Evolution of fixed access networks

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Contents

Section

1. Overview 2
2. Technology evolution 6
3. Methodology and acknowledgment 29

Scope of this report

The availability of high performance and reliable fixed broadband access is vital for consumers to access digital and online services, as well as for driving economic growth in the UK. Ofcom has a duty to report on different types of networks provided in the UK, including reporting on fixed broadband coverage and performance in our Connected Nations reports. The technologies underpinning these network infrastructures continue to evolve, and we continually monitor their developments to ensure that our policy teams are well-informed and can take these developments into account when shaping new policies.

While the Connected Nations report focuses on the current state of coverage and performance, our report on the evolution of fixed access networks complements this perspective by providing a summary of likely future developments of technologies that may become important for delivering fixed broadband services in the UK. While technical details are provided for a more comprehensive understanding, this should not hinder the overall message of our report.

1. Overview

For well over a century, copper systems underpinned telecommunications' infrastructure in the UK and worldwide.[1] Fixed broadband access has become an integral part of consumers' lives, empowering them with access to information, education, entertainment, and knowledge for personal and professional growth. The availability of high-quality broadband plays a vital role in connecting communities, driving innovation, and delivering economic growth. Its significance continues to grow as society becomes increasingly dependent on digital technologies and online services.

The vital fixed access link has been a bottleneck on service delivery, which will be unlocked for many decades by the installation of full fibre. Fixed broadband infrastructure in the UK is undergoing a rapid transformation, from copper to gigabit-capable and full-fibre infrastructure.[2] Our interim Connected Nations Summer Update 2023 reported that gigabit-capable broadband and full-fibre coverage were available for 75% and 52% of UK residential premises, respectively, as of May 2023.[3] If all network deployments are realised as planned, gigabit-capable broadband could reach to 92% of UK residential premises, and full fibre coverage could reach to 84% of UK residential premises, by March 2025.[4,5]

Gigabit-capable broadband is able to provide downstream speeds of 1Gbit/s or higher and can be delivered over full fibre and some hybrid fibre-copper networks. Hybrid fibre-copper networks include hybrid fibre with coaxial cable networks as well as hybrid fibre with twisted pair networks. Hybrid-Fibre Coaxial (HFC) networks have been already providing gigabit speeds (with DOCSIS 3.1), and the next generation technology standard (DOCSIS 4.0) provides enhancement to upstream data rates compared to earlier technology generations. On the other hand, some hybrid systems based on fibre and twisted pair copper, such as Fibre To The distribution point (FTTdp), can also provide gigabit speeds with existing and emerging standards (such as G.fast[6] and G.mgfast[7]). However, hybrid architectures, often considered as interim solutions, rely on deeper fibre penetration, shorter copper segments and upgraded network electronics. The efforts required for both deploying deeper fibre and

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[1] The inventions of twisted pair by Alexander Graham Bell in 1881 and coaxial cable by Oliver Heaviside in 1880 dominated and shaped telecommunications throughout the 20th century although some of the earliest telegraph cables were considered a form of coaxial cable well before its invention in 1880. The development of single mode fibre by Charles Kao and George Hockam in 1966, along with advances in laser diodes by Charles Townes, and Arthur Schawlow in the late 1950s as a practical source of light, gave birth to the era of optical communications which is expected to dominate this century. Daring to dream | Nature Photonics, [accessed on 6 September 2023].

[2] Infrastructure here refers to the physical connections which could be twisted-pair, coaxial, fibre or hybrid connections connecting terminals belonging to different technology standards, e.g., variety of Digital Subscriber Line (xDSL), Data Over Cable Service Interface Specifications (DOCSIS), Passive Optical Network (PON) and Point-to-Point Ethernet.

[3] Connected Nations update: Summer 2023 - Ofcom, [accessed on 8 September 2023].

[4] Connected Nations - Planned Network Deployments 2022 (ofcom.org.uk), [accessed on 6 September 2023].

[5] The latest government target for gigabit-broadband, i.e., nationwide-by-2030 (at least 99% of UK premises by 2030), was set out in the "Levelling-Up" white paper, published in February 2022. Link, [accessed on 6 September 2023].

[6] G.fast standard spans 2-212 MHz bandwidth which can deliver higher than gigabit speed over shorter copper lines.

