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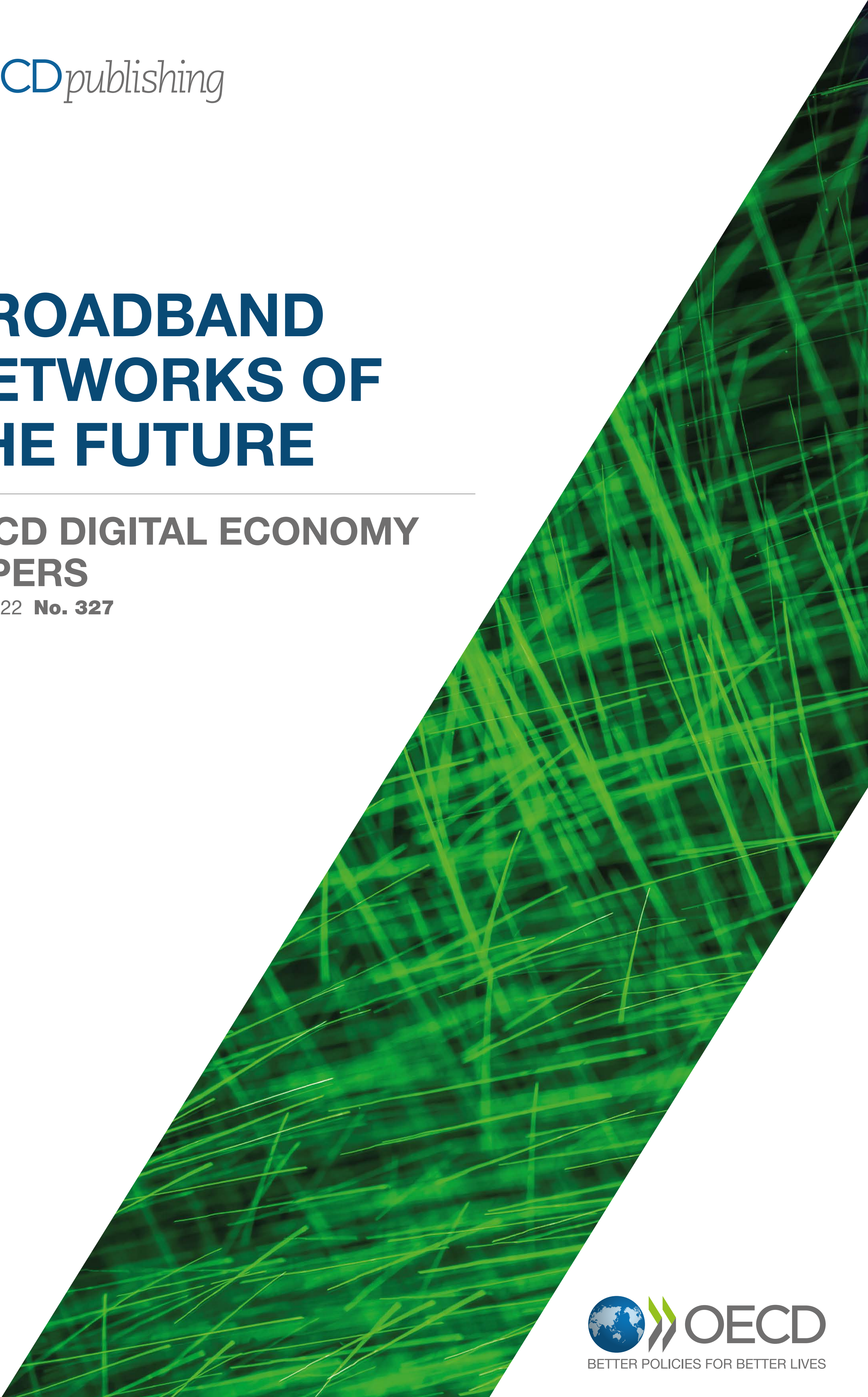

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BETTER POLICIES FOR BETTER LIVES

Foreword

This report on "Broadband Networks of the Future" was prepared by the Working Party on Communication Infrastructure and Services Policy (WPCISP). It provides an overview of the main technological trends in the next evolution of broadband networks, as well as selected regulatory and policy implications for the expansion and development of future broadband networks.

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EXECUTIVE SUMMARY

The recovery from the COVID-19 pandemic leaves no doubt: the future is digital, enabled by globally interconnected high-quality broadband networks. Applications across all sectors of the economy, from online education, telemedicine and sustainable development, to smart factories, smart hospitals to automated vehicles, increase the overall demand on networks. All these applications require the ability to move much more data across networks and require high-quality networks, characterised by high speeds, high reliability (i.e. few errors or delays measured by packet loss), and improved network response times (i.e. low latency). **To meet the increasing demand, networks need to continue to evolve.**

The pandemic, on the other side, has also shown that high-quality networks across the OECD are far from universal. Significant access gaps exist between urban and rural areas, and those access gaps are even more pronounced for high-quality networks**. To allow for equal opportunities, the expansion of high-quality networks at affordable prices to un- and under-served areas needs to be continued, at pace.**

This report investigates how to meet these needs. It explores: (i) how demand on networks has increased and how networks need to evolve, (ii) the main technological trends spurring the evolution of high-quality networks, (iii) how to measure the quality of communication services delivered over those networks to guide policy making, and (iv) how policies and regulation are being shaped to support not only the upgrade of networks across the OECD, but also the expansion of high-quality networks within and among countries.

Surging demand is shaping future networks and their evolution

Demand for high-quality networks is growing in OECD countries. The need to move work and social activities online during the COVID-19 pandemic led to an increase of Internet traffic of 58% in one year (2019-20), and a record 21.15 million new fixed broadband connections in the OECD area from December 2019 to December 2020. Fibre has been the fastest growing technology in OECD countries over the past decade. For the first time in 2020, high-speed fibre subscriptions surpassed copper-wire DSL in the OECD, as companies and citizens upgraded the quality of their broadband connections. 5G commercial deployments have increased and were available in 36 out of 38 OECD countries as of June 2022. While most 5G commercial networks to date have been based on non-standalone (NSA)-5G (i.e. relying on 4G core network infrastructure and using NSA-5G standards in the radio interface), standalone (SA)-5G deployments are on the rise. Given the tendency towards a ‘remote economy’, where more and more business processes move online and people increasingly work and learn from home, alongside the continuous growth of data intensive applications, the demand for high-quality networks is only expected to increase in the future.

While capturing the concept of what the “future” of broadband networks entails is a challenging task as communication networks are in a constant state of evolution, a few findings can be highlighted. Fibre needs to be deployed deeper into networks to increase broadband performance across all access technologies, including mobile networks. In particular, network densification inherent to 5G will require greater fibre roll out to support backhaul capacity. In addition, more fibre is needed to bring emerging technologies, such as the Internet of Things (IoT) and artificial intelligence (AI), to their full potential. There is also an increasing need for networks to be tailored in a flexible way to cater to multiple use cases in different sectors. Furthermore, a broad array of connectivity solutions, many of them complementary to each other, are required to face the demands placed on broadband networks of the future and to ensure seamless connectivity to users. Going forward, the important question to be posed may not only be the one of co-existence of connectivity solutions, but rather how to leverage this co-existence to take full advantage of synergies, where questions of interoperability will likely gain importance.

Four technological trends are driving the future of both fixed and mobile networks

Responding to the need of increased flexibility in network design, and the provision of high-quality communication services in a cost-effective way, four main trends are likely to shape the communication industry: i) the move towards virtualisation, ii) an integration of cloud services into networks, iii) increased use of AI systems in networks and iv) openness of networks. With respect to 5G networks, there has been a recent move in the industry from a “monolithic” radio access network (RAN) configuration towards a disaggregated RAN with a combination of virtualised and/or open interfaces of the RAN. Networks are also integrating cloud and edge computing solutions. Partnerships with cloud service providers have recently illustrated the possibility of outsourcing 5G core services. Automation and machine learning (the use of AI systems) are increasingly being used by operators to improve and optimise network management, undertake predictive maintenance, and reduce the energy consumption of broadband networks.

These four main trends are accompanied by further developments in satellite broadband solutions, and early discussions of “beyond 5G” technologies, which are important to follow as these may play a role in achieving ubiquitous high-quality connectivity. In recent years, different companies have launched low earth orbit (LEO) satellite constellations with the aim of providing high-speed broadband in rural and remote areas. There is also a trend towards developing hybrid satellite and terrestrial wireless networks to provide connectivity solutions for corporate customers using IoT, maritime and aviation applications. A handful of countries around the world, as well as some in the communication industry, have started to embark on research activities on what may be the next steps of convergence of communication networks beyond 5G.

Measuring the quality of future networks is a compass for policy makers to guide broadband development

Given the increasing demand for high-quality connectivity, apace with technological trends, developing indicators on broadband performance has become more relevant than ever. Ensuring user transparency has tangible benefits for consumers and adds new dimensions for competition in these markets. Indicators such as upload speeds, latency and reliability are becoming key for networks. This report proposes a set of broadband performance indicators for OECD countries, including the first measurements on latency for OECD countries. It also presents “user-centric” approaches to understand and assess network experience, which has led to advances in measures of quality of experience (QoE).

As networks evolve, regulation and policies also need to adapt to foster network upgrades and roll-out

OECD countries have worked on policies and regulation to promote the next generation of networks. These include policies to ease network roll-out (e.g. promoting efficient spectrum management, infrastructure sharing, easing barriers to deployment for players of all sizes, including social-purpose operators, and extending access to backhaul connectivity). Several countries are adapting regulation to provide incentives to boost fibre deployment and to ease the shutdown of legacy networks. To close access gaps, OECD countries have further included broadband connectivity as a fundamental element in their economic recovery packages. Policy makers across the OECD are also working on improving measurement and publishing data on the quality of broadband networks.

Going forward, the technological and policy trends discussed in this report highlight that important questions remain to be explored in future work. Given the importance of broadband networks on the one hand, and increasing challenges like power outages and natural disasters on the other, further efforts need to be made to render networks more resilient and increase their redundancy. There is also a rising need to look at the environmental sustainability of networks. On the policy side, the measurement of quality components of communication services need to be further expanded and made comparable across OECD countries. Finally, to end with a holistic approach and challenge, given that our digital future relies on the performance of high-quality networks, it will be key to assess how regulatory frameworks across the OECD can best evolve to ensure responsiveness to the continuous evolution of networks.

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Broadband Networks of the Future

Introduction

Reliable connectivity is fundamental for the digital transformation facilitating interactions between people, organisations and machines. The COVID-19 health emergency has further accentuated awareness of how the resilience and quality of broadband networks are becoming even more critical. As we increasingly move towards a "remote economy" (e.g. remote learning, telehealth, automated driving, etc.), ensuring reliable, fast and ubiquitous connectivity becomes crucial, as highlighted in the 2021 O*ECD Council Recommendation on Broadband Connectivity* [OECD/LEGAL/0322].[1]

Today's digital economies rely on the data and information transmitted over high-speed networks to support developments in areas such as artificial intelligence (AI)[2] and the Internet of Things (IoT). High- capacity access networks both fixed and wireless are rapidly becoming the underlying connectivity across all sectors of the economy. For example, connected devices used in critical contexts, including in health, energy or transport such as air traffic control, require time-sensitive upload or download of data, underscoring the need for ultra-reliable networks with improved response times (i.e. low-latency).[3]

Communication networks are being conceived to support growing requirements for instant and seamless data transmission, which is critical to continued digital transformation. In addition, they are being designed with enough "flexibility" to cater to a variety of use cases, including enhanced broadband solutions for consumers, as well as connected devices either requiring massive coverage (e.g. smart grids, smart cities, precision agriculture), or high performance and reliability (e.g. critical applications). To cater to these demands, broadband service providers are embracing new trends such as a move towards virtualisation and openness of networks. Furthermore, operators are enhancing their network capabilities and operations by the use of AI systems, and by building new partnerships with cloud service providers.

Communication networks, both fixed and mobile, are in a constant state of evolution. Therefore it is challenging to capture the concept of what the "future" of these networks entails. For example, 5G, represents an evolutionary process of previous generations of wireless networks (i.e. 2G, 3G, and 4G), and research is currently taking place with respect to "beyond 5G" technologies that may see the light of day in about 8 to 10 years' time. Likewise, fixed networks are also evolving constantly as access technologies progress and with Gigabit speed networks rapidly becoming 10 Gbps networks in several OECD countries. These advances are paralleled by new developments in wireless local access network (WLAN) technologies, commonly known as Wi-Fi.

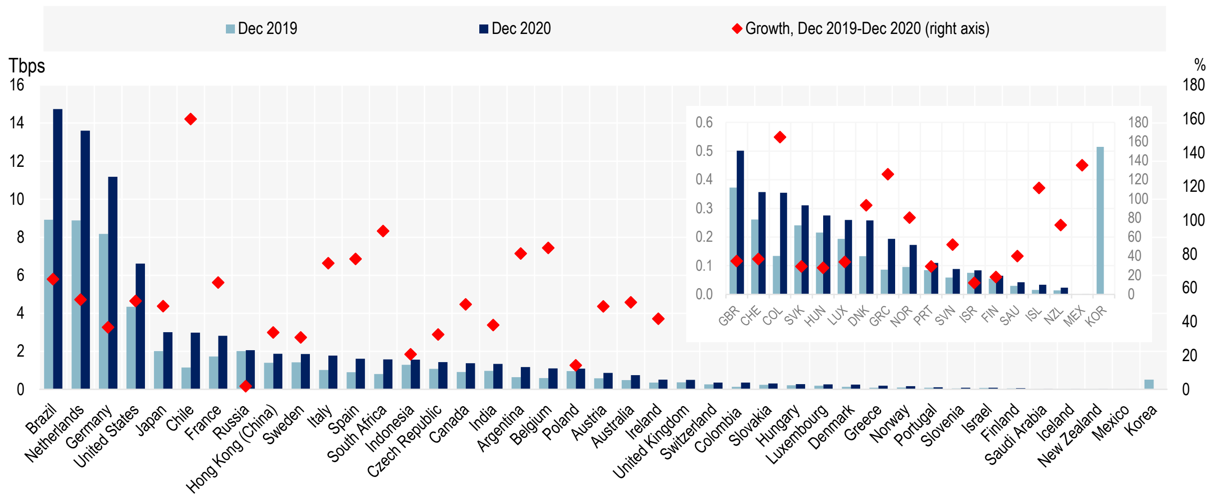
Assessing the changing landscape of broadband networks and the technological trends shaping how these networks are being designed and deployed allows policymakers and regulators to gauge where broadband networks may be headed in the mid-term future (i.e. 5 to 10 years), which is the focus of this report. The report analyses developments in 5G and high-capacity fixed networks in various OECD countries, the transformative effects of their use in several economic sectors, and the convergence of broadband networks with AI, cloud and edge computing. It addresses the increased importance of quality for the next evolution of broadband networks and identifies policy developments in OECD countries to foster the deployment of the next evolution of fixed and mobile broadband networks.

Networks adapting to the global COVID-19 health emergency

Mobility restrictions due to the coronavirus (COVID-19) have resulted in an increasing number of the estimated 1.3 billion citizens of OECD countries working and studying from home. This has caused a surge of traffic on communication networks, as well as along the entire Internet value chain (e.g. content and cloud providers, Internet exchange points [IXPs]). In one year (2019-20), Internet traffic exchanged at IXPs soared by more than 58% on average in the OECD area and even grew by 160% in Chile (Figure 1). The countries with the largest IXPs in the world in terms of terabits per second (Tbps) exchanged (i.e. Brazil, the Netherlands, Germany, and the United States) experienced an increase of traffic of 52-65%.

Figure 1. In one year (2019-20), bandwidth produced at Internet Exchange Points in OECD and G20 countries soared

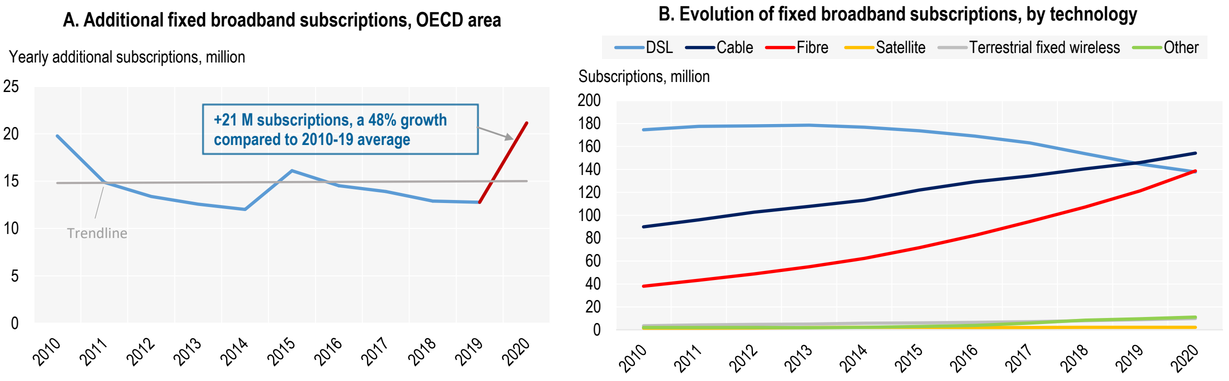
Terabits per second



Notes: Hong Kong (China): Data from Hong Kong Exchange HKIX. Estonia and Latvia: Data are not available for Dec 2020.
Source: PCH (2021) and NAP.co (https://www.nap.co/) for data on Colombia's IXP.

Taking a more granular view, data from the OECD Broadband Portal reveals that the pandemic spurred the uptake of high-speed broadband subscriptions. The need to move work and home life activities online during the COVID-19 pandemic led to a record 21.15 million new fixed broadband connections (including fibre, DSL, cable and others) in the OECD area at the end of December 2020 (OECD, 2022[1]), representing a 48% growth compared to the average of yearly additional subscriptions observed since 2010 (Figure 2.A).[4] In addition, users have been upgrading their connections in a move towards symmetrical upload and download speeds to work and study from home. For the first time in 2020, high- speed fibre broadband surpassed copper-wire DSL connections across OECD countries (Figure 2.B). Fibre subscriptions grew by 14% in 2019-20, outpacing a 5% rise in overall fixed broadband subscriptions.

Figure 2. During the pandemic year (2020), high-speed fibre overtakes DSL as OECD countries add 21 million fixed broadband connections



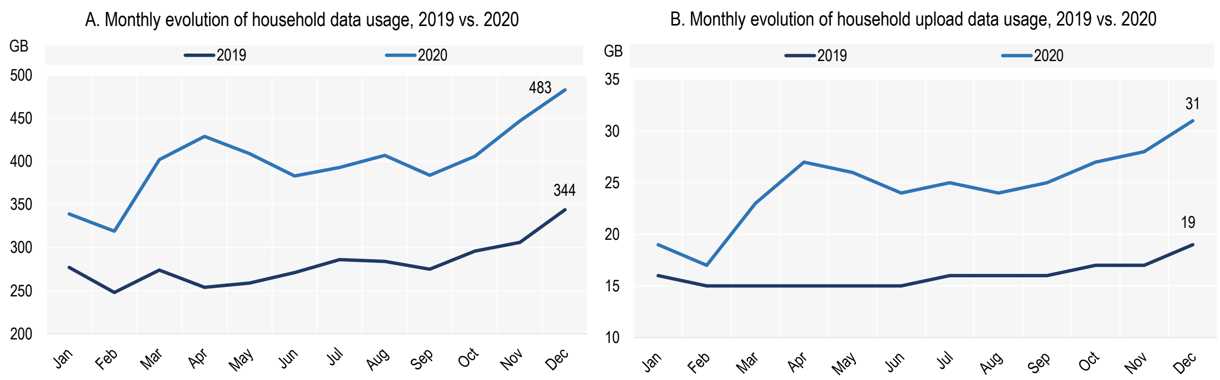
Source: OECD (2022[2]), *OECD Broadband Portal*, https://www.oecd.org/sti/broadband/broadband-statistics/ (database)

The pandemic also changed the trend of household broadband data consumption, which has surged between the end of 2019 and 2020. According to the OpenVault Broadband Insights (OBVI) report,[5] average monthly broadband data usage in households in the United States at the end of 2020 grew by 40% compared to 4Q 2019, reaching 482.6 Gigabytes (GB) per month (OpenVault, 2020[3]).[6]

An important indicator of the increase of remote activities during the COVID-19 pandemic, such as teleworking and remote learning, are upload (upstream) data usage. In March 2020, the average upload volume of data consumed by households in the United States was 23 gigabytes (GB), which compares to 15 GB one year earlier, in March 2019 (Figure 3). Overall monthly household data usage in the first quarter of 2021 was 461.7 GB, which compares to 402.5 GB a year earlier (1Q2020), and 273.5 in 1Q2019 (OpenVault, 2021[4]).

Figure 3. Monthly household data usage* (GB) in the United States** grew in one year (2019 vs. 2020)

Monthly household data usage (LHS, Figure A) and monthly household upload data usage (RHS, Figure B)

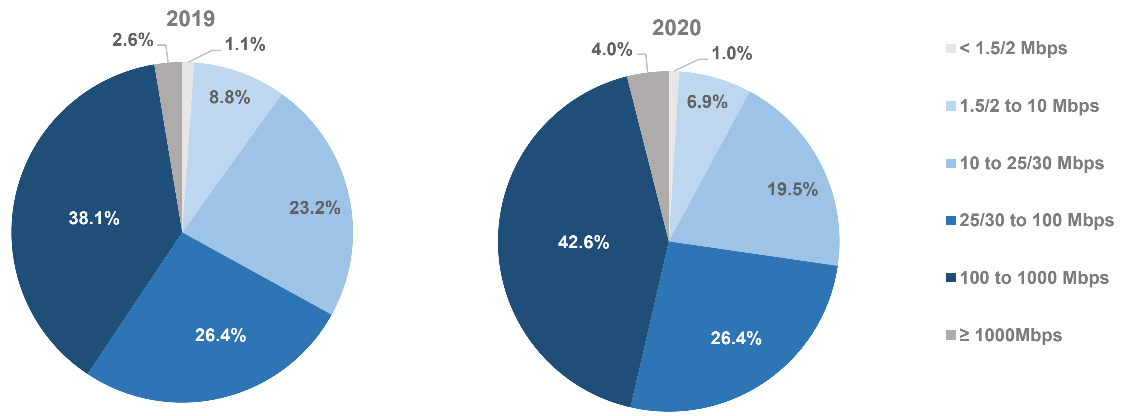


Note: GB= gigabytes. *Weighted average data usage represents data usage trends for both flat-rate billing (FRB) and usage-based billing (UBB) subscribers. Data consumption includes both upload and download data. **OpenVault's platform captures broadband usage data from millions of residential and commercial subscribers across the United States and Europe, from more than 150 service providers. The data presented here concerns the United States.
Source: OpenVault (2020[3]), *Broadband Insights Report (OBVI), 4Q 2020*, https://openvault.com/thank-you-4q20-ovbi/

Commercial offers and subscription types also evolved during the pandemic. According to OpenVault data, the category of broadband subscriptions by speed tiers that grew the most by the end of the first quarter of 2021 were offers with Gigabit speeds, that tripled from 3.8% of homes in March 2020 to 9.8% in the first quarter of 2021, followed by offers between 100-200 Mbps that went from 38.1% in the first quarter of 2020 to 48.7% in 2021 (OpenVault, 2020[3]; OpenVault, 2021[4]). OECD Broadband Portal data reveals that the share of gigabit fixed broadband offers (i.e. with speeds above 1 Gbps) across the OECD grew more than 53%, from 2.6% at the end of 2019 to 4% by December 2020 (Figure 4).

Figure 4. In one year, the average share of fixed broadband subscriptions across the OECD with speeds above 1 Gbps increased by more than 53%

Share of fixed broadband subscriptions by speed tiers, 2019 versus 2020



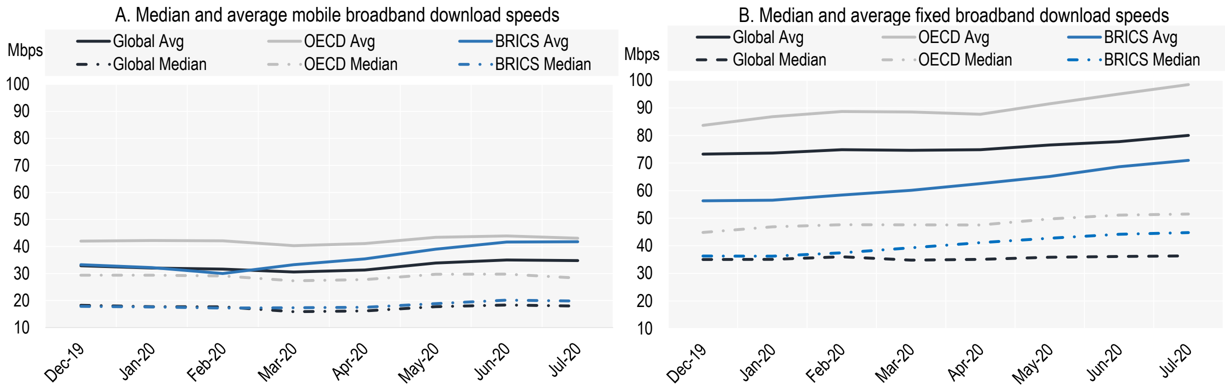
Note: Simple average of countries where data was available (i.e. 35 out of 38 OECD countries).
Source: OECD (2022[2]), *OECD Broadband Portal*, https://www.oecd.org/sti/broadband/broadband-statistics/ (database)

Some broadband technologies currently present inherent difficulties to provide symmetrical upload and download speeds (e.g. DSL, Satellite or DOCSIS 3.1). As a result, during 2020 some operators in certain markets placed data usage allowances or caps.[7] The latter can have significant effects on people teleworking or joining online courses via video conferencing applications that require upload throughput. On the other hand, some operators decided to accelerate their fibre deployment strategy as they face increased demand by customers requiring both higher upload and download speeds in a remote setting. For example, in Germany, Deutsche Telekom doubled in 2020 the number of households that could receive fibre-to-the-home (FTTH) to more than half a million, with plans of having all households in Germany with direct access to fibre by 2030 (Deutsche Telekom, 2020[5]).

Notwithstanding the surge of data traffic that networks have endured, networks have, in general, successfully managed to cope with the increased demand in times of COVID-19 without major network outages. When looking at one quality indicator, speeds, results from self-administered connection speed tests by Ookla on broadband download speeds show that for the OECD area, average download speeds on both fixed and mobile networks remained relatively stable during the pandemic, with fixed broadband speeds increasing from April 2020 onwards (Figure 5). The latter may be due to customers upgrading their offers to higher speed plans. Global speeds on mobile networks went slowly down when the pandemic started, but rose again to pre-pandemic speed levels by July 2020.

Figure 5. Broadband performance measured by speeds remained stable during the first phase of the pandemic (4Q2019-3Q 2020)

Evolution of fixed and mobile broadband speeds, Ookla (4Q2019-3Q 2020)



Source: Ookla (2020[6]), "Tracking COVID-19's Impact on Global Internet Performance", https://www.speedtest.net/insights/blog/tracking-covid-19-impact-global-internet-performance/#/

To cope with the significant traffic increases, network operators and governments across the globe have been working to ensure that connectivity and communication services operate in a reliable, stable and secure manner. Fixed and mobile broadband operators, as well as content providers, have successfully managed their networks to accommodate changes in utilisation patterns, respond to overall increased demand and avoid congestion that influences working and studying from home, while supporting critical services such as telemedicine and emergency response.

Examples of emergency policy responses taken by some regulators and policy makers was to make additional spectrum available on a temporary basis for mobile operators to add capacity to the over-the-air interface (e.g. the FCC in the United Stated and ComReg in Ireland). Other policy efforts included measures to facilitate the necessary mobility of the engineering workforce of network operators and content providers to maintain functionality of the core and access networks and still be able to connect homes at customers' sites (e.g. Australia and Colombia). Some OECD countries, undertook data collection in a granular way to monitor and assess the changes in Internet traffic patterns during the health emergency (e.g. Colombia).[8] Looking ahead, and considering the effects of the pandemic and the number of natural disasters and energy outages in OECD countries, measures to increase the resilience of networks will increasingly become important. The resilience of a communication network refers to the ability of a network to cope with shocks and still maintain an acceptable level of service, despite the presence of such challenges. Resilience can be strengthened by ensuring network diversity and redundancy when planning and rolling out infrastructure. Some countries have started to invest in making networks more resilient. Australia, for example, set up an AUS 37.1 million (USD 25.52 million)[9] programme called "Strengthening Telecommunications Against Natural Disasters" (STAND) to render networks more resilient in response to natural disasters.

Boosting high-quality connectivity for economic recovery and growth

High-quality broadband by all segments of the population is critical for economic recovery in an increasingly "remote economy" where many business processes are undertaken remotely and a significant share of the population either works in a hybrid manner or from home for the majority of the time. Therefore, several OECD countries have included connectivity as a fundamental element in economic recovery packages or have included broadband deployment projects as key elements in 2021 government budget proposals (Box 1). Within these economic recovery packages, several governments have allocated funds with the aim of enhancing the deployment of fibre and 5G.

Box 1. Economic recovery plans including connectivity features, selected examples

Canada

The Government of Canada has highlighted that access to high-speed Internet is essential for all Canadians, regardless of where they live. With the proposed Budget 2021, Canada has allocated CAD 2.75 billion (USD 2.17 billion)[10] to the Universal Broadband Fund to support projects seeking to expand access to high-speed broadband (i.e. connections with least 50 Mbps download and 10 Mbps upload speeds) across the country over the next six years, starting in 2021-22. It is mainly targeted to fund broadband infrastructure projects in rural and remote communities (Government of Canada, 2021[7]).

The European Union

The EU Recovery and Resilience Facility, as part of the NextGeneration EU programme, a EUR 750 billion (USD 856 billion)[11] temporary recovery instrument, makes available EUR 672.5 billion (USD 768 billion) in grants and loans for public investment and reforms in the 27 member states. The aim is to help them address the impact of the COVID-19 pandemic, to foster the green and digital transitions and to build resilient and inclusive societies (European Council, 2021[8]). The grants and loans can be used for reforms and investments for communication infrastructure such as fibre and 5G technology (European Commission, 2021[9]). In addition, many countries identified 5G as a key lever for recovery after the pandemic, and the Recovery and Resilience Facility (RRF) has allocated up to EUR 130 billion (USD 148.4 billion)[12] to boost 5G deployment (5G EU Observatory, 2021[10]).

France

"France Relance" or "Relaunch France", is the economic stimulus plan presented by the French government in September 2020, as part of France's response to the COVID-19 crisis. The plan started its implementation in 2020 and will run through 2022. With a budget of EUR 100 billion (USD 114 billion), of which 40% are financed by the EU Recovery and Resilience Facility, "France Relance" has the objective of "rebuilding the French economy". A key aspect of this recovery plan is the goal to extend the coverage of high-capacity fibre networks in the entire French territory by 2025 ("Poursuite du plan France Très Haut Débit (Gouvernement de France, 2020, p. 267[11]). In January 2021, the government announced a EUR 570 million (USD 650 million) fund to boost fibre deployment, out of which EUR 240 million (USD 274 million) had already been invested to achieve this aim in 2020 (Gouvernement de France, 2021[12]).[13]

Korea

The Korean government launched the "New Deal" in July 2020 to foster the economic recovery of the country by 2025. The Korean New Deal (also referred as the "National Strategy for the Great Transformation") places digital policies, together with sustainability, as the two key pillars, where connectivity plays a key role. The digital component focuses on a "smart country that is at the centre of a digital transformation based on data, network and artificial intelligence (DNA) infrastructure." Namely, it proposes projects to integrate 5G and AI into all sectors of the economy and promote the digital transformation of industries (Ministry of Economy and Finance of Korea, 2020[13]).

Spain

Connectivity and 5G have been identified as the key pillars for economic recovery and the main levers for the digital transformation of Spain. On 27 April 2021, the Government of Spain published the Recovery, Transformation and Resilience Plan, designed for the management and development of the European Recovery Funds - Next Generation EU - which amount to the receipt of EUR 140 billion (USD 159.8 billion)[14] in transfers and credits over the period of 2021 to 2026 (Government of Spain, 2021[14]). The Plan, according to the President, is “the most ambitious in Spain's recent economic history.” The investments will mobilise close to EUR 70 billion (USD 79.9 billion) over the 2021-23 period. Green and digital areas will be crucial, and will receive 39% and 29% of investments respectively; education and training will obtain 10.5% of the resources and R&D will receive 7%. In particular, EUR 4.3 billion (USD 4.9 billion) of public investment have been allocated for the 5G Roadmap for the period 2020-25 (EUR 883 million [USD 1008 million] already foreseen in the 2021 Budget) (Government of Spain, 2021[15]). With this plan, the Spanish government expects to mobilise additional EUR 24 billion (USD 27.4 billion) investments in 5G from the private sector (Government of Spain, 2021[14]).[15]

The United States

In the United States, President Biden announced on 31 March 2021 the proposal of the “American Jobs Plan”, which would allocate USD 100 billion (of a total USD 2 trillion) to expand broadband access to every American, if passed (The White House, 2021[16]). On 24 June 2021, the White House announced a “bipartisan proposal”, reducing the broadband infrastructure funds to USD 65 billion (The White House, 2021[17]). The United States Senate passed the bill at the beginning of August 2021, which was approved by Congress on 5 November 2021. It was signed by President Biden on 15 November 2021 becoming legislation as the “Infrastructure Investment and Jobs Act” (CNN, 2021[18]; The New York Times, 2021[19]; United States Congress, 2021[20]). Out of the USD 65 billion for broadband projects, most of the funding (i.e. USD 42.45 billion) will be devoted to improve broadband connections in currently underserved areas through the Broadband Equity, Access and Deployment Program (BEAD) to be administered by the National Telecommunications and Information Administration (NTIA, 2022[21]). Through this programme, states will receive federal grants for projects to build out broadband access for “unserved” and “underserved” areas where broadband connection exhibit lower speeds than 100 Mbps In addition, there is USD 1 billion of funding for “middle mile” broadband infrastructure such as undersea cables, internet exchange points (IXPs) to connect networks (NTIA, 2022[21]).

Governors of two states (i.e. California and Virginia) earmarked a combined budget of USD 6.7 billion to expand broadband in their respective states (FierceTelecom, 2021[22]). California’s legislature approved the deployment of a state-wide open access fibre network, providing a USD 3.23 billion funding, and allocated an additional USD 2 billion for the last mile to complement the open access network (ArsTechnica, 2021[23]) .

Earlier in 2021, the United States President announced the “American Rescue Plan Act of 2021”, which allocates USD 7.1 billion out of USD 1.9 trillion, for broadband connectivity and infrastructure funding. This recovery plan was approved by Congress, and includes the provision of emergency funding to upgrade federal information technology infrastructure and address the recent breaches of federal government data systems (White House, 2021[24]). Furthermore, on 25 February 2021, the communication regulator in the United States, the FCC, adopted a Report and Order that established the Emergency Broadband Benefit Programme, a USD 3.2 billion federal initiative to help lower the cost of high-speed Internet for eligible households during the on-going COVID-19 pandemic. At the time of writing, more than 6 million households in the United States had enrolled in this programme (FCC, 2021[25]) .The Emergency Broadband Benefit Program was developed by Congress in the Consolidated Appropriations Act of 2021 (FCC, 2021[26]).

