffic increase occurred during off-peak periods (i.e. filling in pre-COVID-19 troughs).[10] Thus, the strain on ISP capacity was significantly easier to accommodate than if aggregate increases had occurred at the peaks and been accommodated with a per-period usage profile mirroring pre-COVID-19 usage profiles. Peak period traffic did increase, arguably to varying extents in different networks and geographies (see Fig. 2.1 and Table 2.2 below). While Feldmann et al. (2020, 2021) reported that peak traffic growth was much less than the 30% that was experienced in aggregate traffic for the (representative) set of vantage points they analysed, Labovitz (2020a) reports an increase of 25–30% in global peak Internet traffic. When comparing data on peak traffic changes, it is important to note that definitions of peak traffic and measurement techniques may vary across different measurement studies, thus rendering comparisons difficult. While Feldmann et al. (2020, 2021) consider peaks as an average based on an hourly or daily basis, other studies like those of Liu et al. (2021) or Labovitz (2020a) use more short-term measures.[11]

Had traffic peak increases been on the order of 60% or well above that would likely have resulted in much more significant disruptions since that level of demand growth is out-of-scope for reasonable planning efforts.[12] Had traffic peaks grown by that amount or more, ISPs would probably have needed to be (more aggressive in) adopting their traffic management strategies and throttle or reduce the data throughput or rate for traffic that is deemed 'less important' (e.g. pure entertainment content like video streaming) to ensure high service availability and customer experience for essential online services (e.g. those related to remote work or education). The fact that ISPs have the decision authority upon relevant prioritisations is also presumably why, for example, BEREC (2020) provided some policy guidance on what traffic management practices would be acceptable during exceptional circumstances in the pandemic (see Section 2.3.1).[13]

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[10]Pointing to difference between aggregate traffic growth and peak traffic growth, Sandvine (2020, p. 5) stated: "Fortunately, this [aggregate] traffic increase was not solely centered around peak hour increases (although there was some of that), and many networks were able to survive the initial onslaught of traffic increases."

[11]For example, Labovitz (2020a) speaks of recording peak levels in five-minute intervals and finds that aggregate traffic levels are about 25% above pre-COVID levels and peak traffic levels have increased by 25–30%.

[12]This is akin to the challenge of planning for floods – most planners may plan for a 100-year flood, but they do not plan for 500-year floods (i.e. floods that are likely to occur only once every 500 years).

[13]The decision of what constitutes 'less important' traffic is ultimately a policy decision that ISPs or content providers may be ill-suited to make. Some might argue streaming video is 'less important' than video conferencing since the former is entertainment-oriented while the latter is work-oriented. However, the providers of video streaming content or parents seeking to keep their at-home children occupied so they can be freed to work may disagree. Moreover, determining what is entertainment versus work is not easily accomplished on an application-by-application basis (e.g. is a family video-chat more important than watching real-time news reports? Or, what

2.2.2.2. How Traffic Patterns Have Changed. Apart from traffic increases, the pandemic has caused changes in traffic patterns. While traffic patterns pre-COVID-19 were characterised by peaks and troughs, especially during weekdays, social distancing and lockdowns have changed this. Importantly, although peaks were higher, it is also the case that traffic is spread out more evenly throughout the day. That is, previous troughs have been partially filled in. Whereas traffic peaks have slightly shifted, traffic patterns on weekdays have converged to those that previously characterised weekends (Feldmann et al., 2020; SamKnows, 2020a; Sandvine, 2020; Stocker & Whalley, 2021). For example, there has been a considerable increase in traffic levels during the daytime as network users adapted to new COVID-19 lifestyles, mixing online playtime and worktime to correspond more to at-home schedules than the traditional at-work-during-the-day/at-home-at-night scheduling that prevailed pre-COVID-19. Work, education, entertainment, and maintaining social contacts were shifted as much as possible to the virtual sphere. Not only did the patterns in Internet usage by time-of-day/day-of-week change due to COVID-19, but so too did the application mix and application usage in general, both in terms of intensity as well as in terms of structure. Finally, changing traffic matrices imply changes in interconnection traffic and the changing application mix manifests itself in changing downstream-to-upstream traffic ratios (e.g. Feldmann et al., 2020; OpenVault, 2020a, 2020b).

2.2.2.3. Summary and (Tentative) Outlook – The Future Course of the Pandemic Effect. The findings summarised above have been largely confirmed by a series of publications. Appendix 2.1 provides an overview and brief characterisation of some important reports and articles. Whereas different actors in the ecosystem have managed to weather the pandemic-related storm, within-group experiences (e.g. among ISPs, IXPs, or CDNs) varied significantly. Additionally, the effects of the pandemic on Internet traffic, network utilisation and congestion, as well as on customer experience, have varied locally. Fig. 2.1 and Tables 2.2a and 2.2b provide representative examples of traffic changes during the pandemic as experienced from different vantage points and by different actors.

In spite of anecdotal evidence of local problems and the existence of short-lived or transient congestion issues or failures – for example, websites crashed (e.g. unemployment benefit sites hosted by some agencies in the United States [Riley, 2020]) and other localised network and application disruptions occurred – the publications we analysed widely support the conclusion that the Internet coped well with the pandemic (see Appendix 2.1 and also, e.g., Böttger et al., 2020; Clark, 2020; Fontugne et al., 2020; Medina, 2020; S. Miller, 2020; ThousandEyes, 2020; Warren, 2020). Apart from the fact that one cannot unambiguously infer from a measured state of network congestion that this has caused or materialised a degradation in customer experience

if the same service (e.g. Zoom) is used for business-related and leisure purposes?) and even detecting what the application is may not be readily accomplished in all networking contexts (e.g. because of encryption and port-hopping applications).

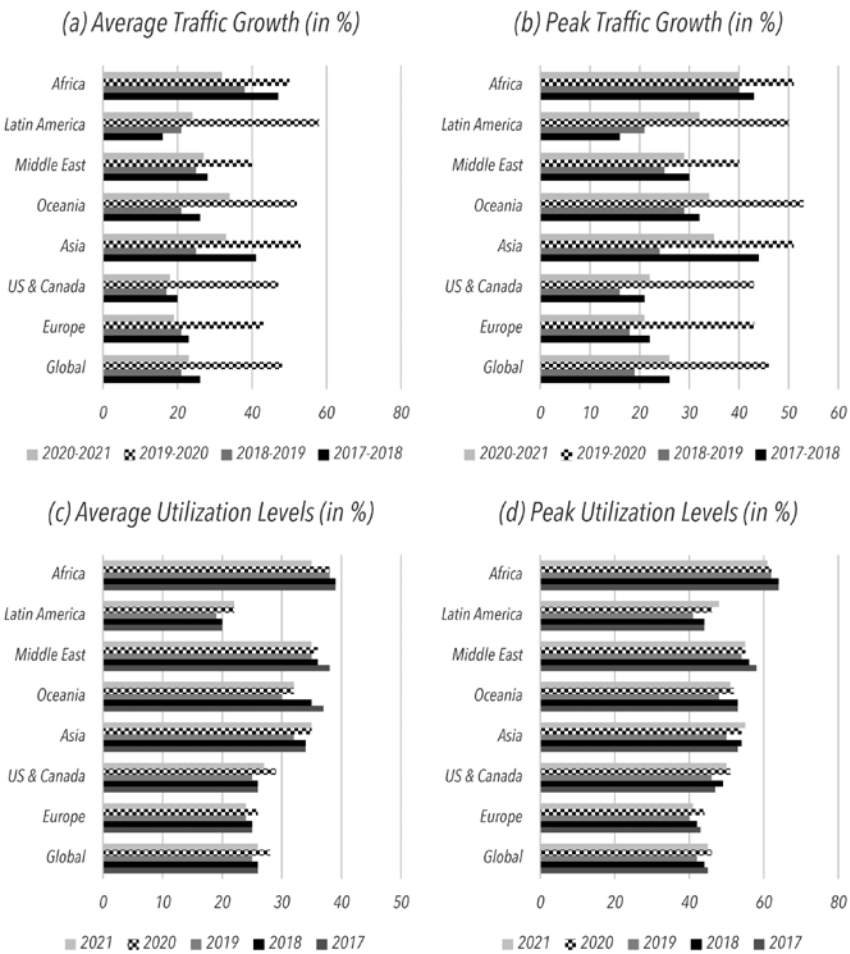

Fig. 2.1. Annual Changes in Cross-country Internet Traffic.
Source: Authors' own construct based on data from TeleGeography (2021).

(Clark, 2020), persistent states of congestion and corresponding performance problems over the course of the pandemic or longer stretches of time since the first wave have not been reported in the publications we analysed.[14] Quite to the contrary, the research has emphasised the Internet's resilience and ability to adapt and failed to reveal any systemic structural problems.

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[14]See Appendix 2.1. See also, for example, Böttger et al. (2020) who point to some problems in the use of Facebook outside the EU and the United States, for example, in South America. Medina (2020) provides an overview of effects on (i) ISPs (more outages but no systematic problems); (ii) public cloud provider networks (coped very well); and (iii) collaboration applications (only minor problems/degradations).

Table 2.2a. Examples of Changes in Internet Traffic (by Region).