[7] G.mgfast (also referred to as MGfast) standard utilises frequencies up to 424 MHz and is specified to deliver speeds up to 8 Gbit/s over much shorter copper segments.

higher density network electronics can be challenging when considering future network scalability to support higher capacities and reduced latencies for upcoming services.[8]

Passive Optical Network (PON) technologies constitute approximately 95% of full-fibre solutions globally.[9] Full fibre is often referred to as Fibre To The Premise (FTTP) or Fibre To The Home (FTTH). In the UK, a mixture of GPON[10] (2.5 Gbit/s downstream and 1.25 Gbit/s upstream rate) and XGS-PON[11] (10 Gbit/s symmetrical rates) are being widely deployed, while Point-to-Point (PtP) Ethernet and 25G-PON[12] technologies are deployed at much smaller scales for residential broadband and small businesses. The consumer benefits of full fibre, such as higher broadband speeds and lower latencies, are well understood; however, there are also broader benefits for operators and for the environment.[13] For example, full-fibre networks are less distant dependent due to low transmission losses over fibre connections which as a result require much lower energy-per-bit delivered than alternative technologies based on copper and wireless systems. Adding to the energy efficiency, full-fibre networks have generally lower density in network electronics since the distribution and aggregation of traffic over PON systems benefit from energy-free passive splitters and combiners rather than active switching[14], despite the dominating insertion loss of the passive splitters in the end-to-end Optical Distribution Network (ODN).[15]

Full-fibre technologies are evolving at the optical component and the architectural levels:

- Optical components of current standards rely on intensity modulation and they have increased in data rates per wavelength from 10 Gbit/s to 25 Gbit/s[16,17] and 50 Gbit/s[18,19] while future developments are considering 100 Gbit/s[20] and beyond - benefiting from advanced transmission and coherent detection techniques matured over copper and RF (Radio Frequency) systems over many decades and initially introduced for long-haul and subsea optical point-to-point links since 2009.[21] PON systems equipped with advanced transmission and coherent detection, referred to as Coherent PON, enable future optical terminals to utilise the phase, amplitude, and polarisation of optical signals. This allows encoding more bits per Hertz,

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[8] Fibre in Europe - final version for publication (analysysmason.com), [accessed on 6 September 2023].
[9] Full-fibre access as strategic infrastructure: strengthening public policy for Europe (analysysmason.com), [accessed on 6 September 2023].
[10] GPON stands for Gigabit Passive Optical Network.
[11] XGS-PON stands for 10 Gigabit Symmetrical Passive Optical Network, where the letter 'X' represents the number 10, and the letter 'S' stands for symmetrical.
[12] Ogi Become First UK ISP to Deploy Nokia's 25Gbps Full Fibre Tech - ISPreview UK, [accessed on 6 September 2023].
[13] Copper switch-off - White Paper (wik.org), [accessed on 6 September 2023].
[14] Point-to-Point (PtP) Ethernet technology could use active switching in the access network.
[15] ODN loss can range from 29 dB to a maximum 35 dB. Link, [accessed on 6 September 2023].
[16] P802.3ca/D3.1, Jan 2020 - IEEE Draft Standard for Ethernet Amendment: Physical Layer Specifications and Management Parameters for 25 Gb/s and 50 Gb/s Passive Optical Networks | IEEE Standard | IEEE Xplore, [accessed on 6 September 2023].
[17] 25GS-PON MSA Group (25gspon-msa.org), [accessed on 6 September 2023].
[18] New ITU standards to boost Fibre to the Home from 10G to 50G - ITU Hub, [accessed on 6 September 2023].
[19] IEEE 50 Gb/s EPON (50G-EPON) | IEEE Conference Publication | IEEE Xplore, [accessed on 6 September 2023].
[20] A quarter century of increasing fixed-broadband speeds - ITU Hub, [accessed on 6 September 2023].
[21] NANOG 85 Tutorial: Optical Fiber Capacity Limits – Where Do We Go Next? - www.infinera.com, [accessed on 6 September 2023].

enhancing detection sensitivity, and improving both capacity and range. Coherent PON with off-the-shelf advanced digital signal processing techniques may facilitate innovation at a much faster pace than PON's predecessor access technologies.