The United Kingdom

The United Kingdom aims to provide GBP 900 million (USD 1.154 billion) for a range of 'shovel ready' local growth projects in England over the course of 2020 and 2021. These investments aim to enable local areas to invest in priority infrastructure projects to drive local growth and jobs and may include communication infrastructure projects (UK Government, 2020[27]).[16]

In March 2021, the UK Government launched the 'Project Gigabit' with GBP 5 billion (USD 6.41 billion)[17] of funds to ensure that 85% of the country is covered with Gigabit broadband by 2025 (UK Government, 2021[28]). On 2 August 2021, the UK Government expanded the scope of this infrastructure initiative and targeted broadband upgrades for 2.2 million locations across the country (UK Government, 2021[29]). The aim of "Project Gigabit" is to complement private sector investment and provide incentives for operators to extend coverage. Since the announcement in March 2021, the UK Government stated that a number of communication infrastructure providers have secured funding and accelerated plans to upgrade their networks in the next few years (e.g. Openreach and Virgin Media O2). For example, Openreach announced in May 2021 an increase of its fibre deployment target from 20 to 25 million homes by 2026 (FierceTelecom, 2021[30]). The UK Government expects that with these commercial investments, approximately 60% of the country will have access to gigabit speeds by the end of 2021, and well on track for their 2025 goal (UK Department for Digital Culture Media & Sport, 2021[31]).

Deployment status of high-capacity broadband networks

Continued investments in broadband networks are required to face increasing connectivity demands, to upgrade fixed and mobile networks and to extend coverage of high-capacity networks. In particular, upgrading networks to "future proof" technologies, such as fibre, are key to supporting increases in speed and capacity across all next generation technologies.

OECD countries increasingly invest in high-capacity fixed networks

Fibre has been the fastest growing fixed broadband technology in OECD countries over the past decade (Q2 2011-Q2 2021). The share of fibre in all fixed broadband subscriptions in OECD countries rose to 32.1% in June 2021, up from 13% ten years earlier, allowing for high-bandwidth online activities, such as video streaming services, multiple screens services and home-connected devices. Over the Q2 2011- Q2 2021 period, total fibre subscriptions have shown a constant annual growth of 13.8% (i.e. compound annual growth rate, CAGR), while DSL has decreased -2.8% annually during the past decade Figure 6). Austria, Belgium, Chile, Costa Rica, Greece, Ireland, Israel and t Italy all increased their total fibre connections by more than 50% in the Q2 2020-Q2 2021 period.

In more and more OECD countries, the majority of broadband connections are now fibre. By June 2021, twelve OECD countries had high-speed fibre making up 50% or more of their fixed broadband connections. In seven of these countries, fibre represented more than 70% of total fixed broadband subscriptions (i.e. Korea, Japan, Lithuania, Spain, Sweden, Iceland and Latvia).

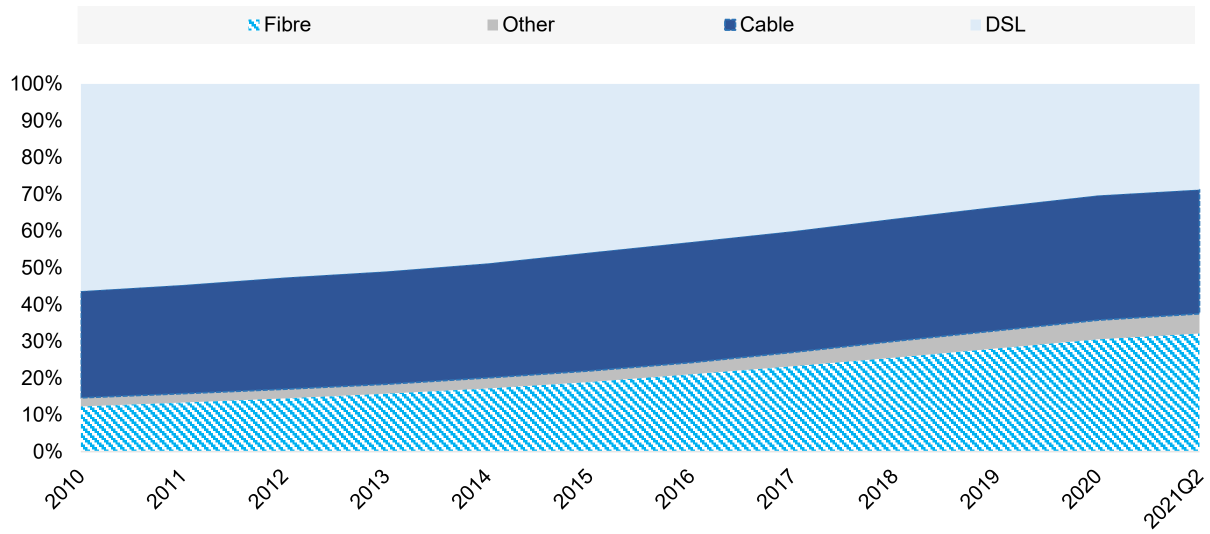
DSL technology has continued to decline, being gradually replaced by fibre. In June 2021 DSL accounted for 29% of total fixed broadband subscriptions, while fixed wireless access (FWA) represented only 2.3% and satellite broadband 0.5% of fixed broadband subscriptions in the OECD area.

Cable was the prevalent fixed broadband technology slightly surpassing fibre by June 2021, making up 33.8% of subscriptions, with a rise of 4% between Q2 2020-Q2 2021. Data over Cable Service Interface Specification (DOCSIS) is a standard that allows to deliver broadband on an existing Hybrid Fibre-Coaxial (HFC) cable technology. The standard has evolved to its current version DOCSIS 3.1. While DOCSIS 3.1

may provide a viable alternative to FTTH in terms of download speeds, it does not achieve symmetrical upload speeds. In the future, the scalability of these cable networks depend on the evolution of the DOCSIS standard. DOCSIS 4.0 envisions to achieve 10 Gbps symmetrical speeds and lower latency. It is currently in trials, with no available commercial equipment yet (Intraway, 2020[32]; CableLabs, 2020[33]).

Figure 6. Fibre has been the fastest growing fixed broadband technology over the past decade

Evolution of fixed broadband technologies in OECD countries, 2010-2021 (Q2)



Note: Fibre subscriptions data includes fibre-to-the-home (FTTH) also known as fibre-to-the-premise (FTTP), and fibre-to-the-building (FTTB); it excludes fibre-to-the-curb (FTTC) and fibre-to-the-node (FTTN). "Other" includes fixed wireless access (FWA), satellite and other technologies.
Source: OECD (2022[2]), *OECD Broadband Portal*, https://www.oecd.org/sti/broadband/broadband-statistics/ (database)

Broadband subscriptions in higher speed tier categories (advertised data as provided by countries) are becoming more common in OECD countries. For example, seventeen OECD countries had more than 50% of their subscriptions above 100 Mbps in December 2020 (Belgium, Chile, Denmark, Hungary, Iceland, Italy, Korea, Latvia, Lithuania, Luxembourg, Norway, Poland, Portugal, Spain, Sweden, Switzerland and United States). The share of fixed broadband subscriptions above 100 Mbps across the OECD (average across countries where data was available) was 47.6% in December 2020,[18] which compares to 41.8% a year earlier. In addition, 1 Gbps offers have been introduced in several OECD countries as well as first 10 Gbps offers. In December 2020, eight OECD countries had at least 5% of their overall fixed broadband subscriptions with advertised speeds above 1 Gbps (e.g. Canada, Denmark, Hungary, Iceland, Korea, Sweden, Switzerland and United States). The share of subscriptions above 1 Gbps reached 4.1% across the OECD in December 2020,[19] compared to 2.7% at the end of 2019 (OECD, 2022[2]).

While overall broadband speeds have been uniformly increasing across countries, important disparities still exist, often reflecting the technology mix in countries. Countries with a high share of fibre-to-the home connections, for example, such as Korea and Japan, tend to display a higher number of high-quality connections than countries that still rely on an important share of copper (xDSL) networks.

Availability and access to wholesale fibre connectivity may play a crucial role for the development of broadband networks of the future for two main reasons. First, a growth in fibre backhaul availability should help support projected capacity demands of these networks. Secondly, wholesale access to fibre can foster retail-based competition in both fixed and mobile broadband markets (OECD, 2021[34]). While there are many approaches used at the wholesale level of OECD broadband markets, there is an increasing emergence of fixed- and mobile wholesale-only providers that play an important role to provide fibre backhaul connectivity. Examples of wholesale (vertically separated) operators can be found in Australia, Czech Republic, France, Ireland, Italy, Mexico, New Zealand, Sweden, Switzerland, and Singapore (OECD, 2019[35]).[20]

Recent developments in regional and municipal fibre networks in the OECD area

Recent trends in regional and municipal fibre networks suggest that some cities and regions across the OECD view wholesale fibre as a utility. Municipal networks are high-speed networks that have been fully or partially facilitated, built, operated or financed by local governments, public bodies, utilities, organisations, or co-operatives that have some type of public involvement (OECD, 2015[36]).

Fibre regional and municipal networks can be designed as open access dark fibre networks. If designed and managed well, i.e. if these networks provide wholesale capacity on fair and reasonable terms, in a transparent and non-discriminatory way, this model enables competition and innovation at the retail level. Open access fibre networks may also facilitate the transition of cities to smart cities, given the need to connect numerous objects, and devices, to high-capacity networks.

Regional open access fibre networks are currently under development. For example, the region of Brussels, which counts on an extensive fibre network that was only used to date by regional and local public authorities, plans to open up its fibre network to commercialisation and lease 80% of its capacity (Samian, 2021[37]). Meanwhile, KKR, a private equity firm announced a deal with Telefónica Colombia to create an open access fibre network, based on Telefónica’s existing network, with KKR being the majority shareholder (Telefónica, 2021[38]; La República, 2021[39]). Telefónica has also reached similar partnerships to deploy fibre through an open wholesale company in Brazil with CDPQ (Telefónica, 2021[40]), and in Germany with Allianz (Telefónica, 2020[41]).

In the United States, California aims at building a state-wide, open-access fibre network to function as “middle-mile” for all ISPs which would initially target locations where there is no residential access to 25 Mbps download and 3 Mbps upload speeds (Box 1) (ArsTechnica, 2021[23]).

Previous OECD work looked at municipal fibre networks, highlighting examples across the OECD. In the United States, Chattanooga, Tennessee provides an example of a successful municipal network by the Electric Power Board (EPB) which is currently offering advertised speeds of up to 10 Gbps (Quartz, 2021[42]; BroadbandNow, 2021[43]). LUSfiber in Louisiana is a similar case, which has been a utility provider for 120 years. After winning a Supreme Court case in 2009, LUSfiber was able to operate as an ISP in Lafayette, Louisiana (Talbot, Hessekiel and Kehl, 2018[44]). Like EPB in Chattanooga, LUSfiber is offering advertised speeds up to 10 Gbps (BroadbandNow, 2021[45]). Nevertheless, there are still hurdles for municipal fibre networks in the United States, as 17 states have legal restrictions that render it difficult (or even ban) local governments wishing to offer broadband services if there are commercial providers already present in the market (BroadbandNow, 2021[46]).

Upgrading to “future-proof” technologies with sustainability considerations in mind

Another reason to support the transition to fibre is not only the “future proof” aspects of symmetrical broadband speeds and the scalability of networks, but also environmental sustainability considerations. Several reports suggest that FTTH networks may prove to be more energy efficient than traditional copper connections. A report by the French communication regulator, Arcep, cited that fixed fibre networks consumed on average 0.5 Watts (W) per line, which translates into three times less energy consumption than an ADSL line (1.8 W) and four times less than a traditional PSTN line (2.1 W) (Arcep, 2019[47]). This finding was referenced by one of the main operators in Europe, Orange, when expressing its support for the European Green Deal and reiterating the communication industry’s commitment for sustainable broadband networks. Orange has pledged to become carbon neutral by 2040, and mentioned that a way governments can help support the communication industry's efforts toward lowering greenhouse gas emissions is by easing the deployment of "state-of-the-art" communication networks, such as FTTH and 5G, and by supporting voluntary network sharing agreements to reduce the environmental impact of deployment (Orange, 2020[48]).

In recent years, the communication industry has undertaken various efforts to promote the sustainability of networks (Box 2). Three large operators in Europe, for example, have categorised fibre roll-out as part of their environmental sustainability agenda, and have linked "green" credit funding to achieve this objective. KPN, a fixed and mobile operator in the Netherlands, refinanced its existing credit line by tying the new interest rates to the company's performance in its sustainability strategy, such as fibre deployment and reduction of energy consumption (Telecoms.com, 2021[49]). KPN plans to invest EUR 3.5 billion (USD 3.99 billion)[21] by 2024 as it aims for nationwide fibre deployment (Telecom Review, 2020[50]). In a similar way, the Swedish operator Telia used two "Green Bonds" fund for fibre investments given that the company sees fibre roll-out as energy saving and as a key enabler of IoT solutions that help reduce carbon emissions (Telecoms.com, 2021[49]). For example, fibre-connected street furniture may enable IoT sensors across cities to optimise energy consumption and traffic management resulting in less CO_2 emissions. In the same vein, Telefónica issued its first "sustainable perpetual hybrid" bond amounting to EUR 1 billion (USD 1.142 billion)[22] in February 2021. This bond will be used by the company to finance environmental projects in Spain, Germany and Brazil, focusing on the transformation of copper networks to more reliable and energy-efficient fibre (i.e. 85% more energy efficient) (Telefónica, 2021[51]).

Fibre-connected sensors in Sweden have already helped optimise energy use in buildings. According to a report by WIK, Sisab, the entity responsible for maintaining Stockholm's schools, was able to save 35% of energy between 2012 and 2019 by using "smart building" solutions supported by fibre (WIK-Consult, 2020[52]). This report also assessed the environmental effects of changes in the fixed broadband technology mix in Europe. Under the assumption that current power sources remain unchanged, a complete migration from the current fixed broadband technology mix in the European Union to 100% fibre would reduce CO_2 emissions from 15.5 million tons to 3.2 million tons per year (i.e. a 79% yearly reduction) as FTTH is more energy efficient. Moreover, the transition of all broadband connections in Europe to point-to-point (P2P) FTTH would further reduce annual greenhouse gases to 1.1 million tons per year, which represents a reduction of more than 90% of total emissions per year compared to the current fixed broadband technology mix (WIK-Consult, 2020[52]).

Box 2 Communication industry efforts towards ensuring the sustainability of networks

The GSMA reported in January 2021 that 31% of mobile operators (measured by subscriptions) committed to net-zero carbon emissions by 2050 or earlier, placing the industry "at the highest levels of private sector ambition" (Mobile World Live, 2021[53]). In addition, the GSMA developed a Sustainability Assessment Framework in collaboration with Yale University to better understand mobile operators' efforts in social and environmental sustainability (GSMA, 2021[54]).

The Next Generation Mobile Networks (NGMN) Alliance, an open forum founded by mobile network operators,[23] is working towards aligned "green targets" concerning environmental sustainability across the communication ecosystem. The project strives to address the impact of the mobile ecosystem on the environment by improving energy efficiency, reducing carbon emissions and increasing the use of recyclable materials (NGMN, 2020[55]).

In the United Kingdom, Vodafone UK has announced an ambitious target for net-zero carbon emissions across its operations in the country by 2027. Vodafone's fixed and mobile networks connect 16 million people in the United Kingdom, and powering these networks accounts for 95% of its total energy usage.

In July 2021, the company reached the milestone of having 100% of its business in the United Kingdom– including its network, data centres, retail stores and offices –powered by electricity from renewable sources (Vodafone UK, 2021[56]).

At a global level, Orange committed to net-zero carbon emissions by 2040 of its networks for the entire Group footprint through its strategic plan "Engage 2025" (Orange, 2020[57]). Orange has determined the following intermediary objectives:

- Reducing CO_2 emissions by 30% between 2015 and 2025;
- Using more than 50% renewable electricity by 2025.

Telefonica's Executive Committee approved the goal of having net zero emissions by 2025: a 90% reduction in energy consumption per unit of traffic (MWh/PB) and net zero emissions in the company's four main markets, going one step further the Paris Agreement. By 2040, Telefónica has committed to fulfil these goals in both operations in Latin America and its full value chain and the company has already made progress. In Europe, Brazil and Peru, Telefonica networks are based 100% on renewable sources of energy, with the aim of having all networks at global level based on renewables by 2030. Furthermore, Telefonica is boosting the transition to fibre, which it considers 85% more energy efficient than copper, and is accelerating 5G deployment, which the company claims is 90% more energy efficient than 4G networks (Telefónica, 2021[58]; Telefónica, 2021[51]).

Sources: Mobile World Live (2021[53]) "Mobile industry reaches climate action breakthrough" https://www.mobileworldlive.com/featured-content/top-three/mobile-industry-climate-breakthrough; GSMA (2021[54]), "The GSMA Sustainability Assessment Framework 2020", https://www.gsma.com/betterfuture/resources/the-gsma-sustainability-assessment-framework; NGMN (2020[55]), "5G White Paper 2 by NGMN Alliance", https://www.ngmn.org/work-programme/5g-white-paper-2.html; Vodafone UK (2021[56]), "Vodafone hits UK renewable milestone on the road to 'net zero'", https://newscentre.vodafone.co.uk/news/vodafone-hits-uk-renewable-milestone-on-road-to-net-zero-carbon-emissions/; Orange (2020[57]) "Engage 2025: our strategic plan", https://www.orange.com/en/node/1259; Telefónica (2021[58]), "Energy and Climate Change", https://www.telefonica.com/en/web/responsible-business/environment/energy-and-climate-change-2; Telefónica (2021[51]), "Telefónica issues the first sustainable hybrid bond of the telco sector, amounting to 1 Billion euros", https://www.telefonica.com/en/web/press-office/-/telefonica-issues-the-first-sustainable-hybrid-bond-of-the-telco-sector-amounting-to-1-billion-euros.

Towards 5G commercial offers across the OECD, private 5G networks and standalone (SA) 5G

The fifth generation of mobile networks, 5G, refers to networks designed to support enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), as well as critical communications and applications (ultra-reliable and low-latency communications, URLLC).[24] These networks have the potential to provide increased data transfer speeds, lower latency, combined with heightened processing power. 5G may further allow services and objects with diverse quality features to be catered for in the same network (e.g. through network slicing) (OECD, 2019[59]).

OECD countries have made significant progress in 5G commercial deployments. By June 2022, 5G commercial services were available in 36 out of the 38 OECD countries considering both FWA and mobile deployments (Table 1.A.1 in the Annex). The coverage of 5G within OECD countries is constantly evolving as most operators are currently expanding their networks. Most commercial 5G services are currently based on non-standalone (NSA)-5G deployments for enhanced mobile broadband, relying on presently deployed 4G core networks and using NSA-5G standards in the radio interface (5G New Radio).

In some OECD countries, operators are offering 5G as an alternative to fixed broadband through fixed wireless access (FWA) solutions (e.g. Australia, Colombia, Italy, Switzerland and the United States).[25] For example, Optus in Australia offers FWA 5G to selected areas of the country (Optus, 2019[60]), and in Switzerland, Sunrise offers to replace slow fixed broadband lines with its offer "Home 5G". In the

United States, a similar move can be observed by Verizon with their "5G Home" offer available in 62 cities as of December 2021 (Verizon, 2021[61]). In Italy, FastWeb launched its 5G-FWA commercial service in 50 cities at the end of 2020, reaching 400 cities in February 2022 (Qualcomm, 2022[62]; Fierce Wireless, 2020[63]). According to the GSMA, at the end of 2020 approximately 50% of the mobile communication sector had launched 4G-FWA services, and as of January 2021, around 40% of the 135 5G commercial launches worldwide contained an FWA offering (GSMA Intelligence, 2021[64]). Nevertheless, 5G deployments, in particular of this nature, will increasingly require high-capacity fibre backhaul connectivity to be extended closer to the end-user's premise (OECD, 2020[65]).

An open question, for the moment, is to what extent FWA solutions, including wireless solutions based on 5G, will be able to provide a viable alternative to fixed broadband technologies, such as FTTH. While the vast majority of OECD countries currently conceive mobile and fixed communication services as complementary rather than substitutes, some potential advantages of 5G over 4G have led a number of industry experts to believe that 5G FWA networks could be able to compete with wireline broadband services in the future (OECD, 2019[59]). According to these experts, FWA in some circumstances could help bridge connectivity gaps in rural areas. However, some remain sceptical of the short-term potential of 5G-FWA to compete with fixed broadband services, namely given that 5G roll-out requires fibre to be deployed deeper into networks, and in many rural areas, towers and cell sites also need to be deployed due to network densification requirements by the use of higher spectrum bands. Therefore, even as 5G- FWA starts to be deployed in some urban areas in OECD countries, considering it a viable alternative (or substitute) of other fixed broadband technologies is premature.

While many operators in the OECD area are predominately relying on low and mid-range spectrum for 5G commercial network deployments (e.g. 700 MHz and 3.5 GHz frequency bands), some operators have started to deploy commercial networks making use of higher spectrum frequency bands, i.e. millimetre (mmWave) spectrum, in Australia, Japan and the United States.

The use of mmWave spectrum for 5G mobile networks has to overcome major technical challenges, as these can be susceptible to attenuation from obstacles and present difficulties penetrating walls to reach indoors (Agnoletto et al., 2021[66]). This may necessitate the use of complementary connectivity solutions to resolve indoor network coverage, as seen in recent partnerships that have arisen in the United States between mobile operators and neutral hosts (i.e. "a service provider that builds and operates an integrated technology platform that is solely for sharing purposes" (Lähteenmäki, 2021[67])) offering indoor solutions or for dense public spaces. Another question being raised is whether mmWave 5G resembles Wi-Fi connectivity solutions. In one study, Opensignal found that mmWave 5G (i.e. 28 GHz and 39 GHz spectrum bands) in the United States was almost thirty times faster than the public Wi-Fi tested, but with similar reach given propagation features of this spectrum band (Opensignal, 2021[68]). However, public Wi-Fi, as noted by Opensignal's study, presents some differences with respect to cellular connectivity partially explaining the weaker download speeds.[26] (See more on the complementarity of Wi-Fi and cellular connectivity in the section *Complementarity of fixed and mobile networks*).

The benefits of the use of mmWave spectrum (high capacity and the availability of spectrum) may help support a wide range of applications requiring low-latency, high-bandwidth services, such as mission- critical or virtual reality (VR) and augmented reality (AR) applications. In November 2020, Nokia, Elisa and Qualcomm achieved a 5G speed record (8 Gbps) in Finland in a trial using mmWave spectrum (Nokia, 2020[69]). In the United States, commercially deployed mmWave 5G networks exhibited an average download speed of 640 Mbps compared to 64 Mbps experienced in "nationwide" sub-6 GHz 5G networks (Opensignal, 2021[68]).[27]

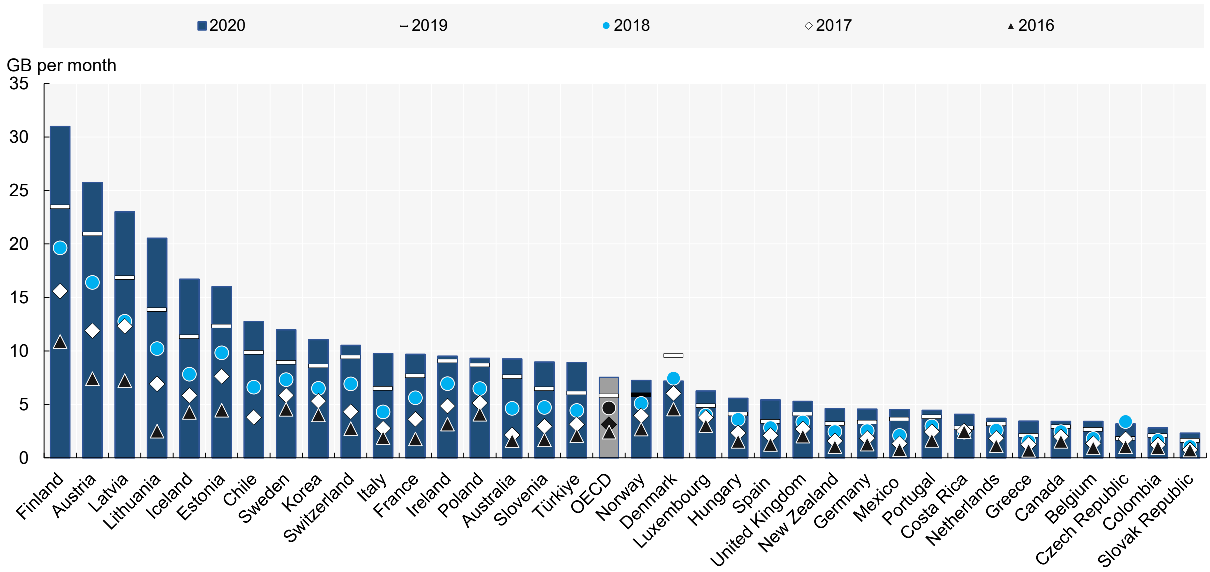
Given the network densification requirements of small cell deployment for the use of mmWave deployments, a key question is whether they are a cost-effective solution for 5G. In January 2021, GSMA Intelligence published a report analysing the cost-effectiveness of mmWave spectrum for 5G deployments. The report findings mention that while mmWave bands are not suitable for every purpose, they can be very cost-effective when combined with mid-band spectrum for many use cases, in particular for applications featuring higher shares of upload traffic, such as gaming and video conferencing. For example, for FWA scenarios, the deployment costs of using 3.5 GHz combined with mmWave are lower than those relying solely on 3.5 GHz spectrum (Agnoletto et al., 2021[66]). These developments suggest that operators in the OECD may opt in the future for the use of multiple bands that will complement each other to accommodate a variety of use cases, as was the case for previous mobile network generations.[28] In addition, new trials are underway on spectrum "carrier aggregation" (i.e. aggregating several frequency bands with the aim of achieving higher speeds and increased coverage), whereby operators are experimenting the joint use of mmWave and lower band spectrum (sub-6 GHz) with devices that can combine both technologies on a single chip (FierceWireless, 2021[70]).

Evolving nature of mobile traffic with 5G

As OECD countries witness an acceleration of 5G commercial deployments, monthly mobile data traffic use continues to grow. In 2020, mobile data usage soared by more than 30% on average across the 35 OECD countries for which data were available, with 29 countries showing an increase of over 20% (OECD, 2022[1]). Finland remains the OECD leader for data consumption at a total of 31 Gigabytes (GB) per subscription per month by the end of 2020, followed by Austria (25.8 GB), Latvia (23 GB), Lithuania (20.5 GB), Iceland (16.7 GB), Estonia (16 GB), Chile (12.8 GB) and Sweden (12 GB). On average, users downloaded 7.5 GB of data per month per subscription in 2020, up from 5.8 GB in 2019 in those countries for which data was available (Figure 7).

Figure 7. Mobile data usage continues to grow in the OECD area

Mobile data usage per mobile broadband subscription per month, 2020



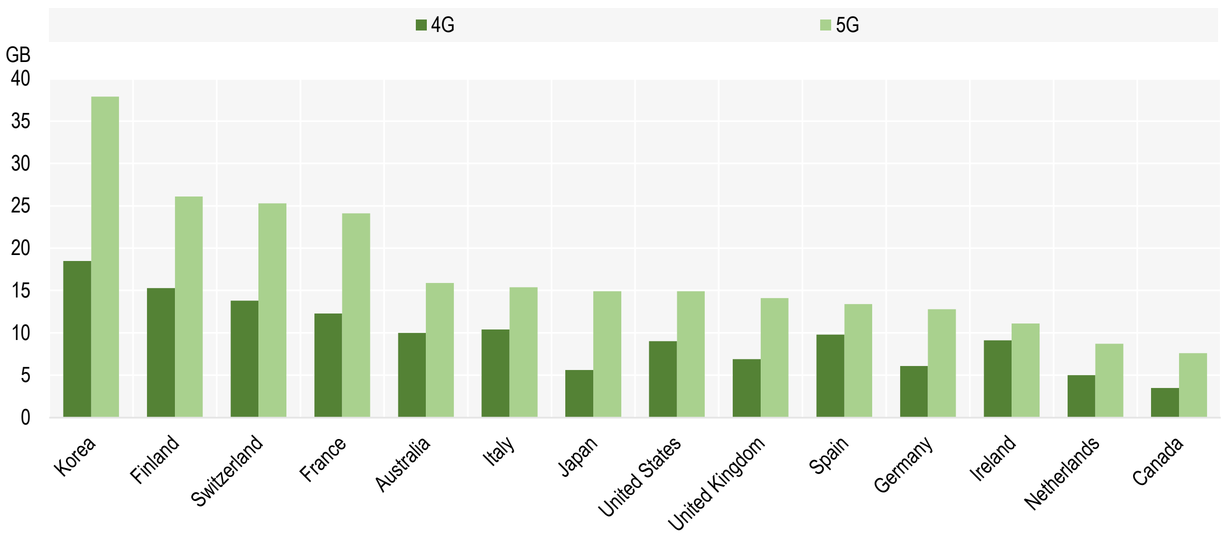
Note: The multiplier 1024 is used to convert TB into GB; the total amount of GB is divided by the yearly average number of Mobile broadband subscriptions. Australia: Data reported for December 2018 and onwards is being collected by a new entity using a different methodology. Figures reported from December 2018 comprise a series break and are incomparable with previous data for any broadband measures Australia reports to the OECD. Data for Switzerland are preliminary. Data for 2020 are not yet available for Japan and United States. OECD average includes estimates.
Source: OECD (2022[2]), OECD Broadband Portal, https://www.oecd.org/digital/broadband/broadband-statistics/ (database)

5G can be regarded as a driver for mobile data consumption. For example, in Korea, according to data by the National Information Society Agency (NIA) and the Ministry of Science and ICT (MSIT), monthly average data traffic in September 2020 was 25.7 GB for a 5G subscription compared to 9.96 GB for 4G (i.e. 2.6 times more traffic than for a 4G user). According to Opensignal for the OECD countries where data was available, 5G smartphone users consumed on average 2.7 times more monthly mobile data than 4G users in June 2021 (Opensignal, 2021[71]) (Figure 8).

This increase in data consumption might reflect the fact that 5G enables the use of more "data intensive" applications such as videoconferencing, streaming and gaming applications. Although services such as Augmented Reality (AR) and Virtual Reality (VR) primarily rely at present on fixed broadband connections, there may be also an increase in traffic of these services in 5G networks. For example, for one operator in Korea (LGU+), AR and VR accounted for 20% of mobile traffic by May 2019 (Mobile World Live, 2019[72]). Likewise, the Korean operator, SKT, reported that by the end of February 2020, new 5G subscribers used seven times more VR services, 3.6 times more video streaming services and 2.7 times more gaming applications compared to 4G subscribers. New services featuring AR and VR functions already account for 20% of 5G traffic in Korea, compared to just 5% for 4G subscriptions (OECD, 2020[65]). In the near future, the demand on communication infrastructures is only expected to further increase with advanced AI systems and critical IoT applications entering the market (e.g. fully automated vehicles).

Figure 8. 5G users consume on average 2.7 times more traffic than 4G users, Opensignal

Average monthly mobile data consumption per user for 4G and 5G, June 2021



Note: Data collection period: 1 January- 31 March 2021.
Source: Opensignal (2021[71]), "Quantifying the Impact of 5G and Covid-19 on Mobile Data Consumption", https://www.opensignal.com/reports/2021/06/quantifying-the-impact-of-5G-and-covid-19-on-mobile-data-consumption

Developments in 5G private networks

Around the OECD, 5G private networks have been emerging in several countries. Private 5G networks are local or non-public 5G networks, dedicated to the owner of the network. A local access network (LAN) will use 5G to create a dedicated network with unified connectivity and optimised services within a specific area (e.g. a factory or a plant) (Kavanagh, 2020[73]). Companies from different industrial sectors relying on smart factories or industrial IoT applications have raised interest in such networks that could enhance network security. Local 5G private networks can be fostered either by enterprises accessing directly spectrum resources and managing their network, or by mobile operators offering such capabilities to industry verticals.

5G private networks in smart factories around the world

In Germany, Telefonica and Mercedes Benz 5G Automobile Factory opened the “Factory 56” in Sindelfingen (Germany) on 4 September 2020. The factory is fully digitalised with a 5G WLAN network (Daimler, 2020[74]). Vodafone, together with Ericsson, deployed a private network for e.GO, an electric vehicle company in Germany. Mobile network slicing is being used to dedicate a slice of spectrum for e.GO’s ‘Industry 4.0’ factory to ensure that critical manufacturing processes are not interrupted. Communication is ensured through encryption. The e.Go factory also uses multi-access edge computing (MEC) (IoT Automotive News, 2020[75]).

In the United States, GM inaugurated “Factory Zero” in Detroit on 20 November 2020 which uses a dedicated 5G network. The company expects that the “5G network will give the various connected machines and devices in the plant, such as robotics, sensors and the Automated Guided Vehicles (AGV) […] a fast and reliable network to operate on” (GM Authority Blog, 2020[76]).

Reserving spectrum and spectrum sharing for local use and 5G private networks

A major hurdle for the development of 5G private networks is access to spectrum on appropriate terms or viable solutions provided by operators or systems integrators. Some countries have started the process of opening up spectrum for local use in specific bands, which would enable the deployment of private 5G networks (Kavanagh, 2020[73]).

In Germany, the communication regulator Bundesnetzagentur (BNetzA) set aside 100 MHz of spectrum in the 3.7-3.8 GHz band specifically for industrial use for local campus licenses. By September 2021, it awarded 148 licences to applicants for deploying private 5G networks, almost double compared to the 74 licences it had awarded in September 2020 (Bundesnetzagentur, 2021[77]).

In the United Kingdom, Ofcom published in July 2021 their spectrum management strategy for the next decade (Ofcom, 2021[78]). Ofcom seeks to support the growing diversity of wireless services and providers by considering further options for localised spectrum access when authorising new access to spectrum. It had already introduced a new licensing system in July 2019 covering localised access to the 3.8-4.2 GHz band, 1800 MHz and 2300 MHz and mmWave shared spectrum. In addition, Ofcom has also introduced a local access licence, which enables shared use of spectrum that is already licensed on a national basis to a mobile network operator (MNO) in locations where a particular frequency is not being used (Ofcom, 2019[79]).[29]

Another trend in spectrum management is fostering coordinated sharing of licensed bands among operators to boost 5G deployments. Such is the case of the 3.5 GHz band in the United States, also known as Citizens Broadband Radio Service (CBRS), which was approved for wireless use by the FCC in January 2020. This band operates on a three-tiered spectrum authorisation framework to accommodate a variety of commercial uses on a shared basis with incumbent federal and non-federal users of the band (FCC, 2021[26]). In a similar move, several communication regulators around the OECD are looking into coordinated approaches of licensed bands for the proliferation of 5G local networks (e.g. Australia, France, Germany, Japan, the Netherlands, and the United Kingdom) (FierceWireless, 2021[80]).