Where? (What?)	Metric	Change (Time Period; Location/Network[a])	Source
Global	Global Peak Internet Traffic	+25–30% (May 2020 vs. First Week of Feb. 2020)	Labovitz (2020b)
	Global Internet Traffic	+25% (May 2020 vs. First Week of Feb. 2020)	
	Global Internet Traffic	+38% (19 Apr. 2020 vs. 1 Feb. 2020)	Sandvine (2020)
	Global Upstream Traffic	+121% (19 Apr. 2020 vs. 1 Feb. 2020)	
	Global Downstream Traffic	+23% (19 Apr. 2020 vs. 1 Feb. 2020)	
	Global Internet Traffic	ca. +30% (Mar. 2020 to Apr. 2020; Akamai CDN)	Leighton (2020b)
Other	Aggregate Traffic	ca. +20–30% (Mar. 2020 to Apr. 2020; First Lockdowns in Europe)[b]	Feldmann et al. (2021)
	Downstream-to-upstream Traffic Ratio	18% Relative Increase in Upstream Traffic; Ratio Changes from ca. 9:1 (Pre-COVID) to 8:1 (Early 2021) (Weekdays)[b]	
Different Countries (CDN)	Traffic Change (Italy)	+109.3% (31 Mar. 2020 vs. 20 Feb. 2020; Fastly)	Bergman and Iyengar (2020)
	Traffic Change (Japan)	+31.5% (31 Mar. 2020 vs. 18 Feb. 2020; Fastly)	
	Traffic Change (UK)	+78.6% (31 Mar. 2020 vs. 27 Feb. 2020; Fastly)	
	Traffic Change (France)	+38.4% (31 Mar. 2020 vs. 26 Feb. 2020; Fastly)	
	Traffic Change (Spain)	+39.4% (31 Mar. 2020 vs. 1 Mar. 2020; Fastly)	
	Traffic Change (NY & NJ, USA)	+44.6% (31 Mar. 2020 vs. 1 Mar. 2020; Fastly)	
	Traffic Change (CA, USA)	+46.5% (31 Mar. 2020 vs. 1 Mar. 2020; Fastly)	
	Traffic Change (MI, USA)	+37.9% (31 Mar. 2020 vs. 1 Mar. 2020; Fastly)	

Table 2.2b. Examples of Changes in Internet Traffic (by Provider).

Category	Provider(s)	Change (Time Period; Location/Network[a])	Source
Communications Service Providers	Cable ISPs in the USA	+20.1% Downstream Peak Traffic (28 Mar. 2020 vs. 3 Jan. 2020; USA)	NCTA (2021)
		+27.7% Upstream Peak Traffic (28 Mar. 2020 vs. 3 Jan. 2020; USA)	
	Comcast	+32% Peak Traffic (Compared to Pre-pandemic Levels)	Comcast (2021)
		+38% Downstream Peak Traffic (Compared to 2019 Levels)	
		+56% Upstream Peak Traffic (Compared to 2019 Levels)	
	Verizon	+30% Web Traffic Peak Usage (22 Apr. 2020 vs. Typical Pre-pandemic Day)	Verizon (2020)
		+24% Web Traffic [Peak Usage] (2 Apr. 2020 vs. Typical Pre-pandemic Day)[c]	
	NTT Communications	+30–40% Internet Traffic [Weekdays between 9 a.m. and 6 p.m.] (Mar. 2020; Japan)	NHK (2020)
	Telefonica	+35% Fixed Data Traffic (mid-Apr. 2020 vs. mid-Mar. 2020)	Robuck (2020)
	Telia Carrier	>+50% Overall Traffic (Begin of Pandemic until mid-Apr. 2020)	Robuck (2020)
	BT	+35–60% Weekday Daytime Traffic (20 Mar. 2020 vs. 17 Mar. 2020)	Watson (2020)[d]
	AT&T	+40% Daily Network Traffic (Year-on-year: 2020–2021; Average Day)	Chow and Mair (2021)
		+22% Core Network Traffic (30 Apr. 2020 vs. End of Feb. 2020)	AT&T (2021)[e]
		+25% Core Network Traffic (17 Apr. 2020 vs. End of Feb. 2020)	
		+24% Core Network Traffic (7 Apr. 2020 vs. End of Feb. 2020)	

(*Continued*)

Table 2.2b. *(Continued)*

Category	Provider(s)	Change (Time Period; Location/Network[a])	Source
	Vodafone	>+50% Fixed Broadband Usage (ca. 3 Apr. 2020 vs. Pre-pandemic Levels; Italy & Spain)	Vodafone (2020a)
		+100% Upstream Traffic (ca. 3 Apr. 2020 vs. Pre-pandemic Levels; in Some Markets)	
		+44% Aggregate Downstream Traffic (ca. 3 Apr. 2020 vs. Pre-pandemic levels)	
Internet Exchange Points (IXPs)	DE-CIX	>+10% Peak Traffic (June 2020 vs. Pre-pandemic Levels; IXP in Frankfurt)	Dietzel (2020)
		>+20% Peak Traffic (June 2020 vs. Pre-pandemic levels; IXP in Düsseldorf)	
	AMS-IX	+17% Traffic Volume (22 Mar. 2020 vs. Previous Month; Amsterdam)	AMS-IX (2020)
		+35% Total Data Traffic (2020, annual; Amsterdam)	AMS-IX (2021)

Notes for Tables 2.2a and 2.2b: The numbers presented here, even if they refer to global traffic changes, are based on measurements from different vantage points and may involve extrapolations. To provide a more complete picture, we chose to provide measurements from different providers, regions, and vantage points. However, we want to emphasise that results (and measurement techniques) may differ between different (types of) companies and networks, regions, and the scope considered both in terms of geography and actors.

[a] Information only provided if deviating from the overall footprint of the provider.

[b] Feldmann et al. utilise data from a set of vantage points: one large European ISP which operates a Tier-1 network, three IXPs (a major IXP in Central Europe; an IXP in Southern Europe; and an IXP at the US East Coast), and one metropolitan educational network (REDImadrid).

[c] The data provided for 2 April do not explicitly state that it is about peak usage but those provided for 22 April do. It is to be assumed that both refer to peak usage.

[d] Watson, Chief Technology and Information Officer at BT, states: "Since Tuesday this week, as people started to work from home more extensively, we've seen weekday daytime traffic increase 35–60% compared with similar days on the fixed network, peaking at 7.5Tb/s. This is still only around half the average evening peak, and nowhere near the 17.5 Tb/s we have proved the network can handle." (Watson, 2020)

[e] Core network traffic comprises "business, home broadband and wireless usage" (AT&T, 2021).

Before we move on to explore the responses by private and public actors and investigate their strategies to weather the pandemic effects in the next section, it is worth looking ahead. Although the unexpected demand shock associated with the pandemic resulted in an unprecedented growth in traffic over a short time period, experts expected traffic growth rates to return in 2021 and subsequent years to pre-pandemic levels (e.g. Mauldin, 2021; Munson, 2021a, 2021b; Sangani, 2020; TeleGeography, 2021).

Data gathered by the Body of European Regulators for Electronic Communications (BEREC) in their various *Reports on the status of internet capacity during coronavirus confinement measures* (BEREC, 2021a) supports this conclusion. For example, in their summary report from 25 June 2021, BEREC identified three phases of how the pandemic affected Internet traffic: "a sharp increase in its early weeks, a subsequent stabilisation and, through the latter part of 2020 and 2021 thus far, a decrease from the peak (experienced early in the crisis)" (BEREC, 2021b, p. 2). In their summary report from November 29, they state:

> In general, while traffic on fixed and mobile networks have increased during the (approximate) twenty months of the COVID-19 crisis, no major congestion issues have ever been reported by NRAs to BEREC. (BEREC, 2021c, p. 1)

2.3. Government and Private Sector Responses

Policy-makers and industry responded to the crisis in a variety of ways, mostly uncoordinated in time and choice of response as the crisis spread unevenly across countries. Both sought to implement strategies to facilitate the successful migration of activities to the virtual sphere to enable the continuation of economic and social activities disrupted by the stay-at-home and business lockdowns and operating restriction mandates and resulting health crises posed by the pandemic. Despite the lack of coordination, the availability and performance of online services that run over the Internet during the pandemic were not severely affected. Nevertheless, substantial digital divide and inclusion failures arose (or were highlighted in sharpened relief) as a result of the crisis and the uneven effectiveness and reach of the remedial actions taken (e.g. Bronzino et al., 2021; Gross, 2020; OECD, 2020b; Schilirò, 2021). Those problems were evident in both the European Union (EU) (e.g. ITU, 2021; Sostero et al., 2020) and the USA (e.g. Lai & Widmar, 2020; Vogels, 2021). While the term 'homework gap' (Basu, 2020) coined by then-FCC[15] Commissioner Jessica Rosenworcel gained prominence, the United Nations stated that "[t]he digital divide is the new face of inequality in the COVID-19 era" (Bozkir, 2021, p. 3).

In the following, we will provide a brief and selective overview of the measures taken by public and private actors to respond to the crisis.

[15]FCC stands for Federal Communications Commission.

2.3.1. Government Responses in the USA and the EU

The reaction of governments varied across different jurisdictions as the pandemic spread unevenly across nations and populations, both with respect to the policies implemented and their timing. These policies reflected the political, economic, and technical challenges of responding to a crisis that although previously anticipated still confronted many unknowns and unknowables. Also, the challenge of planning for future crises is far less daunting than coping with a real one in real-time as it evolves. In the following, we place focus on responses by policy-makers in the EU and the USA that had a direct impact on the digital ecosystem of the Internet.

2.3.1.1. Responses in the EU. At the EU level, a comprehensive set of general responses to the pandemic was introduced (EC, 2021a, 2021b; Council of the EU & European Council, 2022).[16] Digital policy responses included, for example, policies designed to support eGovernment, eHealth, and online learning. Moreover, they emphasised specific aspects such as the use of artificial intelligence (AI) in combination with high-capacity computing to analyse the spread of the virus, supported contact tracing and warning apps to help interrupt transmission chains and the fight against disinformation on online platforms. A common denominator of the different initiatives undertaken was the recognition of the critical role of digital technologies in general, and adequate connectivity, in particular, to cushion the negative effects of the crisis – both economically and socially.