- Full-fibre architectures are increasingly adopting disaggregation.[22] Software-Defined Networking (SDN[23]) and Network Function Virtualisation (NFV[24]) are the key building blocks of disaggregated architectures. Originally adopted by cloud systems and data centres more than a decade ago, these technologies are now flowing to the core and access networks.[25] SDN first emerged following a whitepaper[26] in 2008 which proposed an open interface (i.e., OpenFlow) between the network's control plane and data plane, which, in principle, offered a centralised intelligence and configurable control plane for more optimised traffic engineering. On the other hand, NFV allowed to abstract the network functions (e.g., firewall, routing, switching, etc.) from the network hardware and allow them to operate on commodity hardware. SDN and NFV are complementary features, which together can make it possible to decouple the network innovation cycle to hardware and software and improve network scalability based on changing demands. Architectures adopted by data centres and cloud systems, such as leaf-spine, started to emerge in core and access networks, promise to provide scalable and cost-effective topologies with better ability to manage traffic.[27]

Wireless networks are also playing an important role in delivering broadband services, especially in areas that are hard-to-reach by wireline (fixed) networks. Fixed Wireless Access (FWA) benefits from more powerful outdoor user terminals and 5G enhanced key features such as Multiple-Input Multiple-Output (MIMO), beamforming, and carrier aggregation, allowing FWA to enhance both peak speeds and coverage.[28,29,30,31]

Advancements in the satellite sector, especially satellite launching and antenna technology, have enabled massive constellations on Lower Earth Orbit (LEO) to provide satellite broadband services.

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[22] Disaggregation of network refers to the separation of network software from specialised hardware, eventually leading to the virtualisation of network software, thus enabling network functions to be hosted on general-purpose, commercial-off-the-shelf (COTS) hardware. The key benefit of disaggregation is resource optimisation of the network functions, which in turn helps with the reduction in cost through economies of scale.

[23] The term was first coined in 2009 - Software-Defined Networking | MIT Technology Review, [accessed on 6 September 2023].

[24] First proposed in ETSI white paper in 2012, leveraging standard IT virtualisation technology (e.g., Virtual Machines) to run network functions on commodity hardware Microsoft Word - NFV_White_Paper_ETSI_CM, [accessed on 6 September 2023].

[25] Cloud - Broadband Forum (broadband-forum.org), [accessed on 6 September 2023].

[26] openflow_whitepaper.pdf (princeton.edu), [accessed on 6 September 2023].

[27] WT-408 - Cloud CO Migration and Coexistence (broadband-forum.org), [accessed on 6 September 2023].

[28] Samsung Electronics Reaches Top Speeds Over 10km Distance for 5G mmWave in Australia – Samsung Global Newsroom, [accessed on 6 September 2023].

[29] Nokia hits extended range mmWave 5G speed record in Finland | Nokia, [accessed on 6 September 2023].

[30] 5G fixed wireless access using mmWave extended range - Ericsson, [accessed on 6 September 2023].

[31] Ofcom is publishing a report to explore the latest developments in wireless broadband technologies.

Current generation of satellites are able to support broadband services reaching 100s of Mbit/s.[32] Next generation of satellite systems are expected to have optical/RF cross-links which reduce overall network latency by routing traffic in orbit and freeing up radio resources to drive up network capacity. In addition to current satellite broadband services using proprietary technologies, there is an ongoing standardisation effort towards 3GPP[33] compliant satellite broadband services.

Migration to gigabit-capable and full-fibre broadband may continue to drive greater usage and faster broadband products including indoor technologies, e.g., Wi-Fi. This is because fibre has ultimately much greater capacity potential and better energy efficiency than existing copper infrastructure. We also expect that a multiplicity of access technologies (fibre, twisted pair and coaxial cable as well as fixed wireless access and satellite broadband) will coexist over this decade to meet consumer demands under different network conditions and scenarios.

We note that each area covered in this short report will be considered on its own merits and the report does not seek to make wider judgements or conclusions on the economics, policy implications, or likelihood of technology adoption or technology retirement.

[32] Starlink Specifications - Starlink, [accessed on 6 September 2023].

[33] The 3rd Generation Partnership Project (3GPP) covers cellular telecommunications technologies, including radio access, core network and service capabilities, which provide a complete system description for mobile telecommunications.