Other private networks

In addition to mobile private networks, there are also advances in enterprise owned fixed broadband private networks, such as SD-WAN.[30] A wide-area network (WAN) is a collection of local-area networks (LANs) or other networks that communicate with one another, with the Internet being the largest WAN (Cisco, n.d.[81]). The traditional wide area access (WAN) function was to connect users at the branch or campus to applications hosted on servers in the data centre, typically through dedicated virtual private networks (VPN) to help ensure security and reliable connectivity. In a cloud-centric environment, with applications distributed across the World, this no longer works; therefore WAN architecture evolved to SD-WAN, a software-defined approach to managing the WAN (Cisco, n.d.[81]). Further to these developments in IT, several offerings of secure access SD-WAN are underway combining SD-WAN with cloud-based solutions that have embedded additional security features (e.g. Secure Access Service Edge, SASE), which may become an important networking technology for enterprises.

Deployments of Standalone (SA) 5G networks

While in its initial stages, 5G is being deployed in the radio access network to provide enhanced mobile broadband (eMBB) with higher speeds and more capacity for applications such as virtual and augmented reality, in a second stage, the introduction of 5G core networks is enabling bespoke business applications across different sectors, such as health, energy, mining, robotics, or automotive. Consequently, the second phase of deployment of 5G networks also focuses on ultra-reliable and low-latency communications (URLLC), and massive machine type communications (mMTC).[31] One of its main features, network slicing, allows to tailor connectivity to diverse use cases and applications across all sectors of the economy, including innovative AI and IoT business models.

These transformational aspects of 5G are likely to commence with “standalone” (SA) 5G networks. The difference between NSA-5G and SA-5G is that the former is built using current 4G core networks, while the latter requires deploying an entire new network end-to-end. Namely, SA-5G uses both the 3GPP core network architecture for 5G (i.e. 5G Core, 5GC), as well as the 5G radio interface (i.e. New Radio, NR).

According to the report by the Global Mobile Suppliers Association (GSA), 99 operators in 50 countries worldwide were investing in public SA-5G networks by the end of 2021 (i.e. trials, planned or actual deployments), compared to 481 operators worldwide investing in 5G overall. In addition, 20 operators had launched SA-5G networks worldwide as of December 2021 (GSA, 2022[82]). In July 2021, the GSMA reported that 38% of mobile network operators (MNOs) had announced SA-5G launches and deployment plans, as they consider it key for achieving success with enterprises (GSMA Intelligence, 2021[83]).

There are several developments in SA-5G network deployments in OECD countries. For example, in Australia, Telstra’s 5G coverage reached 75% of the population by June 2021, and the company announced it would upgrade its 5G radio access network (RAN) footprint across Australia by connecting it to a cloud-native 5G Core (5GC) network with the aim of handling SA-5G traffic once a sufficient range of suitable devices would be available in the market (RCR Wireless, 2021[84]; GSA, 2021[85]). In Colombia, DirectTV launched SA-5G for FWA in certain parts of Bogota in 2020 (GSA, 2021[85]). The company’s mobile operation is expected to be acquired by Telefónica Colombia, according to a business negotiation conducted in May 2021, pending for confirmation from public authorities s (Forbes Colombia, 2021[86]).

In Finland, Telia launched in November 2021 the first commercially available SA-5G core network in the Nordics and Baltic countries using Nokia as a partner. This network will allow making use of network slicing, and was launched in 20 geographical areas of Finland (Telia, 2021[87]). Nokia started in 2021 to deploy its SA-5G core for Telia in Denmark, Estonia, Lithuania, Norway and Sweden (Nokia, 2021[88]).

In Germany, Vodafone announced in November 2021 that it had activated a large area of the country with SA-5G (i.e. 35 million people). The company is aiming to connect 60 million people in 2022 and reach full SA network coverage by 2023, with the expectation of saving 40% in energy consumption (Vodafone DE, 2021[89]). In Korea, KT claimed launching Korea’s first commercial SA-5G network on 15 July 2021 (Mobile World Live, 2021[90]). The other two Korean operators have plans to deploy SA-5G networks in the near future.

In the United States, T- Mobile started to deploy SA-5G nationwide in August 2020 using the 600 MHz (Telecoms, 2020[91]). In a similar move, Verizon and AT&T are testing their SA-5G core networks with deployment plans in 2022 (FierceWireless, 2021[92]).

In the United Kingdom, Vodafone displayed in July 2020 a SA-5G deployment at Coventry University, initially being used to train nurses using virtual reality (RCRWireless, 2020[93]). In June 2021, Vodafone launched SA-5G commercial pilots in London, Manchester and Cardiff (Vodafone UK, 2021[94]).

In non-OECD countries, there are also examples of SA-5G launches. For example, in Singapore, Singtel launched its SA-5G network in May 2021 (Singtel, 2021[95]). In the People's Republic of China (hereafter "China"), all three operators (China Mobile, China Unicom and China Telecom) have launched SA-5G networks. China Mobile has deployed or upgraded 400 000 base stations to support standalone services, while China Telecom announced SA- 5G service to be launched in more than 300 cities (GSA, 2021[85]).

Standalone 5G deployments, with the use of network slicing (i.e. the capacity of catering to a diversity of applications over one physical network through several "virtual" layers or slices), could enable a vast range of applications across all sectors. A recent example in the electricity sector is Vodafone UK's announcement in July 2021 of a partnership with UK Power Networks, the country's largest electricity network operator. Vodafone UK and UK Power Networks are trialling a "smart substations"[32] project called "Constellation", to manage the electricity grid in real time. These substations, that transform voltage in the electricity grid, will communicate with each other over a dedicated, highly secure slice of Vodafone's SA-5G network. If rolled out across the United Kingdom, this solution could save 63 702 tonnes of CO_2 by 2050 – equivalent to the CO_2 emissions of 38 607 return flights from London to New York (Vodafone, 2021[96]). In the United States, Verizon expects that once it deploys SA-5G, the company will be able commercialise a broad range of new applications (e.g. IoT, AR, VR and mixed reality applications, etc.) given that standalone 5G would allow for higher bandwidth and lower latency combined with network slicing (Mobile World Live, 2020[97]).

An enabler of the deployment of SA-5G networks is a feature called dynamic spectrum sharing (DSS), which is a tool helping operators balance spectrum between 4G and 5G traffic, in real-time, removing the need of spectrum re-farming. That is, DSS allows for 5G to run simultaneously on the same spectrum bands as 4G, and can be considered an "intra-operator" type of spectrum sharing[33] as it allows the operator to dynamically manage its frequency resources among users/devices based on network conditions and traffic needs (RSPG, 2021[98]). For example, Verizon in the United States announced in October 2020 that it activated a new "nationwide" 5G service, covering 200 million people by using Dynamic Spectrum Sharing (DSS) technology (Comms Update, 2020[99]). Developments on DSS and on SA-5G network deployments in OECD countries will be interesting to follow in upcoming years.

Technological trends shaping the broadband networks of the future

Networks of the future must meet at least two main demands: the ability to handle an increase in data transmission requirements, and an evolving and broad array of use cases and applications. To increase the performance of networks and optimise their operation, while keeping enough flexibility to cater to new business models, communication service providers are embracing four main trends made possible through different technological advances. These main trends are: i) a move towards virtualisation, ii) increased "openness" (e.g. the use of interoperable non-proprietary hardware and software components, including interfaces), iii) an integration of cloud services, and iv) an increased use of AI systems in networks. While these trends can be perceived in the developments of fixed and mobile networks, the section concentrates on mobile networks to exemplify and further describe these trends.

Trends in virtualisation, openness and the integration of the cloud illustrated through the lens of 5G

The next evolution of broadband networks will perhaps be pivotal for AI systems and IoT application business models to see the light of day, especially when it comes to mobile applications. The main reason for this is the fact that new functions in 5G networks, such as network slicing, would allow one physical network to cater to a diversity of applications with different capacity requirements through the "virtualisation" of the network in several layers (or slices).

A move towards virtualisation of networks

In broad terms, network virtualisation is the transformation of a network that was once hardware-dependent into a network that is software-based. Network virtualisation can combine multiple physical networks to one virtual, software-based network, or it can divide one physical network into separate, independent virtual networks (VMware, 2021[100]).

Most communication service providers use some sort of network function virtualisation (NFV) (RedHat, 2021[101]). Network function virtualisation (NFV) decouples network functions, such as network address translation (NAT), firewalling, intrusion detection, domain name service (DNS), and caching from proprietary hardware appliances so they can run in software (OECD, 2019[59]).[34] Virtualising network functions allows them to be commonly pooled, enabling more efficient use of resources and the ability to adjust resources according to changing demands (ETSI, 2014[102]). Therefore, introducing network virtualisation may provide advantages to operators in terms of adding flexibility and an increased ability to cater to diverse use cases, in particular in the Radio Access Network (RAN). It can further spur innovation in different network function areas.

Complementary to NFV, software-defined networks (SDN) separate the control plane from the user plane (also called "forwarding" or data plane) in the network (SDxCentral, 2016[103]).[35] Namely, SDN transfers network functions, such as switching, from the hardware to the software layer. For example, a software-defined network for the transport network could make it possible to configure a virtual private network (VPN). SDN introduces automation, as one control panel, called an SDN controller, can manage and define policies for the whole network. The centralisation of control reduces operational costs by automating software updates and changes in policy across the network. Together, NFV virtualises the different components of networks and SDN centralises network control.

These two technical developments, NFV and SDN, in combination make network slicing in mobile networks possible. They have been standardised by ETSI, and are the basis to allow a network resource to be controlled in a decentralised manner by third parties that manage a "virtual slice" of the network that meets a given set of requirements (i.e. network slicing) (OECD, 2019[59]). Both of these developments have been trialled for 4G, but are available features for 5G from the start (Cave, 2018[104]). Software-defined access networks (SDAN) also leverage the benefits of SDN and NFV for fixed networks, including cost savings, better network management, and flexibility (Nokia, 2021[105]).

In addition, NFV and SDN are complementary to cloud architectures and are increasingly interwoven. SDN can manage cloud-based infrastructure and provide useful visibility and automation into the entire network, even in hybrid cloud environments whereby a network includes both a public and private cloud. NFV infrastructure can all be hosted on the cloud, and can use cloud-native software.[36] Cloud native is a term used to describe "architectures and technologies that consistently, reliably and at scale fully take advantage of the possibilities of the cloud to support cloud-oriented business models" (Ericsson, 2021[106]).

Network slicing

5G will accommodate a large variety of scenarios in terms of usage; therefore, the network architecture needs to be flexible to meet this demand. One way to introduce this flexibility is through network slicing, which would allow operators to create customised virtual networks for specific applications and quality of service (QoS) requirements. For example, industrial users may have different needs than emergency networks. This might pave the way for innovative IoT and or AI business models, whereby diverse applications have different network requirements.

This "virtualisation" is a key characteristic proposed for 5G networks (OECD, 2019[59]) as it would allow access to new business segments without a significant cost increase. Several parameters may vary between different slices of the network such as latency, throughput (i.e. how much data is transferred from a source in the network at a given time), the degree of mobility, the level of security, business model (operator vs. customer-managed), and geographical distribution. In this sense, operators may be able to charge differently based on service characteristics of the slice. A Service Level Agreement (SLA), for example, could be set up where the operator agrees to deliver a service at a given quality within a slice. In addition, network slicing could be used for Radio Access Network (RAN) sharing between operators (OECD, 2019[59]). The full potential of network slicing, however, will probably occur when the core network is replaced or upgraded in the transition from 4G networks to 5G, that is with standalone 5G networks (OECD, 2019[59]).

Therefore, the main advantage of network slicing is the ability for operators to allocate the required network resources for a specific use case, providing specific quality features for different applications that run on the network, which might, in some cases, translate into efficiency gains and lower costs. For example, one slice could be devoted to connected IoT sensors that need high-coverage, with specific latency and throughput requirements, while a different slice can be used for critical applications needing low latency and high throughput. This would enable networks to cater "on a per service basis", increasing overall network efficiency with potential reductions in operational and capital expenditures (OPEX and CAPEX). On the other hand, there are also challenges to implement network slicing. Network slicing is usually applied in the core part of the network, although in some cases in can be based in the RAN, and thus requiring SA-5G deployments. Interoperability needs to be tested and ensured, requiring industry consensus on the implementation of the network slicing in practice. Finally, although it offers more efficient use of shared radio resources, it also depends on more sophisticated techniques to isolate these resources.

There has been network slicing tests and planned deployments based on SA-5G in Spain, where Cisco, Telefónica and the University of Vigo announced in February 2021 a trial to run three slices on a 5G network of the University of Vigo. These slices are targeted to offer distinctive services: low latency, high bandwidth and emergencies (Telefónica, 2021[107]). In Austria, Nokia, the operator A1 and the railway network provider ÖBB, trialled network slicing on A1's existing 4G core network. The pilot consisted of testing a dedicated slice for the real-time data transmission between ÖBB's control centre and traction vehicles (OBB, 2020[108]). In France, Orange and Nokia announced in June 2021 the deployment of a 4G/5G private network combined with network slicing at Schneider Electric's plant in Le Vaudreuil, France (Orange, 2021[109]).

Recent pilots and planned implementations of network slicing have occurred in SA-5G networks as well. For example, in Germany, Ericsson, Deutsche Telekom, and Samsung completed in June 2021 what they claimed to be the "world's first 5G end-to-end" (i.e. SA-5G) network slicing trial, which included a 5G Cloud Core and 5G RAN. They optimised two slices: one for cloud virtual reality gaming and one for enhanced mobile broadband (Ericsson, 2021[110]). In July 2021, Vodafone UK announced a partnership with UK Power Networks to devote a "slice" of its recently deployed SA-5G network for a smart energy grid in the United Kingdom (see more details of this example in section *Deployments of Standalone (SA) 5G networks*) (Vodafone, 2021[96]).

With regards to the potential regulatory implications of network slicing, some concerns have been raised on whether it would be consistent with "network neutrality" regulation or open Internet principles. As highlighted by previous OECD work, the implications may depend on how different 5G elements evolve, on how the slices are implemented, on the eventual technological capabilities, but also market demand, degree of competition, and commercial strategies (OECD, 2019[59]). Nevertheless, according to the current understanding of the Body of European Regulators for Electronic Communications (BEREC), Open Internet Regulation in Europe respects the principle of technological neutrality and seems to leave room for the implementation of 5G technologies, such as network slicing (BEREC, 2018[111]; BEREC, 2021[112]). In the United Kingdom, Ofcom begun in September 2021 a review of how their network neutrality[37] framework is functioning. In particular, Ofcom seeks to better understand how technological developments, such as network slicing, among others, "either create or solve particular issues, and whether the current framework is sufficiently flexible to address them" (Ofcom, 2021[113]).

Multi-access edge computing (MEC)

Once networks are "virtualised", it is possible to shift computing resources to the "edge" of the network to reduce latency. One such technological advance for 5G is multi-access edge computing (MEC), previously referred to as mobile edge computing in 2017. MEC is a computing architecture with the primary aim of improving content delivery to users. It "offers application developers and content providers cloud-computing capabilities and an IT service environment at the edge of the network" (ETSI, 2020[114]). In other words, it takes the computing of traffic and services from a centralised cloud to the edge of the network and closer to the customer. The network edge analyses, processes, and stores the data, and as a result, it helps reduce latency and increase the performance of high-bandwidth applications (Juniper, 2020[115]).

MEC has the potential to enable a new value chain, as operators can open their RAN edge to authorised third-parties, allowing them to deploy "innovative applications" in both business-to-business (B2B) and business-to-consumer (B2C) segments (ETSI, 2020[114]). For example, in December 2020 Verizon Business together with Deloitte announced the launch of a retail platform that makes use of 5G and MEC. This application aims to improve inventory, customer service and optimally display merchandise to maximise sales. Verizon's 5G network would collect data from video cameras and IoT sensors, and its MEC platform would analyse the data with the help of AI. Verizon currently has two 5G-MEC solutions: one using the public cloud via a partnership with Amazon Web Services (AWS), and another "5G-MEC private solution" that is using in this project with Deloitte (FierceWireless, 2021[116]).

Another example of innovative business models using 5G-MEC is a trial by Vodafone Germany. In June 2021, HERE Technologies, Porsche and Vodafone trialled the use of MEC with 5G and highly precise location tracking at Vodafone's 5G Mobility Lab in Aldenhoven, Germany. The aim is to improve traffic safety in the future. The platform uses cameras and sensors powered by AI and precise mapping technology. The data is then processed on the edge of the network through MEC via Vodafone's 5G network (Vodafone, 2021[117]).

A move towards "openness" of mobile networks: Virtualised and/or open RAN interfaces

Wireless mobile networks have four main elements: the core network, the transport network (i.e. backhaul), the radio access network (RAN), and the users' terminal device. The core connects to the access network through backhaul, and the RAN connects to the users' terminal device via the air interface (spectrum) (Figure 10).

The RAN in previous mobile generations used to consist of a "monolithic" configuration provided by a single vendor (and proprietary solution), while there is now the possibility to decouple hardware and software elements of the RAN via virtualisation and open interfaces (Figure 9). The basic elements of a monolithic RAN base station of previous mobile generations consist of a baseband unit (BBU), composed by an integrated centralised unit (CU) and distributed unit (DU), which is connected to the

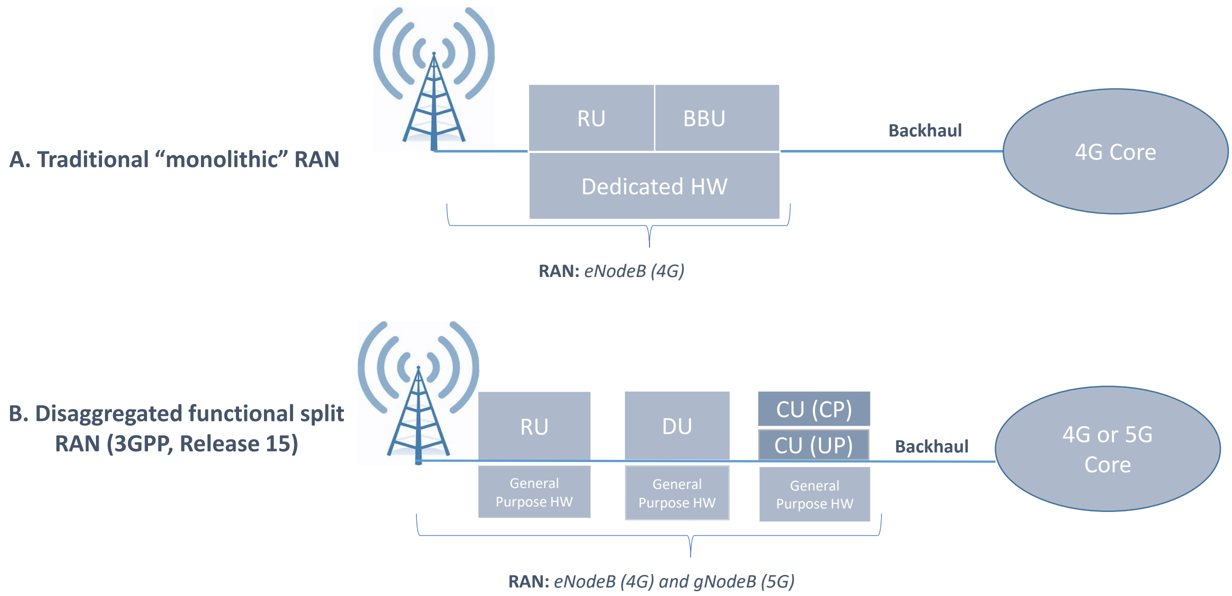
Remote Radio Unit (RU)[38] through what is referred to as "fronthaul" (Table 1). The RU consists of antennas that receive and transmit all wireless signals from the air interface (i.e. hardware), while the baseband unit (BBU) consists of digital modules that process these signals and provides the communication interface to the core network via the backhaul (i.e. BBU contains both software and hardware). With the 5G standard Release 15 (i.e. 3GPP standard specification TS 38.401), there is a possibility of splitting or disaggregating the BBU into the CU and the DU (ETSI, 2018[118]) (Figure 9). This allows operators the flexibility of placing these RAN functions in different physical sites when planning their deployments adapted to different use cases (e.g. low-latency cases).

Table 1. Elements of the Radio Access Network (RAN) across wireless generations

Wireless generation	Radio Technology	Base Station Name	RAN base station elements
2G	GSM (Global System for Mobile Communications)	BTS (Base Transceiver Station)	"Monolithic node" via single vendor: Baseband unit (BBU) and radio unit (RU) are integrated
3G	UMTS (Universal Mobile Telecommunications System)	NodeB	"Monolithic node" via a single vendor: BBU and RU are integrated
4G	LTE (Long Term Evolution)	eNodeB (**E**volved **N**ode**B**)	"Monolithic node" via a single vendor: BBU [composed of both the centralised unit (CU) and distributed unit (DU)] + a separate RU
5G	NR (New Radio)	gNodeB (Next **G**eneration **N**ode**B**)	Disaggregation of BBU into CU and DU + a separate RU with the potential of a multi-vendor ecosystem

Note: RU=Remote Radio Unit, BBU=baseband unit, CU=Centralised Unit, DU=Distributed Unit.
Source: OECD based on ETSI (2018[118]) "Release 15: NG-RAN" https://www.etsi.org/deliver/etsi_ts/138400_138499/138401/15.02.00_60/ts_138401v150200p.pdf , and Keysight Technologies (2020), "Enabling Interoperability & Adherence to O-RAN Fronthaul Interface", presentation at webinar Keysight World 2020.

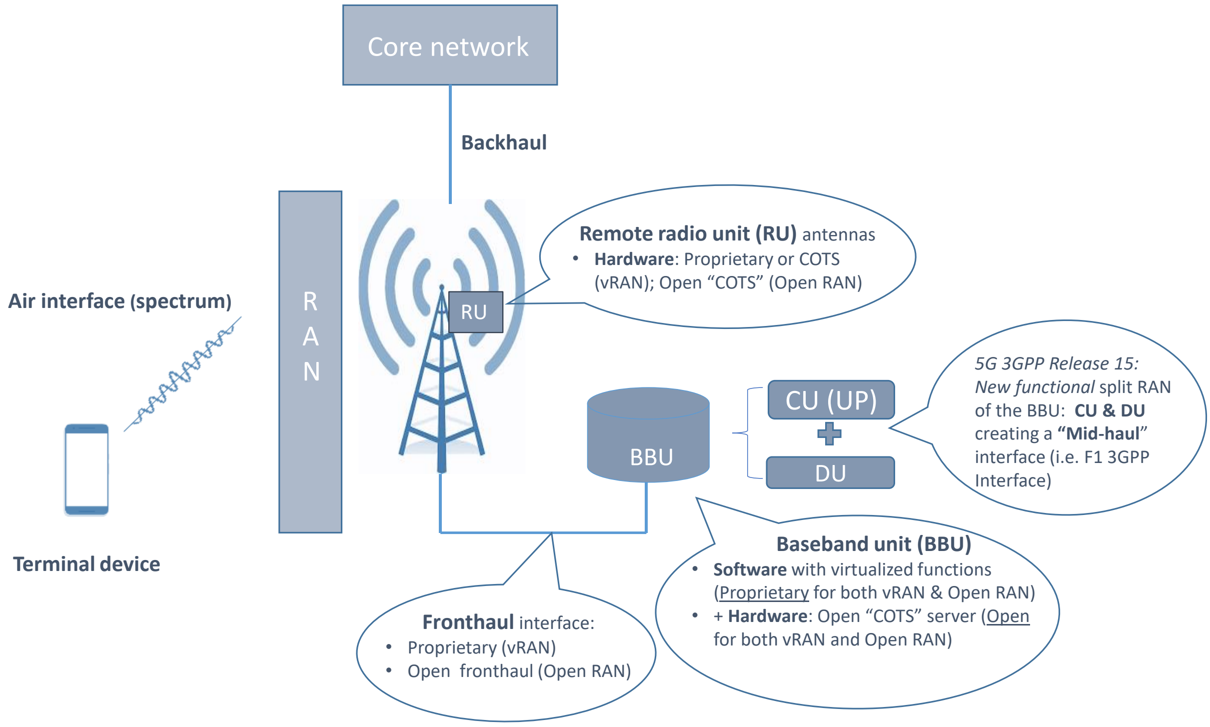
Figure 9. Traditional "monolithic" RAN versus disaggregated RAN



Note: RU=Radio Unit, BBU=Baseband Unit, DU= Distributed Unit, CU= Centralised Unit, CP=Control Plane, UP=User Plane.
Source: Own elaboration based on Red Hat (2021[119]).

In simple terms, there has been a recent move in the industry from a “monolithic RAN” configuration towards a disaggregated RAN (Figure 9) with a combination of virtualisation and/or open interfaces of the RAN (i.e. open and virtualised RAN) as seen in Figure 10. The rationale behind this trend is to increase flexibility in networks, improve efficiency in both network management and deployment, reduce costs, and develop a more diversified network equipment ecosystem that is currently a vertically-integrated and concentrated market segment.

Figure 10 Elements of a 5G wireless network: Understanding vRAN and open RAN



Note: COTS= commercially available off-the shelf equipment.
Source: OECD elaboration based on several sources.

A virtualised RAN decouples hardware from software elements with virtualised functions (VNF) for the baseband unit (i.e. CU and DU). Open RAN, in principle, would allow communication operators to select modules of network equipment and “mix-and-match” different vendors according to their goals through open (i.e. non-proprietary) and interoperable interfaces between modules. Therefore, open RAN is not a technology *per se*, but rather an ongoing shift in mobile network architecture that can be implemented with vendor-neutral hardware and software-defined technology based on open interfaces and industry-developed specifications (Mavenir, 2021[120]).

In both the virtualised RAN (vRAN) and open RAN solutions, there is a disaggregation of the functional split of the RAN (Figure 9), i.e. the separation of the radio functionality from the baseband functionality that is further split into the distributed unit and the centralised unit requiring an additional “mid- haul” interface (i.e. the F1 3GPP interface, as seen in Figure 10). Open RAN mainly refers to “open” interfaces between the different modules of the RAN, and can potentially also include the virtualisation of the RAN part of the network by decoupling hardware from software components in combination with non-proprietary interfaces. Therefore, some open RAN systems use virtualisation in addition to open interfaces, but not necessarily all open RAN systems are virtualised. The main difference between virtualised RAN (vRAN) and open RAN is the fact that the fronthaul interface can be proprietary (in the case of vRAN) or open, in the case of open RAN (Figure 10).

On the one hand, open RAN may foster innovation and diversification of the equipment vendor ecosystem, which, in turn, can foster competition in this concentrated market segment. On the other, it may also increase the level of complexity of this ecosystem, which might require new skill sets within ISPs or system integrators.

In recent years, there has been a concerted effort in the industry to promote the open RAN architecture model. For example, in 2016 several companies launched the Telecom Infra Project (TIP), that describes itself as a "global community of companies and organisations working together to accelerate the development and deployment of open, disaggregated, and standards-based technology solutions that deliver the high quality connectivity" (Telecom Infra Project, n.d.[121]). In 2018, global operators established the O-RAN Alliance to promote specifications for open RAN and foster vendor interoperability (O-RAN Alliance, n.d.[122]). In February 2020, the Telecom Infra Project (TIP) and the O-RAN Alliance announced an agreement to ensure their alignment in developing interoperable open RAN solutions. In May 2020, several major global companies formed the Open RAN Policy Coalition "to promote policies that will advance the adoption of open and interoperable solutions in the Radio Access Network (RAN)" (Open RAN Policy Coalition, n.d.[123]).

The "O- RAN Alliance" has made efforts to promote specifications for open RAN. As defined by the O-RAN Alliance, open RAN "is the foundation for building the virtualised RAN on open hardware and cloud, with embedded AI-powered radio control" (O-RAN Alliance, n.d.[122]). However, some stakeholders have voiced the concern that the O-RAN Alliance does not operate under an "open" standard-setting process, such as 3GPP, meaning that only members involved in setting the specifications have the visibility and ability to scrutinise the process and that it is thus not open for the different stakeholder groups (European Commission, 2021[124]; LightReading, 2021[125]).[39] This can be regarded as a major roadblock for regulators or governments working on policy making for network diversification due to the lack of transparency. Transitioning to an open standard setting process would enable all stakeholders to participate in the design of the specifications for open RAN.

With respect to the effects of open RAN developments on digital security, proponents of open RAN argue that it has the potential to foster "security by design" and "security by transparency". Others argue that a "single vendor" ecosystem may provide more digital security as the "threat surface" increases in a multi-vendor setting and systems gain in complexity (Cisco, 2020[126]). The digital security aspects of this trend is discussed in a separate upcoming OECD report on the security of communication network infrastructure.

Open RAN developments in OECD countries

Several open RAN initiatives have developed in OECD countries. For example, in Japan, the Ministry of Internal Affairs and Communications (MIC) considers that 5G infrastructure that enables AI to analyse information is indispensable for the digital transformation. Therefore, Japan has a policy focusing on technologies that support 5G, in particular virtualised and open RAN. NTT DoCoMo announced a cooperation with 12 companies to create a 5G open RAN ecosystem to accelerate open RAN globally and to commercialise and manage open RAN solutions for other operators. The company has furthermore plans to develop vRAN solutions to drive open RAN with a targeted commercialisation in 2022, and published in June 2021 a white paper on "5G open RAN Ecosystem" (NTT DoCoMo, 2021[127]). In April 2020, Rakuten Mobile –traditionally an e-commerce player-, entered the Japanese mobile market as a "greenfield" network (i.e. installation and configuration of a network where none existed before), via a virtualised cloud-native open RAN network. In August 2021, the company (through its branch Rakuten Symphony) made a deal with the new entrant to the German mobile market, 1&1, to design, build and operate 1&1's open RAN network and to provide 1&1 access to its cloud-native mobile communication platform. The CEO of 1&1, Ralph Dommermuth, claims to set up the first fully virtualised open RAN network in a manufacturer-independent way (Handelsblatt, 2021[128]; RCRWireless, 2021[129]).

In the United States, the FCC sought comment on open RAN initiatives through a notice of inquiry (NOI) published in March 2021. The FCC engaged in a public consultation regarding the steps needed to deploy open RAN at larger scale, and start a formal discussion on opportunities and potential challenges presented by open and virtualised RAN (FCC, 2021[130]). In response to this consultation, two operators expressed support for broader open RAN principles regarding vendor diversity and open interfaces; however, they also voiced concerns over the feasibility of implementing open RAN in existing networks. Therefore, they commented that timing, implementation and deployment of open RAN should be market-driven as opposed to a government mandate (Sharkey, Hunter and Wiecxorek, 2021[131]; Johnson and Fetchko, 2021[132]). One operator made the observation that while open RAN "greenfield" deployments can be feasible, deploying it on existing networks may be more challenging (Sharkey, Hunter and Wiecxorek, 2021[131]).

The new entrant in the mobile market of the United States, Dish,[40] plans to launch an 5G open RAN "greenfield" deployment in major cities by the end of 2021 (Baumgartner, 2021[133]). Verizon said that its hardware vendors (i.e. Ericsson, Samsung and Nokia) will start supplying its network with open RAN compliant equipment in 2021. The operator plans to use this network equipment to build a 5G network over the next three years with its mmWave and C-band (3.7 GHz) spectrum holdings and through an additional USD 10 billion investment (Dano, 2021[134]).

There has also been several open RAN initiatives in Europe by industry players and countries. In January 2021, Deutsche Telekom, Orange, Telefónica, TIM and Vodafone signed a Memorandum of Understanding (MoU), committing to implement and deploy open RAN solutions in Europe that "take advantage of new open virtualised architectures, software and hardware to build more agile and flexible mobile networks in the 5G era" (Deutsche Telekom et al., 2021[135]). The German Government allocated EUR 2 billion (USD 2.28 billion) to support the development of open RAN architectures in its last stimulus package, including EUR 250 million (USD 285.4 million) for 5G network deployment, EUR 237 million (USD 270.55 million) for 6G research, and over EUR 300 million (USD 342.47 million) intended boost the open RAN ecosystem (Handelsblatt, 2021[136]; TechTimes, 2021[137]).[41] Deutsche Telekom announced in June 2021 that it had switched on its deployment of open RAN with Massive MIMO radio units in Neubrandenburg (Deutsche Telekom, 2021[138]). In Italy, TIM launched an open RAN network in Faenza and Matera in collaboration with Mavenir, Dell Technologies and MTI in May 2021 (TIM, 2021[139]). In addition, TIM's Innovation Lab in Turin established in September 2021 the first open RAN 5G standalone connection using 3.7 GHz spectrum and the company expects to deploy this solution in the near future in the city of Matera (TIM, 2021[140]). Telefónica entered into an agreement with NEC to conduct open RAN pre-commercial trials in its four core markets (i.e. Spain, Germany, the United Kingdom and Brazil) with the aim of scaling up commercial open RAN networks in 2022 (Telefónica, 2021[141]).

The United Kingdom is actively promoting open RAN as a key part of its "5G Supply Chain Diversification strategy" that provides GBP 250 million (USD 349.6 million)[42] to implement priority measures in this regard (UK Government, 2020[142]). In April 2021, the Department for Digital, Culture, Media and Sport (DCMS) of the United Kingdom published the report "Telecoms Diversification Taskforce" that outlines findings and recommendations to the government in the context of its supply chain diversification strategy (UK Government, 2021[143]). In July 2021, the UK Government responded to the Taskforce's report and recommendations, outlining actions it had already taken and those planned for the future (UK Government, 2021[144]). For example, DCMS launched the Future RAN Competition (FRANC), which will invest up to GBP 30 million (USD 41.95 million)[43] in projects aiming to address the technological challenges of open RAN (UK Government, 2021[145]). FRANC is part of a long-term program to support open RAN R&D, together with two other open RAN projects, SmartRAN Open Network Interoperability Centre (SONIC) and NeutrORAN. In addition, five of the nine sponsored projects in the "5G Create Programme" will test the possibilities of open RAN. 5G Create is part of the UK government's GBP 200 million (USD 279.7 million)[44] investment in trials and testbeds for 5G. Announced as part of the United Kingdom's government strategy, the SmartRAN Open Network Interoperability Centre (SONIC Labs) is a joint programme between Ofcom and Digital Catapult, an agency accelerating early adoption of advanced digital technologies, to foster emergence of new services in the communication supply chain in the country, focusing on multi-vendor open, disaggregated and software-centric network products and services, starting with open RAN. Launched in June 2021, the SONIC network has been built across different locations in the United Kingdom with different providers with products of varying maturity, to test and combine technology and learn what benefits Open RAN could bring (UK Government, 2021[146]).

Open RAN may also be used for private 5G networks. In Germany, using the local spectrum licenses that BNetzA awarded, the research institute "Fraunhofer IIS" is building a 5G private network based on the specifications of the O-RAN Alliance at its sites in Erlangen and Nuremburg (Counterpoint, 2020[147]). For 5G private network solutions, Nokia and Ericsson are "launching their own cloud RAN-based disaggregated solutions which aim at competing with O-RAN based systems" (Counterpoint, 2020[147]).

An integration of cloud services into communication networks

Cloud computing can be understood as "a service model for computing services based on a set of computing resources that can be accessed in a flexible, elastic, on-demand way with low management effort" (OECD, 2014[148]). In recent years, cloud technology has been evolving with the aim of increasing efficiency and has allowed for the introduction of different types of virtualisation with varying degrees of capabilities (Ofcom, 2021[149]). Virtualisation is a fundamental technology behind cloud computing, as it increases the efficiency of compute resources (Armbrust et al., 2009[150]).