In the early stages of the first lockdowns in Europe, in March 2020, the Commission and BEREC published a joint statement (BEREC, 2020). The statement provided guidelines for broadband service providers on how they can respond to unexpected and increased connectivity demands. Notably, the statement recognised that the circumstances of the crisis were exceptional, thus authorising relevant providers (in compliance with the network neutrality regulations/Open Internet Access provisions of Regulation (EU) 2015/2120)

> to apply *exceptional* traffic management measures, *inter alia*, to **prevent impending network congestion** and to mitigate the effects of exceptional or temporary network congestion, always under the condition that equivalent categories of traffic are treated equally. (BEREC, 2020, p. 1, emphasis in original)

While this can be interpreted as a temporary relaxation of existing regulations in light of exceptional circumstances caused by the pandemic,[17] additional measures were taken to support essential services for remote work and learning.

One specific measure intended to support these services and relieve strain from networks through reducing network usage by non-essential services. To do so, and

[16]A timeline of EU responses and action can be found here: https://ec.europa.eu/info/live-work-travel-eu/coronavirus-response/timeline-eu-action_en.

[17]In Chapter 9 of this volume, Layton and Jamison (2023) use the differential responses to COVID-19 as a natural experiment of the efficacy of Network Neutrality regulations which impose *ex ante* constraints on broadband providers abilities to manage their networks.

responding to the increased demands for entertainment, in particular, streaming services, during the early stages of the pandemic, Commissioner Thierry Breton approached OTT-provider Netflix with a request for the temporary suspension of delivering their video content at the highest available video resolution. Thus, the idea went, network capacities could be spared and traffic loads reduced by around 25%. Netflix agreed and other providers like Apple, Amazon, Disney+, and YouTube followed suit, throttling their data rates by temporarily reducing streaming quality (Archer, 2020a, 2020b, 2020c). In addition to the impact that such measures may have had on actual network congestion (which was questioned by some network researchers and industry representatives) (e.g. Castor, 2020; Heaven, 2020), such initiatives may have served a salubrious political purpose in signalling to a distraught populace that policy-makers and industry were working together to address the crisis and its ill effects. It should be noted here that some of these companies introduced the same strategies not only in the EU but globally (Thorbecke, 2020). Moreover, Netflix began to restore its streaming quality in May 2020 (Alexander, 2020) and so did others when it became apparent that the Internet was not in danger of collapse.

Besides these responses, BEREC was quick to collect information on the status of networks and the problems they might be confronting (e.g. regarding traffic management needs and practices, outages, etc.). Within the member states, national regulators collected, aggregated, and periodically published data from relevant market participants. The reports were released weekly in the beginning and with longer periods later (BEREC, 2021a, 2021c). In the later stages of the pandemic, summary reports were published. The latest of these reports is from November 2021 (BEREC, 2021c). Neither the individual reports nor the summary reports reveal severe and persistent systemic problems within networks. No significant large network disruptions were noted, and overall, the Internet never appears to have come close to collapsing.[18] This supports what we explained in Section 2.2 above – one lesson is that the Internet in the EU has coped quite well in the pandemic. Another lesson is the importance and value of publicly sharing additional information early in the crisis when the magnitude of traffic loads, and their implications for network resiliency, were uncertain. As it became clear that the networks were coping well, the urgent need for current data was reduced and efforts to publicise traffic data were scaled back.

Despite the reassurance given that the Internet was able to weather the COVID-19-related demand shocks, complementary measures were taken to tackle issues of (growing) digital divides and promote digital inclusion. For example, the European Commission published its Recommendation (EU) 2020/1307 (EC, 2020) in September 2020 which acknowledged the crucial role of ubiquitous

[18]See Briglauer and Stocker (2020) as well as Thousand Eyes (2020), Valenzuela-Gómez (2020a, 2020b), and Medina (2020). By a significant disruption, we mean a disruption that occurs simultaneously across multiple geographies and makes the use of many applications impossible (because of a loss of connectivity or inadequate performance) for a long period of time (as measured in many hours).

connectivity via high-capacity fixed and 5G broadband networks to support economic recovery.[19]

A general strategy to foster digital transformation has been integrated into the EU's pandemic recovery plan and the Next Generation EU (NGEU) instrument. One of its major pillars is the *Recovery and Resilience Facility* (RRF). The RRF, which was established through Regulation (EU) 2021/241 of the European Parliament and of the Council (EU, 2021), will provide member states with €672.5 billion of funding (i.e. loans and grants until 2026). Importantly, the RRF emphasises its objective to support a sustainable recovery, thus promoting a comprehensive "twin transition: green and digital" (EC, n.d.). Accordingly, national recovery and resilience plans by member states must include a minimum of 20% of the total expenditure on measures to foster the digital transition, for example, via rolling out high-capacity broadband, scaling-up cloud infrastructures, providing educational and training measures to support digital skills, as well as making public services digitally available and accessible (EC, n.d.).[20]

On top of that, the EU adopted an ambitious agenda for fostering the roll-out and adoption of digital infrastructures, services, and skills. Its 2030 Digital Decade program (EC, 2021c, Article 4) introduced various digital targets that shall be met by 2030. Beyond targets related to digital skills, the 'digital transformation of businesses', and the 'digitalisation of public services', the program introduced targets related to 'secure, performant and sustainable digital infrastructures'. The latter includes connectivity targets (all EU households should have gigabit Internet access, and 5G coverage should include all populated areas) and targets for the deployment of 10,000 edge nodes (enabling local data storage and processing) (EC, 2021c, p. 24).

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[19]Recital 2 (EC, 2020, p. 33) of the Recommendation "… indicates how Member States can deploy simple and realistic measures to assign radio spectrum for the fifth generation (5G) networks under investment-friendly conditions, and how they can facilitate the deployment of very high capacity fixed and wireless networks by, for example, removing unnecessary administrative hurdles and streamlining permit granting procedures." See also Chapter 8 of this volume by El-Moghazi (2023) on spectrum use and management.
[20]The different intervention fields are provided in Appendix VII of the Regulation (EU, 2021, pp. 73–75). See, for example, the German plan for which the EC already disbursed €2.25 billion. More information is provided here: https://ec.europa.eu/commission/presscorner/detail/en/ip_21_4402. Moreover, data by Bruegel (Darvas et al., 2022) provides detailed insights into the recovery and resilience plans of different member states. For example, it shows that the German plan amounts to €27.95 billion of grants and loans. More specifically, €2.2 billion are dedicated to the *roll-out of rapid broadband services*, €7.89 billion to the *digitalization of public administration*, €0.75 billion to *scaling-up data cloud capabilities and sustainable processors*, and €1.47 billion to *reskilling and upskilling via education and training to support digital skills*. Tables and visualizations of the plans of different Member States are provided in Darvas et al. (2022). In addition, the European Commission set up a website that provides a scoreboard and overview of the (state of) different national recovery and resilience plans. It can be accessed under this link: https://ec.europa.eu/economy_finance/recovery-and-resilience-scoreboard/index.html

As this shows, policy-makers in the EU have shifted their focus from ensuring that networks can cope with the shock caused by the pandemic towards rather broad measures to close digital divides and ensure digital inclusion in a world in which the essentiality of broadband access and the ability to effectively use online services has now been accepted nearly universally as an urgent and key priority for policy-makers across Europe (and elsewhere). Although broadband inclusion policies had been being promoted by the EU and member states prior to COVID-19, progress towards reaching a consensus on their design and implementation had lagged. The pandemic helped coalesce support and recognition of the importance of ensuring universal access to broadband as critical basic infrastructure and helped advance ambitious plans to achieve those goals – also by launching and extending measures to help citizens to acquire the required digital skills.

2.3.1.2. Responses in the United States. Also in the United States, broad and comprehensive measures were taken to cushion the negative effects of the pandemic and promote a strong recovery (USA.gov, 2022; U.S. Department of Treasury, 2022).[21] In the early stages of the crisis, the FCC launched a program that contained various measures directed at helping to keep Americans connected during the pandemic. The so-called *Keep Americans Connected* pledge was initiated in March 2020. The initiative presented a joint effort – more than 800 relevant companies (e.g. ISPs or MNOs) voluntarily subscribed.[22] Subscribers pledged to:

1. not terminate service to any residential or small business customers because of their inability to pay their bills due to the disruptions caused by the coronavirus pandemic;
2. waive any late fees that any residential or small business customers incur because of their economic circumstances related to the coronavirus pandemic; and
3. open its Wi-Fi hotspots to any American who needs them. (FCC, 2020a)

While then-FCC Chairman Ajit Pai reported in April 2020 that US networks were performing well under the new strain of the crisis (FCC, 2020b), the FCC

[21]See also the *Coronavirus Aid, Relief, and Economic Security (CARES) Act*. The document can be accessed under this link: https://www.congress.gov

[22]In the near-term, actions included efforts to forestall users being disconnected for bill payment issues and to address accessibility problems in communities lacking adequate access options (e.g. to provide subsidies to support deployment of Internet connectable devices to schools and under-served communities). A number of fixed and mobile broadband providers in the United States announced plans for waiving late fees and service suspensions for non-payment of bills during the early months of the COVID-19 crisis (see Bomey, 2020). Also, the FCC induced many providers to sign its *Keep Americans Connected* pledge to "open up public Wi-Fi networks, waive late fees, and refrain from disconnecting consumers for the next 60 days" (see FCC, 2020a). See also Section 2.3.2.

introduced a variety of other measures to facilitate participation and reduce the negative effects of digital divides. Apart from measures to encourage free or affordable broadband access for every citizen, especially those in need, they introduced elements like regulatory relief for OTT-based video conferencing services WebEx and Zoom, granted relevant mobile providers temporary access to additional spectrum to help them meet the unexpected increases in demands they were facing, and provided support for services that became essential during the pandemic, such as remote learning and telehealth (FCC, 2020a).