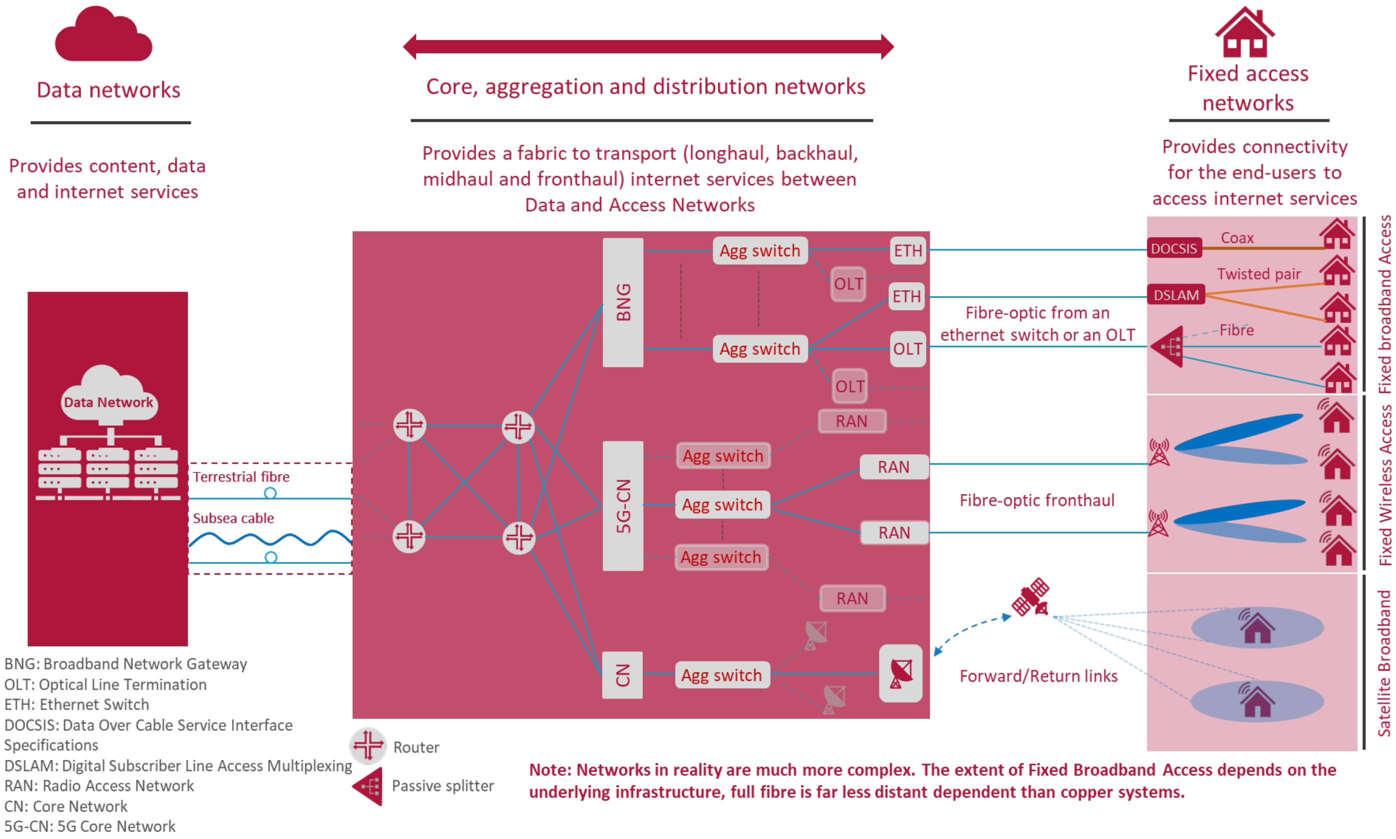
2. Technology evolution

Recent developments in coverage and performance

- Average monthly data use has grown to 482 Gigabyte per fixed connection in 2022. Compared to 2021, this is an increase of about 6%.[34] Although the growth trend has been slowing down compared to earlier years, fixed connections continue to deliver a circa 94% of the total fixed and mobile data traffic.[35]
- The average download speed for fixed connections has been growing steadily. In 2022, it increased to 112 Mbit/s, an increase of circa 30% from 2021.[36]
- Coverage of full fibre has increased to 52% of UK premises in May 2023[37] and it will continue to grow steadily throughout the first half of this decade, with coverage planned to reach 84% of all premises by March 2025.[38] According to forecasts from Analysys Mason, the growth in full-fibre coverage will slow down in the second half of the decade, but full-fibre take-up may grow rapidly to reach the majority of UK households by 2027.[39]
- While the government remains committed to at least 85% gigabit-capable broadband coverage by 2025, the 'nationwide-by-2030' target sets out a timeline for connecting the remaining 15% of premises, most of which will require public funding support.[40] Our updated Connected Nations report from September 2023 reported that gigabit-capable broadband coverage were available for 75% of UK residential premises as of May 2023.[41] If all network deployments are realised as planned, gigabit-capable broadband could reach to 92% of UK residential premises by March 2025.[42]
- Multiplicity of access technologies (fibre, twisted pair, and coaxial cable as well as fixed wireless access and satellite broadband) will coexist over this decade to meet consumer demands under varied network conditions and scenarios as showed in Figure 1.