Cloud technologies are considered a key enabler to support networks and to meet increasing data transmission requirements across networks. While operators have long recognised the benefits of leveraging cloud processing, storage and computing resources in their networks, they are now considering how well their cloud strategies support future needs. In addition, operators may seek to adapt different cloud models depending on the use case. The latter may entail a complex orchestration of these models. At the same time, cloud service providers have been investing into building up their own communication infrastructure.[45]

Several cloud models are currently used in the communication sector: public, private and hybrid cloud models.[46] Services in a public cloud are typically shared by various customers, while private clouds are typically designed for a specific customer and can be managed either at the customer's site or at the data centre of the cloud provider. Hybrid cloud models employ both private and public cloud infrastructure (OECD, 2014[148]).

In conjunction to "traditional" or centralised cloud platforms, there has also been a trend towards edge computing solutions by cloud providers. Edge computing is a broad term for a set architectures and distributed computing techniques aiming to placing information processing (i.e. content, compute and storage resources) closer to where users are concentrated (Ofcom, 2021[149]; Akamai, 2020[151]). Furthermore, there is a trend whereby traditional cloud infrastructure (large and regional data centres) seems to be merging with the edge, sometimes referred to as the "cloud-edge continuum" (Ofcom, 2021[149]).

An early mover in the edge computing ecosystem has been Akamai. It started 23 years ago to build its content delivery network (CDN) that works as an edge platform, leveraging communication networks around the World. Akamai took a different approach than traditional CDNs at the time that were placing their CDNs in major cities. Akamai rather sought partnerships with operators to be as close to the user as possible in order to reduce latency and ensure redundancy (FierceTelecom, 2021[152]).

At present, major cloud providers are seeking to move closer to the edge by striking partnerships with communication service providers. At the same time, with the evolution to 5G, operators are looking to increase cloud functions in their networks to deliver higher speeds and reduced latency.

5G cloud and edge solution models

While still at an early stage, different approaches towards the use of the cloud in networks can be identified. Some operators are currently in the process of developing their own cloud solutions. Others engage in partnerships with cloud providers.

BT is an example of an operator having been developing its own “BT Network Cloud” at a global scale aiming to launch it in 2021 (FierceTelecom, 2020[153]). In September 2020, Telefonica Germany announced plans to build 5G core and network functions in the cloud, specifically for industry-specific use cases for which it will collaborate with AWS and Ericsson (SDxCentral, 2020[154]).[47]

Several important cloud providers are designing specific cloud services for the communication sector. Microsoft is one of the main players, leveraging its acquisitions of Metaswitch, a company in the United Kingdom that develops software for both fixed and mobile networks, and Affirmed Networks that specialises in virtualised, cloud-native mobile network solutions for operators (FierceTelecom, 2020[155]; FierceWireless, 2020[156]). In July 2021, AT&T and Microsoft announced the acquisition of AT&T’s Network Cloud platform technology by Microsoft Azure. Microsoft would support AT&T’s network computing functions (i.e. workloads) through the Microsoft Azure for Operators cloud platform, and develop scaled compute and storage capabilities for AT&T. The aim is for AT&T to increase productivity, cost efficiency, and focus on the delivery of large-scale network services. In return, Microsoft will acquire AT&T’s Network Cloud platform technology, a technology that AT&T has employed to run cloud applications for third-party customers, and AT&T’s technical expertise to inform Microsoft’s “Azure for Operators” communication operator offering (AT&T, 2021[157]; Microsoft, 2021[158]).

Amazon Web Services (AWS) provides “AWS Wavelength” for edge computing since 2019, which embeds AWS compute and storage services within communication service providers’ data centres at the edge of their 5G network (AWS, 2020[159]). AWS has struck partnerships with companies such as Verizon, Vodafone, KDDI and SK Telecom (Telecompaper, 2020[160]). Telstra also signed a memorandum of understanding (MoU) with AWS to “explore differentiated multi-access network edge computing”, namely to integrate AWS’ edge compute solutions into Telstra’s network, which would enable devices to access edge compute applications without leaving its network (Telstra, 2021[161]). In the United States, Dish and Amazon Web Services (AWS) announced a strategic collaboration in April 2021 to deploy Dish’s “standalone, cloud-based 5G Open Radio Access Network” during 2021. Dish selected AWS as its cloud provider to build its 5G network (Amazon, 2021[162])

Google Cloud is also offering communication service providers cloud and edge computing solutions. In 2020, Google Cloud announced “Anthos for Telecom”, a platform to deliver communication network workload to the edge through an “open hybrid and multi-cloud application platform”, allowing communication service providers enough flexibility to upgrade applications and build new ones across multiple “clouds”. In addition, the “Virtual Private Cloud” uses Google’s own network infrastructure, allowing private networks to bypass the public Internet (Google, 2021[163]). Google Cloud is working with Intel to jointly develop cloud architectures for 5G operators across multiple clouds and edge locations (FierceWireless, 2021[164]), and in March 2020, engaged in a partnership with AT&T for edge computing solutions for enterprises (FierceTelecom, 2020[165]). In May 2021, Vodafone and Google Cloud announced a six-year partnership to jointly develop a new integrated data platform with additional capability to process and move large volumes of data globally from different systems to the cloud (Vodafone, 2021[166]). In March 2020, TIM and Google Cloud signed an official agreement for a joint technology collaboration, following the Memorandum of Understanding (MoU) signed in November 2019 between both companies. TIM and Google Cloud have agreed to work together to build innovative Public, Private and Hybrid Cloud services for TIM’s expanding technology services portfolio (TIM, 2020[167]).

AI for networks: The promise of applying AI to the next evolution of broadband networks

AI promises to increase the efficiency and effectiveness of entire sectors (e.g. energy, transport, communication sector), including the delivery of public services. Applied wisely, AI can improve well-being in areas like education, public safety, and health. In 2019, the OECD Council adopted the *Recommendation on Artificial Intelligence* [OECD/LEGAL/0449] that establishes principles focused on how governments and other actors can shape a human-centric approach to trustworthy AI.[48] New forms of machine learning and automation are leading connectivity providers to reimagine the way they operate and manage their communication networks. This section refers to AI systems applied to enhancing communication networks' performance.

Implementing AI systems in both fixed and mobile broadband networks, including machine learning and automation of networks, may yield several benefits. It can help communication service providers improve network operations performance and reliability, contribute to incident prevention and predictive maintenance, increase digital security, and facilitate the analysis of customer behaviour and demand. It can further reduce energy consumption, and prevent network outages, and thus increase the reliability or availability of networks. As a result, the use of AI may reduce operational costs. In addition, operators may pursue the adoption of AI in networks with the aim of increasing the sustainability of networks which becomes a critical issue for OECD countries.

With respect to mobile networks, the use of AI systems in 5G networks may help improve overall network performance and reliability, simplify network management linked to network slicing, help optimise network capacity, aid in improving digital security features, and optimise energy consumption of mobile antennas. For example, AI may help in the development of new open vendor ecosystems for mobile networks (e.g. virtualised and open RAN). In some OECD countries, with large rural areas, the geographical context may be a natural barrier to maintain and operate communication networks. Virtualisation of networks that allow for network updates via software, in conjunction with AI techniques that automate network operations and management (including predictive maintenance), may be key to lower operational and maintenance costs of 5G networks. Therefore, an additional benefit of the use of AI in networks could be to lower operational expenditure of networks that in turn may help to bridge connectivity divides.

According to a survey conducted by Ericsson among communication providers in 2018 on "Employing AI techniques to enhance returns on 5G network investments", more than half of communication service providers (53%) expected to have adopted AI within their networks by the end of 2020 (Ericsson, 2019[168]). Operators believed that the highest potential return from AI adoption would be in network planning (70 %), while 64% intended to maximise their returns by focusing their AI adoption efforts on network performance management (Ericsson, 2019[168]). According to another survey directed at communication operators, in 2020, around 25.9% of communication service providers had already introduced systems using AI, while 44.5% planned to do it within the next two years (Comarch, 2020[169]).

A communication operator that provides an example of the use of AI and machine learning in its network is Elisa (Finland). With the aim of reducing operating and capital expenditure of running its network, Elisa has been developing different automation levels in its networks for the past decade. The company believes that the use of AI and machine learning algorithms in its network will allow it to keep its competitive edge as the industry moves towards 5G where network densification will increase the need for what they call "collective network optimisation". In 2017, the company created a spin-off, "Elisa Automate", to offer their in-house solution to other communication operators interested in automation solutions for network management (Box 3).

Box 3. Case study: Elisa Automate

Elisa Automate offers multivendor network solutions and services that enable operators to automate network management and operations. These solutions can improve service quality and operator cost efficiency. Elisa Automate uses AI systems, including machine learning and aims at bringing advanced predictive analytics and preventive maintenance to the networks.

Elisa Automate is a spin-off from Elisa, a finish mobile operator. When Elisa launched unlimited mobile data packages in 2007, it sought to do so without increasing operating expenses (OPEX) and capital expenses (CAPEX). The three challenges recognised by the company that would need to be addressed were managing data growth, maintaining consistent quality, and operating an increasingly complex network environment. Automation provided a solution for these challenges, and Elisa consequently worked on achieving a completely automated network (GSMA, 2020[170]).

Afterwards, Elisa chose to make a business model out of its automation solutions and now has 120 use cases (Elisa Automate, 2020[171]). For example, Elisa Automate was selected by Deutsche Telekom Group affiliates, (T-Mobile Czech Republic and Slovak Telekom) in November 2020 to deliver a software solution to support the automation of their networks (Polystar, 2020[172]).

Sources: GSMA (2020[170]), "Case Study: Elisa Automate", https://www.gsma.com/futurenetworks/wiki/elisa-automate-intelligent-energy-saver/; Elisa Automate (2020[171]), "A Decade of Experience in Automation", https://elisaautomate.com/elisa-story/; Polystar (2020[172]), "Elisa Automate to deliver zero-touch, fully automated network operations to T-Mobile Czech Republic and Slovak Telekom", https://www.polystar.com/2020/11/t-mobile_elisa-automate-deal-announcement/.

In July 2021, Vodafone and Nokia announced the introduction of a new machine learning system, "anomaly detection service" that can detect mobile network anomalies quickly in order to correct them before they impact Vodafone's customers. Vodafone expects that the ML system will be able to detect and address 80% of all anomalous mobile network issues and capacity demands. The solution will run on Google Cloud and will stream data to Vodafone's analytics platform to allow analysis of aggregated network data from various points across multi-vendor environments at once. This allows the ML system to detect patterns from the data and categorise network behaviour and find anomalies. Anomaly detection service is offered as a service on Nokia's Cloud and Network services (Vodafone, 2021[173]).

Equipment vendors and operators are also finding new ways of making networks more energy efficient without impacting network performance, for both cost and sustainability reasons. In this sense, AI may help reduce energy consumption costs of networks. Ericsson has been exploring the use of AI and ML in network management. The company automated MIMO energy management in a trial with ML and AI in cell sites in Vodafone's network in Portugal. A Machine Learning (ML) algorithm was developed to observe, predict, and respond to user traffic, with a "MIMO Sleep Mode" when units were not active to save on energy consumption across the network. The results show energy savings of up to 14% with no impact on network performance. Therefore, tailoring energy efficiency of each cell site by the use of automation at an international level could translate into significant cost savings for Vodafone with a positive environmental impact (Ericsson, 2019[174]). Vodafone is an operator simultaneously present in many domestic OECD mobile communication markets (i.e. 13 OECD countries) (OECD, 2021[34]), as well as in many African countries; therefore energy savings at an international level for this company could translate in a significant positive environmental impact.

Dynamics of 5G, Gigabit networks and Wi-Fi 6

Complementarity of fixed and mobile networks

Mobile networks are increasingly an extension of fixed networks at their core. This trend is even more acute in 5G as it is becoming increasingly critical to deploy fibre further into fixed networks to support increases in speed and capacity to connect small cells ("network densification"). Fixed networks can be used to more effectively take on the 'heavy lifting' of the increasing demands on wireless networks, especially where radio spectrum is scarce (OECD, 2019[59]).

The complementarity of core fixed and mobile communication infrastructure reflects two main trends. First, network densification inherent to 5G deployments requiring to install small cells closer to users to increase network speeds and capacity. These cells will need backhaul connectivity, predominantly connected today by fixed lines (fibre) and to a lesser extent via wireless microwave connections. However, at some point in the backhaul, there needs to be fibre, and as fibre is deployed deeper into mobile networks, the capacity of these networks increases. Therefore, 5G network expansion (mobile cellular or FWA access) may be affected by the extent and speed of fibre deployment. Second, mobile cellular data traffic is expected to grow exponentially driven by increased data requirements of the digital transformation with the proliferation of IoT applications and AI systems. Fixed networks alleviate the "load" of mobile networks. For example, according to Cisco's estimates, globally already 54% of mobile data traffic was offloaded to Wi-Fi fixed networks in 2017, with the forecast that by 2022, 4G devices will offload 59% of their traffic into fixed Wi- Fi networks while 5G devices will offload 71% of their traffic into fixed Wi- Fi (Cisco, 2019[175]).

Increasing fibre and mobile network convergence

Considerable deployment savings could potentially occur when considering FTTH and 5G converged networks. According to a study conducted by the Fibre to the Home (FTTH) Council Europe, around 74% of costs of deploying fibre backhaul for 5G can be saved by conceiving and deploying an optimised future proof fibre converged fibre-5G network. For already installed FTTH networks, the additional investment to make it 5G ready is about 5.6% (FTTH Council Europe, 2020[176]).

An example of a move toward a converged mobile and fibre network is BT in the United Kingdom. BT, a fixed broadband operator, acquired the mobile operator EE in 2015. In July 2021, BT unveiled plans to offer 5G across the entire United Kingdom combining its mobile, Wi-Fi and fibre infrastructures to become what it considers the first fully converged network in the country. Furthermore, BT will use its own distributed network cloud infrastructure, instead of relying on public cloud providers (FierceWireless, 2021[177]).

Wi-Fi 6 and Wi-Fi 6E

In broad terms, Wi-Fi refers to the wireless local area network (WLAN) technologies.[49] Wi-Fi uses license-exempt or unlicensed spectrum and is primarily used indoors, for example it can be used for both residential use, as well as local area networks for enterprises. In addition, in several countries Wi-Fi networks hotspots in public buildings and transports are also becoming more common, including for outdoor use. The year 2019 marked two decades of the Wi-Fi standard. Members of the Wi-Fi alliance highlight that the keys of the success of Wi-Fi have been a community actively developing the standards, its use of unlicensed spectrum, convenience and ease of use, and a cost effective solution that complements other connectivity solutions such as 5G (Wi-Fi Alliance, 2019[178]).

In 2019, Wi-Fi equipment manufacturers started launching the sixth generation of the Wi-Fi standard (Wi- Fi6) offering higher speeds (e.g. 1.2-4.8 Gbps), a higher density of devices and lower latency. Traditionally, Wi-Fi has used unlicensed spectrum in the 2.4 GHz and 5 GHz spectrum bands. With the

Wi-Fi 6 standard, a new generation of devices is being introduced that can operate in the 6 GHz spectrum band, called Wi-Fi 6E.

A thriving Wi-Fi 6 ecosystem will depend in great measure on whether countries decide to allocate parts of the 6 GHz band for unlicensed use, as well as the overall number of terminal devices supporting Wi- Fi 6. The United Kingdom has already made the lower part of the 6 GHz available in 2020 (Ofcom, 2020[179]) and companies have worked on their Wi-Fi 6 and 6E commercialisation strategies. For example, in January 2021 Samsung launched the first smartphone supporting Wi-Fi 6 (Samsung, 2021[180]). On 10 August 2021, several companies (i.e. Broadcom, Cisco, and Facebook) launched the "Open Automated Frequency Coordination (Open AFC) Software Group" within the Telecom Infra Project (TIP). The aim of this group is to accelerate the commercialization of Wi-Fi devices capable of using 6 GHz spectrum (BusinessWire, 2021[181]).

Some Wi-Fi 6E ecosystem innovations may include prioritizing bandwidth based on user's capacity needs, much like 5G promises via network slicing (FierceWireless, 2021[182]). The use of MEC with Wi-Fi 6 will also be a key element and will depend on the use cases or applications (e.g. industrial IoT).

A number of stakeholders in the Wi-Fi ecosystem have mentioned that an ongoing issue is how to deal with congestion of devices within a LAN network and the potential interferences of access points. However, Wi-Fi management platforms have emerged. For example, Plume offers a cloud-based platform for Wi-Fi, and makes use of AI to understand device use and interference in each home to optimise traffic (BusinessWire, 2021[183]).

Complementarity of Wi-Fi and 5G

As the interest of private 5G networks increases for industrial applications, questions may arise on whether Wi-Fi is a complementary solution to 5G or rather a substitute. Wi-Fi6 brings cellular-like capabilities such as traffic steering, among others; however, some stakeholders make the case that 5G private networks may be better suited than Wi-Fi for industrial applications because of the reliability and security features of 5G, and potentially less interference between access points as may happen with Wi-Fi (FierceWireless, 2021[182]). Depending on the application, Wi-Fi and private 5G networks may offer different advantages. However, the consensus appears to favour the view that a mix of technologies is needed. In other words, that these networks offer complementary connectivity solutions (Intel, 2021[184]).

For example, in Korea, several mobile operators leverage Multipath TCP[50] that enables smartphones to use both Wi-Fi and cellular (4G and 5G) interfaces simultaneously (Tessares, 2020[185]).[51] According to a survey conducted by the Wireless Broadband Alliance, an industry association formed to promote interoperability in the Wi-Fi ecosystem, converged cellular and Wi-Fi networks will account for most private, city, and Industrial IoT deployments by the end of 2023 (6G World, 2021[186]).

This dual-network approach, Wi-Fi combined with 5G connectivity solutions, is already being used, especially in locations with a high-density of connected devices, such as airports and sport stadiums. For example, in the United States, mobile operators that have deployed 5G networks using mmWave spectrum have struck partnerships with neutral hosts specialised in connectivity solutions for indoors and dense public places (Box 4). Neutral hosts, such as Boingo in the United States, can be defined as "a service provider that builds and operates an integrated technology platform that is solely for sharing purposes", (Lähteenmäki, 2021[67]), and they usually operate at a wholesale level serving third-party carriers.

Going forward, the important question to be posed may not only be of the one of co-existence of connectivity solutions, but how to ensure their co-integration. That is, how synergies provided by complementary solutions are exploited, and how different network solutions operate in a seamless manner, which may require partnership management. Questions of interoperability will be crucial, as well as the possibility of "open" roaming among devices.

Box 4. Boingo partnering with mobile operators in the United States to complement connectivity solutions for 5G

Boingo is a company in the United States that uses a “neutral host” approach to provide wireless network solutions to third parties (operators and private networks), mainly targeted for indoor venues with a high density of people (e.g. airports, transportation hubs, campuses, sport stadiums, etc.). These solutions include cellular distributed antenna systems (DAS) to boost cellular coverage inside buildings, small cell deployment, Wi-Fi, and 5G.

In 2019, Verizon partnered with Boingo, to leverage the company’s experience with “distributed antenna systems (DAS), small cells and Wi-Fi” to expand its 5G service indoors and to public spaces (The Verge, 2019[187]). Small Cells and Distributed Antenna Systems (DAS) networks are being deployed in cities and towns across the United States to augment mobile towers.

In 2020, Boingo partnered with all three wireless carriers in the United States to facilitate mmWave connectivity for 5G deployments as a neutral host partner making use of the Citizens Broadband Radio Service (CBRS) spectrum that dynamically allocates the 3.5 GHz band on demand (Boingo, 2021[188]). CBRS spectrum refers to 150 MHz of the 3.5 GHz band, out of which 70 MHz is licensed spectrum and 80 MHz is unlicensed. CBRS is a shared spectrum license model, where there is a three-tiered access and authorisation framework to accommodate shared national and local use of the band. The CBRS Auction 105, for the licensed portion of the spectrum, concluded on 2 September 2020 (FCC, 2020[189]). It is expected that CBRS will allow for neutral host and private network models to proliferate further (Dgtl Infra, 2020[190]).

In July 2021, Boingo struck a deal with AT&T to bring mmWave 5G connectivity from AT&T’s network to 12 airports in the United States. The deal includes using AT&T’s network and leveraging on Boingo’s distributed antenna system (DAS) and Wi-Fi expertise (FierceWireless, 2021[191]).

Source: The Verge, (2019[187]) “Verizon just announced a partnership with Boingo to solve its biggest 5G problem”, https://www.theverge.com/2019/8/22/20827985/verizon-5g-indoor-boingo-partnership-problem-solution-phoenix; Boingo (2021[188]), “5G & CBRS”, https://www.boingo.com/5g/; FCC (2020[189]), “3.5 GHz Band Overview”, https://www.fcc.gov/35-ghz-band-overview; Dgtl Infra (2020[190]), “Boingo to be a Key Beneficiary from the Winners of CBRS Auction 105”, https://dgtlinfra.com/boingo-to-be-a-key-beneficiary-from-the-winners-of-cbrs-auction-105/; FierceWireless (2021[191]), “Boingo to equip 12 airports with AT&T’s mmWave 5G”, https://www.fiercewireless.com/wireless/boingo-to-equip-12-airports-at-t-s-mmwave-5g.

Developments in Satellite

There have been recent developments in low earth orbit (LEO) satellites with the aim of providing high-speed broadband in rural and remote areas. One example is Starlink by SpaceX, a LEO satellite constellation, which launched commercial services in various OECD countries. As of August 2021, Starlink had launched 1 740 LEO satellites and was building a system of ground stations as well as terminal equipment. The company aims to launch as many as 42 000 LEO satellites to form a “mega-constellation” (Space.com, 2021[192]).

Starlink has received regulatory approval for operating its commercial services such as in the United Kingdom or Germany. In the United Kingdom, Starlink received approval for its end-user terminals from Ofcom in January 2021 (Comms Update, 2021[193]). In 2020, the German regulator, the Bundesnetzagentur, allocated frequencies to Starlink, the satellite Internet constellation operated by SpaceX, and is currently developing a scheme to speed up rural Internet access by subsidizing LEO hardware systems. As such, a subsidy is planned for subscribers to Starlink, but also other wireless broadband providers to urban areas (Lightreading, 2021[194]). In the United States, SpaceX had sought approval to the FCC to launch 2 824 satellites at a lower orbit as part of the plan to bridge the digital divide, and the FCC approved this request in April 2021 (FCC, 2021[195]). SpaceX (Starlink) was also one of the main winners of the FCC's Rural Digital Opportunity Fund (RDOF) auction at the end of 2020, and has been awarded USD 885.51 million to connect 642 925 rural homes and businesses in 35 states (ArsTechnica, 2020[196]).

The first measurements of the speeds have been undertaken for satellite broadband, taking into account that many more satellites still have to been launched and that the company terms its offer so far as a beta offer. In terms of speeds, the German regulator measured download speeds of 100 Mbps and uploads speeds of 25 Mbps in March 2021. In the United Kingdom, results from Ookla's speed test in August 2020 revealed that download speeds of the Starlink constellation were about 35-60 Mbps (Inverse, 2020[197]) lower than what SpaceX originally claimed (i.e. 1 Gbps). The service is priced at EUR 99 (USD 119) per month in Europe, which adds to another EUR 499 (USD 601)[52] for the equipment.

The satellite company OneWeb launched 36 satellites to deliver broadband connectivity, bringing the total of LEO satellites up to 218. The satellite company aims to deliver commercial service across the United Kingdom, Alaska, Northern Europe, Greenland, Iceland, the Arctic Seas and Canada, targeting global availability in 2022 using 648 satellites in total for its first-generation system (OneWeb, 2021[198]). Another company that will be entering the satellite broadband market in the United States is Amazon. In July 2020, Amazon received FCC's approval for its project Kuiper that aims to build a LEO constellation of 3 236 satellites to provide broadband in rural areas of the United States (Amazon, 2020[199]).

Some satellite broadband providers are exploring ways in which satellite connectivity may complement existing 5G terrestrial networks. According to SpaceX founder Elon Musk, Starlink offers a complement to fibre and 5G technology and the service could be a cost-effective method for data backhaul for communication companies. In addition to backhaul, another route SpaceX is pursuing is regions where governments require operators to deliver service to rural areas in order to obtain 5G licenses (FierceWireless, 2021[200]). Omnispace is developing a hybrid satellite and ground network to provide connectivity, using 5G standards, with aims to target IoT applications for enterprises. In February 2021, it raised USD 60 million in funding, and in March 2021, Omnispace signed an agreement with Lockheed Martin to collaborate on developing 5G connectivity using satellite in part. Lockheed Martin is a United States defence contractor (Spacenews, 2021[201]). Inmarsat recently announced a plan to invest USD 100 million in the next five years to create a new type of "converged" network with its current Geosynchronous Earth Orbit (GEO) satellites, a forthcoming constellation of 150 to 175 LEO satellites, and a 5G terrestrial network. "Orchestra" will be the name of the combined offer aimed at a range of corporate customers (e.g. maritime, aviation and government organisations) (Mobile World Live, 2021[202]).

"Beyond 5G" technologies

The network industry and the technical community, along with several countries and organisations have started to work on "beyond 5G mobile technologies". The ITU-R Working Party D started its work on the "Vision of IMT beyond 2030" in 2021 (ITU, 2021[203]). Therefore, discussions on what 6G may look like are forward looking given that it took about 8 to 12 years for previous mobile generations from the agreement on technical standards to commercialisation of the networks. Nevertheless, government, industry and research initiatives that may shape the vision on what may be the next steps of convergence of communication networks beyond 5G are already taking place around the world (e.g. China, the European Union, Finland, Germany, Japan, Korea, the United Kingdom and the United States).

Like with previous mobile generations, there will likely be evolutionary aspects of the next generation of wireless networks, as well as revolutionary aspects such as new technologies that are being developed (e.g. terahertz communication and sensing, immersive extended reality (XR), holograms, etc.) combined with new frequency bands being used. For example, the development of terahertz systems using spectrum frequencies (above 100 GHz),[53] is being driven by the vision of providing a design for joint communication, localisation and sensing (Ofcom, 2021[204]; Bourdoux et al., 2020[205]). In particular, some researchers believe that 6G may catalyse new use cases providing ubiquitous communication as well as high accuracy localisation and high-resolution sensing services (Bourdoux et al., 2020[205]).

Some use cases being discussed that would use terahertz spectrum bands for beyond 5G technologies include: advanced multimedia services such as immersive extended reality (XR), holograms, digital twins, three-dimensional (3D) calls, haptic communication (i.e. the transmission of touch and motion), fully automated mobility solutions, and nano-technology-inspired IoT sensors (FierceWireless, 2021[206]). A report by Ofcom on "Technology Futures" provides a vast overview of the future technologies for both wireless and fixed networks that may come to fruition in the medium and long term, i.e. in the next 10-20 years (Ofcom, 2021[204]). These technologies may also shape "beyond 5G" discussions (Box 5).

Box 5. A focus on Ofcom's (2021) report, "Technology Futures – spotlight on the technologies shaping communications for the future"

In this report, Ofcom focuses on technologies in the mobile and wireless, fixed and optical, broadcasting and satellite sectors and on emerging immersive communication services, and found that a number of technology developments will impact more than one of these sectors (e.g. AI, "cloudification", "softwarisation", openness and disaggregation, hybrid topologies, evolving computer architectures, energy reduction, quantum and metamaterials). With respect to mobile and wireless technologies, Ofcom highlights four particular areas considered to have major impacts in the medium and long term:

- Going beyond the traditional physical wireless limits, by using smart surfaces made of artificial materials ("metamaterials") deployed along streets and building able to direct wireless signals, with enhancements in coverage as well as energy efficiency.
- AI native systems that may require conceiving new computing architectures for the communication sector. For example, researchers are exploring computing and communication architectures working in a similar fashion to the human brain (neural networks) that could lead to important reduction in energy consumption and latencies.
- Hybrid terrestrial/aerial topologies, meaning moving away from a "cell centric" approach in mobile networks, and converge mobile terrestrial networks with LEO satellites and drones, to provide ubiquitous coverage and enhanced quality of experience.
- Joint communication and sensing. Historically radar or sensing systems were developed independently from mobile communication technologies. There is growing interest in merging these two technologies. Namely, the use of mmWave or terahertz frequencies used in combination with massive MIMO and machine learning techniques may enable a finer spatial resolution to detect even subtle movements, such as finger gestures.

Terahertz communication and sensing

Communication systems using terahertz spectrum may allow for very high throughput and very low latency, providing an opportunity to conceive joint communication, sensing and positioning systems. Thus, it is being regarded as a promising technology for future 6G systems. Although terahertz spectrum may provide advantages compared to mmWave, at the same time, it has to overcome major challenges due to the nature of the propagation features of such high bands.

Source: Ofcom (2021[204]), "Technology Futures – spotlight on the technologies shaping communications for the future", 14 January 2021. https://www.ofcom.org.uk/consultations-and-statements/category-2/emerging-technologies

What are the implications of a hyper- and inter-connected world in 2030? Importantly, what are the requirements and demand for networks and how can those networks reach the entire society? Several stakeholders involved in recent 6G global initiatives highlight that the technological standards for 6G should not only should seek to bring to market new innovative applications, but that they should be built with societal goals in mind, such as a "green G" (energy and spectral efficiency), the need to take into account affordability and accessibility, and trust (privacy and security). In addition, new technologies being developed that will be made possible by new forms of connectivity should follow a human-centric approach. That is, stakeholders have voiced that these elements should be included "by design" in the vision of what "Beyond 5G" will become, that would in turn shape the standard setting process in years to come (6G Symposium, 2021[207]).

A hand-full of countries around the world have started to embark in research activities on what beyond 5G technologies will look like with the aim of contributing to the vision of the standards in the near future (Table 2).

Table 2. Global 6G initiatives

	Name of initiative	Links
European Union	**July 2021**: EC adopts a legislative proposal for a strategic European partnership on 6G Smart Networks and Services Joint Undertaking, with a public R&D investment of EUR 900 million (USD 1.027 billion)[54] over the new long-term budget period 2021-2027 (European Commission, 2021[208]). • The Joint Undertaking will coordinate research activities on 6G technology under the European Union's key funding programme for research and innovation "Horizon Europe" (February 2021) (European Council, 2021[8]) as well as 5G deployment initiatives under the Connecting Europe Facility Digital and other programmes. *EU Member States Initiatives: Finland, Germany*	Industry 6G Partnership Proposal-Smart Networks & Services Joint Undertaking https://ec.europa.eu/info/files/european-partnership-smart-networks-and-services_en Horizon Europe Partnerships (23 Feb 2021, Press Release)
Finland	**2018:** The University of Oulu 6G Flagship Programme (University of Oulu, 2021[209]).	https://www.oulu.fi/6gflagship/
Germany	**April 2021:** German government funding for 6G technologies • In Germany, the Government plans to provide up to EUR 700 million (USD 799 million) to finance research on 6G technologies by 2025, in the aim of creating the basis for an innovation ecosystem for future communication technologies around 6G (RCR Wireless, 2021[210]).	
Japan	**June 2020:** Ministry of Internal Affairs and Communications (MIC) launched a "Beyond 5G Promotion strategy –Roadmap towards 6G", which includes R&D strategies, IP/standardisation strategies, and international expansion strategies (MIC, 2020[211]) **December 2020:** The "Beyond 5G Promotion Consortium" was established to promote the "Beyond 5G Promotion Strategy" **March 2021:** KDDI published 6G white paper on 6G use cases (KDDI, 2021[212]). **April 2021**: Open RAN & 6G collaboration with the United States (USD 2 billion): • The United States and Japan sign an agreement to join forces in research and development for "beyond 5G" technologies with a joint fund of USD 4.5 billion (i.e. USD 2.5 billion and USD 2 billion contributed by each country, respectively) (TelecomTV, 2021[213]). **April 2021:** NTT and Fujitsu agreed on a strategic alliance regarding 6G, and will collaborate globally with a wide range of partners who support the IOWN (Innovative Optical and Wireless Network)[55] concept, aiming to realise a new digital society with low energy consumption and high efficiency (NTT and Fujitsu, 2021[214]). **June 2021:** The Beyond 5G Promotion Consortium of MIC signed a MoU with the Finnish 6G Flagship research programme (NikkeiAsia, 2021[215]). **July 2021**: Softbank announced its 6G concept note (SoftBank, 2021[216]).	www.soumu.go.jp/main_sosiki/joho_tsusin/eng/presentation/pdf/Beyond_5G_Promotion_Strategy_Roundtable_Recommendations.pdf https://b5g.jp/en/
Korea	**September 2020:** The Korean Ministry of Science, Technology and ICTs (MSIT) establishes a Next-Gen 6G R&D project. **June 2021**: The Korean Ministry of Science, Technology and ICTs (MSIT) announces an investment of KRW 220 billion (USD 196 million)[56] for the Next-Gen 6G R&D project (KoreaTechToday, 2021[217]). • MSIT said that the initiative would develop core 6G technologies,	Press Release MSIT: https://english.msit.go.kr/eng/bbs/view.do?sCode=eng&mId=4&mPid=2&pageIndex=&bbsSeqNo=42&nttSeqNo=515&searchOpt=ALL&searchTxt=

	including integrated terrestrial and satellite networks. • As part of the 6G network development, MSIT plans to launch 14 LEO telecommunication satellites. By 2031, the country aims to test the new LEO satellite network. **August 2021**: A 6G research centre in Korea formed by LGE and the state-run Korea Advanced Institute of Science & Technology (KAIST) claimed to have demonstrated that beamforming works in terahertz spectrum bands making it suitable for 6G (Aju Business Daily, 2021[218]).	
The United Kingdom	**Nov. 2020**: University of Surrey commenced 6G research by launching the 6GIC project (5GIC, 2020[219]). • Among the different aspects to be included in the vision for beyond 5G technologies, 6GIC considers that it should support transformative services that address major societal challenges such as climate change, pandemic control, and economic growth (TechRadar, 2020[220]). **June 2021**: The United States and the United Kingdom agreed to strengthen ties on science and technology through partnerships in key areas such as 6G, and increase collaboration on digital technical standards (LightReading, 2021[221]).	https://www.surrey.ac.uk/sites/default/files/2020-11/6g-wireless-a-new-strategic-vision-paper.pdf
The United States	**March 2019:** The FCC opened 10-year spectrum in the 95 gigahertz (GHz) to 3 THz range for companies to test and verify their potential new products and services for beyond 5G technologies (FCC, 2019[222]). **October 2020:** The communication industry the United States set up the Next G Alliance to work on a North American 6G roadmap.[57] **April 2021:** Open RAN & 6G collaboration with Japan, USD 2.5 billion **July 2021:** "6G Task Force" bill that requires the Federal Communications Commission (FCC) to establish a "6G Task Force" to investigate how to design and deploy 6G technologies. **July 2021:** the University of Texas at Austin launches a 6G research centre that will focus on research regarding advanced sensing, location, machine learning capabilities and use of terahertz spectrum (FierceWireless, 2021[223]).	Task Force bill: https://www.congress.gov/bill/117th-congress/house-bill/4045/text?r=67&s=1 Next-G Alliance: https://nextgalliance.org/
China	**January 2018:** The Ministry of Science and Technology of China (MOST) starts the Beyond 5G (B5G)and 6G research on four topics: • Fundamental theory for massive communications • mmWave & THz communications • Space-Air-Ground Integrated Networks • Network Intelligence **May 2019:** Ministry of Industry and Information Technologies (MII) launches 6G Technical Working Group **November 2019:** MOST launches "National 6G Expert Committee" (IMT 2030 promotion committee) **July 2020 and December 2020**: MOST releases call for proposals on 6G research, and granted 15 research projects by December 2020.	China launches research and development of 6G technology, https://news.cgtn.com/news/2019-11-06/China-launches-research-and-development-of-6G-technology-Lpdw0kAYec/index.html

Source: Own elaboration based on several sources, including discussions and presentations in the panel on "Global 6G Initiatives", during the 6G symposium in May 2021 (6G Symposium, 2021[207]).