The range of measures taken by the FCC was broad – and it changed over time. Although the pledge expired by the end of June 2020, other measures were developed and established (FCC, 2022a) as policy-makers were forced to confront the unhappy realisation that the pandemic was not ending as soon as hoped. Support came through the established Universal Service Fund and responses in the context of the *E-Rate*, *Rural Health Care*, *Lifeline*, and *High Cost* programs (Universal Service Administrative Company, 2022a), but also through other instruments. For example, the *Emergency Broadband Benefit* program was established to support low-income households and the citizens living in those households to have basic access to connectivity and services like telehealth or education (FCC, 2022c). In late 2021, the program was extended and modified to the longer-term *Affordable Connectivity Program* (FCC, 2022d). The *Emergency Connectivity Fund* was established to support schools and libraries to purchase equipment required by "students, staff, and patrons" to access and use the services (in particular, remote learning) these institutions provide (Universal Service Administrative Company, 2022b). Moreover, the *COVID-19 Telehealth Program* was installed to provide support connected care services offered by health care providers (FCC, 2022b).

With the Biden administration taking office, an infrastructure bill dubbed *Infrastructure Investment and Jobs Act* (IIJA; H.R. 3684)[23] was signed in November 2021. While the IIJA's mission statement was to grow the economy and make it more just and resilient, an important element of the Act is Division F. There, the bill contains rather comprehensive measures to address digital divides in broadband access. Notably, $65 billion are dedicated to broadband investment to close digital divides at an infrastructural level (Fandos, 2021; Tankersley, 2021; The White House, 2021b). Title I of Division F of the Act states (p. 1182):

> The 2019 novel coronavirus pandemic has underscored the critical importance of affordable, high-speed broadband for individuals, families, and communities to be able to work, learn, and connect remotely while supporting social distancing.

In this spirit, the Act defines a location as being *underserved*, if it has no access to a broadband connection that provides at least 100 Mbps downstream and 20 Mbps upstream, *and* latencies that "support real-time, interactive applications" (p. 1183).

[23]Text – H.R.3684 – 117th Congress (2021–2022): Infrastructure Investment and Jobs Act. (2021, November 15). https://www.congress.gov/bill/117th-congress/house-bill/3684/text

Similarly, the Act defines a location as being *unserved*, if it has no access to a broadband connection that provides at least 25 Mbps downstream, 3 Mbps upstream, *and* latencies that "support real-time, interactive applications" (p. 1182). The broadband targets thus contain both a static quantitative as well as a qualitative element. In addition to this, Title III of Division F of the Act dubbed *Digital Equity Act of 2021* contains measures to support the development of digital skills and literacy. Title IV of Division F of the Act contains measures to support middle-mile broadband infrastructures while Title V deals with broadband affordability. Similar as in the EU, policy-makers in the United States have shifted their focus towards rather broad measures to close digital divides and ensure digital inclusion.

Despite the similarities in the approaches in the USA and the EU, there are also differences. In the United States, depending on the instrument explained above, the decision authority either resides at the federal level (e.g. with the FCC) or is more devolved (e.g. at the state level or below). Notably, states play an important role in developing plans on how to spend the federal funds provided via the IIJA, thus making it likely that decisions, strategies, and outcomes will differ across different states (e.g. Whitacre & Biedny, 2021). Moreover, the politisation of COVID-19 responses (including differing views on business restrictions and vaccinations) across Republican versus Democratic states has had a significant impact on the need for and the efficacy of State-level responses to COVID-19. The magnitude and scope of these differences have yet to be fully sorted out, but certainly, actions that more (or less) effectively addressed the health issues are likely to have concurrent impacts on the need for rapid responses to address broadband networking shortfalls. Additionally, in contrast to the EU, network neutrality regulations have not played a significant role since the United States net neutrality regulatory framework instantiated in the Open Internet Order of 2015 was reversed in the United States in 2017 (see, e.g., Stocker et al., 2020 and Layton & Jamison, 2023, this volume).[24]

2.3.2. Responses by the Private Sector

The need to rapidly adapt and expand capacity impacted network operators and service providers across the Internet ecosystem of ISPs, IXPs, colocation and connectivity providers, cloud and content providers, and ancillary service providers (including providers of software and hardware for end-user and network devices, cloud services, etc.). Private sector communications service providers like ISPs and MNOs and content and cloud providers stepped up efforts to handle the surge and changing traffic patterns resulting from the COVID-19-induced changes in network user behaviour. Often, the efforts were made individually but

[24]In April 2020, a News Release by the FCC (2020b) quoted then-Chairman Ajit Pai saying: "It appears that our nation's communications networks are holding up very well amid the increase in traffic and change in usage patterns. That's thanks in part to networks being designed to handle ever-higher peak traffic loads and in part to a market-based regulatory framework that has promoted infrastructure investment and deployment." In July 2021, President Biden issued an Executive Order in which he requested the FCC to consider reinstating strict net neutrality regulations similar to the Open Internet Order of 2015 (The White House, 2021a).

sometimes also jointly to expand capacity and invest in communications capacities and servers and adapt their network management strategies to cope with surging traffic demands and changing traffic patterns while striving to sustain high and stable levels of customer experience.

The need to expand capacity is normal for actors like ISPs, IXPs, and most content and cloud providers. They regularly expand their capacities to accommodate the continuously growing demands for online services and thus for network and cloud capacities. For example, in pre-COVID-19 times, the annual constant average growth rate of global Internet traffic was about 30% (e.g. Cisco, 2020). When providers invest and upgrade capacities, they must also account for excess peak capacity to provide headroom to meet normal traffic fluctuations. Moreover, they need to consider changing traffic matrices and recognise local differences in the need for capacity upgrades to adapt or develop their server presence or interconnection strategy to new demands. The pandemic has created a sudden and unexpected demand shock, quantitatively and structurally. The resulting challenges were profound for many different actors in the ecosystem.

2.3.2.1. Capacity Expansion and Upgrades in Interconnection Strategies. Communications service providers in developed countries had to manage the traffic growth of an entire year within a few weeks, network capacities had to be scaled up rapidly. Moreover, their interconnection strategy had to be updated and capacities had to be scaled quickly. That scaling benefitted from automation (e.g. BITAG, 2021; Clark, 2020; Feldmann et al., 2020, 2021; OECD, 2020a). To illustrate these strategies by some examples, colocation provider Equinix reported that it upgraded capacities for customers from 10G to 100G (Long, 2020). Vodafone (2020a) reported that they upgraded their capacities by four Tbps during March and April 2020. Wireless providers in the United States also acted to upgrade their capacity significantly (CTIA, 2021). TeleGeography (2021) data used in Fig. 2.1 further shows that international bandwidth capacities were expanded at higher levels in 2020 than in previous years – globally as well as in different parts of the world.

As the demand for certain online applications skyrocketed and access points became more geographically dispersed (see Table 2.1), cloud and content providers were confronted with demands that necessitated capacity expansions and upgrades in their interconnection strategies. In Section 2.2, we explained that demand surges experienced by specific cloud-based applications in general and, in particular, video conferencing significantly exceeded growth rates of global aggregate Internet traffic. For example, Jennings and Kozanian (2020) report for Cisco WebEx that meeting minutes, the number of meetings, and the number of participants roughly doubled within a month (February to March 2020) and roughly tripled within two months (February to April 2020). Enterprise customers seeking to rapidly adapt to the changing needs of servicing their employee and customer needs from new locations, rather than their traditional work environments, accelerated the systemic shift to cloud-based services. During the crisis, enterprises with VPNs that were more advanced in employing cloud services and cloud-based applications (e.g. Office360 instead of *in situ* hosted applications) were better positioned to dynamically reconfigure and provision for their network needs on-demand.

The example of Zoom, one of the success stories of the pandemic, provides some interesting insights into their response to the pandemic and the tremendous surge in demand they experienced as a result of their outstanding growth in popularity and adoption. Coping with such demand surges has not been trivial and was – as anecdotal evidence shows – fraught with difficulty. To manage the tremendously increased demands for its services (Labovitz, 2020a; Sandvine, 2020), Zoom stepped up its efforts on several fronts. First, the company upgraded existing peering capacities and initiated new peering arrangements (typically local, i.e., close to end-users) and transit agreements to support the exponential growth in video conferencing usage during the pandemic. Second, whereas capacity headroom typically is about 50% (Svedlik, 2020), the company opted for a hybrid multicloud strategy – they combined server capacities from their own data centres with public cloud capacities (via AWS). Interestingly, it has been reported that scaling their own server capacities was more problematic than scaling in the public cloud due to lockdown-related issues with the supply chain (Bednarz, 2020; Labovitz, 2020b; Svedlik, 2020; Zoom, 2020).

Netflix also expanded its server infrastructure to cope with the increased demands (Florance, 2020). Their strategy can be divided into two stages. In the first stage, the short term, the company upgraded interconnections and scaled up public cloud-based control plane services via AWS (Barr, 2020)[25] to meet the surging demands. Whereas the expansion of their own serving infrastructure, their CDN called Netflix Open Connect, was suffering from supply chain issues to get more servers (Kentik, 2020; O'Brien, 2020), research by Labovitz (2020a) reports how the share of Netflix traffic delivered from outside of eyeball ISP networks has increased compared to the share of Netflix traffic delivered from Netflix servers deployed deep within eyeball ISP networks.[26] This finding is in line with Gigis et al. (2021) who have shown how – arguably with some time delay due to the aforementioned supply chain issues but with increasing pace from late 2020 – Netflix has in a second stage aggressively expanded the capacities and footprint of their serving infrastructures via off-net server deployments deep within ISP networks. The same article shows that many hypergiant providers like Google and Facebook responded to the crisis by expanding their serving infrastructures' footprints via such intra-ISP server deployments.