[34] Connected Nations 2022 - Ofcom, [accessed on 6 September 2023].
[35] The c.94% figure is derived from Connected Nations Data using the ratio of total monthly fixed data traffic to the total monthly sum of fixed and mobile data traffic.
[36] Interactive report - Ofcom, [accessed on 6 September 2023].
[37] Connected Nations update: Summer 2023 - Ofcom, [accessed on 8 September 2023].
[38] Connected Nations - Planned Network Deployments 2022 (ofcom.org.uk), [accessed on 6 September 2023].
[39] FTTx conversion: worldwide trends and forecasts (analysysmason.com), [accessed on 6 September 2023].
[40] Gigabit broadband in the UK: Government targets, policy, and funding - House of Commons Library (parliament.uk), [accessed on 6 September 2023].
[41] Connected Nations update: Summer 2023 - Ofcom, [accessed on 8 September 2023].
[42] Connected Nations - Planned Network Deployments 2022 (ofcom.org.uk), [accessed on 6 September 2023].

Figure 1 Simplified end-to-end network connectivity over diverse technologies expected to coexist throughout this decade.



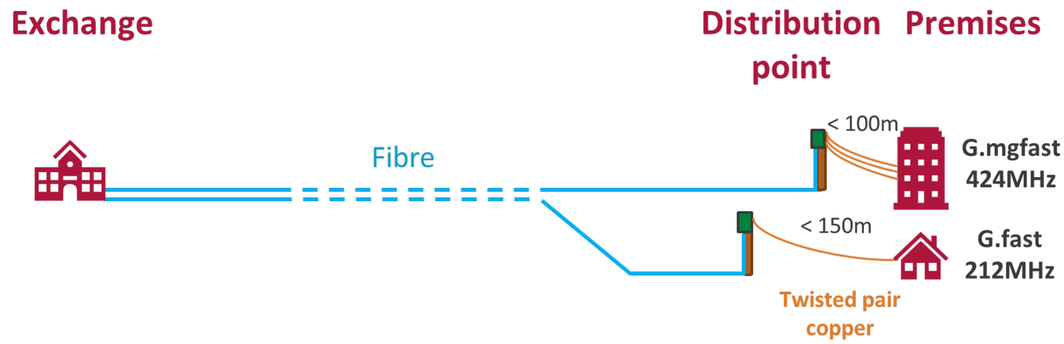
[Source: Adapted from the ITU[43]]

[43] Global Connectivity Report 2022 - ITU Publication, [accessed on 6 September 2023].

Gigabit-capable hybrid broadband access solutions

- Emerging standards such as G.mgfast[44] and DOCSIS 4.0[45] can support multi-gigabit line speeds over hybrid fibre-copper connections, i.e., FTTdp[46] and HFC respectively. These standards rely on deeper fibre penetration, shorter copper segments, increased bandwidth, and advanced digital signal processing (DSP) techniques, including vectoring[47] and Full Duplex[48] (FDX). Multi-dwelling units and historical buildings may benefit from technologies where the final distribution is carried out over existing copper wiring. However, due to the sheer volume of network upgrades required behind such solutions, they might prove more challenging in comparison to full fibre. For illustration, see Figure 2 and Figure 3.

Figure 2 Fibre To-The distribution point (FTTdp) using G.mgfast (oversimplified).



[Source: Ofcom]

Figure 3 Hybrid Fibre and Coaxial Cable using DOCSIS 4.0 (oversimplified).

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[44] G.mgfast implementations can support aggregates of 8 Gbit/s with Full Duplex and 4 Gbit/s with Time Division Duplex (TDD), [Up to 8 Gbit/s broadband with new ITU standard MGfast - ITU Hub,] [accessed on 6 September 2023].

[45] DOCSIS 4.0 supports 10 Gbit/s downstream and 6 Gbit/s upstream data rates, [DOCSIS® 4.0 Technology - CableLabs], [accessed on 6 September 2023].

[46] FTTdp is acronym for Fibre To The distribution point. FTTdp is similar to FTTC but it brings the fibre much closer to customer's premises.

[47] Vectoring is a technique used for far-end crosstalk cancellation between twisted pairs within a cable binder. In G.(mg)fast, it is mandatory and subject to transmit power limits due to extreme crosstalk levels over higher frequencies and shorter cable drops. Implementation may allow targeted vectoring group, implicitly allowing use of crosstalk for data transmission.