Network performance: Quality of service and quality of experience

With the increased digital transformation of our economies and societies, network performance and the quality of communication networks is gaining importance. It is therefore essential to measure actual broadband performance to inform policy-making and regulation, and to empower consumer and business users.

The OECD has worked systematically on broadband performance since 2012 and has developed a harmonised measurement approach for one dimension of broadband quality: advertised download speeds, which have been integrated into the OECD Broadband Portal.[58] It has since then published a number of reports related to this subject (OECD, 2013[224]; OECD, 2014[225]).[59] Besides speeds, other quality indicators like latency and reliability measures are becoming increasingly important with the next evolution of broadband networks together with the measurement of the underlying wholesale inputs directly influencing broadband performance, such as backhaul availability.

Broadband performance: Advertised versus actual download and upload speeds

Advertised broadband speeds may differ from actual speeds experienced by users. Regulatory authorities across the OECD have increasingly monitored the significant gaps between "advertised" and actual speeds experienced. In this sense, it is useful to observe data from different sources measuring actual speeds. This section provides an overview on actual speeds from several sources such as Ookla, M-Lab, Steam, SpeedChecker and Opensignal (Figure 11 to Figure 14).

Third-party sources measuring broadband performance use different methodologies and thus have different perspectives on the Internet. This is important to understand when drawing conclusions from these data. M-Lab and Ookla compile results from speed tests by users who actively measure their actual speed to access the Internet. Data from Steam is a further way to consider broadband speeds across countries, which reflects the speeds of users using one of the most Internet Protocol (IP) intensive applications: online games. Steam collects data on the speeds experienced by gamers over fixed and mobile networks, representing one of the most demanding user groups on the Internet that seek higher performance levels. Opensignal is an additional source that collates real-world data from smartphone users through both automatic and manual testing to provide insights on users' mobile network experience. More details on the different sources measuring broadband performance can be found in Box 6.

Box 6. Methodological considerations when relying on third-party sources measuring actual broadband performance

Different sources offer complementary insights of the user's broadband performance experience

Previous OECD work examined approaches being taken in OECD countries to measure broadband performance, particularly actual broadband speeds experienced by fixed broadband users. This work noted that several factors may influence the actual experience of users, such as equipment at an end user's premise and the exchange of traffic between different networks that provide access and the source of content. Nonetheless, there are a growing number of tools and services provided by public and private sources, which attempt to provide greater knowledge to all stakeholders on network performance (OECD, 2014[225]). The methodological considerations of four different third-party sources measuring broadband performance are presented here.

SpeedChecker[60] measures broadband performance by targeting tests to a global content distribution network (CDN) called Cloudflare, and shows a user experience of accessing content on this CDN (see Annex 1.B for more details on SpeedChecker's methodology). That is, the main difference between Ookla and SpeedChecker's tests would be CDN measurements compared to "on-net" measurements conducted by Ookla. "On-net" measurements are performed on the same network as though the network itself (e.g. an ISP) was measuring the data route, capturing the shortest path that data may traverse (Worldwide Broadband Speed League, 2020[226]). On the other hand, directing tests to a CDN may reflect in the performance measurement additional variables that may influence how consumers experience the Internet, such as peering relationships, performance issues between provider networks and CDNs, among others (Ookla, 2020[227]).

Ookla's methodology relies on user initiated tests that are directed to Ookla's "test servers" dedicated to these measurements rather than a CDN. The data for average fixed and mobile broadband download and upload Speedtests reported by Ookla measures the sustained peak throughput achieved by users of the network. In practice, when a user asks for a Speedtest, the device pings nearby dedicated testing servers, saturates the network connection, and measures the sustained peak speed achieved by the device during the test window. Therefore, the measured indicator does not reflect the day-to-day speeds experienced by users, but rather the actual maximum speeds attainable by the network connection at a certain moment in time, when a users' device sends the maximum amount of data to one of 14 000 testing servers. Speed tests are performed at any hour of the day. Ookla's Speedtest results by country show an aggregate data from all of the tests received, where each unique Speedtest user's results is averaged to create a single sample that summarises their Internet experience for that time period and geographic area (Ookla, 2020[227]). According to Ookla, its vast testing infrastructure worldwide allows to capture a meaningful view of network performance. At the same time, Ookla's methodology that reflects "peak speeds" by individual tests helps explain in part why on average Speedtest results display higher download speed averages than other sources. Furthermore, like M-Lab, Ookla does not run "background" tests and depends on the users activating these tests. Therefore, users that initiate these tests may, for example, experience a connection issue or be "tech-savvy" potentially creating a sample selection bias.

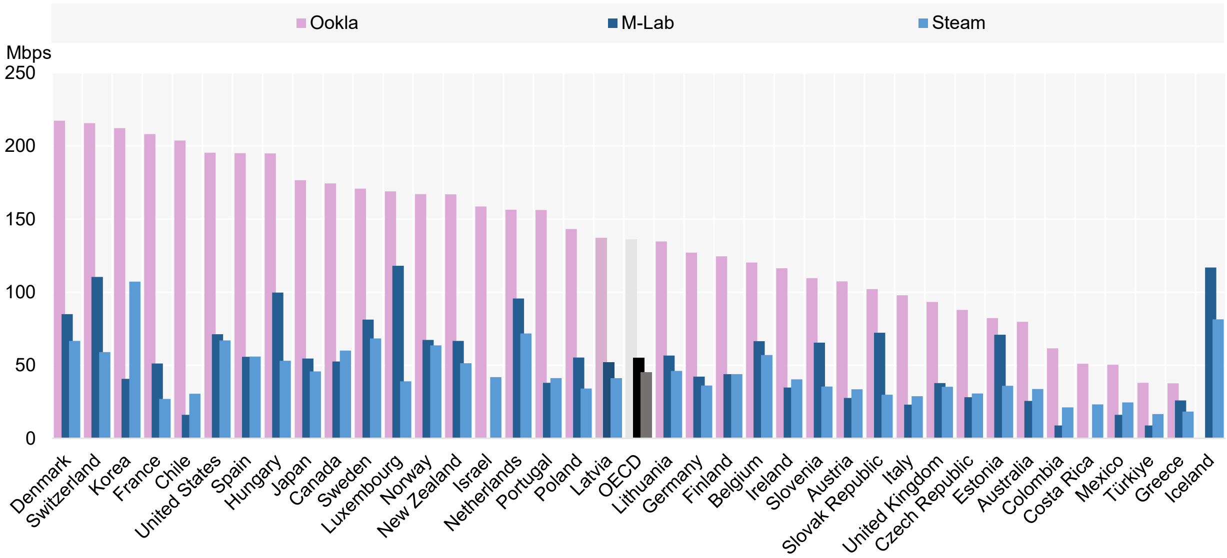
M-Lab is an open source tool that measures broadband speeds in a similar way to Ookla (i.e. user initiated tests), but with certain differences. It provides a broad view on broadband speeds due to the large amount of speed tests it compiles (over 500 million). A single speed test is not a direct measure of the maximum speed available to a household router, but rather the speed available to a device via the router (that may be affected by the Wi-Fi connection). Like with Ookla, the tool that users download when using M-Lab, Network Diagnostic Tool (NDT) application, measures the throughput by saturating the user's connection. However, unlike Ookla that provides more of an "on-net" measurement, all of M- Lab's measurement claim to undertake "off-net" measurements. That is, the measurement extends beyond a user's access provider's network to measure the complete path across the Internet from user to content including interconnections (Worldwide Broadband Speed League, 2020[226]). While Ookla's test servers are placed within the ISP's premises, M-Lab's servers are usually placed at more distant interconnection points (usually at Internet Exchange Points). The latter may explain why M-Lab exhibits lower averages than Ookla. In addition, Ookla uses multiple parallel connections (at least 4 connections) to measure throughput, whereas M-Lab (NDT) uses a thread single connection. As the main purpose of the M- Lab NDT tool is to diagnose connectivity issues, it may lead to sample selection bias, which needs to be considered when interpreting connection speed results (Clark and Wedeman, 2021[228]). In January 2020, M-Lab upgraded its measurement platform, which caused results to be higher in 2020, and therefore cannot be compared with the historical time series of measurements (Worldwide Broadband Speed League, 2020[226]).

For mobile broadband speeds, two main sources are used in this report: Ookla and Opensignal. Opensignal's aim is "to report as accurately as possible the real-world mobile experience as recorded by mobile network users" (Opensignal, 2021[229]). Opensignal's methodology for broadband speeds measures "end-to-end" consumer network experience, and does not rely on dedicated test servers (like Ookla), but rather the full path from the user device all the way to the CDNs, such as Google, Akamai and Amazon. In addition, it collects measurements of network speeds based on both user-initiated tests and automated background tests, to avoid sample selection bias (Opensignal, 2021[229]). In addition, Opensignal has developed a range of new measures that characterise users' multiplayer online gaming, Games Experience (Opensignal, 2020[230]; Frog Capital, 2020[231]), on streaming Video Experience (Opensignal, 2018[232]), and for over-the-top VoIP applications with Voice App Experience.

Sources: OECD (2014[225]), "Access Network Speed Tests", https://doi.org/10.1787/5jz2m5mr66f5-en; Ookla (2020[227]), "Speedtest methodology",https://resources.ookla.com/hubfs/Ookla%20Speedtest%20Methodology%202020.pdf;
Worldwide Broadband Speed League (2020[226]), "Methodology", https://www.cable.co.uk/broadband/worldwide-speed-league/2021/worldwide_speed_league_methodology.pdf; Opensignal (2021[229]), "Methodology Overview: How Opensignal measures mobile network experience", https://www.opensignal.com/sites/opensignal-com/files/opensignal_methdology_overview_july_2021_3.pdf.

The average connection download speed measured by M-Lab for fixed broadband networks in OECD countries was 55 Mbps during the period of July 2019 to June 2020. The average download speeds as reported by Steam for OECD countries was 45 Mbps in February 2021, while Ookla's measure for fixed broadband speeds (average of peak speeds experienced by users) in June 2021 was 136 Mbps in June 2021 (Figure 11). Similar to M-Lab's and Steam's measurement, average download speeds measured by SpeedChecker in December 2020 for OECD countries was 58.7 Mbps (Figure 12). Average speeds reported on by Steam are usually higher than the M-Lab data as only gamer subscriptions are being considered. However, M-Lab had a platform upgrade in 2020; therefore speed results rose considerably in 2020 and cannot be compared with previous years due to the methodological change.

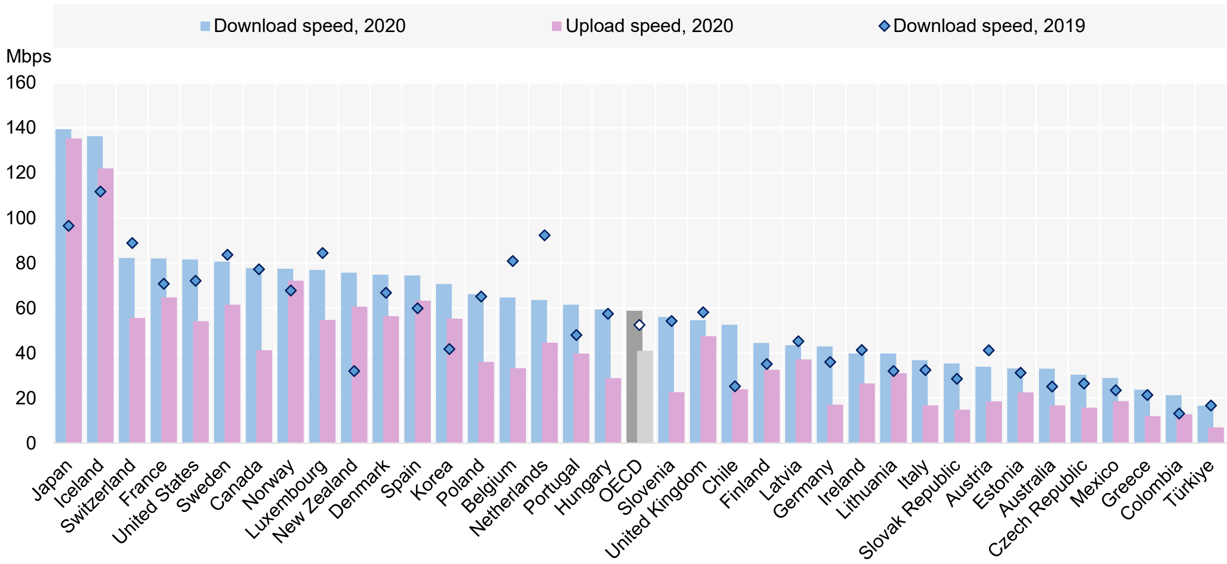
Figure 11. Average fixed broadband download speeds from Ookla, M-Lab and Steam, 2021*



Notes: Speedtest (Ookla) data are for June 2021;* M-Lab (Worldwide Broadband Speed League) speeds were measured from 1 July 2019 to 30 June 2020; and Steam data are for February 2021.
Sources: Ookla (2021), "Speedtest Global Index", www.speedtest.net/global-index; M-Lab (2021), "Worldwide Broadband Speed League", www.cable.co.uk/broadband/speed/worldwide-speed-league; Steam (2021) "Steam Global Traffic Map", https://store.steampowered.com/stats/content.

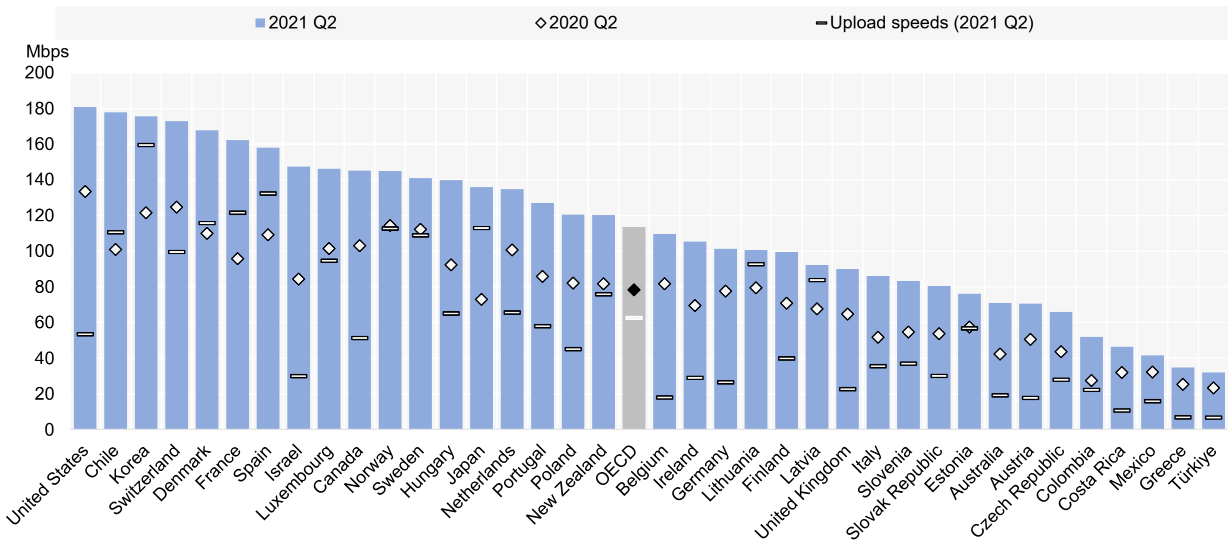
Measures of upload speeds are increasingly important as countries experience a surge of applications to keep economic activities going on a remote setting. For example, video conferencing applications require high uplink throughput. Download and upload speeds of fixed broadband connections in OECD countries are on average asymmetrical, with a higher degree of asymmetry depending on the underlying main access technology used in each country. For example, according to SpeedChecker's measurement, the average upload speed in the OECD was 40.9 Mbps in 2020, compared to 58.7 Mbps download. Using Ookla as source, the fixed broadband upload speeds (average of peak speeds experienced by users) in 2021 was 75.7 Mbps, which contrasts to 136.2 Mbps download speeds (Figure 13). Ookla's data for mobile broadband speeds in 2021 shows even more asymmetry between download and upload speeds (i.e. the OECD average was 73.5 Mbps download vs. 15.3 Mbps upload speeds).

Figure 12. Average download and upload speeds from SpeedChecker, 2020 and 2019



Note: Speeds shown are average. Median speeds are also available.
Source: SpeedChecker.

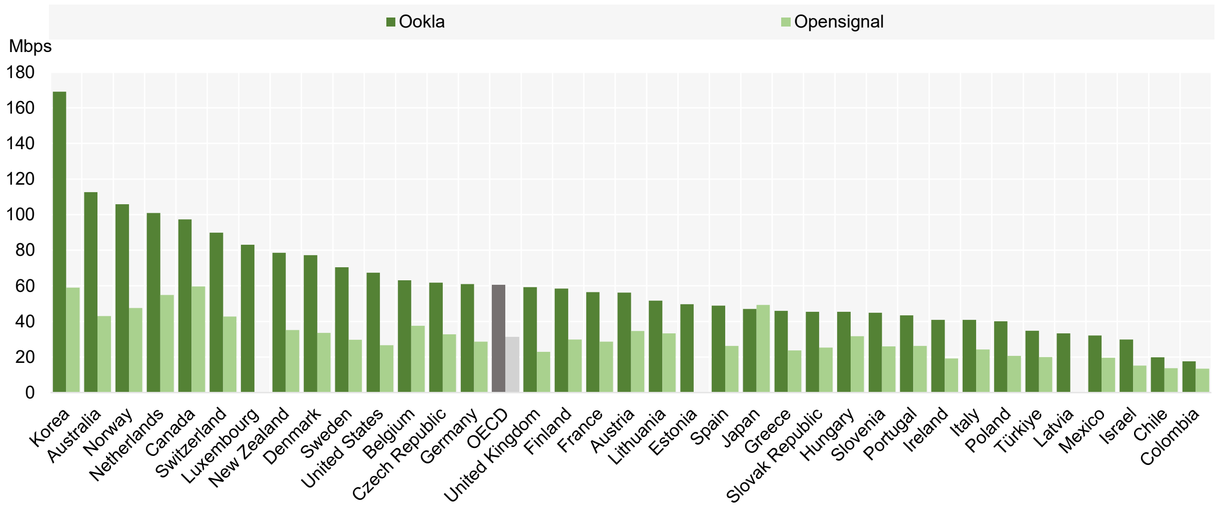
Figure 13. Ookla average download and upload fixed broadband speeds, 2020 Q2 and 2021 Q2



Note: Speedtest data corresponds to 2021 Q2 and 2020 Q2. The data for average fixed and mobile broadband download Speedtests reported by Ookla measures the sustained peak throughput achieved by users of the network. Measurements are based on self-administered tests by users, carried over iOS and mobile devices. The figure presents average peak speed tests, weighted by the number of tests.
Source: OECD calculations based on Speedtest® by Ookla® Global Fixed and Mobile Network Performance Maps. Based on analysis by Ookla of Speedtest Intelligence® data for 2020Q4. Provided by Ookla and accessed 2021-01-27. Ookla trademarks used under license and reprinted with permission.

Data collected by Ookla and Opensignal[61] can provide a perspective on mobile network performance. Opensignal's measure of average download mobile broadband connection speeds for the OECD was of 34.4 Mbps in the first quarter of 2020. When considering Ookla speed tests for mobile networks, the OECD average download speed was 60.6 Mbps in December 2020 (Figure 14).

Figure 14. Mobile broadband download speeds in the OECD (2020), Ookla and Opensignal

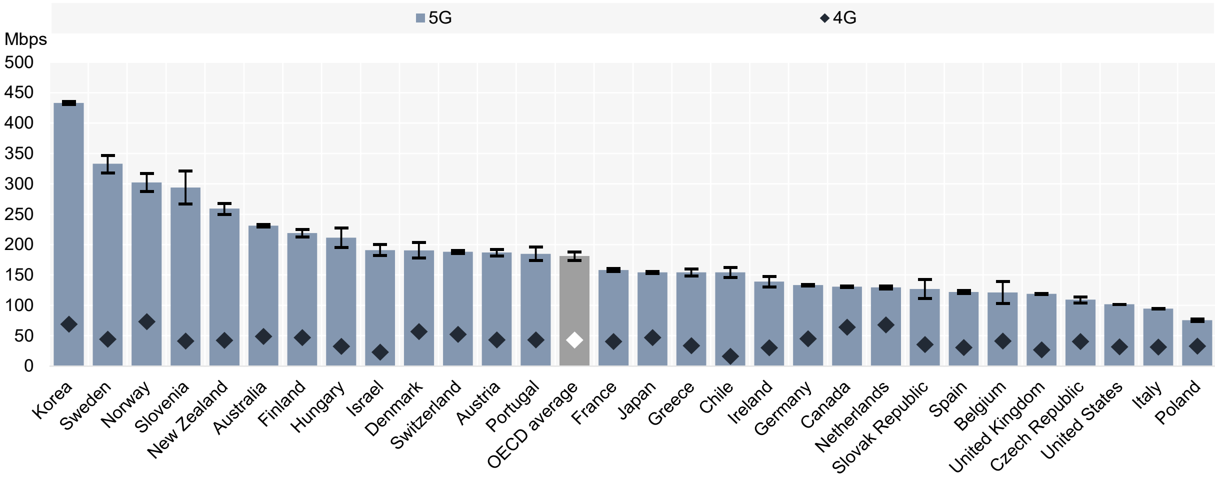


Notes: Speedtest (Ookla) data are for December 2020; Opensignal data were collected from 1 January to 30 March 2020. The definition of download speeds for Opensignal is "Download Speed Experience represents the typical everyday speeds a user experiences across an operator's mobile data networks."
Sources: Ookla (2021), "Speedtest Global Index", www.speedtest.net/global-index; Opensignal (2020), "The state of mobile network experience 2020: One year into the 5G era, Mobile Network Experience Report", May 2020, https://www.opensignal.com/sites/opensignal-com/files/data/reports/pdf-only/data-2020-05/state_of_mobile_experience_may_2020_opensignal_3_0.pdf

Regarding experienced download speeds of 5G networks, according to Opensignal data, in 4Q 2021 these ranged from 75.7 Mbps (Poland) to 433.2 Mbps (Korea)[62] for OECD countries where data was available (Figure 15). The average experienced 5G download speed in OECD countries was 3.7 times higher than the experienced speed in 4G networks in 4Q 2021 (i.e. 155.6 Mbps vs. 42.6 Mbps).

Experienced 5G speeds by country may vary depending on both consumer demand, network design, spectrum holdings by operators, as well as the type of spectrum used to deploy 5G networks. For example, speeds are likely to be faster if higher spectrum bands are used (e.g. mmWave). As noted in the section *Towards 5G commercial offers across the OECD, private 5G networks and standalone (SA) 5G*, for example, smartphone users of commercially deployed mmWave 5G networks in the United States experienced average download speeds ten times faster than 5G networks using sub- 6 GHz spectrum (Opensignal, 2021[68]).[63] However, coverage is also an important metric for users. Opensignal also has indicators on 5G network availability, which measure "the proportion of time Opensignal users with a 5G device and subscription have a 5G connection" (Opensignal, 2021[229]).

Figure 15. Experienced 5G and 4G download speeds in OECD countries* in Q4 2021, Opensignal



Notes: *The OECD average is for available countries only; upper and lower confidence intervals for 5G only. Data collection period: October 2021 to December 2021. Opensignal definition: "5G Download Speed shows the average download speed experienced by Opensignal users across an operator's 5G network. 5G Download Speed for each operator is calculated in Mbps (Megabits per second)" Opensignal notes the following: "Using billions of measurements collected 24/7 from tens of millions of smartphones, Opensignal analyzes real-world mobile network experience at the largest scale and frequency in the wireless industry: by operator and country, regionally and worldwide. Opensignal believes measuring how the network performs directly through users' eyes is key to building better wireless networks. Network operators, telecoms regulators, equipment makers and analysts use Opensignal's mobile analytics insights to inform industry analysis and make key business decisions. For more information or any questions about the data, please visit the Opensignal website (http://www.opensignal.com/)."
Source: Opensignal Limited © 2022.

To improve the performance experienced by users in terms of speed, a key element is investing in upgrading communication networks. To that end, operators should seek to extend backbone and backhaul connectivity, as well as pursue other avenues such as increased peering relationships. In addition, ISPs across OECD member countries that provide the highest speeds to their users often note the prevalence of Internet Exchange Points (IXPs) as a main attribute to improve broadband quality.

Beyond speeds: Latency indicators across OECD countries

While bandwidth speed is one metric to gauge overall performance, other measures of quality are becoming increasingly important. The need for improved response times (i.e. latency) between devices and compute nodes will grow, supporting many applications across different sectors (e.g. fully automated vehicles, remote surgery, etc.) and networks will increasingly be measured by assurance of delivery. Latency can be defined as the round trip time for information between two devices across the network, and it is often referred to as delay or ping rate (OECD, 2019[35]). This section presents the first latency measurements for OECD countries.

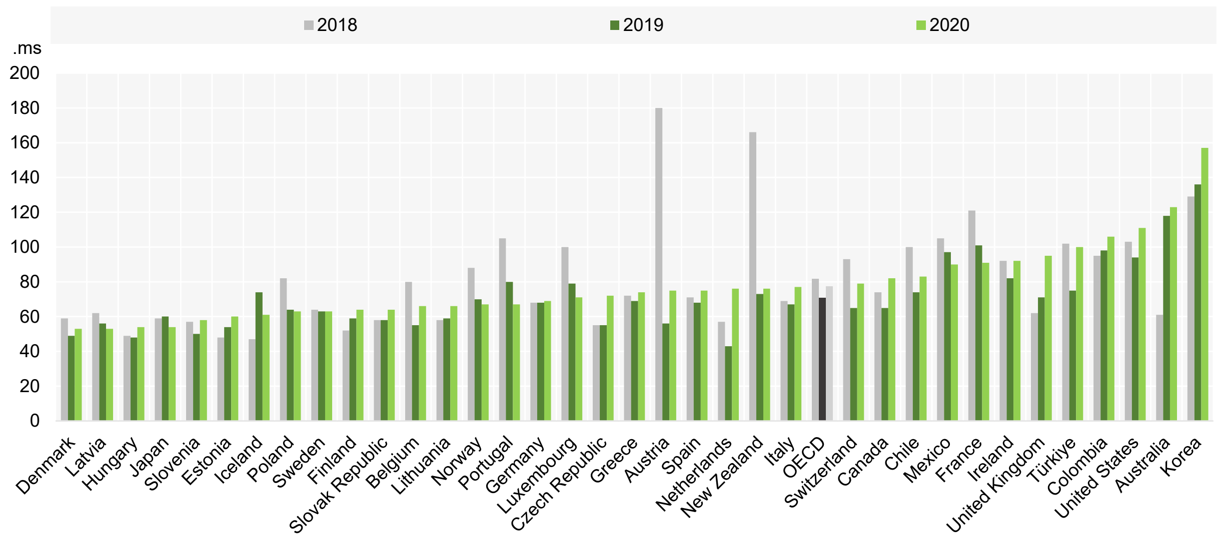
Latency measurement data from SpeedChecker and Ookla

The SpeedChecker test algorithm for speeds and latency provides results across all devices, platforms and operating systems. The company operates several national speed test websites for OECD countries, such as France, the Netherlands, Japan, Poland, and the United Kingdom. The measurements are targeted towards the Cloudflare Content Delivery Network (CDN). A CDN is a geographically distributed group of servers that work together to minimise delays in loading webpage content by reducing the physical distance between the server and the user. Cloudflare is being used by 10% of websites around the world.

As SpeedChecker uses the Cloudflare CDN as a measurement target for their tests, it means that the throughput (i.e. how much data makes it to its destination in a certain amount of time) is more representative of the users' experience rather than measuring access link capacity (for example, what Ookla's measurement shows). More details on Speed Checker's methodology can be found on Annex 1.B.

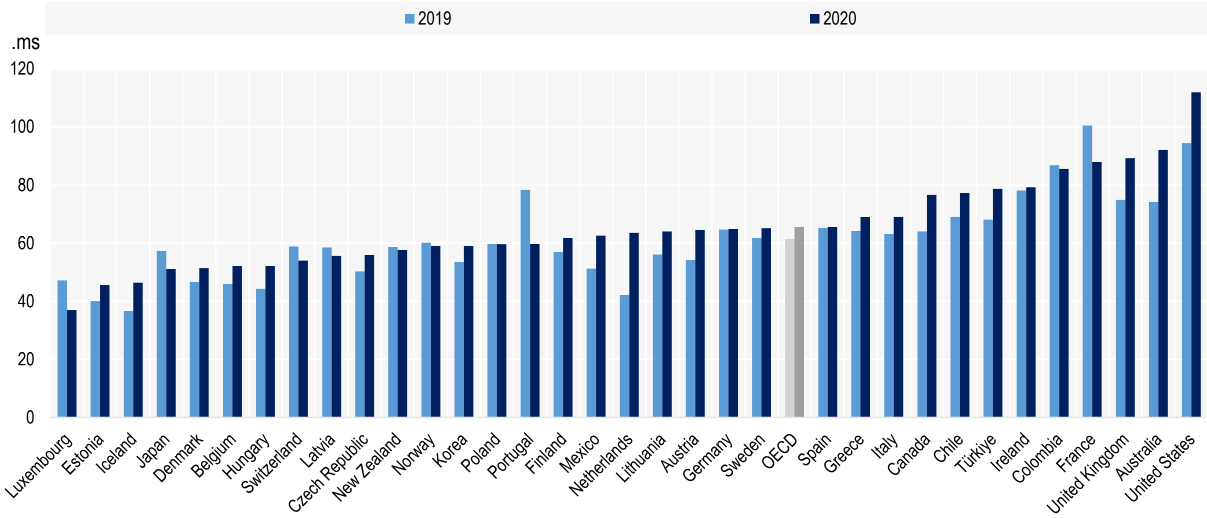
According to SpeedChecker data, the OECD average latency in 2020 was 77 ms (compared to 71 ms in 2019), with countries ranging from a minimum of 53 ms and a maximum of 157 ms (Figure 16). One possible explanation for the increase in latency might be an increased demand on networks due to Covid-19. SpeedChecker also provides latency data for local points of presence (POPs). For some OECD countries, the measurement of latency of local POPs versus the average latency of all POPs seems to be consistent, with some exceptions (Figure 17). For example in Korea, most of the measurements are using foreign POPs (located in the United States, Japan or Singapore) and this may result in high overall latency results of 157 ms (as opposed to a small minority of Korean users using local POPs experiencing 53.4 ms latency). The use of foreign POPs in countries within regions such as Europe and North America seems to have little effect on overall latency, while in some countries within other regions (e.g. LAC and Asia) there seems to be a considerable effect. For Europe and North America, this may be linked to lower geographical distances.

Figure 16. SpeedChecker data on overall* average latency experienced by users in OECD countries measured towards Cloudflare's CDN, 2019-20



Notes: *Overall measurement includes both foreign and local Points of Presence (POPs), and thus may differ from domestic (local) latency rates measured by OECD member countries. Slovak Republic and Slovenia do not have a local POPs in Cloudflare. See Cloudflare network map. SpeedChecker latency measurements across countries may vary according to the location of POPs and the ratio of local POPs within the country.
Source: SpeedChecker

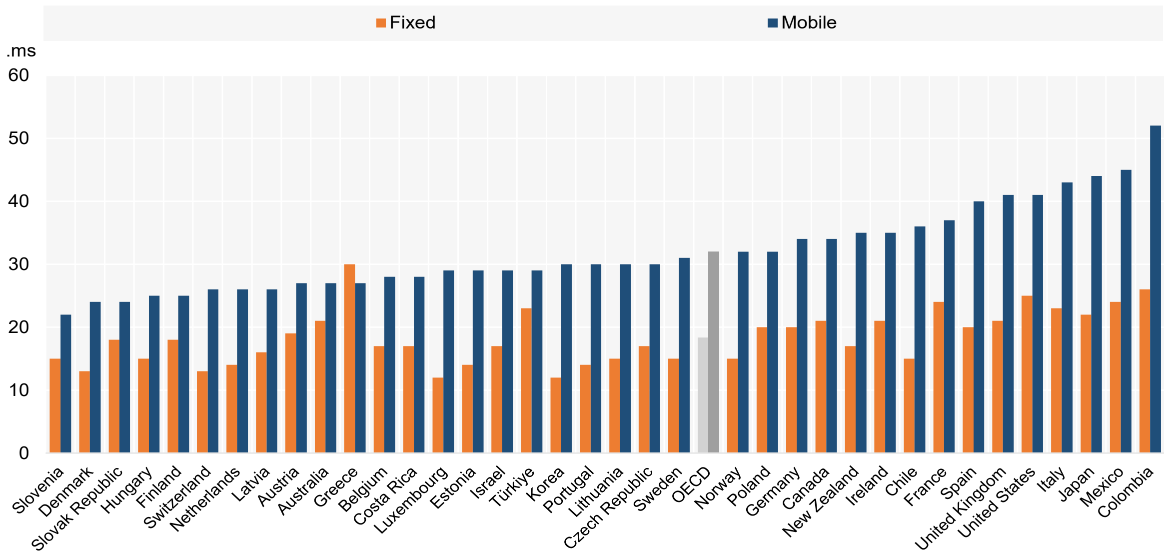
Figure 17. SpeedChecker data on latency experienced by users using local Points of Presence (POPs) in OECD countries measured towards Cloudflare's CDN, 2019-20



Note: Slovak Republic and Slovenia do not have a local POPs in Cloudflare. See Cloudflare network map.
Source: SpeedChecker

As with broadband speeds, given different measurement methodologies may be offering different views of the "Internet" experience, to complement the metrics presented by SpeedChecker, latency measures by Ookla are presented below for both fixed and mobile networks. Similar to what happens with Ookla's measurement of broadband speeds, given that part of Ookla's methodology to test broadband performance is to direct tests to their nearest "testing server" and selecting the server with the lowest latency to conduct the tests, this means that results in this case may be skewed downwards (Figure 18).

Figure 18. Ookla data on fixed and mobile broadband average "minimum" latency in the OECD area, June 2021



Source: Ookla (2021), "Speedtest Global Index", www.speedtest.net/global-index

IP interconnection and broadband performance

One factor for the performance of networks is efficient Internet traffic exchange. IXPs, national fibre backbones, and submarine cables play a crucial role in IP interconnection. IXPs allow for access providers to interconnect with each other and the national backbone, fostering Internet traffic exchange (OECD, 2014[233]).