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[25]An article by Barr (2020) emphasizes the collaboration between Netflix and AWS in this context, quoting Nils Pommerien (then Director of Cloud Infrastructure Engineering at Netflix) as follows: "In order to meet this demand our control plane services needed to scale very quickly. This is where the value of AWS' cloud and our strong partnership became apparent, both in being able to meet capacity needs in compute, storage, as well as providing the necessary infrastructure, such as AWS Auto Scaling, which is deeply ingrained in Netflix's operations model."

[26]See also the explanations in Briglauer and Stocker (2020). One may, in this regard, also speculate to what extent the voluntary, temporary suspension of delivering video content at the highest quality (see Section 2.3) has relaxed the challenges Netflix was facing with scaling up their serving infrastructure due to the supply chain problems they encountered. The suspension was intended to reduce the strain on ISP networks but also reduced the strain on Netflix's serving infrastructure.

A different example is Dropbox. The company was confronted with demands that were more decentralised and geographically dispersed than before the pandemic. Since this can be explained by the fact that the location of access shifted from enterprise and campus environments to residential broadband access, their interconnection strategy had to be updated accordingly. Dropbox upgraded its interconnection strategy and engaged in more direct and local peerings with eyeball ISPs. Moreover, while the company had moved most of its operations to its own custom-built data centres,[27] it relied on the public cloud as a fallback in case of unexpected events and bursts and thus to scale to the pandemic-related demands (Svedlik, 2020).

2.3.2.2. Network Management, Throttling of Sending Rates, and Rescheduling. Besides capacity expansion and upgrades in their interconnection strategies, several communications service providers used optimisation and network management strategies to maintain high service availability and customer experience during the pandemic (e.g. Vodafone, 2020a). While softwarisation has helped to quickly adapt and reconfigure their networks, some providers have used solutions based on machine learning (ML)/AI to enhance predictability and the ability to efficiently adapt to changes in the demand (e.g. AT&T, 2021; Comcast, 2021; Wiggers, 2020). Moreover, as we have already described above, some content and cloud providers chose to temporarily throttle sending rates to reduce network loads (see also, e.g., Florance, 2020). Besides reducing available resolutions of video content, thus reducing data rates when streaming associated content, other providers have throttled sending rates of downloads and updates for video games or rescheduled them to off-peak hours, thus reducing strain from networks during peak times (Heaven, 2020; Leighton, 2020b; Ryan, 2020). Such strategies were supported by content delivery networks as exemplified by the joint efforts of Akamai and Sony (Leighton, 2020a, 2020b; McKeay, 2020; S. Miller, 2020).

2.3.2.3. Free Services to Keep End-users Connected. Also, several providers offered their services temporarily for free in order to help cushion the negative social and economic effects of the pandemic. For example, Microsoft Teams was offered for free (Spataro, 2020). Apart from this, some content on Apple TV+ or Amazon Prime was unlocked and offered for free, Adobe made Photoshop freely accessible from home for educators and students (Rose, 2020). Adult entertainment video platform Pornhub made their premium services temporarily free for viewers in Italy from 12 March and to those in Spain and France from 16 March 2020. Consequently, relevant daily traffic in the three countries increased dramatically (up to more than 60% in Spain) (Pornhub, 2020). Zoom has offered calls up to 45 minutes for free and offered to lift time limits on requests for schools while Google provided free access to some of their premium enterprise video conferencing features to their customers (Molla, 2020a).

Similarly, a wide range of broadband providers introduced measures to reduce the negative effects of digital divides and the lack of access to content/information

[27] Dropbox moved most of their data from AWS to their own custom-built infrastructure for data centers in 2015 (Henderson, 2016).

and applications during the pandemic. In the United States, those companies that had subscribed to the *Keep Americans Connected* pledge as described above introduced and maintained a broad range of measures to keep their customers connected and provide a good customer experience during the pandemic (e.g. AT&T, 2022; Comcast, 2022; Liu et al., 2021). CTIA (2021) provides an overview of the measures taken by wireless providers ranging from capacity expansion over shifting consumers from metered to unlimited data plans and waiving of data overage charges as well as to providing specific low-income support. Similar offers were made in Europe. For example, Telefonica increased monthly data caps for their customers without extra charge and offered specific entertainment services for free (Álvarez-Pallete, 2020). Vodafone has published a five-point plan in which the company pledged, among other things, to maintain high levels of quality of service, support healthcare services, and make access to Government-supported healthcare sites and governments' educational resources free (Vodafone, 2020b).

2.3.2.4. Other Innovations. Finally, the pandemic has given rise to new (commercial) opportunities for specific businesses and services based on innovation in the application sphere. Previously offline services were augmented with virtual elements – for example, restaurants embraced online food delivery platforms and retail shops set up online shops – or entirely moved online, thus changing the innovation and competitive dynamics between and within offline and online services and markets. For example, the pandemic has propelled the importance and monetisation potentials of specific services such as video conferencing. There, market players like Cisco, Microsoft, Zoom, and Google made significant efforts to improve their video-conferencing applications in real-time, as the pandemic progressed, to respond to user feedback and to keep abreast of competitor innovations that enhanced usability and functionality (e.g. Amadeo, 2020; Hacker et al., 2020; J. Miller, 2020; Molla, 2020b). For example, the sudden demand surge in Zoom revealed severe security and privacy issues that induced the company to quickly react and address them to enhance security and privacy (Warren, 2020). Other innovations have greatly expanded the range of remote interactions and video conferencing formats that can be supported from regular multiparty two-way video conferencing to webinars and virtual meeting rooms with enhanced user interfaces. An interesting innovation in this context is Instagram Lite. While originally developed years ago, it was launched in March 2021 in 170 countries to, very much similar to Facebook Lite, provide a lightweight version of the full app that provides good customer experience for end-users living in areas of poor connectivity or that have limited data plans (Meta, 2021). Innovation efforts are ongoing and, since many of these innovations are here to stay, they have paved the way for a post-COVID-19 world in which the virtual sphere and online activity, in general, will play a more important role than before the pandemic.

2.4. Collective Insights for a Post-COVID-19 Future

Clearly, the crisis played a dual role as an impulse and catalyst for investment and innovation and a change agent that promoted a step-change increase in efforts to advance the progress of digitalisation of our networking infrastructure, and digital economy activity. The resulting advances and changes are profound. They expand greatly the opportunity space for use and service innovation and at the same time are changing social and economic dynamics. Also, interactions and dynamics between the real and virtual worlds have changed during the pandemic. More specifically, lockdowns, social distancing, and other measures to contain the spread of the virus have impacted the real world *and* the virtual world. Real-world changes spur innovation in the virtual world. The virtual world, in turn, provides (partial) substitutes for actions, tasks, and processes of the physical world. These, in turn, might feedback on the real world. These interdependent dynamics and interactions create new realities, most notably perhaps, in that physical activity or interactions can be partly or entirely shifted online, thus facilitating new modes of living and work during the pandemic and also paving the way for a future post-COVID-19 world characterised by more online interaction and more hybrid/remote work and education, broad online-based social and commercial innovation and new offers in the virtual sphere.

When comparing the pre-COVID-19 Internet with the ecosystem we can observe today, we can identify a set of changes related to the spheres of networks and online services. Even though much of this may be temporary and has been spurred by an external shock, we do not expect the post-COVID-19 Internet ecosystem to return to pre-COVID-19 standards. Some of the changes and adaptations to enabling the virtual sphere to accommodate the changing demands will likely become integral to future societies and economies, and thereby become the 'new normal' (e.g. BCG, 2021). Other lessons learned may be temporary but become part of our toolset for responding to future crises.

In other words, some of the changes will be permanent and systematically change not only the virtual sphere but also the real world, for example, in terms of education, work, entertainment, and social interaction, as well as health services. However, the interplay between real world and virtual world effects is determined by the degree of transferability of activities, that is, the extent to which virtual (partial or full) substitutes exist or can be created (see, e.g., Pérez et al., 2020). While the degree of transferability to the virtual sphere varies quite significantly across different activities, it is fair to say that 'structural' problems associated with certain occupations or activities (e.g. workers doing physical labour often cannot stay at home and do their jobs remotely) or the lack of connectivity, adequate devices, or skill and knowledge to leverage the connectivity and digital technologies that exist create barriers, exclusion, and divides.[28]

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[28]Some occupations (e.g. waste collection services or physical delivery service of parcels, food, etc.) and tasks may be so essential that demands have even increased (e.g. via more online grocery shopping and ecommerce in general; see Chapter 6 by Whalley & Curwen, 2023, in this volume). They might, however, also require enhanced safety measures during the crisis as in many cases distancing provisions cannot be maintained. See in this context also Dingel and Neiman (2020), Bartik et al. (2020), Avdiu and Nayyar (2020), Tomer and Kane (2020), and Stocker and Whalley (2021).

As of mid-2022, we continue to be in the midst of the crisis so the lessons we might learn of relevance to a future post-COVID-19 world need to be speculative at this time. Nevertheless, certain effects appear likely to be enduring. For example, the COVID-19 pandemic has nurtured digital innovation and efforts by private and public entities to foster digital transformation processes. While the changing realities of the physical world boosted innovation in the virtual world, the crisis increased the criticality and emphasised the essentiality of broadband and digital infrastructures.