[48] Full Duplex (FDX) allows the use of the same spectrum resource in both downstream and upstream directions simultaneously. An expansion of the DOCSIS 3.1, DOCSIS 4.0 relies on FDX to increase the upstream capacity.

[Source: Ofcom]

- There is a growing consensus that copper solutions are reaching their limits,[49,50,51] adding to the rising costs of maintenance and energy bills,[52] which may suggest that further standardisation efforts beyond what have been introduced already is uncertain.[53] Note, that the number of properties with fixed broadband available solely via all-copper connections is now very small (2-3%).[54] The majority of connections in the UK use fibre partially, such as FTTC (Fibre To The Cabinet) and HFC.[55,56] In these cases, deeper fibre penetration and upgraded network equipment allow the final copper segment to provide higher speed connectivity to the customer's premises. It is worth noting that some of the existing FTTC deployments, using G.fast, can offer aggregate rates of 100s of Mbit/s while HFC, using DOCSIS 3.1, can support gigabit-capable broadband products.

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[49] Fiber to the Tap: Pushing Coaxial Cable Networks to Their Limits | IEEE Journals & Magazine | IEEE Xplore, [accessed on 6 September 2023].

[50] Investigating the upper bound of high-frequency electromagnetic waves on unshielded twisted copper pairs | Nature Communications, [accessed on 6 September 2023].

[51] Dielectric-induced surface wave radiation loss | Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences (royalsocietypublishing.org) , [accessed on 6 September 2023].

[52] High inflation may force operators to accelerate copper decommissioning (analysysmason.com), [accessed on 6 September 2023].

[53] Cable network strategies in an age of fibre | Analysys Mason (sample version), [accessed on 6 September 2023].

[54] Connected Nations update: Spring 2023 - Ofcom – click here for the relevant data, [accessed on 6 September 2023].

[55] Although the use of VDSL2 technology dominates the FTTC deployment, G.fast technology can also be used for FTTC deployment and is capable of achieving hundreds of Mbit/s reaching up to 1 Gbit/s over less than 150 metres.

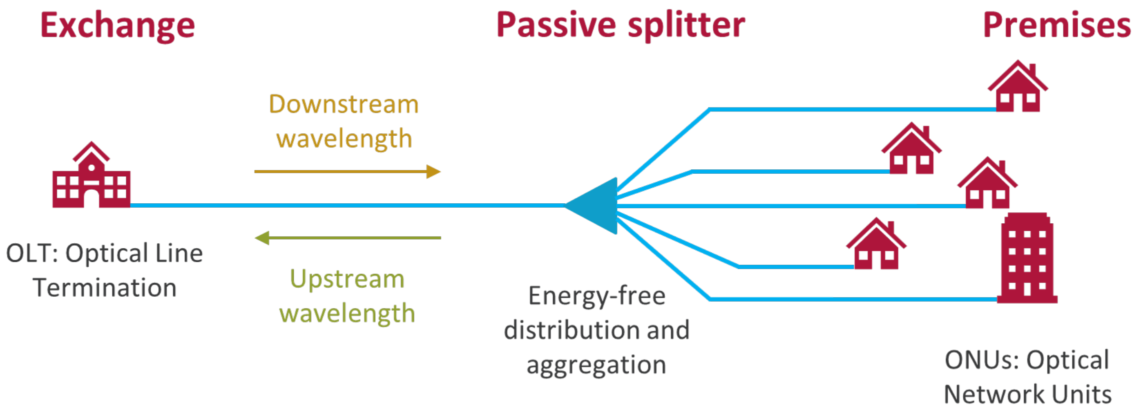
[56] HFC refers to Hybrid Fibre-Coaxial infrastructure over which DOCSIS technologies can deliver (shared) 10Gbit/s downstream data rates (for both DOCSIS 3.1 and DOCSIS 4.0) while 1Gbit/s and 6 Gbit/s upstream data rates with DOCSIS 3.1 and DOCSIS 4.0, respectively.