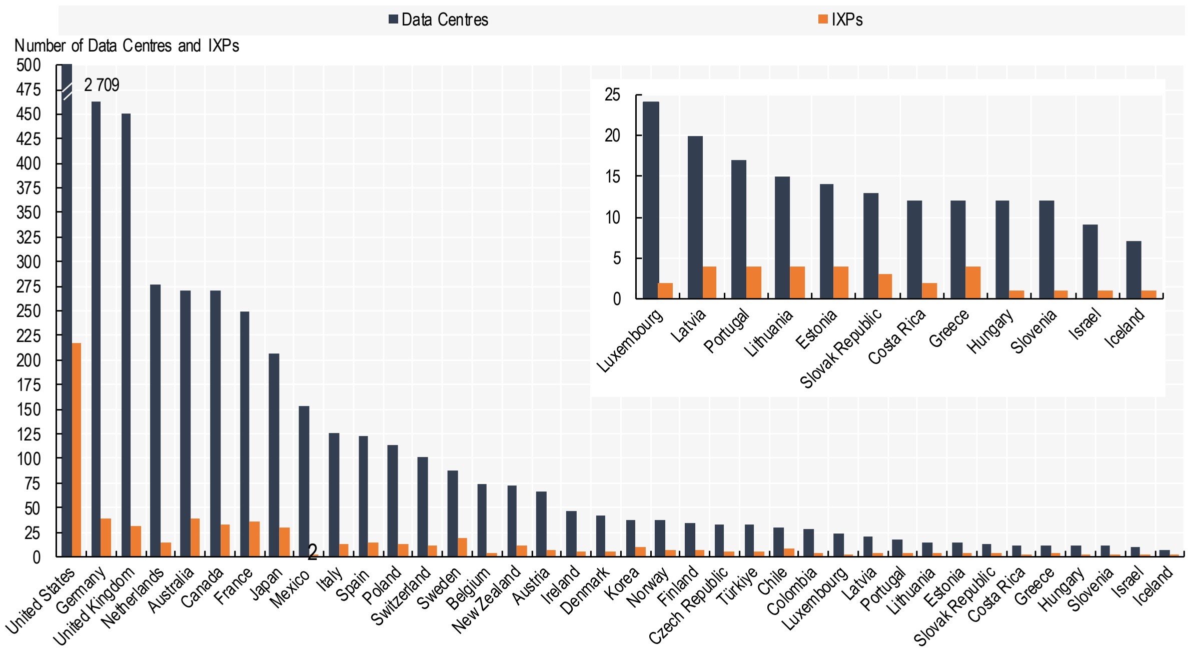
Several elements contribute to making IP traffic routing more direct, and thus, reduce latency and overall quality of the Internet. For example, these elements include a reduced reliance on transit, local availability of Internet Exchange Points (IXPs), direct delivery of traffic by CDNs, and caching of content closer to the user (Weller and Woodcock, 2013[234]).

The Internet, or network of networks, consists of Internet Service Providers (ISP) or carrier networks, which are interconnected with one another in a sparse mesh. Each of the interconnecting links takes one of two forms of agreements: transit or peering. Transit agreements are commercial contracts in which, typically, a customer pays a service provider for access to the Internet; these agreements are most common at the edges of the Internet. Peering agreements are carrier interconnection agreements that allow carriers to exchange traffic bound for one another's customers; they are most common in the core of the Internet (Weller and Woodcock, 2013[234]). Most IP traffic interconnection agreements rely on peering.[64]

Content providers in many countries use local caches to reduce latency and/or peer with communication companies. For caching, a CDN improves the user's experience by delivering a local copy of the requested content from a nearby cache edge, or Point of Presence (PoP). That is, CDN caching eliminates the need for a request to travel all the way to the origin. If there was a move to impose high interconnection fees for Internet traffic charged by local Internet Service Providers (ISPs), this may result in content providers removing local caches, which could be reflected in higher latency results.

ISPs across OECD countries that provide the highest speeds to their users often note the prevalence of IXPs as a main attribute to improve broadband quality. For example, IXPs play a role to reduce latency by keeping traffic local (Weller and Woodcock, 2013[234]). For an IXP to function well, multiple players would ideally exchange an important amount of traffic in the Internet ecosystem. Websites and content should also be ideally hosted in close proximity. This keeps the exchange of traffic local rather than routing data via other countries, which would increase latency and might be more costly. A significant amount of data routed via other countries often indicates a suboptimal development of the Internet traffic exchange market in a given country. In addition, data centres and CDNs are key elements for cloud and edge infrastructure. Figure 19 shows the number of IXPs and co-location data centres in OECD countries in 2021.

Figure 19. Number of co-location Data Centres and Internet Exchange Points (IXPs) in OECD countries, 2021



Note: Cloudscene is a directory of colocation data centres, cloud services, and interconnected fabrics.
Source: Cloudscene (2021), "Compare Data Centers", https://www.cloudscene.com/; and PCH (2021), *Global Directory of IXPs*, https://www.pch.net/ixp/dir.

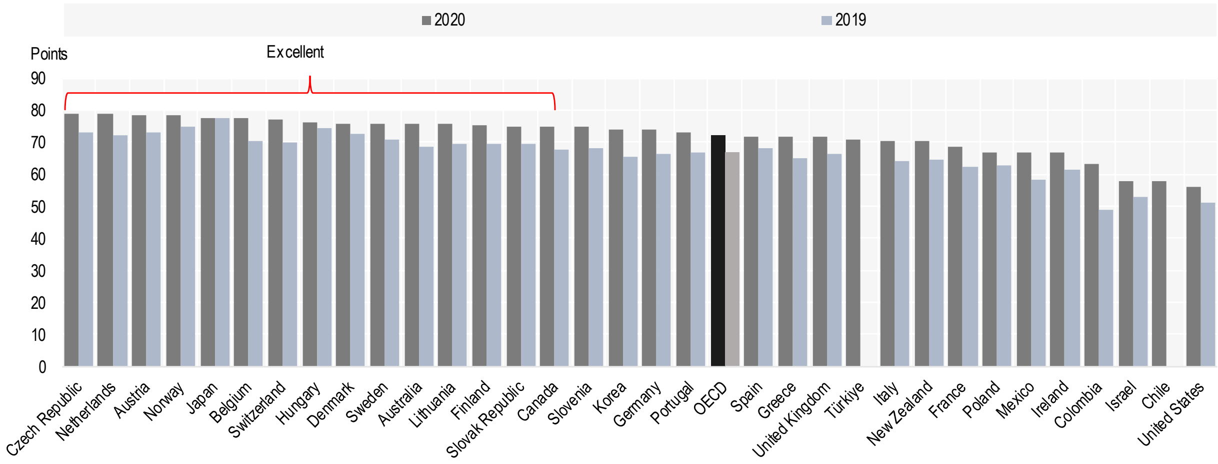
Innovations in measurement: A focus on quality of experience

Increasingly, recognising the primacy of providing service quality to fulfil user needs, regulators and firms engaged in broadband performance measurement are looking towards incorporating "user-centric" approaches to understand and assess network experience, which has led to advances in measures of quality of experience (QoE).

In simple terms, quality of service (QoS) concerns performance measurement of a network and terminal equipment up to the user interface by using objective measures from technical point of view. Quality of experience (QoE) is a broader concepts and relates to how the user perceives the service performance (i.e. overall level of satisfaction), which may also include non-technical factors influencing the user's perception and context.[65]

This type of approach may also shed light on the users' experience of certain applications that may be subject to throttling. For example, Opensignal conducts broadband performance measurements from the perspective of the end-user, and attempts to measure their network experience as well as their experience accessing certain services. One of their latest innovations in this realm was in 2018, when they launched a measure of mobile video experience (Figure 20), spanning multiple video content platforms (Opensignal, 2021[229]).

Figure 20. Opensignal - Quality of the mobile video experience



Notes: *Excellent (75 or above). Data collection period: 1 January to 30 March, 2019 and 2020. Opensignal's video experience metric measures that quality of experience of users when they watch video streaming. "It is built on an International Telecommunication Union (ITU)-based approach for measuring video quality, it is derived from several underlying parameters based on real-world measurements of video streams from the world's largest video content providers" (Opensignal, 2018[232]). "The various parameters measured by the Video Experience metric are combined using an algorithm based on ITU recommendations to calculate a Mean Opinion Score (MOS), which is then translated to a scale of 0-100" (Opensignal, 2021[229]).

Source: Opensignal (2020): The state of mobile network experience 2020: One year into the 5G era, Mobile Network Experience Report, May 2020, https://www.opensignal.com/sites/opensignal-com/files/data/reports/pdf-only/data-2020-05/state_of_mobile_experience_may_2020_opensignal_3_0.pdf.

Policies and regulatory measures for broadband networks of the future

The evolution of fixed and mobile networks (i.e. 5G and high-capacity fixed networks), in conjunction with new technological trends, the convergence between formerly distinct sectors, and the increasing complementarity of fixed and mobile networks, raises new questions in the area of communication policy and regulation.

OECD countries have worked on policies and regulation directed at promoting the next generation of fixed and mobile networks by measures that ease network roll-out. Several OECD countries are also exploring ways to accelerate the transition to next generation networks by adapting wholesale regulatory measures as to provide incentives to boost the fibre deployment, or by adapting their regulatory framework to close down legacy networks. In addition, there is a keen interest by policy makers across the OECD to inform users (consumers and businesses) regarding broadband performance, and public entities are increasingly publishing data on the quality of broadband networks and following innovative techniques to ensure transparency to users.

Apart from these communication issues that only grow in importance to foster the next generation of broadband networks, there are new issues gaining prominence in the heart of the policy agenda, such as the sustainability of communication networks.

This section provides a short overview of policies followed at present by OECD countries to foster high-quality connectivity through the expansion of the next generation of fixed and wireless networks.

Measures to facilitate the roll-out of broadband networks of the future

Efficient spectrum management, promoting infrastructure sharing, easing network roll-out, reducing network deployment costs, and facilitating deployment and access to backhaul and backbone facilities, have been key measures in many OECD countries to foster the deployment of the next evolution of broadband networks. As mobile networks at their core become a further extension of fixed networks, these key regulatory issues become fundamental to deploy broadband networks. In other words, traditional "communication issues" are likely to be exacerbated, and therefore policies and regulations that foster competition, promote investment in fixed and mobile networks and spur innovation will become key for a successful and inclusive digital transformation.

Promoting efficient spectrum management

Spectrum is a key asset for all wireless communications, from Wi-Fi to radar, satellite to mobile, audio and broadcasting. Its timely availability for a range of services and applications, such as the next generation mobile networks is critical (OECD, 2019[59]). Therefore, efficient spectrum management, -i.e. spectrum planning, balancing the needs of all sort of uses and users, efficient allocation and effective assignment-, is key to face the increased demand on communication networks and to bridge connectivity divides.

With regards to spectrum planning and allocation, OECD countries are preparing for the World Radiocommunication Conference in 2023 (WRC-23), where the allocation of additional spectrum resources for IMT-2020 (5G) will be discussed, among other services and applications. Appropriate and necessary spectrum harmonisation at the global level is a desirable long-term goal that has the potential to enhance economies of scale for network deployment, by reducing the costs of device manufacturing and consumer equipment. However, harmonisation needs to be balanced with other goals, such as promoting flexible use of spectrum to ensure that it is used optimally to support all aspects of society (OECD, 2014[235]).

Well-designed spectrum assignment procedures provide legal certainty in the aim of fostering long-term investment. Market mechanisms, such as auctions, are best practice in OECD countries to assign spectrum. Increasingly, OECD countries seek to incorporate several policy objectives in licensing procedures (e.g. enhancing competition, providing incentives to expand coverage of mobile networks in rural and remote areas, etc.), making the design of these procedures inherently important. Many auctions in OECD countries in recent years have included means to promote market competition (e.g. giving priority to new entrants, spectrum caps or commitments to host mobile virtual network operators [MVNOs]), as well as included coverage obligations.

License-exempt (or unlicensed) spectrum is also a market assignment mechanism, with no entry price attached, but rather conditions of shared use set by authorities, usually based on standards. This approach has proven its merits for a number of cost effective applications, such as wide-range and short-range devices (SRDs) and access equipment for Wi-Fi networks (OECD, 2014[235]). It can also lower barriers to entry faced by social-purpose operators (APC, 2019[236]). The role of unlicensed spectrum may gain prominence in OECD countries with greater deployment of Wi- Fi 6.

OECD countries are also exploring innovative approaches to spectrum management in light of emerging technologies and the evolving market landscape. For example, new forms of spectrum sharing, flexibility in licensing to cater to local and national needs, secondary markets of spectrum, as well as dynamic spectrum allocation. These approaches, such as spectrum sharing, can help ensure efficient use of licensed spectrum. Finally, several countries are taking measures to support wireless innovation (e.g. making spectrum available for innovation before its long-term use is known).

Infrastructure sharing agreements on the rise

With the increasing need for high-quality networks, infrastructure sharing agreements among operators are on the rise to mitigate the costs of deployment of the next evolution of broadband networks. The nature of these infrastructure-sharing agreements is changing, as they sometimes relate to deeper forms of network and spectrum sharing (i.e. in the active layer of networks compared to only passive infrastructure sharing agreements), which raises new competition and regulatory challenges.

Infrastructure sharing agreements can be either in the form of passive infrastructure sharing (e.g. masts, towers, sites, etc.) or active mobile infrastructure sharing agreements (e.g. radio access network [RAN] sharing, roaming, software elements, etc.).[66] Most OECD countries encourage infrastructure sharing, provided that the advantages outweigh the drawbacks, i.e. that sharing is not detrimental to competition. In the past, passive infrastructure sharing has been more common in OECD countries than active forms of sharing, although there are increasing examples of RAN sharing agreements.

In France, there is a RAN sharing agreement between Bouygues Telecom and SFR. In Switzerland, there exists a RAN sharing agreement between Sunrise and Salt that only concerns a limited number of locations. In Portugal, Vodafone Portugal and NOS signed a networks sharing agreement in October 2020, with the aim of having common use of the network (RAN) in less densely populated areas, while engaging in passive infrastructure sharing in highly densely populated areas (Vodafone Portugal, 2020[237]). In Denmark, Telia and Telenor haven been engaged in RAN sharing since 2012. In Sweden, Telenor and Tele2 have a joint mobile network collaboration through JV Net4Mobility. In Germany, Telefonica/O2 and Deutsche Telekom signed a RAN agreement in January 2021 to cover “grey areas” of the 4G network using the 800 MHz spectrum band (Telefónica DE, 2021[238]). In Korea, SK Telecom, KT, and LGU+ signed a sharing agreement in April 2021 to allow shared access to their respective 5G networks in 131 rural and coastal locations (The Korean Bizwire, 2021[239]). Given network densification with the further deployment of 5G and related costs, it is expected that the number of sharing agreements increases across the OECD.

OECD countries have also seen an increase of fixed network sharing agreements in order to reduce fibre deployment costs. For example, in December 2020 two Slovakian operators (Slovak Telecom and Orange Slovensko) signed an agreement to share their fibre networks using “GPON technology”[67] to provide service to customers (Orange Sk, 2020[240]).

Facilitating network roll-out and reducing deployment costs

An enabling domestic environment plays a large role in attracting investments, and one way of providing incentives to invest is by reducing network deployment costs. Therefore, policies that reduce barriers to broadband deployment and thus make investments easier by communication operators are further key drivers of expanding and upgrading communication networks (OECD, 2021[241]).

Streamlining access to rights of way can reduce the costs of civil works and therefore provide an important impetus to stimulating the roll-out of next generation networks and, in particular, fibre. In addition, increased access to information and public assets also plays a crucial role for broadband deployment. For example, when deploying mobile infrastructure, much time may be spent on determining and acquiring locations to build towers. To ease this process, countries can increase the transparency of and access to information about public assets.

Furthermore, a number of OECD countries have focused on “dig-once” policies to leverage non-broadband infrastructure projects (e.g. utilities, street light providers, and highway/ road construction) and reduce the costs of broadband network deployment.

In recent years, co-investment initiatives to deploy fibre-to-the-home (FTTH) and 5G networks have also been on the rise in OECD countries, where regulators have had to evaluate the effects to competition. Examples of recent co-investment initiatives can be found below.

Co-investment initiatives

An increasing number of OECD countries have implemented policies on co-investment, or joint deployment of broadband networks. For example, in the European Union, the European Electronic Communications Code (EECC) creates incentives for co-investment in new fibre networks by providing for regulatory relief to operators entering in such agreements.[68] In Italy, Telecom Italia (TIM) proposed to the regulator (AGCOM) a co-investment plan to deploy FTTH networks through its FiberCop unit, and the company published the related wholesale offer in January 2021 (TIM Group, 2021[242]).[69] The network deployment plan aims to cover 75% premises in 1 610 urban and semi-urban municipalities. The deployments would be open to all operators, either on a market-by-market basis or for all areas (TIM Group, 2021[242]). In Portugal, Vodafone and NOS signed a commercial co-investment deal in 2017 to share dark fibre for around 2.6 million homes (Bourreau, Hoernig and Maxwell, 2020[243]).

In Australia, the NBN Co plans to roll out more fibre deeper into its network with an investment package of AUS 4.5 billion (USD 3.09 billion).[70] It will create 240 business fibre zones across Australia (including 85 in regional centres) by seeking co-investment opportunities with state, territories and local councils to deliver access to high speed broadband services on the NBN for homes and businesses in regional and remote areas of Australia, including upgrading services from fixed wireless or satellite to fixed line at gigabit speeds to around 8 million premises (up to 75% of Australian homes and business) by the end of 2023.

Joint deployment initiatives for mobile networks are also increasing. In Portugal, there has been co- investment agreements in recent years (e.g. between the mobile operators NOS, Optimus and Vodafone, and between MEO and Vodafone). In Lithuania and Latvia, the MNOs Tele2 and Bite Latvija, signed a network sharing agreement in June 2019 that included plans to co-invest and deploy a joint RAN for 5G in both countries (Tele2, 2019[244]). In Denmark, Telenor and Telia submitted a joint bid in the 5G auction that took place in April 2021 through a joint venture called “TTN”, and these two MNOs plan to deploy a joint 5G shared network in partnership with Nokia (Nokia, 2021[245]).

Expanding access to backhaul connectivity

Taking fibre backhaul closer to the end-user, whether the business location or residential dwelling, is important to increase speeds across all access technologies, not only 5G. Several OECD countries have adopted policies to enhance backhaul and backbone connectivity.

For example, regulation in Korea requires network operators to share fibre, including backhaul, while maintaining incentives to invest. In the United Kingdom, the government set out measures in the “Future Telecoms Infrastructure Review” such as allowing “unrestricted access” to Openreach ducts and poles (i.e. BT’s physical infrastructure company) for both residential and business broadband use, including for essential mobile infrastructure (United Kingdom Department for Digital, Culture, Media and Sport, 2018[246]). The Irish communication regulator (ComReg) has mandated access to dark fibre on the operator with Significant Market Power (SMP) in certain circumstances. In Sweden, the operator with SMP, Telia, is subject to provide access to a backhaul connection between an operator's co-located equipment and a point no more than 50 km away where connection could be established for transport to the operator's own network, so-called backhaul connection (PTS, 2019[247]).[71]

Measures to boost the transition to “future-proof” technologies

Wholesale access remedies with the aim of providing incentives to upgrade networks

Several approaches have been taken by OECD countries to promote broadband development and foster competition, including the promotion of infrastructure competition, but also the promotion of common wholesale infrastructures with regulated or non-regulated wholesale access to increase competition at the retail level (i.e. last mile or access part of the network). Insufficient infrastructure competition in some instances may require on-going regulatory intervention or oversight, which explains why integrated incumbents in OECD countries were, and in many cases still are, subject to wholesale regulatory measures (OECD, 2021[34]).

With the aim of fostering fibre deployment, regulators are both looking to safeguard competition while incentivising investments in networks. Some OECD countries are promoting infrastructure-based competition, including through physical infrastructure access, to boost fibre deployment (e.g. Spain and Portugal). Some implement this through asymmetric wholesale access remedies, while others have applied symmetric regulation for fibre wholesale products based on geographical segmentation. A summary table of the developments in wholesale access regulation of fixed networks in OECD countries since 2016 can be found in Annex 1.C.

In the European Union, countries such as Spain and Portugal have been highly successful in promoting fibre-to-the-home (FTTH) deployment in recent years. Portugal focused initially only on regulating access to ducts, poles and in-building wiring, to consider in a later phase potential asymmetric access regulation to fibre for those holding significant market power (SMP). Spain in 2016, after seven years of the initial phase, applied fibre wholesale access regulation based on geographical segmentation of competitive versus non-competitive areas (Godlovitch et al., 2019[248]).

France took a slightly different approach and was an early mover in promoting fibre deployment. From the onset (2008), Arcep applied symmetric regulation for fibre wholesale products based on geographical segmentation, combined with co-investment incentives (*mutualisation passive de la boucle locale optique combinée au co-investissement*). Symmetric regulation of fibre in France imposes that the firm exploiting a fibre cable must provide reasonable open access to other firms in non-discriminatory terms.[72]

In the United Kingdom, Ofcom aims to boost fibre expansion by supporting Openreach in retiring its old copper network, and by considering keeping wholesale remedies on fibre on in some areas while deregulating areas where there is efficient competition of fibre-to-the-premises (FTTP) networks (Ofcom, 2020[249]). Ofcom's key objective when conceiving wholesale regulatory approaches to regulate fibre in areas where there is prospective infrastructure competition is striking the delicate balance between preserving incentives to invest (medium and long-term aims) and protecting consumers in the short term. If the measures are asymmetric (i.e. applied to the incumbent), a "high" wholesale access price may provide incentives for the entrants in the fibre market to deploy their own infrastructure (instead of using the existing infrastructure of the incumbent). However, if there is pass-through of costs to final retail prices, then this measure impacts consumers in the short term. Such was the dilemma that Ofcom faced in the "Ofcom Wholesale Local Access Market Review 2018 (2018-21)" (Ofcom, 2018[250]). Ideally, the regulator initially would have liked to split the country into geographical zones by likelihood of infrastructure competition. In 2018, Ofcom deemed too complex identifying the areas of prospective competition, and decided for a speed-tier solution by imposing wholesale remedies on BT/Openreach for FTTC, virtual unbundled local access (VULA), with a price cap for speeds up to 40 Mbps. In 2020, Ofcom submitted a public consultation for its wholesale fixed market review 2021-26 (Ofcom, 2020[251]), and published the final decision on 18 March 2021, with an update on 15 July 2021 pertaining a modification to the SMP conditions (Ofcom, 2021[252]).[73] With this decision, Ofcom aims to boost fibre expansion by supporting Openreach in retiring its old copper network, and by considering keeping VULA regulation in some areas while deregulating areas where there is efficient competition of FTTP networks (Ofcom, 2021[252]).

With aim of safeguarding competition while incentivising investments in networks, the European Commission updated in December 2020 its "Recommendation" on relevant wholesale communication markets that still warrant ex-ante regulation (European Commission, 2020[253]). The new list of relevant markets includes two wholesale connectivity markets that previously existed in the 2014 recommendation, i.e. the market for wholesale local access (WLA, previously known as market 3a) and the market for wholesale access to dedicated connectivity (previously known as market 4). According to the European Commission, "The market for wholesale local access will ensure access based competition in the broadband mass market. The market for wholesale-dedicated connectivity will be instrumental to ensure access based competition for business grade connectivity".

Adapting the regulatory framework for the closing down of legacy networks

A number of OECD countries have started to see efforts to shut down legacy networks and services, such as copper fixed networks, and regulatory frameworks have had to adapt to the evolving nature of networks. With numerous players and stakeholders involved in the communication sector, meeting the needs for high-quality connectivity networks requires collaboration among all key actors. This is particularly relevant when it comes to phasing out mobile legacy networks (e.g. 2G or 3G networks for 4G and 5G), which can, in particular, affect IoT devices and systems running on those older generation of networks, but also fixed networks (copper transition to fibre) that might affect wholesale offers. When taking a decision of phasing out a legacy network, the needs among operators, the users of these networks and the government need to be considered.

In the European Union, the EECC (Article 81) establishes that operators with significant market power in one or several markets should notify in a timely manner their plan to migrate from legacy infrastructure (including copper networks), and the regulator should ensure that this transition occurs in a timely and transparent manner. In addition, the regulator should ensure the availability of alternative products to access an upgraded network in the areas concerned with the migration of legacy networks to safeguard competition and end-users' rights (European Commission, 2018[254]).

In Italy, AGCOM adopted in 2019 a regulatory framework for the migration from legacy copper network to a Next Generation Access (NGA) network by a transition plan of the incumbent operator.[74] In Japan the operator NTT announced it would transition its PSTN networks to IP by 2025. In response to this, the Ministry of Internal Affairs and Communications (MIC) in Japan established a "Committee for Smooth Migration of PSTN" to ensure a smooth transition.

In Colombia, certain obligations of the spectrum auction for the 700 MHz band finalised in January 2020, compels auction winners to phase out 2G and 3G networks in all municipalities with less than 100 000 people where the operator already has coverage.

In Mexico, asymmetric regulation has been imposed to the "preponderant" economic agent in the communication sector (i.e. a similar notion to the player with significant market power), which requires this agent to transition its legacy network to fibre, and to provide non-discriminatory access to wholesale services to rival operators.

In Portugal, the fixed incumbent operator announced to the regulator (ANACOM) its intention to initiate the phase-out of its copper network, as increasingly fibre deployment reaches its geographical footprint. In its initial stage, the "copper switch-off" will occur in areas where there is fibre coverage, and where no other operator accesses the incumbent's copper network. The fixed incumbent currently has access obligations associated with its public switched telephone network (PSTN). Therefore, in areas where other operators provide services using (regulated) wholesale access offers, the copper network can only be closed if the regulator is informed five years beforehand or if an alternative solution is provided (and agreed with) other operators.

In the United Kingdom, the communication regulator, Ofcom, has noted the need for regulatory approaches that encourage investment in fibre to the premises (FTTP) deployment, or what the United Kingdom calls "full-fibre broadband". Some of the changes announced in January 2020 include that wherever FTTP is deployed, regulation will be removed for copper products. The aim is to incentivise stakeholders to invest more in FTTP solutions (Ofcom, 2020[255]).

The importance of ensuring transparency for users: Monitoring broadband performance

Broadband users across OECD countries require information on the availability, quality and prices of communication services to make informed choices. Publishing coverage and network quality data not only contributes to increased transparency, but also enhances competitive pressure that may lead to improved quality of broadband networks.

Policy makers have an important role to play in increasing the transparency of broadband offers for users. The importance, and potentially the complexity, of ensuring transparency of information on broadband performance will increase in upcoming years due to developments in 5G and Gigabit networks. Concerning 5G, with tailor-made services for specific user groups in business-to-consumer (B2C) and business-to-business (B2B) segments, information of the availability of a service (e.g. geographically or in a roaming situation) will become crucial. Namely, regulators will need to work on indicators on coverage and QoS of 5G networks to enable informed choices both in the B2B segment, but also for consumers.

Ensuring transparency for users (consumers or businesses) of the coverage and quality of broadband subscriptions is key to foster high-quality connectivity. It is a tool for policymakers to foster competition and increase consumer choice. Namely, it creates new dimensions of competition among operators (i.e. not only price competition but also quality of the connections). This subsection provides an overview of efforts undertaken across OECD countries to improve their broadband maps, examples of innovative approaches such as crowd-sourcing techniques to measure quality and coverage of broadband networks, as well as some examples of information on the underlying wholesale infrastructure that affect broadband performance (e.g. backhaul and backbone connectivity).

Broadband maps

Granular data on the available fixed broadband offers and their advertised speeds may be required for a household to make an informed choice. Regulators around the world have made efforts for several years to improve their broadband maps, so that consumers are aware of broadband offers by speed-tiers (and/or technology) in their neighbourhood, and as such, choose according to the best local offers available.

The OECD Broadband Portal provides links to national broadband maps of 30 out of 38 OECD countries. In these maps, it is possible to consult which technologies are used for broadband access and how much speed is provided in a location along with names of service providers (if a detailed interactive map has been established in the country). For example, in Sweden, PTS provides a detailed broadband coverage map according to speed tiers available aggregated by all operators available in a certain location (http://bredbandskartan.pts.se/). In Switzerland, the Broadband Atlas is an interactive application managed by the Swiss Confederation with information from the regulator, OFCOM (www.atlaslargebande.ch). It consists of 18 layers, 15 of them describing fixed network coverage (by technology and speeds) and three layers concerning the availability of mobile networks (by technology). This map also includes 5G coverage, and by the end of April 2021, 5G networks covered 82% of Switzerland's territory (Swiss Confederation, 2021[256]), where operators reported more than 90% of the population being covered by 5G networks (see Annex 1.A on 5G status in OECD countries).[75] Some countries may also opt to publish data per communication service provider to increase dimensions of competition among providers.

OECD countries are also stepping up efforts to improve these broadband maps, in particular if they influence the allocation of funds to bridge connectivity divides in underserved areas. For example, the United States Congress passed the "Broadband Deployment Accuracy and Technological Availability (DATA) Act" in 2020 instructing the FCC to improve its broadband maps. With the aim of improving the accuracy of broadband maps, and anticipating the broadband funds that were allocated in 2021 through the infrastructure bill (USD 65 billion), the FCC launched in February 2021 a "Broadband Data Task Force". The aim of the Task Force is to "lead a cross-agency effort to collect detailed data and develop more precise maps about broadband availability" (FCC, 2021[257]).[76]

Data driven regulation and user-centric approaches to improve broadband performance

OECD countries increasingly make use of data-driven regulation to complement traditional regulatory tools, by relying on the power of disclosing information to steer communication markets in the right direction for operators to "self-regulate" and make network improvements. These type of measures may become increasingly important with the next evolution of fixed and mobile networks.

Some regulators are using innovative approaches, such as "crowd-sourcing" techniques and volunteer tests with whiteboxes to measure the quality and coverage of broadband networks (e.g. Australia, Austria, Belgium, Canada, Colombia, Czech Republic, France, Germany, Greece, Italy, Lithuania, Luxembourg, Norway, Slovak Republic, Slovenia, the United Kingdom, and the United States). For example, France is conducting quality of service tests on fixed broadband connections using "crowdsourcing" techniques, which are complemented by an application protocol interface (API) to be installed in set-top boxes that allow to control for a number of technical features that may influence the quality measurement. In 2018, the French regulator built together with the operators the API that is placed on set-top boxes, with the regulatory decision adopted in October 2019.

In the United Kingdom, Ofcom has been relying on their technical partner, SamKnows, since 2008. SamKnows sets up a panel of people in the United Kingdom who connect a hardware monitoring unit to their broadband router (i.e. a whitebox). This enables them to measure the broadband performance delivered by different services and assess how they vary by factors including technology, provider, offer, where people live and when they use their service (Ofcom, 2021[258]). The SamKnows routers used in the United Kingdom for test both Quality of Service (e.g. speeds, jitter, latency, packet loss) and Quality of Experience measures (e.g. testing Netflix video streaming performance) (Ofcom, 2021[259]). Likewise, in the United States, the FCC has also had a voluntary QoS measurement programme in place in collaboration with SamKnows since 2011 and publishes yearly reports (FCC, 2021[260]). The project is called "Measuring Broadband America", and released in January 2021 its tenth annual report (FCC, 2021[261]). In a similar fashion, the Australian Competition and Consumer Commission (ACCC) launched its project to measure Internet performance by partnering with SamKnows. These reports publish metrics on NBN Co broadband performance (including average network congestion and network availability) and are made publicly available for consumers in a quarterly basis (ACCC, 2021[262]).

Another example of broadband quality measurements conducted by regulatory authorities are those done in Germany. The German communication regulator, Bundesnetzagentur (BNetzA), operates a broadband measurement tool since October 2015. Users can measure the download and upload speeds of their fixed and mobile broadband connections. Moreover, by way of an installable version of the broadband measurement tool, users can measure the speeds of their fixed broadband connections and use the results in order to prove contractual mal-performance vis-à-vis their provider or in court proceedings. Since 2018, the so-called "Funkloch-App" ("dead spot" app) can be downloaded for Android and iOS smartphones. With this app, users can measure network coverage in a given area. Measurements taken by users of the Funkloch-App are displayed in an interactive online map accessible by the public.

Some countries conduct their own "in field" measurements of actual broadband performance. For example, the Korean government, through the National Information Society Agency (NIA), monitors the quality of broadband providers and renders the results publicly available. The NIA has gone to great lengths to measure the quality of both fixed and mobile broadband in order to contrast the advertised speeds with actual speeds experienced by users. The first communication service quality evaluations by the NIA started in 1999 for wired telephones, 2G, and fixed broadband. It now encompasses various services including LTE services and Gigabit wired Internet, with the aim of covering 5G networks in the future. Network quality measurement is rather a complex endeavour in Korea, as it involves "in the field" measurement of quality with a vehicle, and requires a precise sampling technique across the country. According to the NIA, the service quality evaluation has significantly contributed to broadband development, as operators increased network quality each publication of the results. Furthermore, it has helped increase competition by providing users with objective quality information on communication services, so that they can choose providers accordingly.

In a similar vein, the Hungarian regulatory authority, NMHH, launched in 2012 the “SZÉP” project to gain an accurate picture of the real broadband performance experienced by Hungarian users. As part of the project, in 2015 NMHH deployed an interactive system publishing the results of its measurements of certain quality indicators for broadband services and network neutrality measures. Broadband performance parameters include download and upload speeds, latency, jitter and packet loss. Mobile broadband measurements are carried out by sensor-equipped cars, which check the coverage, signal strength and download and upload speeds of mobile networks for each technology throughout the whole country. In addition, the “Mobile neutrality” measuring system scans the various tariff plans of the operators for port openness and service quality according to a pre-set program. Measurements related to fixed broadband are carried out through whiteboxes, which measure the actual quality of fixed broadband access services and different plans on an hourly basis.

Mapping underlying wholesale infrastructure that may influence broadband performance

Several OECD countries have an “infrastructure atlas” available for communication service providers, that allows them to access information on the specific location of backbone and backhaul connectivity as well as other types of wholesale infrastructures (e.g. Austria, Colombia, Germany, Greece, Korea, Mexico[77] and France). While most regulators do not render public this wholesale infrastructure information in their website, the data is available to all operators in the market as well as other interested parties upon request.

Other countries, such as Latvia, provide non-discriminatory access to information to third parties on fibre network infrastructure deployed within a State-Aid project, or as part of the *ex-ante* asymmetric regulations imposed to the player with significant market power (SMP) through wholesale reference offers.

On the other hand, France at the end of 2017 launched a public website cartefibre.arcep.fr, where consumers, operators, and all sector stakeholders can visualise the deployment of FTTH. This tool was further enriched in 2018, where several layers of infrastructure were added, such as the fibre “co- investment” access points (*points de* “*mutualisation*”), part of the symmetric regulation on fibre by geographic segmentation. This tool, which is updated each quarter, serves a dual purpose: 1) inform consumers of available fibre offers in their locality, and 2) monitor the investment commitments by operators. In April 2020, Arcep launched the beta version of the tool “Ma connexion internet”, that would allow users to know the access technologies near their address, as well as the offers by different providers by speed-tiers (Arcep, 2020[263]).

Towards assessing the environmental sustainability of networks

Ensuring a sustainable future is at the heart of the policy agenda across the World, with many countries viewing climate change as one of the main policy challenges to tackle in the upcoming decades. For example, the European Green Deal recognises this, and in July 2021, the European Commission adopted a set of proposals to change energy, transport and taxation policies in order to reduce net greenhouse gas emissions by at least 55% by 2030 (European Commission, 2021[264]).