With this in mind, there are two main high-level insights. *First*, the Internet has coped quite well with the pandemic. In previous sections, we have explained what changes have occurred and how the responses by private and public actors have helped to weather the unexpected demand shock. *Second*, while broadband has become essential for individuals and businesses, the Internet could only provide a lifeline and cushion the negative social and economic effects of the pandemic for those with adequate connectivity, devices, and the necessary skills to access the widening range of offers in the virtual. Thus, an important lesson learned from COVID-19 is the importance of a public commitment to ensuring universal access to broadband and support for cloud services as critical infrastructure to enable the digital economy to adapt and respond to future crises. In the same vein, complementary measures to support participation and digital inclusion are essential to reap the benefits of those infrastructures.

In the following, we will briefly summarise and discuss in more detail six lessons learned for the Internet.

#1: The future is (more) digital – Beware of digital divides and support inclusion

As other chapters in this book explain for different sectors, the pre-pandemic commercial sphere as well as work and social norms will be different in a 'new normal'. We anticipate changing usage habits and embedding more/new online services in the workplace, education, commerce, etc. (hybrid offline/online forms as the new default). This will change the innovation and competitive dynamics between and within offline and online services.

Not only is access to adequate and affordable connectivity a problem in certain regions and for certain parts of the population, but the lack of devices and also of skills may also interfere with individuals' ability to take advantage of online services. In addition, it should not be forgotten that only some fraction of jobs and activity can be migrated to the virtual world, thus creating a fundamental source of future divides. Such barriers constrain the ability to exploit the potentials of the virtual world, thus also impacting the degree to which the negative effects of future crises can be cushioned, and social and economic resilience be maintained. Digital divides must be recognised in all their dimensions (infrastructural, skills, and literacy), and tackled by appropriate, comprehensive measures. New forms of divides may emerge due to differences in the transferability or migratability of activities or tasks to the virtual sphere – some may be easily transferable while others can only partially be migrated and others not at all (e.g. Stocker & Whalley, 2021; see also Bai et al., 2021).

Even though entrepreneurial innovation in the private sector is important to create solutions to facilitate participation and digital inclusion, it cannot fully resolve the multifaceted divides that have occurred at various levels. Government action via suitable policies and subsidy schemes may be needed; and during the crisis, relaxing non-crisis regulatory frameworks may be called for to give network providers the flexibility they need to respond quickly to rapidly changing needs. Governments may improve participation and inclusion by supporting access to adequate and affordable broadband connectivity. Notably, the US approach via the IIJA has added a quality component (i.e. the ability to "support real-time, interactive applications" [pp. 1182 and 1183]) to the static data rate criteria of 100 Mbps downstream and 20 Mbps upstream for an underserved location, and 25 Mbps downstream and 3 Mbps upstream for an unserved location respectively. In the EU, Appendix V of Directive (EU) 2018/1972 specifies a dynamised universal service objective for adequate broadband Internet access services which must be able to support the delivery of a prespecified set of desirable/essential online services and activities – including video calls in standard definition and online tools for remote learning (e.g. Briglauer & Stocker, 2020). With its 2030 Digital Decade targets (EC, 2021), the EU has introduced much more ambitious targets regarding aspects like connectivity in terms of gigabit access and 5G coverage, but also regarding skills and other aspects (see also Section 2.3.1.1).

While the universal service measures focus on the availability of adequate access infrastructures and affordable connectivity services, additional measures are required to prevent digital exclusion (e.g. due to a lack of access to devices or skills to use the devices or take advantage of the range of online services). Apart from these measures, governments may want to consider supporting entrepreneurial efforts to invent and develop solutions and services that can reduce the fragility of societies and economies in times of crisis and enhance resilience.

#2: The crisis has boosted investment and innovation

The crisis played a dual role as an impulse and catalyst of investment and innovation. The resulting advances and changes are profound. They expand greatly the opportunity space for use and service innovation and at the same time are changing social and economic dynamics. Non-orchestrated investments and innovation have produced an outcome that was not characterised by network islands or other forms of fragmentation as could have been feared in scenarios in which different, and perhaps competing, entities have to invest and innovate while being jointly involved in service provision. As we can observe today, the first wave arguably had the most significant impact on boosting innovation and investment, and generally in triggering responses to enhance the toolkit available to weather the pandemic effects on the Internet, societies, and economies, and to provide the capabilities needed in a future post-COVID-19 world.

#3: The crisis has accelerated networking trends and made the ecosystem more robust and adaptive

The pandemic has accelerated networking trends, changed the topology of the Internet and the underlying connectivity fabric, and made the ecosystem more robust and adaptive. Much of the resilience was due to the ability to scale and elastically provide cloud-based services. Expansion of server capacity and interconnection/bandwidth capacity could be achieved rather quickly so that no systematic problems with application functionality or customer experience have occurred. Instead, capacity-on-demand has emerged as a vital enabler of elastic service provision and thus networking resilience and adaptability. Topological responses are here to stay; large cloud and content providers have invested in and upgraded their infrastructures and adopted hybrid models involving public cloud capacities to better scale to unexpected bursts. Moreover, peering diversity and adaptations in peering strategies were facilitated by IXPs and other interconnection strategies.

Updates were required to respond to a mismatch between traffic demands and matrices and pre-COVID-19 capacities and serving and peering strategies. ISPs updated their internal routing and link provisioning; this involved capacity expansion in their networks and adaptations in peering capacities and strategies (i.e. more direct and local peering) (e.g. Verizon, 2020). To some extent, this was also true for cloud and content providers, as the examples of Netflix and Dropbox suggest. CDN provider Cloudflare recently announced that they now connect directly to more than 10,000 networks. This means that they can reach more than 14% of the networks (i.e. autonomous systems, ASes) of the Internet – and thus probably a large majority of connected end-users – within a single network hop (Takami, 2021).[29] Whereas these developments have all contributed to a less fragile and more resilient ecosystem during the pandemic, they have accelerated or amplified pre-pandemic trends of cloudification, a denser and flattening interconnection ecosystem, and the localisation of networked computing resources and network traffic (see, e.g., Stocker et al., 2021). Respective topological changes are permanent.

The pre-pandemic progress in cloudification helped provide the infrastructural and technological basis and capacity to allow providers to quickly adapt to the changing demands. The pandemic showed that the immediacy and extent to which capacities had to be scaled up resulted in many cases of a relative shift towards the public cloud, where fast adaptations were possible (see, e.g., Labovitz, 2020a). Despite this ability to scale up and adapt quickly, Gigis et al. (2021) have shown that hypergiants like Netflix have adapted their serving infrastructures and tremendously expanded their footprints (i.e. their presence within ASes in which they have deployed off-net servers) (see also Section 2.3.2). These enhancements to their networks imply permanent topological changes and suggest they have adopted such provisioning strategies as their preferred response to future similar events. For example, Gigis et al. (2021) show that in April 2021, Google's footprint allowed them to reach 77.5% of the European user population and 70.6% of the user population in North America via their off-net serving infrastructure.[30] In other words, cloud-based or hybrid cloud strategies might be

[29]In the same article, it is estimated that Google has direct connections with 12,000–15,000 networks (Takami, 2021). Similarly, TeleGeography (2021, Fig. 5 at p. 7) shows that many of the top backbone providers have increased the number of ASes to which they directly connect.

[30]For numbers related to other geographical areas and other hypergiants, see Gigis et al. (2021).

preferred as short-term responses since they allow providers to quickly adapt and scale in response to rapidly changing demand. In the medium or longer-term, however, off-net (zero-hop) strategies seem to be preferred by many hypergiants like Google, Facebook, or Netflix. The expansion in these capacities suggests that these providers anticipate that the new normal for demand will continue to reflect the higher demand levels first experienced during the pandemic.

Over the last couple of years, the growth in IXPs and other distributed interconnection facilities has facilitated more local and direct peerings, thus making the interconnection ecosystem denser and flatter. On the one hand, these interconnection facilities have provided places for networks to meet and exchange traffic close to their customers/end-users, thus facilitating the establishment of direct and local peerings. On the other hand, these facilities typically have significant spare capacity that can be used in case of unexpected events. Moreover, they have ways to rapidly expand, adjust and allocate capacities (Dietzel, 2020; Feldmann et al., 2020).[31] Thus, they were able to rapidly establish and accommodate the demands that arose due to new or upgraded interconnections and capacity requests.

#4: The future of networking is more adaptive and agile

The delivery of a lot of entertainment content as well as real-time communications services like video conferencing is based on algorithms that enable adaptive sending rates and thus network usage that is responsive to the current network situation. Since large shares of traffic are already delivered in this way (e.g. Labovitz, 2019), the Internet has acquired the ability to resiliently cope with sudden increases in traffic and to manage, mitigate or avoid congestion. Since these capabilities are deeply engrained in today's ecosystem, the necessity of the measures taken by commissioner Breton (see Section 2.2) have been scrutinised and called into question (e.g. Castor, 2020; see also Briglauer & Stocker, 2020). Besides the server-sided ability to dynamically adapt sending rates according to the current network situation, automation arguably helped a lot to quickly and efficiently upgrade and scale capacities both at IXPs as well as in networks and data centres. Furthermore, technologies and innovations based on softwarisation and virtualisation of network resources enhance the general agility and adaptability of networks and data centres, that is, how networks are managed, traffic is routed, and resources are allocated. This agility creates more flexibility and facilitates real-time adaptations to sudden changes in demands. Moreover, the use of AI/ML has enhanced the ability of many providers to rapidly adjust to changing demands. Finally, such technological advances have been accompanied by a trend towards more contractual flexibility. Contracts are becoming increasingly customisable and short term.