Full-fibre access technology in deployment and in development

- There is a 'tidal surge' of optical fibre, which has replaced copper in the whole of the core network over the last few decades and is finally reaching the individual user. Fibre will make access networks less distance dependent and may have the potential to address the last mile problem and provide more Gigabit-capable broadband services.
- Passive Optical Network (PON)[57] constitutes approximately 95% of full-fibre solutions world-wide.[58] In the UK, a mixture of GPON (2.5 Gbit/s downstream and 1.25 Gbit/s upstream rate) and XGS-PON (10Gbit/s symmetrical rates) are being widely deployed while Point-to-Point (PtP) Ethernet and 25G-PON are deployed at much smaller scales for residential and small businesses.
- PON architectures are 'Point-to-multi-point (PtMP)' which employ a single higher capacity central terminal shared among many connections, as shown in Figure 4. The traffic distribution and aggregation are carried out by energy-free (passive) splitters and combiners which is intrinsically cheaper than a 'Point-to-Point (PtP)' solution with active switching and one-central-terminal-per-connection. PONs use the same fibre for upstream (US) and downstream (DS) signalling, however on different wavelengths as shown in Figure 4.[59] Generally, PON employs Time Division Multiplexing (TDM) which is used to allow the ONUs (Optical Network Units) to communicate using reoccurring timeslots over the upstream wavelengths, widely referred to as Burst mode.[60] Wavelength Division Multiplexing (WDM) based PON, e.g., NG-PON2 is available, however envisaged for enterprise use since it requires tuneable and more costly network terminals.[61]

[57] Of note, BT developed Telephony over Passive Optical Network (TPON) in the mid-1980s and launched the world's first PON trial at Bishop's Stortford which aimed to connect up to 400 homes and 28 businesses, Optical Fibre Networks - POST Briefing Note 13 (May 1990) (parliament.uk), [accessed on 6 September 2023].
[58] Full-fibre access as strategic infrastructure: strengthening public policy for Europe (analysysmason.com), [accessed on 6 September 2023].
[59] Access networks largely employ ITU-T G.652 Single Mode Fibre (SMF). SMF has non-linear attenuation between 1200 nm and 1700 nm, the lowest attenuation loss occurs over 1550 nm (~0.2 dB/km) whilst highest at 1400 nm, however modern SMFs exhibit lower losses around the 1400 nm. Chromatic dispersion is quasilinear with the wavelength – approximately zero around 1300 nm; G.9804.1 : (itu.int), [accessed on 6 September 2023].
[60] G.984.3 : Gigabit-capable passive optical networks (G-PON): Transmission convergence layer specification (itu.int), [accessed on 6 September 2023].
[61] Time Wavelength Division Multiplexing (TWDM) combines the features of TDM-PON and WDM-PON, and provides increased capacity and flexibility to support different types of end-users and applications - G.989 : 40-Gigabit-capable passive optical networks (NG-PON2): Definitions, abbreviations and acronyms (itu.int), [accessed on 6 September 2023].

Figure 4 PON architecture



[Source: Ofcom]

- Continuous growth in high-speed service take-up and growing demand of higher data rate applications are the main drivers for the evolution of PON. The general rule of thumb is that technology progresses every 5-7 years by a factor of 4x in capacity subject to market demands and conditions.[62,63] The PON standards (by ITU-T[64] and IEEE[65]) have achieved progress in converging the design specification of the physical media layer and optical components in an attempt to improve interoperability, scale up demand and drive costs down. Figure 5 shows the evolution of the PON standards over the per-wavelength data rates, initially starting at sub-gigabit speeds, then to 1 Gbit/s, 2.5 Gbit/s, 10 Gbit/s, 25 Gbit/s, and 50 Gbit/s. It is worth noting that 25G(S)-PON, where S is for symmetric, borrows in its make-up from both the ITU and IEEE standards.[66]
- Coexistence between PON generations over existing ODNs is one of the driving principles of both existing and developing standards. This requires blocking filters in the ONU (user-side equipment) and a wavelength multiplexer (known as a coexistence element or CEx) to be installed at the OLT (Optical Line Terminal) end (exchange-side equipment). An alternative approach is to use multi-PON module (MPM) – also referred to as combo-PON or combo-optics. MPM eliminates the need for additional cabling or managing two different types of OLT line cards, and potentially even two different types of OLT chassis.[67]

[62] Technology Roadmap for Passive Optical Networks: The Next Step is 50G PON (strategyanalytics.com), [accessed on 6 September 2023].
[63] Full-Service Access Network (FSAN) is a world-wide industry association of operators and system vendors, established in 1995 to drive the evolution of PON in collaboration with the ITU to ensure that technology development is relevant to market demands while supporting coexistence between PON generations - FSAN Roadmap | FSAN, [accessed on 6 September 2023].
[64] ITU-T is the Telecommunication Standardisation Sector for the International Telecommunication Union.
[65] IEEE is The Institute of Electrical and Electronics Engineers (IEEE).
[66] 25GS-PON MSA Group (25gspon-msa.org), [accessed on 6 September 2023].
[67] Gigabit Passive Optical Networks: Enhancement band and PON Coexistence - PowerPoint Presentation (itu.int), [accessed on 6 September 2023].