Economic recovery packages from the crisis have also placed emphasis on structural reforms to reduce carbon emissions by acknowledging that digital and “green” policies are intertwined, and together may help achieve this objective. For example, the Korean Government launched the “New Deal” in July 2020, which places digital policies, together with sustainability, as the two key pillars of their “National Strategy for a Great Transformation”, where connectivity plays a key role (Ministry of Economy and Finance of Korea, 2020[13]).

More specifically, there is increased interest in measures to ensure the environmental sustainability of communication networks. Communication networks have their own impact, both positive and negative, on the environment, and at the same time, have an indirect or catalyst effect on other sectors. Regulators across the OECD recognise the importance of this issue, as made evident in the *OECD Council Recommendation Broadband Connectivity* adopted in February 2021 [OECD/LEGAL/0322]. The Recommendation is forward looking in the sense that it highlights that for the future, the environmental sustainability of communication networks is of paramount importance. Namely, it recommends adherent countries to minimise the negative environmental impacts of communication networks, by: 1) fostering smart and sustainable networks and devices (e.g. the IoT), and 2) by encouraging operators to periodically report on their environmental impacts and on the positive environmental effects of connectivity.[78] In addition, certain communication regulators in the OECD, such as Arcep in France, have been working on the topic of ensuring the environmental sustainability of networks of the future (Arcep, 2019[47]).

Given the importance of the issue for policy makers across the OECD, analysing broadband networks of the future without somehow addressing certain aspects of the environmental sustainability of these networks would have been an oversight. In an attempt to mitigate the risk of such an omission, this report partially covered some examples related to sustainability of networks in certain sections. Nevertheless, the topic in itself is complex, and to properly address it, would require an in depth analytical report on its own.

Concluding remarks

The growth of AI systems and IoT are pushing the boundaries of the digital transformation. The next evolution of broadband networks, such as Gigabit fixed networks and 5G, are rapidly becoming the underlying connectivity of the digital transformation with applications across all sectors of the economy. For example, the need for low latency and high capacity networks for smart hospitals, automated vehicles or fully connected factories.

Moreover, what countries have witnessed during the COVID-19 pandemic, has further accentuated the need to foster high-quality broadband networks. In fact, several economic recovery packages from the crisis have included connectivity as fundamental element. This report on “Broadband Networks of the Future” provided an overview of the main trends in the evolution of broadband networks in OECD countries, as well as policy implications of these developments.

The report first started by setting the scene with the status of current networks, as well as how networks adapted during the pandemic. The need to move work and home life activities online during the COVID- 19 pandemic led to an increase of Internet traffic of 58% in one year (2019-20), and a record 21.15 million new fixed broadband connections in the OECD area from December 2019 to December 2020. Fibre has been steadily growing over the past decade in OECD countries, and 5G commercial deployments were available in 36 out of 38 OECD countries as of June 2022.

The report then explored the main technological trends influencing the next stage of convergence of broadband networks, and identified four main technological trends influencing networks with implications for future deployments: the move towards virtualisation, an integration of cloud services into networks, increased use of AI in networks, and openness of networks. Namely, for 5G networks, there has been a recent move in the industry from a “monolithic RAN” configuration towards a disaggregated RAN with a combination of virtualisation and/or open interfaces of the RAN (i.e. open and virtualised RAN). Networks are also integrating cloud and edge solutions for 5G. Beyond virtualisation and the integration of cloud solutions into networks, these partnerships have recently illustrated the possibility of outsourcing 5G network computing functions (i.e. workloads) to cloud providers, which is an important market development to follow. In addition, automation and machine learning (the use of AI systems), are being used by operators to improve and optimise management, predictive maintenance, and energy consumption of networks. The report also presents developments in emerging satellite broadband solutions, and discussions of “beyond 5G” technologies.

The report looks into the increasing complementarity of connectivity solutions, with new dynamics emerging among high-capacity fixed networks, 5G and Wi-Fi. Going forward, the important question to be posed may not only be of the one of co-existence of connectivity solutions, but rather how to ensure their co-integration to ensure synergies are fully taken advantage of, where questions of interoperability will likely gain importance.

The report highlighted the increased importance of high-quality connectivity and introduced new indicators (i.e. latency) to measure the quality of service and experience of networks for OECD countries. Furthermore, the report highlighted how regulators and firms engaged in broadband performance measurement are increasingly looking towards incorporating a “user-centric” approach to understand and assess network experience, which has led to advances in measures of quality of experience (QoE).

Finally, the report provided an overview of the main regulatory and policy measures currently in place to boost the deployment of Broadband Networks of the Future. These include policies to ease network roll-out (e.g. promoting efficient spectrum management, infrastructure sharing, easing barriers to deployment, and extending access to backhaul connectivity). In addition, several OECD countries are adapting regulation to provide incentives to boost fibre deployment and to ease the closing down of legacy networks. Policy makers across the OECD are also working towards ensuring transparency to users regarding broadband performance, as only what can be measured can be improved.

Annex 1.A. 5G status in OECD countries

Annex Table 1.A.1. Status of 5G commercial deployments in OECD countries

Country	Operator	Technology	Launch Date	Coverage	Details
Australia	Telstra	Mobile; FWA	22-May-19	As of June 2021, more than 75% of Australia's population (RCRWireless, 2021[265]). Telstra reported in March 2021 that it had more than 3 000 active 5G sites (Telstra, 2021[266]).	Currently using 3.6 GHz, and plans to combine low band 850 MHz spectrum and mid-band 3.6 GHz spectrum to boost performance of 5G deployments. Telstra acquired 1 000 MHz of 26 GHz spectrum for mmWave 5G, and has 50 mmWave sites live across Sydney, Melbourne, Brisbane, Adelaide, Goulburn and the Gold Coast (RCRWireless, 2021[265]).
	Optus	Mobile; FWA	28-Nov-19	As of April 2021, more than 1 200 sites, covering 830 000 Households (Optus, 2021[267]).	For Q1-Q2, Ookla found that Optus delivered the highest speeds in Australia (median download speeds of 323.94 Mbps) and awarded Optus the titles of "Australia's fastest 5G Mobile Network" (Optus, 2021[268]).
	Vodafone	Mobile (TPG)	05-Mar-20	As of August 2021, coverage in more than 700 suburbs in major Metropolitan areas, with 1 600 sites in the planning phase. Expects to cover 85% of the population of Australia's six largest cities by the end of 2021 (TPG, 2021[269]).	
Austria	Drei (Three) -Austria	Mobile; FWA	19-Jun-19	4 cities (Linz, Wörgl, Pörtschach and Vienna)	
	Magenta Telekom (T-Mobile Austria)	Mobile	26-Mar-19	28 cities	
	A1 Telekom	Mobile	27-Jan-20	129 municipalities	Download and upload speeds from 100Mbps/50Mbps to 500Mbps/70Mbps
Belgium	Proximus	Mobile	02-Apr-20	79 municipalities	
Canada	Bell (National operator)	Mobile	11-Jun-20	5 cities (Calgary, Edmonton, Montréal, Toronto, Vancouver)	
	Rogers (National operator)	Mobile	15-Jan-20	4 cities (Montréal, Ottawa, Toronto, Vancouver)	Using 2.5 GHz and 600 MHz spectrum; Rogers plans to start deploying with 3.5 GHz spectrum and dynamic spectrum sharing (DSS)
	Telus (national operator)	Mobile	18-Jun-20	5 cities (Calgary, Edmonton, Montréal, Toronto, Vancouver)	
	Videotron (regional operator in Quebec)	Mobile	15-Dec-20	Recent launch in December with deployment ongoing in 2021 (Videotron, 2020[270]).	

Country	Operator	Technology	Launch Date	Coverage	Details
Chile	WOM	Mobile	24-March-2022	70% of urban population as of 3 June 2022.	
	Entel	Mobile	16-Dec-2021	45% of the national territory as of March 2022.	
Colombia	DirectTV (AT&T)	FWA	02-Sep-20	1 city (Bogotá), with estimated coverage of 50 000 households	FWA using Wi-Fi 6, with download speeds up to 100 Mbps. Uses equipment from Ericsson, Qualcomm and Gemtek (with cloud native 5G core and employing Massive MIMO technology). Launched using 2.6 GHz spectrum, plus unlicensed spectrum *(2.4GHz + 5GHz).
Czech Republic	O2	Mobile	19-Jun-20	2 cities (Prague and Kolin)	Using 3.7 GHz band
	Vodafone	Mobile	Early Oct-20	5 cities	Using Dynamic Spectrum Sharing (DSS)
Denmark	TDC	Mobile	Sep-20	Nationwide 5G deployment by 1 December 2020 (RCRWireless, 2020[271]).	Using 3.5 GHz spectrum band
	Telenor		Sep-20	Four main cities.	Using 3.5 GHz spectrum band In November 2020 Telenor phasing in 5G connectivity for nearly 600 000 subscriptions by upgrading 4G sites (TeleGeography, 2020[272]).
Estonia	Telia	Mobile	10-11-20	20 cities by the end of 2020.	Using 3.5 GHz spectrum band and DSS (Telia Company, 2020[273]).
Finland	Elisa	Mobile	01-Jul-19	30 cities	
	DNA	Mobile; FWA (5G-Home)	03-Jun-20	21 cities	In Dec 2019 DNA launched “Home 5G” (FWA)
	Telia	Mobile; FWA	09-Oct-19	8 cities	In March 2019 Telia and Nokia introduced Nokia FastMile 5G gateway for 4G-5G Fixed Wireless Access (FWA)
France	Orange	Mobile	03-Dec-20	15 municipalities; by the end of 2020, more than 160 municipalities will be covered	Using the 3.5 GHz band.
	Bouygues Telecom		01-Dec-20	20 major cities	Using the 3.5 GHz and 2.1 GHz bands
	SFR		30-Nov-20	1 city (Nice); plans to extend its coverage to more than 120 municipalities throughout December 2020	
Germany	Vodafone	Mobile	16-Jul-19	96 cities	
	Telekom Deutschland	Mobile	18-Jul-19	5G population coverage exceeds 85% (Telekom Deutschland, 2021[274]).	
	Telefónica Deutschland / O2	Mobile	3-Oct-20	Current: 100 cities and 3 000 sites (Telefónica DE, 2021[275]). Targets: • 30% population coverage end of 2021. • Over 50 % of the German population with 5G by the end of 2022.	Using 3.6 GHz band.

Country	Operator	Technology	Launch Date	Coverage	Details
				• Full coverage end of 2025.	
Greece	Cosmote	Mobile	Dec-20	Launching in December in Athens, Thessaloniki and other Greek cities, the aim is to cover 50% of the population by the end of 2021, and all highways by 2023.	Using 3.5 GHz band.
	Wind Hellas	Mobile	21-Dec-20	Athens and Thessaloniki	
	Vodafone	Mobile	12-Jan-21	Plans to cover 40% of the population with 5G networks by March 2022.	
Hungary	Maygar Telekom	Mobile	19-Apr-20	29 cities and towns (8 cities + 1 area (Budapest, Budaörs, Győr, Kecskemét, Szeged, Debrecen Szombathely, Zalaegerszeg and Lake Balaton area) (Telekom HU, 2021[276]).	Using the 3.6 GHz and 2.1 GHz bands
	Vodafone	Mobile	17-Oct-19	At least 10 cities and towns (Balatonfüred, Budapest, Miskolc, Győr, Székesfehérvár, Pécs, Szeged, Eger, Siófok, Zalaegerszeg) (Budapest Business Journal, 2021[277]).	Using mainly the 3.5 GHz band
Iceland	Nova	Mobile	5-May-20	Reykjavik, Hella, Sandgerdi and Vestmannaeyjar.	
Ireland	Vodafone	Mobile	13-Aug-19	5 cities (Dublin, Cork, Limerick, Waterford and Galway)	
	Eir	Mobile	24-Oct-19	21 cities and towns	
	Three	Mobile	30-Sep-20	315 sites across Ireland, reaching 35% of population coverage; expects to add a further 500 5G-capable sites in 2021	Using Ericsson's fully virtualised 5G Core
Israel	Hot Mobile	Mobile	30-Sep-20	250 5G-capable sites across Israel	
	Pelephone	Mobile	30-Sep-20	150 locations at launch, including Tel Aviv, Haifa, Ra'anana, Dimona and Kiryat Shmona.	
	Partnet	Mobile	30-Sep-20	250 5G-capable sites across Israel	
Italy	Vodafone	Mobile	06-Jun-19	5 cities: Milan, Turin, Bologna, Rome and Naples; (expects 45-50 cities to be covered by the end of 2020)	
	Telecom Italia (TIM)	Mobile	25-Jun-19	8 cities; (expects to cover 120 cities by 2021)	
Japan	NTT Docomo	Mobile	25-Mar-20	35 cities and towns (200 cities are expected to have 5G service by March 2021). In May 2021, 7 100 5G sites, planning to reach 20 000 by March 2022.	Peak speeds of 3.4 Gbps and in June 2020 is max. speed of 4.1 Gbps.
	KDDI	Mobile	26-Mar-20	15 prefectures [19 cities and towns). In May 2021, KDDI had 10 000	First unlimited 5G data plan in Japan.

Country	Operator	Technology	Launch Date	Coverage	Details
				5G sites in Japan, planning to roll-out 50 000 by March 2022.	
	Softbank	Mobile	27-Mar-20	12 cities and towns. Planning to reach 50 000 5G sites by March 2022.	New services, "5G LAB" and "VR SQUARE" deliver immersive viewing experience, and Augmented Reality experiences, respectively. Softbank launched 5G mmWave service in Japan in the 29 GHz band (TeleGeography, 2021[278]).
	Rakuten	Mobile	08-04-20	In May 2021, 1 000 5G sites. In June 2021, Rakuten had 90% of the population covered with 4G networks, and planned to scale this up for 5G (Rakuten, 2021[279]).	Rakuten launched full-scale commercial service with what is considered “the world's first fully virtualised cloud-native Open RAN mobile network” (Rakuten, 2021[279]).
Korea	SKT	Mobile	03-Apr-19	85 cities; 93% of population in 2019	Standalone (SA) 5G to be launched in 2021
	KT	Mobile	03-Apr-19	85 cities; 93% of population in 2019	
	LGU+	Mobile	03-Apr-19	85 cities; 93% of population in 2019	
Latvia	Tele2	Mobile	22-Jan-20	2 cities (Daugavpils and Jelgava)	Peak theoretical download speeds of over 1Gbps
Lithuania	Telia	Mobile	Jan-2022	City of Vilnius.	Using the 2100 MHz frequency band (Telia, 2022[280]).
Luxembourg	Orange	Mobile	23-Nov-20	Luxembourg City and surrounding areas, Kirchberg, Bertrange, Strassen and the airport	4G offers upgraded to 5G at no additional monthly cost. (Telecom Review, 2020[281]).
	Post	Mobile	16-Oct-20		Using the 700MHz and 3.6GHz spectrum bands.
	Tango	Mobile	23-Oct-20	Luxembourg city	
Mexico	Telcel (América Móvil)	Mobile	28-Feb-22	Eighteen major cities including Mexico City, Monterrey and Guadalajara, covering a total population of 48 million people. Telcel expects to expand coverage to 120 cities by the end of 2022.	Using the 3.5 GHz spectrum band.
Netherlands	Vodafoneziggo	Mobile	28-Apr-20	50% of the Netherlands, or around 940 location; (expecting to reach all the country by July 2020)	
New Zealand	Vodafone	Mobile	10-Dec-19	4 cities (Auckland, Wellington, Christchurch and Queenstown)	
	Spark	Mobile	Oct-20	9 cities	Using Nokia equipment.
Norway	Telenor	Mobile	13-Mar-20	4 cities (Oslo, Bergen, Stavanger and Sandnes)	
	Telia	Mobile	12-May-20	2 cities (Lillestrøm and parts of Groruddalen in Oslo); [Nation-wide 5G network by the end of 2023	

Country	Operator	Technology	Launch Date	Coverage	Details
Poland	Plus	Mobile	12-May-20	7 cities; (plans to extend coverage to 3 million people by 2021)	
	T-Mobile	Mobile	09-Jun-20	11 cities	
Portugal	NOS	Mobile	26-Nov-21	Aim to cover 95% of the population by 2025 (NOS, 2021[282]; Observador.pt, 2021[283]).	Using spectrum (700 MHz and 3.6 GHz) from the auction that concluded in October 2021 (NOS, 2021[284]).
Slovak Republic	SWAN Mobile (4ka)	Mobile	Dec-2019 April-2021	1 city (Banska Bystrica), initial limited coverage under commercial test operation 1 city (Bratislava), 30% of population, fully commercial network	Tested 1 Gbps speed, later speed for public test up to 700 Mbps Speed up to theoretical limit 540 Mbps
	O2	Mobile	7-Oct-20	1 city (Bratislava), 25 % of population	Commercial testing using 1 800 MHz and 3.7 GHz spectrum Download up to 700 Mpbs, Upload 70-100 Mbps
	Slovak Telekom	Mobile	10-Dec-20	1 city (Bratislava)	
Slovenia	Telekom Slovenije		July 2020	Initially covering 25% of the population, and reached 33% by the end of 2020.	Using 2.6 GHz spectrum. Using Ericsson's Radio Access Network (RAN) and Cloud Core solutions.
Spain	Vodafone	Mobile	15-Jun-19	22 cities	Using 3.5 GHz spectrum
	Telefónica	Mobile	1-Sep-2020	Over 80% of the population, with nodes covering over 37 million inhabitants and 1300 municipalities across Spain (Telefónica, 2021[285]).	Using 3.5 GHz spectrum, alongside with refarmed 1800MHz and 2100MHz frequencies. Using Nokia equipment.
	Orange Spain	Mobile	7-Sep-2020	Five cities (Madrid, Barcelona, Valencia, Seville and Malaga)	Using 3.6 GHz spectrum.
	Masmovil	Mobile	9-Sep-2020	15 cities	With own infrastructure and with a "virtual active sharing mode" agreement with Orange. Masmovil aims to launch its own 5G SA network with 80 megahertz of spectrum in the 3.4-3.8 GHz band.
Sweden	Tele2	Mobile	24-May-20	Speeds over 1 Gbps in more than 30 cities in Sweden and large parts of Stockholm	Aim to have over 90% geographical coverage and reach 99% of the population by 2024
	3-Sweden	Mobile	17-Jun-20	Cover 16% of the Swedish population, 7 cities (Stockholm, Gothenburg, Uppsala, Västerås, Helsingborg, Lund and Malmö)	
	Telia	Mobile	25-May-20	20 cities	Aim to cover 90% of the population by 2023 and by 2025 reach 99% of the population and over 90% of the country.
	Telenor	Mobile	Oct-2020	36 cities, extensive coverage in Stockholm	Provide services up to 1 Gbps
Switzerland	Sunrise-UPC	Mobile; FWA	01-Apr-19	In September 2021, served 892 cities with 5G (Sunrise, 2021[286]). Sunrise's 5G coverage map is found here.	Vodafone and Sunrise announced partnership on 23 January 2020 to leverage their combined 5G scale.

Country	Operator	Technology	Launch Date	Coverage	Details
	Swisscom	Mobile	17-Apr-19	By end of June 2021, Swisscom reached a 98% population coverage with 5G. Swisscom had 1 558 5G sites, with 693 localities served with 5G+ (i.e. up to 2 Gbps download speeds that may require mmWave and SA-5G) (Swisscom, 2021[287]).	Using 3.5 GHz and 700 MHz spectrum bands. In May 2021, Ericsson and Swisscom signed a deal for SA-5G deployment (FierceWireless, 2021[288]).
	Salt	Mobile	5-Aug-20	99.3% of the Swiss population is covered by Salt 4G services, which they plan to upgrade to 5G sites.	Using 3.5 GHz and 700 MHz spectrum bands.
United Kingdom	Vodafone	Mobile; FWA	03-Jul-19	44 towns and cities	
	EE	Mobile; FWA	30-May-19	80 towns and cities	
	Three	Mobile; FWA	14-Feb-20	66 towns and cities	
	Virgin Media O2	Mobile	17-Oct-19	More than 180 towns and cities (O2, 2021[289]).	
United States	T-Mobile/Sprint	Mobile	01-May-19 [T-Mobile launched in Dec-2019]*	Covering 80% of the US population in 8 300 cities and towns, and 92% of the Interstate Highway miles.	T- Mobile started to deploy SA-5G nationwide in August 2020 using the 600 MHz (Telecoms, 2020[91]). T-Mobile has launched SA-5G.
	Verizon Wireless	Mobile; FWA	03-Apr-19	80 cities by the end of 2021. See Verizon's coverage map here.)	Verizon is using millimetre wave (mmWave) spectrum for 5G. They plan to expand mmWave 5G services to a total of 60 cities during the course of 2020.
	AT&T	Mobile	13-Dec-19	14 000 cities and towns. See AT&T's coverage map here.	In June 2020, AT&T commenced dynamic spectrum sharing (DSS) in parts of Texas

Notes: FWA: Fixed Wireless Access. Survey last updated in June 2022. *In the United States, T-Mobile and Sprint merged in April 2020.
Source: Own elaboration based on data from operators' websites, Ookla (2022[290]), "Ookla 5G Map: Tracking 5G roll-outs around the world", https://www.speedtest.net/ookla-5g-map; European Commission (2022), "5G Observatory", https://5gobservatory.eu/observatory-overview/observatory-reports/; GSMA (2020[291]) "5G Global Launches & Statistics", https://www.gsma.com/futurenetworks/technology/understanding-5g/5g-innovation, and complemented by operators' press releases.

Annex 1.B. SpeedChecker's methodology

The SpeedChecker test algorithm (for speeds and latency) has been developed and improved over time with the aim of providing accurate and consistent results across all devices, platforms and operating systems. The company operates several national speed test websites for OECD countries, such as France, the Netherlands, Japan, Poland, and the United Kingdom.

All measurements are executed towards the Cloudflare Content Delivery Network (CDN). A CDN is a geographically distributed group of servers that work together to minimise delays in loading webpage content by reducing the physical distance between the server and the user. Cloudflare is being used by 10% of websites around the world. From all OECD countries, only Slovenia and the Slovak Republic do not have a Cloudflare server on their territory.

Annex Figure 1.B.1. Cloudflare CDN map

Source: Cloudflare (2021), "The Cloudflare Global Anycast Network", https://www.cloudflare.com/en-gb/network/

The latency measure uses the Transmission Control Protocol (TCP), and sends three packets (i.e. "pings") to the measurement server. The result is an average of those three measurements.

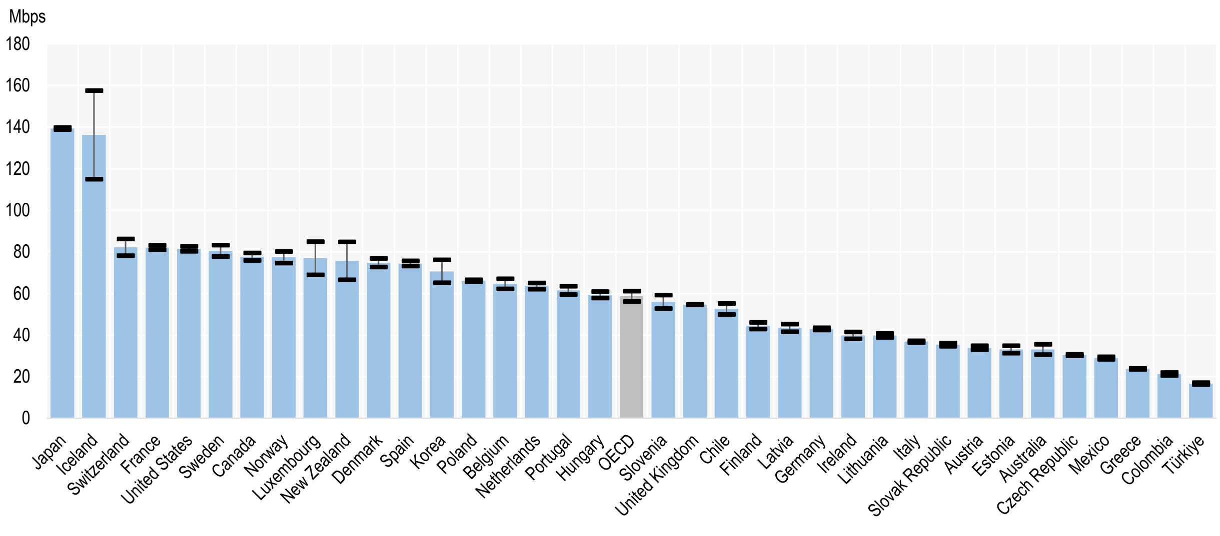
With respect to how local and overall latency measurements are conducted, typically, with a CDN it is not possible to influence how traffic is routed to compare local server latency against foreign server latency. Therefore, SpeedChecker looks both at the collected data and the Internet routes of the tests conducted. Usually, the traffic of some ISPs within a given country may be routed to local points of presence (POPs), while the traffic of other ISPs may be routed to foreign ones. Therefore, SpeedChecker reports on the performance of both local and foreign POPs, separately.

With regards to download and upload speed measurement, the speed tests are embedded in SpeedChecker's Android and iOS Software Development Kit (SDK), as well as in the HTML test. The process runs as follows:

- Testing algorithm uses three parallel threads to saturate the connection and calculate the maximum throughput. In case of connections higher than 200 Mb/s additional thread is added for faster way to saturate the connection.
- Using Hyper Text Transfer Protocol (HTTP) requests to download/upload files between the server and client device. The selected files are large enough to saturate the connection for the whole duration of the test.
- Constantly monitoring the performance and speed profile of HTTP threads during testing to ensure accurate feedback to the end user's screen.
- Every 100 ms, a speed sample is calculated by dividing transferred bytes in the last 100 ms by the sample time (100 ms). After the test completion, the average speed is determined as the average value of all collected samples.
- The samples are reviewed for outliers. If speeds (upload or download) are higher than 10 000 Mbps, or the latency (TCP ping) higher than 1 000 ms in a given test, these results are not considered in the calculation of the median and average.

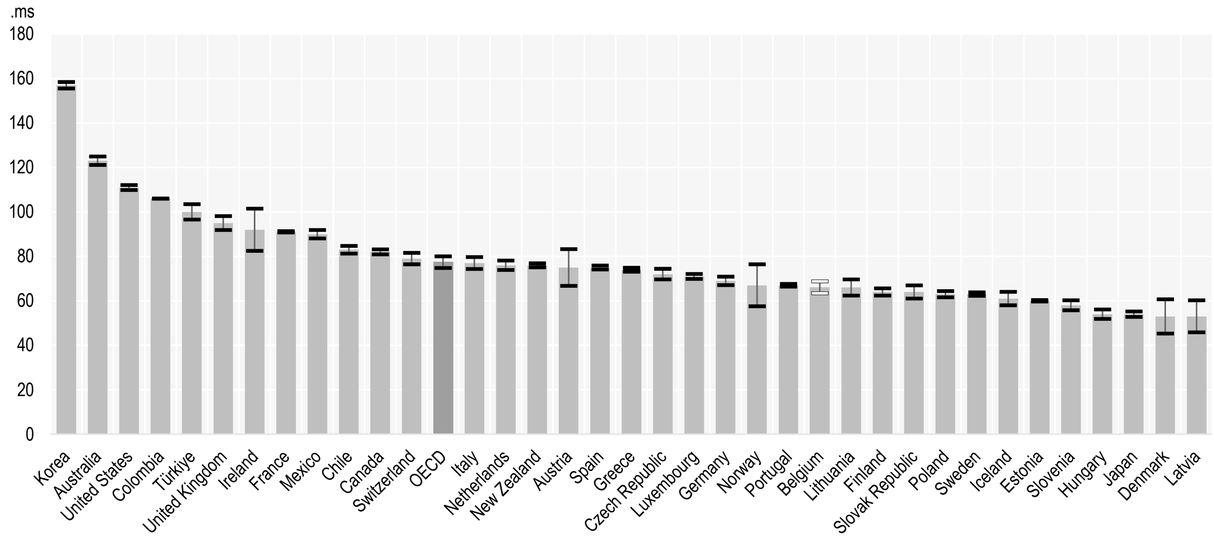
Details on the sample size (Annex Table 1.B.1) and the figures with confidence intervals can be found below (Annex Figures 1.B.1 and 1.B.2). The figures with confidence intervals provide insights regarding data accuracy.

Annex Figure 1.B.2. SpeedChecker average download speeds with confidence intervals, 2020



Note: Confidence interval of 95%.
Source: SpeedChecker

Annex Figure 1.B.3. SpeedChecker average latency with confidence intervals, 2020



Note: Confidence interval of 95%.
Source: SpeedChecker

The 95% confidence level means that there is 5% chance that the true mean (taken from the entire population), lies outside of the range of the confidence levels. This is a standard level of confidence used with the sample sizes of SpeedChecker's tests. The following formula was used to calculate the confidence intervals:

$$\bar{x} \pm \frac{(z * s)}{\sqrt{n}}$$

Where:

- $\bar{x}$ = the mean (i.e. $\frac{\sum_{i=1}^{n} x_i}{n}$),
- z = the chosen z-value in this case corresponding to a 95% confidence interval (i.e. z-value=1.96),
- s = the standard deviation of the sample (i.e. $\frac{\sum_{i=1}^{n}(x_i-\bar{x})}{n}$),
- n = the number of observations.

Given the confidence intervals displayed in Figures 1.B.1 and 1.B.2, it seems that sample size in different countries is not playing a major role in the overall results. Nevertheless, more details on sample sizes by country are found on Annex Table 1.B.1 below.

Annex Table 1.B.1. Sample size* of SpeedChecker tests, by OECD country (2019, 2020)

Country	2018	2019			2020		
	Test count	Test Count	Local Test Count	% of local results	Test Count	Local Test Count	% of local results
Australia	3943	826	465	56%	1660	1164	70%
Austria	19291	9222	8093	88%	9367	6772	72%
Belgium	24303	8285	4845	58%	5981	3976	66%
Canada	45060	27090	5061	19%	21511	5047	23%
Chile	8573	6956	5826	84%	5347	4478	84%
Colombia	18886	11281	7351	65%	9741	3453	35%
Czech Republic	56151	30108	19007	63%	62074	38713	62%
Denmark	15742	11109	8838	80%	11793	10424	88%
Estonia	2997	2992	1150	38%	3294	1275	39%
Finland	14114	10375	9043	87%	10656	9946	93%
France	278742	90033	76581	85%	103835	93583	90%
Germany	80883	54261	36690	68%	58707	46724	80%
Greece	69891	50167	39957	80%	46474	34908	75%
Hungary	19798	18297	9336	51%	21870	15694	72%
Iceland	1420	736	96	13%	335	35	10%
Ireland	18675	5789	4740	82%	7224	4229	59%
Italy	71900	57040	41530	73%	98379	69272	70%
Japan	339443	206886	159342	77%	3404068	2501990	74%
Korea	3269	1466	87	6%	977	72	7%
Latvia	4020	6591	2730	41%	7819	4967	64%
Lithuania	34254	19543	12462	64%	18606	11796	63%
Luxembourg	1685	629	65	10%	653	162	25%
Mexico	20393	17529	549	3%	20312	1285	6%
Netherlands	61841	103878	100107	96%	16567	12101	73%
New Zealand	1997	306	175	57%	675	542	80%
Norway	18051	6588	751	11%	6229	449	7%
Poland	447529	287585	208715	73%	349237	289951	83%
Portugal	10947	10584	8197	77%	10757	9467	88%
Slovak Republic	19216	18375			24278		
Slovenia	3926	2820			2752		
Spain	77567	37960	31068	82%	32558	24041	74%
Sweden	7739	7943	3386	43%	9635	3673	38%
Switzerland	9353	6067	4373	72%	4463	1655	37%
Türkiye	18382	22818	14747	65%	10795	4109	38%
United Kingdom	167241	139637	108994	78%	1023958	813869	79%
United States	22438	39362	38199	97%	60664	58653	97%

Source: SpeedChecker

Annex 1.C. Overview of wholesale access regulation of fixed networks in OECD countries

Annex Table 1.C.1. Summary of developments in wholesale access regulation of fixed networks since 2016

	Full unbundling[1] requirements on the copper network	Unbundling[1] requirements on FTTx or vDSL (e.g. full fibre unbundling, Virtual Unbundled Local Access [VULA])	Bitstream access[2], access to dark fibre, collocation services, access to passive infrastructure	Are cable operators subject to access regulation?
Austria		In July 2017, VULA applied to incumbent A1. With decisions M 1.5/15 and M1 1.6/15, the prices of VULA were reduced and VULA is also available in regional points of hand-over The use of virtual unbundling increased in 2018, while the use of physical unbundling and bitstream services decreased.		
Belgium	Yes, physical and virtual unbundling on the copper network of the dominant operator.	Virtual and wavelength unbundling (applied to Proximus, the dominant operator)	Yes, duct sharing applied to Proximus	Not applicable
Canada	In the past, the CRTC mandated PSTN operators to unbundle local copper loops. However, unbundled local loops are no longer regulated as of July 2018.*	Decision July 2015 (Telecom Regulatory Policy 2015-326), the CRTC determined that wholesale high-speed access (HSA) services would continue to be mandated. The CRTC further decided that the provision of aggregated HSA services would no longer be mandated and would be phased out in conjunction with the implementation of a disaggregated HSA service. In addition to being able to access large incumbent xDSL, coaxial cable (DOCSIS), and fibre-to-the-node (FTTN) networks, which are already available through aggregated HSA, competitors will have virtual access to incumbent fibre-to-the-premise (FTTP) networks through disaggregated HSA. Access to passive infrastructure reviewed as part of Notice of Consultation		The large cable companies and the large telephone companies (the incumbents) are subject to the same access regulation for the provision of wholesale HSA access services. The access rates are regulated.

	Full unbundling[1] requirements on the copper network	Unbundling[1] requirements on FTTx or vDSL (e.g. full fibre unbundling, Virtual Unbundled Local Access [VULA])	Bitstream access[2], access to dark fibre, collocation services, access to passive infrastructure	Are cable operators subject to access regulation?
		2019-406. Decision is expected in FY 2021-2022 (Apr 2021 – Mar 2022). No change in status to dark fibre (not mandated) or co-location (mandated).		
Colombia	There is no unbundling (copper or fibre) requirements for dominant operators.	There is no unbundling (copper or fibre) requirements for dominant operators.	The Colombian regulatory framework includes a set of rules for the interconnection and access in communication networks. This access regime takes into account regulated rates for access to ducts and poles, National Roaming, MVNO, and electric power infrastructure. The access regime can be found in this link. In May 2021, the CRC published the regulatory proposal of the project "Revision of the Access, Use and Interconnection Regime" to update the aforementioned regime in such a way as to recognise the evolution of the sector. The draft framework was under public consultation at the moment of writing.	
Czech Republic	Incumbent is subject to full/shared copper and fibre unbundling. LLU access price control (cost orientation) has not been imposed, but rather price regulation based in an economic replicability test of wholesale products (markets 3a and 3b).	Virtual unbundling (VULA) obligations imposed on the incumbent.	The incumbent has obligations to provide collocation and access to dark fibre based on costs. Obligations to provide access to physical infrastructure were not imposed on the incumbent with regard to the obligations stemming from implementation of Directive 2014/61/EU.	
France	Asymmetric regulation of LLU of the copper network imposed to the dominant operator.	Symmetric obligations on FTTH networks (co-investment), as France does not favour infrastructure based competition (*mutualisation passive de la boucle locale optique combinée au co-investissement*).		As a merger remedy of Altice/SFR and Numericable, the Competition Authority imposed wholesale access obligations to their cable network (Decision n° 14-DCC-160 of 30 October 2014), so that rival networks could replicate retail offers and keep the merging party's incentives to invest in FTTH.
Germany	Telekom Deutschland is obliged to provide access to unbundled local loop (copper).	Companies expanding local areas with vectoring must offer competitors VULA.		