[31] Wagner et al. (2021, p. 8) provide anecdotal evidence for spare capacities at IXPs. Considering 11 IXPs with a total capacity of 65 Tbps, they explain that aggregated peak traffic over all IXPs is at around 11 Tbps, which amounts to roughly 17% and indicates much potential to handle and absorb unexpected peaks in demands.

#5: Home networks may emerge as performance bottlenecks.

Whereas networks have coped rather well with the unexpected shifts in demands, it could well be that the more intense use by multiple users (Sandvine, 2020, p. 5) has caused problems within home networks, thus turning them into performance bottlenecks. This can result from too much simultaneous at-home usage (relative to the broadband access service that the household subscribes to) or from misconfigured or inadequate in-the-home network capacity. These may account for the degraded performance as measured by those speed tests performed by end-users (e.g. BITAG, 2021). Service providers have only limited ability to control such 'user-initiated' congestion, but it does highlight the importance of addressing potential congestion bottlenecks along the end-to-end path that traffic needs to traverse and use a range of approaches appropriate to each element. For example, providing end-customers with better tools to track/monitor their usage may enable end-customers to better match their usage to the service subscription tier that is appropriate to their needs and to better identify congestion sources downstream from the provider's access service (e.g. misconfigured WiFi networks or outdated hardware or software in the home).[32]

#6: The crisis emphasised the role of (publicly available) data

The pandemic has changed attitudes towards the management of privacy and cybersecurity in light of the increased need and capacity for localised/granular traffic/usage management. It has also given rise to an unprecedented wealth of publicly available data, providing new insights into the state of ecosystem evolution, online service usage, and the Internet's ability to accommodate them. These data have informed a growing number of analyses and studies which have and will continue to contribute to a more nuanced understanding of the ecosystem, its strengths and weaknesses, and the factors determining its robustness and resilience. An important finding is that the pandemic has proven the value and need for a continuous and transparent measurement ecosystem. On the one hand, the data and insights into the state of networks during the pandemic were published by different (perhaps competing) private and public actors/stakeholders. On the other hand, measurements are based on differing techniques, vantage points, geographical scope, and aggregation levels. They may also rely on different terminology or concepts (e.g. the definition of peak or average traffic varies considerably). Whereas measurements were highly valuable for optimising responses (e.g. network provisioning and management) of different actors, inferring unanimous observations and comparing insights across the publicly available data thus turns out to be a challenging task.

Especially during the early stages of the pandemic, when concerns regarding the need to track the progress of the pandemic on a local and rapidly dynamic level and regarding the need to accommodate the rapid shift to

[32]For a more detailed discussion of the role of home networks on end-to-end service qualities, see, for example, Sundaresan et al. (2013), Feamster and Livingood (2020), Stocker and Whalley (2018), or Briglauer and Stocker (2020).

Table 2.3. Examples of Permanent Versus Temporary Changes.

Permanent Changes	**Temporary Changes**
• *Life & Work* – Broadband has become essential for individuals and businesses; pandemic-related increase in the degree and rate of reliance on the Internet – More online interaction and more hybrid/remote work and education – Broad online-based social and commercial innovation and new offers in the virtual sphere. Pre-pandemic commercial sphere as well as work and social norms will be different in 'new normal'; changing innovational and competitive dynamics between and within offline and online services – Changing usage habits and embedding of more/new online services in the workplace, education, commerce, etc. (hybrid offline/online forms as new default) – Changes in application variety and usage patterns	• *Life & Work* – Some content and business model innovation has been spurred by and tailored to the pandemic and will lose its value for companies after the crisis is over o Specific apps as well as solutions during social distancing obligations o For example, home-delivery of food and services, adjustments in gig economy supply and demand as social-distancing concerns wane, or shifts in range of media types consulted (more current news heavy consumption during periods of rapid change)
• *Clouds & Networks* – Accelerated and step-change boost of networking trends and cloudification – More network and cloud investments (links, servers, peerings, etc.) – Spurred changes in the topology of the Internet and the underlying connectivity fabric which make the ecosystem more robust and resilient o More peering diversity, denser interconnection topology, and flattened hierarchies	• *Clouds & Networks* – Hybrid/multi-cloud strategies as on-demand strategies to cope in times of crisis for content and cloud providers with own infrastructures o We anticipate that this boundary will remain porous and shifting in response to adjustments in expectations regarding the new normal

(*Continued*)

Table 2.3. *(Continued)*

Permanent Changes	Temporary Changes
o Localisation of networked computing resources and network traffic driven by aggressive expansion of offnet footprint of servers within ISP networks by hypergiants – Boost of automation and adoption of ML/AI-based technologies (i.e. integration of intelligence in networks) enhance agility and versatility, and the providers' ability to quickly scale up and reconfigure their networks to changing traffic matrices and usage patterns	
• *Privacy, Transparency & Cybersecurity* – Changing attitudes towards management of privacy and cybersecurity in light of increased need and capacity for localised/granular traffic/usage management	• *Privacy, Transparency & Cybersecurity* – Pandemic has temporarily increased transparency and created unprecedented wealth of publicly available data o New insights into the state of ecosystem evolution, network, cloud, and online service usage, and the Internet's ability to accommodate them
• *Policies & Regulations for Broadband & Digital Infrastructures* – Governments have recognised essentiality of digital infrastructures and will likely invest more in fostering broadband roll-out as well as skills and literacy to close digital divides and support digital inclusion – Boost of online digital public services (e.g. e-government) adoption of digital vaccination proofs, etc.	• *Policies & Regulations for Broadband & Digital Infrastructures* – *Private and public actors*: Temporarily enhanced contractual flexibility and temporary measures to keep citizens connected (e.g. free mobile or WiFi services, suspended data caps, temporary spectrum usage rights, etc.) – *Public actors*: Temporary measures to protect network operations and maintain high levels of customer experience (e.g. exemptions for network management, temporary access to additional spectrum, or requesting content and cloud providers to suspend delivery of high resolution content)

online for work, education, and entertainment, service providers shared quite detailed location/time/device-specific usage data. At the same time, software developers strove to deliver mobile device-capable applications that could collect and share user-specific data that could contribute to COVID-19 tracing and network provisioning efforts. Were it not for the emergency situation, it is unlikely that such granular information would have been shared so freely. In normal times (i.e. in times in which no external shock is forcing activity to move online), such data is highly valued for its market research potential and is costly to acquire; and concerns about protecting user privacy and commercial confidentiality interests would have impeded the collection and sharing of the data. How this will impact user attitudes towards privacy and data security, commercial practices, application designs, and privacy/security policies in the future remains to be seen. In the meantime, one can observe that both public and private actors have reduced or even stopped providing detailed (real-time) information about the state of their networks. For example, Verizon stopped its reporting in November 2020.

2.4.1. Summary and Overview

Even though a final assessment or quantification of the future 'new normal' can at this point in time not be made since the pandemic is not over yet and post-COVID-19 data do thus not exist, the changes the pandemic has caused can be distinguished into two categories. Table 2.3 provides an overview of the changes we identified in our analysis. By 'permanent changes' we mean those changes that will become permanent and systematic because they create value in 'normal times' for individuals and businesses. By 'temporary changes', we mean those changes that are driven by adaptations to the crisis that will not endure after it. They have the sole function of providing value, functionality, and resilience in times of crisis. These changes might be embedded as permanent optional features that can be activated in times of crisis but will not be part of normal network operation.

2.5. Conclusion

About two years after the first lockdown measures were introduced in the USA and EU, the Internet ecosystem has coped quite well with the sudden and unexpected changes in demand and traffic patterns. Although local and transient problems have occurred (e.g. outages, congestion, or other service quality problems), the networks and services have proved to be relatively resilient, and the customer experience has generally been good. It seems fair to say that the pandemic has served to coalesce broad consensus regarding the conclusion that broadband digital infrastructures are essential facilities for economies, and are necessary for societal and economic participation, growth, and innovation. This was especially true and obvious during the pandemic, but remains true under normal, post-pandemic circumstances as well. To ensure that national communications infrastructures are up to the challenge, policy-makers in the EU and the USA have implemented a range of measures to tackle digital divides and support digital inclusion. Although the enhancement of broadband and related digital infrastructures had been progressing prior to the pandemic, the pandemic accelerated and catalysed digital transformation processes driven by private and public decision-makers.

In hindsight, most of what we observed after the initial shock was to be expected. Put differently, those familiar with the technical and market details regarding the state of content and service delivery, clouds, and interconnection in the pre-Covid Internet ecosystem had largely anticipated what would be needed as early as April 2020. Thus, they were able to accelerate planned responses rather than being forced to respond to wholly new circumstances. What COVID-19 helped do was bring the forecasted Internet future forward in time and convince non-experts of that need. As our chapter has demonstrated, the pandemic has acted as a change agent, not a game changer. That being said, it selectively changed the game for some services and arguably ignited and fuelled the rise and growth of new online services and platforms. For example, the success story of Zoom has been driven by the circumstances caused by the pandemic (BBC, 2021) and the timing of the launch of Disney+ in many countries in March 2020 arguably helped its initial success and growth (Faughnder, 2020). More generally, the pandemic has fuelled, accelerated, and amplified networking trends such as developments towards a denser and flatter interconnection ecosystem but also the cloudification and the growing role of highly distributed (intra-AS and off-net) serving infrastructures for expanding the footprint of hypergiants. Importantly, adaptations to the new demands have resulted in more localised networked computing resources and network traffic.

Resilience is a key capability for communications networks and server infrastructures. A few learnings can be derived. First, whereas connectivity providers (e.g. ISPs and MNOs) and cloud and content providers should (continue to) provision their infrastructures for traffic/demand peaks and have some excess capacity and headroom, changing traffic matrices have led to adaptations in the operations, management, and peering strategies of both communications service providers and cloud and content providers. The ability to rapidly scale up and reconfigure networks and capacities as well as peering strategies is important to achieve resilience and maintain high levels of customer experience. Second, entertainment content is (still) dominating the Internet. Most service provision is adaptable (e.g. via adaptive bit rates) and thus able to mitigate network overloads. While lowering data rates of such applications or rescheduling the delivery of static (bulk) content helps relieve strain in the short term, traffic management within networks can also play an important role in maintaining high levels of customer experience for the relevant range of services delivered. Third, automation has played an essential role in upgrading and scaling capacities and thus in addressing the mismatch between the pre-pandemic status quo and changing usage patterns and subsequent demand structures, requirements, and traffic matrices. Fourth, the interplay and synergies between private and public cloud approaches and underlying cloud-based resource pooling have evolved during the pandemic. While cloudification has been accelerated and amplified, hypergiants have expanded their footprints.

Significantly, many of the changes, especially those that have led to modifications in the topology, are here to stay and contribute to the ecosystem's robustness and resilience. Similarly, a range of virtual substitutes for previously exclusively physical activities will likely be partly or entirely integrated into future life and work after the pandemic. We do not anticipate online versus offline work or social norms to return to pre-COVID-19 patterns. In short, we think increased levels of online interaction, telecommuting, and hybrid solutions that change how online and offline activities are conducted will shift, favouring increased online interaction. However, depending on when the next crisis will hit and what form it will take, the challenges to be met may differ considerably from the ones that had to be overcome in this crisis. On the one hand, industry and employment structures will change over time, and thus also the demands for connectivity and the migratability/transferability of tasks and activities. On the other hand, other crises may differently impact on the physical world and thus require different responses from the virtual world. Several high-level insights are relevant for policy-makers.

First, they must embrace the evolution of the ecosystem and the evolving interplay and ongoing fusion between the real and virtual worlds to develop an understanding of the possible consequences of different crisis scenarios.

Second, safety net broadband objectives inherently represent moving targets. Whereas periodic reassessments of the set of desirable or essential applications and functionality that should be provided by our digital infrastructure for the evolving 'new normal' is warranted, it is also important to better understand and have plans for how to respond in potential crisis scenarios. More interdisciplinary research will be needed to embrace these questions and to provide the insights needed to meaningfully address the challenges ahead and to ensure an ecosystem that is not only technologically resilient but also provides the basis for social and economic participation and resilience.

Third, and finally, as the Internet ecosystem continues to become more complex and the boundaries between edge and core, mobile and fixed, transmission and computing and storage services blur, the number of private and public stakeholders with a joint and co-dependent role in ensuring the smooth operation of the digital infrastructure necessarily leaves significant important decision-making to market-based processes (as opposed to centralised control). This is in keeping with the decades long trend towards more light-handed regulation (as opposed to the legacy model of postal, telegraph, and telephone services and public utility regulation of telecommunication networks). The fact that the Internet ecosystem supported on the networks of competing yet interdependent service provider networks was able to meet the challenge posed by the pandemic attests to the robustness of the market process and helps affirm that although we believe that continued regulatory and policy engagement is necessary to promote the digital future we need and desire, the markets are mostly working, at least so far.

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Appendix 2.1: Selected Reports and Studies About the Impact of COVID-19 on Internet Traffic

Publication	**Publication Type** ***[Publication Date]***	**Focus**	**Brief Description**
BEREC (2021c)	Report (Summary Report) *[30 Nov. 2021]*	• COVID-19 impact on state of internet capacity and regulatory responses in the EU	• Provides an overview of network impact and regulatory measures taken within EU member states • High level insight: "In general, while traffic on fixed and mobile networks have increased during the (approximate) twenty months of the Covid-19 crisis, no major congestion issues have ever been reported by NRAs to BEREC." (p. 1)
BITAG (2021)	Report (Technical Working Group Report) *[5 Apr. 2021]*	• COVID-19 network impact [emphasis is on the USA] and responses • Different actors of the ecosystem • Different applications	• Provides a comprehensive overview of measurement-based studies on the impact of the pandemic on networks and applications (especially on usage, traffic growth, and performance) and the responses to the pandemic by different actors of the ecosystem • The report also offers recommendations for different actors of the ecosystem • High level insight: "The Internet in the United States has performed and continues to perform well during the pandemic, in the face of extraordinary and unprecedented changes in demand and use. This strong performance covers all of the connected parts of the Internet, from user applications to content distribution infrastructure, all types of Internet access networks, and everything in between." (p. 24)

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Publication	**Publication Type *[Publication Date]***	**Focus**	**Brief description**
OECD (2020a)	Report *[4 May 2020]*	• COVID-19 network impact	• Provides an overview of network impacts based on publicly available data from different actors and vantage points and provides recommendations • High level insight: "Network operators and content providers have to date successfully maintained services and efficiently utilised pre-existing capacity, and in certain cases expanded this capacity." (p. 1)
Arkko et al. (2021)	Report (Workshop Report) *[July 2021]*	• COVID-19 network impact • Different actors of the ecosystem	• Provides an overview of measurement-based studies on the impact of the pandemic on networks on traffic growth, changes in usage/user behaviour, last-mile congestion, mobile networks and interconnections; the individual studies considered were conducted by different researchers and teams from academia and industry and considering different vantage points and actors of the ecosystem • Discusses implications on digital divide, applications, observability, and security • High level insight: "Early reports also seem to indicate that the shifts have gone relatively smoothly from the point of view of overall consumer experience." (p. 13)
Internet Health Report (2020)	Report (Website) *[June 2020]*	• COVID-19 impact on (large eyeball) networks	• Measurement-based study: estimated delays (round-trip times, RTTs) are computed based on RIPE Atlas data for connections to different actors, thus combining different vantage points • Data is available for a wide range of countries to provide insights into pandemic-related network congestion • No conclusions are drawn, no assessments are made

Labovitz (2020a)	Report (Workshop presentation) *[1 June 2020]*	• COVID-19 network impact and responses • Different actors of the ecosystem	• Measurement-based study with data of >50 providers • Provides data on traffic changes for global Internet and selected content providers like Zoom and Netflix and also on application usage • High level insight: "Networks met demand and maintained QoE through 'peak Internet'" (p. 3)
SamKnows (2020b)	Report *[n.d.; ca. Apr. 2020]*	• COVID-19 impact on broadband performance	• Measurement-based study based on measurement data gathered in the U.S. (>500,000 homes) • Provides a map that visualises the changes in downstream data rates ('download speeds') between 12 March and 24 March on a state-level • High level insight: "Broadband infrastructure in the US is holding up generally very well given the dramatic increase in internet usage. Whilst most states are seeing some declines in performance, these are very modest."
Sandvine (2020)	Report *[May 2020]*	• COVID-19 impact on networks and applications	• Measurement-based study based on data from >500 operators worldwide (fixed, mobile, and WiFi) • Provides an overview over the global and regional (i.e. per continent) impact of the pandemic on networks and applications • Spotlights on Zoom, video streaming, online gaming, social networking, and messaging • High level insight: "Broadband consumer networks are under the biggest change in history during the COVID-19 worldwide pandemic. Traffic that has normally been distributed among enterprise, education, and public WiFi networks – and to a lesser extent mobile and satellite (more on this later) – has now collapsed onto a single network access − fixed consumer broadband networks." (p. 5)

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Publication	Publication Type *[Publication Date]*	Focus	Brief description
ThousandEyes (2020)	Report *[4 Aug. 2020]*	• COVID-19 impact on Internet performance • Different actors of the ecosystem	• Measurement-based study to measure cloud and network performance and detect disruptions/outages • Comprises analyses of different vantage points and actors of the ecosystem • High level insight: "Overall, Internet-related infrastructures have held up well, suggesting overall healthy capacity, scalability, and operator agility needed to adjust to unforeseen demands." (p. 39)
Belson (2020b)	Blog article *[25 Sept. 2020]*	• COVID-19 impact on the Internet	• Article surveys reported traffic changes across different actors of the ecosystem • Also provides information on shutdowns in certain countries • High level insight: "While many governments were not prepared for COVID-19, the Internet was – thanks to the critical properties that underpin its strength and success. It enabled many people who have stable access to keep working, learning, socializing, and collaborating on solutions to the ongoing pandemic. The Internet's foundation enables it to be resilient, agile, and responsive to the shifting needs of populations worldwide."

McKeay (2020)	Blog article *[13 Apr. 2020]*	• COVID-19 network impact	• Measurement-based (mini) study based on the Akamai vantage point(s) • The article describes the impact on global Internet traffic and also for Italy [note: graph shows data for Spain], Poland, and Spain • High level insights: “Even though we see aligning traffic peaks at the country level, the combined traffic doesn’t exceed a hugely popular streaming event and software patch released on the same day. […] Compressing a year’s growth into a month will not come without growing pains, but it’s not a catastrophic event, at least for the Internet.”
Ookla (2020)	Blog article *[20 July 2020]*	• COVID-19 impact on fixed and mobile broadband performance (‘speed’, i.e. downstream data rates)	• Provides an overview of global and per-country fixed and mobile speed changes between January 6 and 2 March 2020. • Data is crowdsourced based on end-user measurements via their Speedtest® app • No conclusions are drawn, no assessments are made; datasets can be downloaded from their website
Poinsignon (2020)	Blog article *[17 Mar. 2020]*	• COVID-19 network Impact	• The article describes changes that have occurred as could be observed from Cloudflare’s CDN and also provides insights from different IXPs • High level insight: “Even though from time to time individual services, such as a web site or an app, have outages the core of the Internet is robust. Traffic is shifting from corporate and university networks to residential broadband, but the Internet was designed for change.”