	Full unbundling[1] requirements on the copper network	Unbundling[1] requirements on FTTx or vDSL (e.g. full fibre unbundling, Virtual Unbundled Local Access [VULA])	Bitstream access[2], access to dark fibre, collocation services, access to passive infrastructure	Are cable operators subject to access regulation?
Greece	EETT, in the context of the 4th round of market analysis, defined a national wholesale local access market, which includes both copper and fibre infrastructure. Since the analysis of the said market showed lack of competition, EETT imposed a number of appropriate and proportionate obligations on the SMP operator (OTE SA), which include both Local Loop Unbundling ('LLU') and Sub-Loop Unbundling ('SLU') products.	Virtual Local Unbundling (VLU), a VULA type wholesale product offered over FTTH/FTTB and FTTC architectures, has been included in the relative access obligations of markets 3a and 3b. On the other hand, full fibre unbundling was not included in the remedies, since at the time of EETT relative Decision there was not any P2P fibre deployment in Greece.	Bitstream access was imposed in the context of market 3b analysis. Access to dark fibre, as well as duct access, in the section between the outdoor cabinet and the MDF was imposed as an ancillary service in market 3a. Collocation services were included in the ancillary services of markets 3a and 3b.	Not Applicable
Hungary	Dominant operators (with SMP on market 3a) are subject to full and shared unbundled access regulation of cooper loops (and sub-loops). More info: The wholesale prices on both broadband markets (3a and 3b) are based on a BU-LRIC+ cost model (instead of TD-LRIC and Retail-). In areas with retail infrastructure based competitions, operators with SMP on markets 3.a and 3.b are no longer obliged to provide regulated access on their networks.	Dominant operators (with SMP on market 3a) are subject to: a) unbundled access to FTTH point-point NGA loops; b) access to terminating segments of point-to-multipoint NGA networks, and c) provide L2 virtual wholesale access (L2WAP)* on its point-multipoint (FTTC/B/H) new generation access network and access network where vectoring is deployed. *See BEREC 2015 report on L2WAP.	Dominant operator (market 3b) is subject to national bitstream access and local bitstream access (xDSL on copper loops, xDSL on NGA loops, FTTH GPON, FTTH point-point, FTTH-RFoG, Coaxial cabled HFC). Dominant operator (market 3a) is subject to provide access to passive infrastructure (ducts and poles).	Yes, cable operators are subject to access regulation.
Ireland	In November 2018, ComReg reviewed the Wholesale Local Access provided at a fixed location (WLA) and Wholesale Central Access provided at a fixed location for mass market products (WCA) (Markets 3a and 3b in the European Commission's 2014 Guidelines). In this Decision, ComReg defined a single WLA Market (which is national in its geographic scope) and determined that **Eircom** had SMP in the relevant market 3a. This market includes: Current Generation WLA products provided over copper networks, including Local Loop Unbundling ('LLU'), Line Share and Sub-Loop Unbundling	ComReg has imposed a range of obligations on Eircom requiring it to provide a range of access products, including virtual unbundled access.	ComReg defined two separate WCA markets, an Urban WCA Market and a Regional WCA Market. ComReg determined that no service provider has SMP in the Urban WCA Market and that Eircom has SMP in the Regional WCA Market.	

	Full unbundling[1] requirements on the copper network	Unbundling[1] requirements on FTTx or vDSL (e.g. full fibre unbundling, Virtual Unbundled Local Access [VULA])	Bitstream access[2], access to dark fibre, collocation services, access to passive infrastructure	Are cable operators subject to access regulation?
	('SLU') products; and Next Generation ('NG') WLA products provided over FTTx networks, including Virtual Unbundled Local Access ('VULA') products. The obligations of the WLA market include: Access Obligations; Non-Discrimination Obligations; Transparency Obligations; Price Control and Cost Accounting Obligations; and Accounting Separation Obligations.			
Italy	The dominant operator (TIM) is obliged to provide LLU access services, and related ancillary services. In the provision of LLU services, TIM is subject to the following additional regulatory obligations: transparency, non-discrimination, accounting separation, cost accounting and price control (see Decision n. 348/19/CONS). On 18 July 2019, AGCOM defined the market for wholesale local access provided at a fixed location as including services provided over copper, optical fibre and fixed wireless access (FWA) and the market for wholesale central access (WCA) provided at a fixed location for mass-market products as comprising the demand and supply of wholesale services provided over copper and optical fibre. AGCOM also included VULA in the WCA market.	Since 2016, VULA services have experienced significant developments in terms of access bandwidth profiles and geographic coverage, as well as in terms of volumes sold in the market. Specifically, the VULA service has become the most relevant wholesale product for OAO to provide retail NGA services (+600% in two years 2016-2018) reaching 2.5 million active lines at the end of 2018.		
Japan	Copper unbundling on dominant PSTN operators (NTT East and NTT West).	Fibre unbundling imposed to NTT East and NTT West.	*Bitstream* access or shared lines are not regulated ex ante.	No regulation on cable operators.
Korea	There are 3 different types of Local Loop Unbundling (LLU): 1) full unbundling (Metallic Path Facility), 2) Shared Metallic Path Facility and 3) Bitstream Internet Access. Local call services providers owning local loop are obliged		Facilities-based telecommunications service operators whose subscribers are over 500 000 shall allow 3) Bitstream Internet Access. Incumbent operators or related institutions designated by the regulation shall allow access to dark	Cable operators whose subscribers are over 500 000 as Facilities-based telecommunications service operators shall allow 3) Bitstream Internet Access.

	Full unbundling[1] requirements on the copper network	Unbundling[1] requirements on FTTx or vDSL (e.g. full fibre unbundling, Virtual Unbundled Local Access [VULA])	Bitstream access[2], access to dark fibre, collocation services, access to passive infrastructure	Are cable operators subject to access regulation?
	to provide 1) Metallic Path Facility and 2) Shared Metallic Path Facility. **Notes**: *Metallic Path Facility* covers full unbundling allowing both local call and high-speed Internet services, taking into account of incumbent operators' reservation rate by the regulation. *Shared Metallic Path Facility* covers high-frequency bands only for high-speed Internet access, not for local calls. High-speed Internet Access Network covers xDSL and HFC (Hybrid Fibre Coaxial).		fibre, collocation services, and passive infrastructure.	
Mexico	Full fibre unbundling requirements on the copper network imposed on the 'preponderant agent' in the telecommunications market (America Movil) through the Reference Offer (OREDA as per its Spanish acronym).	Virtual unbundled local access imposed on the 'preponderant agent' in the telecommunications market (America Movil) through the Reference Offer (OREDA as per its Spanish acronym).	Bitstream access and collocation services Virtual unbundled local access imposed on the 'preponderant agent' in the telecommunications market (America Movil) through the Reference Offer (OREDA as per its Spanish acronym). For access to dark fibre and access to passive infrastructure, the regulation is imposed on the 'preponderant agent' in the telecommunications market (America Movil) through the Reference Offer (ORCI as per its Spanish acronym).	No
New Zealand		On 1 January 2020, the local fibre companies in New Zealand are required to make FTTH available to access seekers on an equivalent and non-discriminatory basis under the Telecommunications Act and the Fibre Deed (in respect of the Ultrafast Broadband Initiative 1). Physical unbundling is the form of bundling that the local fibre companies in New Zealand have decided to make available for their FTTH service offer on 01/01/2020. No virtual unbundling over FTTx developments in New Zealand since 2016.		
Portugal	In the context of the analysis	ACOM decided not to impose		

	Full unbundling[1] requirements on the copper network	Unbundling[1] requirements on FTTx or vDSL (e.g. full fibre unbundling, Virtual Unbundled Local Access [VULA])	Bitstream access[2], access to dark fibre, collocation services, access to passive infrastructure	Are cable operators subject to access regulation?
	of broadband markets, it has been imposed on the SMP operator (MEO) the obligation to provide access of local loop unbundling access to the copper loop. In the most recent analysis of the local wholesale access market at a fixed location (market 3a) – approved in march 2017 –, ANACOM concluded that, notwithstanding the market developments in terms of NGA networks, it remains essential to maintain the obligation of unbundled access to the copper loop, as contained in the reference unbundling offer (RUO) of MEO.	obligation of access to fibre.		
Slovak Republic	SMP undertaking – Slovak Telekom. Access obligation: full and shared xDSL unbundled local access Transparency obligation - reference offer - plan of migration - KPI/SLA/SLG, Non-discriminations obligation Economical replicability Economic replicability test – unbundling access Accounting separation	SMP undertaking – Slovak Telekom. Access obligation: 1. virtual unbundled local access at MPoP – VULA (FTTH point to multipoint including FTTB/FTTC +VDSL (including vectored) 2. fully unbundled fibre access - FTTB point to point Transparency obligation - reference offer - KPI/SLA/SLG - plan of implementation of Equivalence of Inputs Non-discriminations obligation Technical and economical replicability Economic replicability test – unbundling access Accounting separation	SMP undertaking – Slovak Telekom. Access obligation: 1. Bitstream access: - national IP level at xDSL - national and regional Ethernet level at FTTx and xDSL - access to IPTV through multicast functionality, 2. access to ducts, HDPE pipe and tube 3. collocation Non-discriminations obligation Technical and economical replicability Transparency obligation - reference offer - KPI/SLA/SLG - plan of migration - plan of implementation of Equivalence of Inputs Economic replicability test – bitstream access Accounting separation obligation Price regulation obligation - collocation - ducts, HDPE pipes, tubes	No regulation – cable networks
Spain	On 6 October 2021, CNMC adopted the final decision concerning the fourth review of the wholesale markets for	As to market 3a, CNMC identified 696 municipalities (amounting to 70% of the overall Spanish population)	As to market 3b, the competitive zone (encompassing 758 local exchanges) is considered to	

	Full unbundling[1] requirements on the copper network	Unbundling[1] requirements on FTTx or vDSL (e.g. full fibre unbundling, Virtual Unbundled Local Access [VULA])	Bitstream access[2], access to dark fibre, collocation services, access to passive infrastructure	Are cable operators subject to access regulation?
	(i) local access provided at a fixed location (market 3a/2014, current market 1/2020), and (ii) broadband access market (market 3b/2014, and not included in the current EC recommendation). The high quality broadband access (market 4/2014, current market 2/2020) was reviewed on 24 February 2016 and is currently being assessed. CNMC imposes on Telefónica (the incumbent) different ex-ante obligations as to the access to its fibre and copper networks. As to markets 3a and b, CNMC followed a geographical segmentation approach, whereby separate areas were identified in light of the degree of competition (such segmentation considered the number of operators and their market shares in every local exchange as well as the number of alternative NGA networks). Access to Telefonica's copper network is maintained with a cost orientation approach (BU-LRIC+). As to market 4, CNMC had imposed in 2016 bitstream access over copper (cost-oriented prices) and over fibre (prices under an economic replicability text) in all the territory.	where competition in NGA lines is fully effective. Obligations in these areas only relates to the granting of access for Telefonica's copper network and its passive infrastructure (ducts, manholes, posts, etc.). For non-competitive zones, Telefonica has to provide, additionally to passive infrastructure requirements, a new virtual unbundled local access service to its fibre network (NEBA local). For the virtual unbundling of the incumbent's FTTH network, Telefonica sets prices, but CNMC controls this price, and Telefonica must fulfil a replicability test, (called ERT).	be effectively competitive and no obligation was set upon the incumbent. For the remaining local exchanges, Telefónica is obliged to provide alternative operators with access to its copper network as well as to its FTTH network without speed cap (NEBA Fibra).	
Sweden	The SMP operator is mandated to provide physical unbundling on the copper infrastructure.	Yes, the SMP operator has an obligation to provide physical access to the SMP-operator's copper and fibre infrastructure. There is no obligation to provide virtual access to the fibre infrastructure.	There is no obligation to provide bitstream access. The SMP operator has an obligation under reasonable circumstances to provide backhaul (dark fibre) up to 50 km enabling for alternative operators to connect to their networks.	No
Switzerland	In Switzerland, the unbundling local loop concerns only copper lines. In that case, the legal provisions stipulate that the prices and other conditions charged by the incumbent operator must be	The Telecommunications Act does not currently oblige the dominant operator to offer unbundling on an FFTx line, nor does it provide for virtual unbundling. During the discussions on the partial revision of the law, the Swiss		No

	Full unbundling[1] requirements on the copper network	Unbundling[1] requirements on FTTx or vDSL (e.g. full fibre unbundling, Virtual Unbundled Local Access [VULA])	Bitstream access[2], access to dark fibre, collocation services, access to passive infrastructure	Are cable operators subject to access regulation?
	transparent, non-discriminatory and, above all, aligned with the costs (cf. art. 52, 53 and 54 of the Ordinance on Telecommunications Services (OTS)).	Parliament also decided not to introduce such obligations. In practice, Swisscom freely offers its competitors unbundled fibre-optic lines, but on its own terms (i.e. commercial and unregulated terms). See Swisscom's leasing of optical fibres to connect end customers (ALO product). Furthermore, there are currently no legal provisions regulating unbundling in the case of vectoring and nothing of the kind is planned following the partial revision of the law. It can be assumed that operators negotiate solutions with Swisscom when disturbances are caused by the combination of vectoring and local loop unbundling, as there do not seem to be any real problems on the ground.		
United Kingdom	In March 2018, Ofcom completed its last review of the Wholesale Local Access market (incorporating physical or passive network access via methods such as LLU and duct access). These obligations are set out in the WLA Market Review of 2018. Ofcom found that BT continues to hold Significant Market Power and imposed corresponding remedies on it until April 2021. These remedies include price controls on "virtual" access to its wholesale 40/10 Mbps FTTx product, the maintenance of access and pricing controls on its wholesale copper products and improvements to the existing physical infrastructure access product (third party access to BT's duct and pole estate). The dominant operator BT (in the UK excluding the Hull Area) has unbundling obligation imposed through the Wholesale Local Access Market Review. This	In 2018, Ofcom imposed wholesale remedies on BT/Openreach for FTTC, virtual unbundled local access (VULA), with a price cap for speeds up to 40 Mbps. In 2020, Ofcom submitted to public consultation its wholesale fixed market review 2021-26, and published the final decision in March 2021 (see "Wholesale Fixed Telecoms Market Review 2021-26"). Ofcom aims to boost fibre expansion by supporting Openreach in retiring its old copper network, and by considering keeping VULA regulation in some areas while deregulating areas where there is efficient competition of FTTP networks.[79]		No

	Full unbundling[1] requirements on the copper network	Unbundling[1] requirements on FTTx or vDSL (e.g. full fibre unbundling, Virtual Unbundled Local Access [VULA])	Bitstream access[2], access to dark fibre, collocation services, access to passive infrastructure	Are cable operators subject to access regulation?
	requires BT to provide local loop unbundling on its copper lines at the exchange, sub-loop unbundling obligations on its copper lines at street cabinets and virtual unbundled access over its FTTC and FTTP access lines. KCOM the dominant provider in the Hull Area has general network access obligations but these now explicitly exclude local loop access at the exchange for copper lines as the provider will be have near 100% coverage of the area under a FTTP network in 2020 – see here.			
United States	Copper unbundling requirements to the dominant operator.	In addition to raw copper, the FCC requires unbundling of hybrid loops, fibre-to-the-home loops, and fibre-to-the-curb loops in certain circumstances, as set forth in 47 C.F.R. § 51.319(a).		Yes. Cable operators are subject to interconnection rate approval. Interconnection agreements – including rates for interconnection services – may be voluntarily negotiated between carriers, subject to approval by state FCCs applying FCC standards.

1. In the EU framework is referred to Wholesale Local Access provided at a fixed location (WLA) or market 3a.
2. *Bitstream* or wholesale broadband access in the EU framework is referred to Wholesale Central Access (WCA) at a fixed location for mass market products or market 3b (formerly, wholesale broadband access or Market 5/2007).

Notes: In Canada, the definition of unbundled local loops provide is a transmission path by means of copper facilities between an end-user's premises and an ILEC's central office that can be used by competitors to provide local telephony and lower-speed Internet access services to residential and business customers.

Source: OECD elaboration based on the responses of the DEO 2020 Communication Regulation Questionnaire.

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End Notes

[1] The OECD Recommendation Broadband Connectivity provides a reference for policy makers within and beyond the OECD to unleash the full potential of connectivity for the digital transformation and to ensure equal access to connectivity for all users.

[2] An AI system, as explained by the OECD's AI Experts Group (AIGO), is "a machine-based system that can, for a given set of human-defined objectives, make predictions, recommendations or decisions influencing real or virtual environments. It uses machine and/or human-based inputs to perceive real and/or virtual environments; abstract such perceptions into models (in an automated manner e.g. with ML or manually); and use model inference to formulate options for information or action. AI systems are designed to operate with varying levels of autonomy" (OECD, 2019[308]).

[3] Latency can be defined as the round trip time for information between two devices across the network. It is often referred to as network delay or ping rate to a network device (e.g. router) (OECD, 2019[35]).

[4] From 2011 until 2019, every year around 13.7 million new fixed broadband subscriptions were added in the OECD area.

[5] "OpenVault is a leading provider of software-as-a-service (SaaS) technology solutions and industry analytics for broadband operators worldwide. With over 150 service provider engagements across four continents, OpenVault's platform captures broadband usage data from millions of residential and commercial subscribers across both the U.S. and Europe. Leveraging more than a decade of historical data and industry experience and its unique visibility into real-time broadband usage data, OpenVault publishes the OpenVault Broadband Industry Report (OVBI), providing a quarterly advisory outlining important data usage trends for the broadband industry" (OpenVault, 2020[3]).

[6] This indicator represents a weighted average of data usage trends for both flat-rate billing (FRB) and usage-based billing (UBB) fixed broadband subscribers. In the first quarter of 2021, this number average household data consumption was 461.7 GB (OpenVault, 2021[4]).

[7] After reaching the data allowance, the provider may either throttle the speed or charge extra in the customer's invoice. For example, a cable operator in the United States has resorted to upload data allowance caps during the pandemic (Brodkin, 2021[294]).

[8] For more information concerning Internet traffic in Colombia, please refer to: https://postdata.gov.co/dataflash/data-flash-2021-022-trafico-de-internet-durante-la-pandemia-del-covid-19

[9] An exchange rate of 1.454 AUS/USD for the year 2020 from OECD.stat has been used.

[10] An exchange rate of 1.27 CAD/USD for 1Q 2021 from OECD.stat has been used.

[11] An exchange rate of 0.876 EUR/USD for the year 2020 from OECD.stat has been used.

[12] Idem.

[13] An exchange rate of 0.876 EUR/USD for the year 2020 from OECD.stat has been used.

[14] Idem.

[15] On 1 December 2020, the Council of Ministers in Spain the *Plan for Connectivity and Digital Infrastructures and the Strategy to Promote 5G Technology*, to continue to expand high-speed broadband coverage to reach 100% of the population and boost the development of 5G technology (Government of Spain, 2020[296]). Both plans are part of Plan for the Recovery, Transformation and Resilience of the Spanish economy, presented in October 2020 and approved in April 2021. The total public investment in these two plans is EUR 4.3 billion between 2020-25 (EUR 883 million already foreseen in the 2021 Budget), and the Spanish government expect to mobilise additional EUR 24 billion from the private sector (Government of Spain, 2021[14]).

[16]An exchange rate of 0.780 GBP/USD for the year 2020 from the OECD has been used.

[17] Idem.

[18] For countries where data was available. Simple average over 35 out of 38 OECD countries.

[19] Idem.

[20] As mentioned in the OECD (2019) report, "Wholesale (vertically separated) operators have grown in importance over recent years. They range from backbone wholesalers in the fixed market, to tower companies in the mobile market, to integrated wholesale networks in both the fixed and mobile communication market. This category of operators may significantly change the dynamics of communication markets. It could be a more cost-effective model for investment in broadband networks if these operators can generate attractive propositions for others to use their infrastructure. For operators in the future, the various wholesale-only models could help save costs, increase use of networks and perhaps minimise risk compared to retail businesses. At the same time, wholesale-only players need many service providers to use a network. The key features required for successful wholesale-only businesses are stable financial performance, long investment horizons, strong free cash flows and an incentive to provide upgraded infrastructure as demand arises by retail providers" (OECD, 2019[35]).

[21] An exchange rate of 0.876 EUR/USD for the year 2020 from OECD.stat has been used.

[22] Idem.

[23] "NGMN seeks to incorporate the views of all interested stakeholders in the telecommunications industry and is open to three categories of participants (NGMN Partners): Mobile network operators (members), telco vendors, software companies and many other leading industry players (contributors), and research institutes contributing substantially to mid- to long-term innovation (advisors)" (NGMN, 2020[55]).

[24] The 5G standard is intended to meet the IMT-2020 specifications, which means that it is being developed with three main generic use case scenarios: enhanced mobile broadband (eMBB); massive machine type communications (mMTC); and ultra-reliable and low latency communications (URLLC). The IMT-2020 requirements were developed within ITU-R Working Party 5D. See Recommendation "ITUR, M.2083 - IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond" (ITU, 2015[292]).

[25] FWA offerings through LTE networks have also been prevalent in some markets (e.g. Austria and Latvia).

[26]According to the study by Opensignal, public Wi-Fi has several differences to cellular, which may explain users' weaker speeds compared with cellular or other types of Wi-Fi (home and office). For example, public Wi-Fi uses unlicensed spectrum shared with multiple connections that may cause interference, while 5G and 4G use dedicated wireless spectrum licensed to one carrier. In addition, public Wi-Fi is an "add-on" to

enable users to share and connect to a wired broadband connection, and thus depends on the speed of the fixed network, while cellular carriers usually upgrade the backhaul connections to each base station. Finally, public Wi-Fi may not have enough high-quality access points as it is usually provided for "free", so there may be lower incentives to upgrade these access points (Opensignal, 2021[68]).

27 The fastest average download speed of mmWave 5G download was 692.9 Mbps using Verizon's mmWave network, followed by AT&T and T-Mobile with 232.7 Mbps and 215.3 Mbps, respectively (Opensignal, 2021[298]).

28 In February 2021, the FCC conducted the C-Band (3.7 GHz) auction in the United States, and by March 2021, Verizon outlined its plans to extend its 5G network with the use of the 3.7 GHz band, expecting to offer Gigabit broadband to 250 million Americans by 2024 by investing billion additional USD 10 billion (LightReading, 2021[297]).

29 See Ofcom's "Local-access Licence Guidance Document": https://www.ofcom.org.uk/__data/assets/pdf_file/0037/157888/local-access-licence-guidance.pdf

30 Access to the WAN can be granted via different links, such as virtual private networks (VPNs), wireless networks, cellular networks or a household internet router. Whereas, a WAN, can exist globally without ties to a physical location through the use of a leased network provider, LANs exist within a limited area. A common form of LAN is a Wireless Local Network (WLAN), also commonly known as Wi-Fi networks (CompTIA, n.d.[300]).

31 In 2015 the ITU set forth the "Vision" of the desired capabilities of IMT-2020 (i.e. "5G"), which is set to be more flexible, reliable and secure than previous IMT, with the three main intended usage case scenarios: enhanced mobile broadband (eMBB), ultra-reliable and low-latency communications (URLLC), and massive machine type communications (mMTC) (ITU, 2015[292]).

32 A "substation" is a part of the system of electrical generation, transmission, and distribution that transforms energy.

33 According to the European Radio Spectrum Policy Group (2021[98]): "Dynamic spectrum sharing (DSS) is an "intra operator" spectrum sharing technique allowing to dynamically manage the allocation of frequency resources among users/devices in time and space, which use different radio access technologies of an operator (e.g. LTE and 5G NR), based on network conditions and traffic needs."

34 A virtualised network function (VNF) is a software application that implements network functions of a legacy non-virtualised network, such as firewalls, routing, load balancing, and traffic management, among others (ETSI, 2014[102]).

35 The control plane decides how packets (data) are sent from one point to another, while the forwarding plane actually sends or "forwards" the data (Cloudflare, 2021[295]).

36 A virtual network function (or VNF) is a software implementation of a network function that runs on one or more virtual machines (VMs) on top of the hardware networking infrastructure. ETSI released its first specifications for cloud-native VNF management in November 2020. A cloud-native NFV software is one designed and managed using cloud-native principles from the start (ETSI, 2020[302]). Such principles may include, for example, running "micro-services" in containers rather than a VM, having a container orchestration system, such as Kubernetes, and using cloud-native orchestration paradigms.

37 As defined by Ofcom, "Net Neutrality is the principle of ensuring that users of the internet can control what they see and do online" (Ofcom, 2021[113]).

[38] The remote radio unit (RU) is also known as remote radio head (RRH).

[39] In the study published by the European Commission on market trends and plausible developments of the 5G supply market, the following is stated with regards to process to set O-RAN Alliance specifications:

> *"Representatives of vendors do not perceive ORAN in competition with 3GPP, but more being responsible for the implementation of open-source- based standards or specifications. The governance of the O-RAN Alliance is briefly described in the mentioned MoU. However, the section on the governance provides no indication, whether it complies with the six principles for the development of international standards, guides and recommendations to ensure transparency, openness, impartiality and consensus, effectiveness and relevance, coherence, and to address the concerns of developing countries. In detail, based on publicly available information [https://www.o-ran.org/membership-info] and an interview with a legal expert of the WTO rules also applicable according to EU Regulation No 1025/2012, the following conclusions are derived:*
>
> *First, the required transparency, i.e. all essential information is easily accessible to all interested parties, is only partly fulfilled, e.g. the O-RAN specifications are not accessible at the homepage.*
>
> *Second, the procedure is not open in a non-discriminatory manner during all stages of the standard-setting process, because the founding members have access to more information than the contributors during the process.*
>
> *Third, although interested contributors have opportunities to contribute to the elaboration of the specifications, the founding members have a privilege, because they have the necessary minority of more than 25% to block proposals.*
>
> *Overall, proof that the O-RAN Alliance complies with the various WTO criteria is still missing, although some of their members assure this compliance. Consequently, such an independent assessment is needed, which, however, cannot be realised within the context of this project" (European Commission, 2021[124]).*

[40] Dish acquired spectrum and towers as part of the remedies from the Sprint/T-Mobile merger.

[41] An exchange rate of 0.876 EUR/USD for the year 2020 from OECD.stat has been used.

[42] An exchange rate of 0.715 GBP/USD 2Q 2021 from OECD.stat has been used.

[43] Idem.

[44] Idem.

[45] Going forward, the growing significance of new players in the value chain, such as cloud and content providers, may have implications for competition and regulation. Such challenges, which are not addressed in this report, may be explored in future work of the Working Party.

[46] When referring to cloud computing, it is also helpful to define whether a cloud is deployed within an organisation or more broadly. Four main deployment models can be distinguished: i) private clouds, ii) public clouds iii) community clouds, and iv) hybrid clouds.

[47] In May 2021, AWS signed a partnership with Mavenir to deliver cloud-based 5G solutions. In particular, Mavenir/AWS plan to "offer voice and messaging solutions for core network and RAN customers along with AI/ML solutions for orchestration and observability" (Mobile World Live, 2021[303]).

[48]As an OECD legal instrument, the principles represent a common aspiration for its adhering countries.

[49] That make use of the IEEE 802.11 standards for communications.

[50] Multipath TCP is an extension to the Transmission Control Protocol (TCP) that is used by the majority of Internet applications.

[51] 3GPP has selected Multipath TCP as one of the key component of the Access Traffic Steering, Switching & Splitting (ATSSS) function that enable 5G devices to efficiently combine 5G and Wi-Fi (Tessares, 2020[185]).

[52] An exchange rate of 0.83 EUR/USD for the second quarter of 2021 from OECD.stat has been used.

[53] In the 300 GHz to 3 THz range, although some consider terahertz spectrum defined as frequencies above 100 GHz.

[54] An exchange rate of 0.876 EUR/USD for the year 2020 from OECD.stat has been used.

[55] The IOWN (Innovative Optical and Wireless Network) concept, advocated by NTT, is a network and information processing infrastructure that can provide high-speed, high-capacity communications and vast computing resources using innovative technologies centred on fibre. Research and development has begun with the aim of finalizing specifications in 2024 and launching them in 2030 (NTT, 2021[306]).

[56] An exchange rate of 1121.405 KRW/USD for 2Q 2021 from OECD.stat has been used.

[57] Executives from AT&T and Ericsson are chairs of the full member group, while representatives from Nokia, AT&T and VMWare have been named as co-chairs of the Next G alliance Steering Group to identify key R&D needs in North America (ATIS, 2021[301]).

[58] The OECD Broadband Portal provides a range of key parameters related to connectivity, like for example links to national broadband maps, data on broadband speeds, and broadband coverage.

[59] For many years, OECD member countries have been keenly aware of the importance of measuring actual broadband performance. Since 2012, the OECD has made steps towards the long term goal of a harmonised approach of "measuring actual broadband speeds, with the first step to agree principles of good practices in data collection". The Network of Francophone Telecommunication Regulators (*le réseau francophone de la régulation des télécommunications*, Fratel) has also worked towards the goal of finding good practices in measuring quality of service and quality of experience concerning mobile networks (Fratel, 2019[307]), as well as the Body of European Regulators for Electronic Communications (BEREC) (BEREC and OECD, 2020[293]).

[60] For more information on SpeedChecker methodology please refer to the Annex.

[61] Opensignal collects real-time data from mobile phone users that have downloaded its application on their smartphone. This is done at different times of the day and from different locations (e.g. indoors, outdoors).

[62] Each source measuring broadband performance and quality of experience has its own methodology offering a different picture of the Internet. According to the 5G QoS measurement implemented at the end of 2021 by the MSIT in Korea, 5G average download speeds were 801.48 Mbps and upload speed was 83.01Mbps. This result rose up 16% and 31%, respectively, compared to the previous year (2020). See https://www.msit.go.kr/bbs/view.do?sCode=user&mId=115&mPid=111&bbsSeqNo=86&nttSeqNo=3179854.

63 The fastest average download speed of mmWave 5G download was 692.9 Mbps using Verizon's mmWave network, followed by AT&T and T-Mobile with 232.7 Mbps and 215.3 Mbps, respectively (Opensignal, 2021[298]).

64 A previous OECD report surveyed 142 000 peering agreements (4 331 ISP networks, representing 86% of the world's Internet carriers in 96 countries), and found that most (99.51%) were based on "handshake" agreements in which the parties agreed to informal or commonly understood terms without creating a written document, while contracts only represented 0.49% of all interconnection agreements (Weller and Woodcock, 2013[234]).

65 Definition of QoS: all features of a telecommunications service that bear on its ability to satisfy stated and implied needs of the user of the service (ITU-T Rec. E.800). Definition of QoE: "the degree of delight or annoyance of the user of an application or service" (ITU-T Rec. P.10/G.100).

66 Passive infrastructure sharing refers to common use by two or more operators of their passive elements of their respective networks (e.g. masts, towers, sites, etc.), while active infrastructure sharing is common use of active elements of the network such as backhaul and even spectrum resources allocated individually to each operator (e.g. radio access network [RAN] sharing, roaming, software elements, etc.).

67 Gigabit Passive Optical Network (GPON) technology is a way of providing fibre to the home. GPON is a point-to-multipoint access network which users' passive splitters in the fibre distribution network, connecting multiple homes/business with one feeding fibre connection from the provider.

68 Namely, the EECC establishes that an operator with significant market power (SMP) will be able to propose commitments on offers for co-investment in new networks that consist of optical fibre elements up to the end-user premises or base station. Under the EECC, not all "Very High Capacity Networks" (VHCNs) are eligible for co-investments. To be eligible, they must consist of fibre up to the end-user premises or to the base station.

69 TIM owns 58% of FiberCop, while a United States investment fund (KKR) holds 37.5%, and Fastweb owns the rest (4.5%).

70 An exchange rate of 1.454 AUS/USD for the year 2020 from OECD.stat has been used.

71 The SMP-operator should primarily provide backhaul connection by providing access to fibre-based network infrastructure (dark fibre). As an alternative, the SMP-operator should provide backhaul connection by providing optical wavelength or digital connection capacity, depending on the request from the wholesale buying operator. Source: PTS, decision on market 3a, 2015-02-19.

72 See article L.34-8-3 of the CPCE (Code des postes et des communications électroniques).

73 Previously Ofcom conducted separate reviews of both the Business Connectivity Market (i.e. leased lines and Dark Fibre etc.) and the more residential focused Wholesale Local Access Market, which tended to occur every 3 years. By comparison the new Fixed Telecoms Market Review (FTMR) combines both of those markets and covers a wider 5 year period (from 2021 to 2026).

74 Decision no. 348/19/CONS. There are two conditions to be met before announcing the decommissioning of a given local exchange: i) the coverage to be reached and ii) the percentage of accesses already migrated to NGA from the given local exchange. As regards the coverage, 100% of NGA coverage needs to be reached. To this purpose, also Fixed Wireless Networks are included in the coverage, but only to a limited extent. As regards the take up of NGA it has to be at least the 60% of activated accesses on the given local exchange, both by SMP operator and alternative operators.

[75] It should be noted that the difference between what is measured with the help of the Atlas and what is announced by Swedish operators are two different measures of coverage, where one concerns geographical coverage and the other one percentage of the population covered. The difference can be partially explained by the fact that a significant part of the territory is uninhabited (e.g. the Alpine region).

[76] By the first semester of 2021, the FCC had reached several milestones. On 6 August 2021, FCC published a new map showing mobile coverage and availability based on voluntary data from the main mobile operators, which will serve as a public test of the standardised criteria developed by the FCC to improve broadband maps (FCC, 2021[304]).

[77] The IFT in Mexico was developing at the moment of writing the National Infrastructure Information System (SNII), which will consist of a geo-referenced national database containing information on active infrastructure, means of transmission, passive infrastructure, rights of way, public sites, and private sites.

[78] The OECD Council Recommendation on Broadband Connectivity [OECD/LEGAL/0322] states the following:

> *"**IV. RECOMMENDS** that Adherents minimise negative environmental impacts of communication networks, by:*
>
> *1. Supporting and promoting smart and sustainable networks and devices.*
>
> *2. Encouraging communication network operators to periodically report on their environmental impacts and initiatives taken to improve them and to report on the positive environmental effects of connectivity."*

[79] In the United Kingdom, within the Wholesale Fixed Telecoms Market Review 2021-26 in March 2021, Ofcom published its statement on Promoting competition and investment in fibre networks: Wholesale Fixed Telecoms Market Review 2021-26. Ofcom's intention is to encourage competition between different networks where viable and incentivise investment by giving regulatory certainty and allowing companies to make a fair return. BT Openreach will continue to be required to allow all network operators to lay their own fibre networks using Openreach's infrastructure through its Physical Infrastructure Access product. Ofcom has categorised areas of the country depending on the level of competition in those areas for the purposes of regulating residential broadband products. In both non-competitive areas (~30% of premises) and in potentially competitive areas (~70% of premises), BT Openreach will continue to be required to provide wholesale access to its network. In both areas, Ofcom is setting a flat, inflation-adjusted, regulated prices for Openreach's entry-level superfast broadband service which has a download speed of up to 40 Mbps.