Figure 5 PON standards evolution.

[Source: Ofcom]

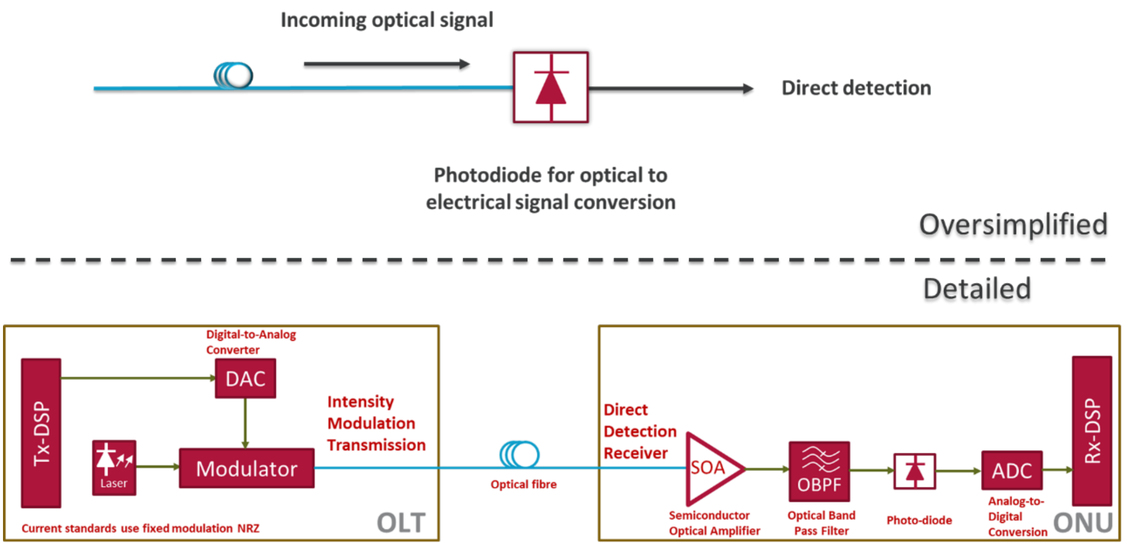
- Symmetric line rates are important for business applications while asymmetric is accepted for residential use cases, although standards consider both consumers (residential) and businesses, reflecting current applications that may change. PON generations beyond XG(S)-PON and 10G EPON are motivated by business use cases in addition to traditional residential use cases. PON is becoming increasingly advocated for use cases beyond consumer broadband access[68], i.e., backhaul, midhaul[69] and fronthaul[70] for radio networks especially with 25G and 50G. For these new use cases and given the PtMP nature of PON systems, there are a number

[68] Efficient Transport of eCPRI Fronthaul over PON | IEEE Conference Publication | IEEE Xplore, [accessed on 6 September 2023].
[69] G.Sup75 : 5G small cell backhaul/midhaul over TDM-PON (itu.int), [accessed on 6 September 2023].
[70] G.Sup66 : 5G wireless fronthaul requirements in a passive optical network context (itu.int), [accessed on 6 September 2023].

of areas that require careful considerations around synchronisation, resilience, latency and scalability.

- Fibres can carry independent parallel signals at several wavelengths. This is used in existing PONs just to separate outgoing and return signals on the same fibre as highlighted earlier but there is enormous potential to do more. In particular, a wavelength can be assigned (perhaps dynamically) to each ONU and those link(s) run effectively as point-to-point (PtP) links over the PON (e.g., PtP WDM overlay over PON). Such approach may involve using a passive wavelength-directing component, such as a low loss Arrayed Waveguide Grating (AWG),[71] instead of an all-band optical splitter and therefore avoiding the split loss discussed above. It is worth noting that XR Optics[72] is a recent development that enables the use of coherent optics in point-to-multipoint topologies.
- All current PON standards rely only on modulating and detecting the intensity levels of light (also known as direct detection), see Figure 6. Despite the low losses of the single mode fibre, i.e., ~0.2 dB/km, this adds a hard limit on how much information or data can be encoded into a single wavelength. The single mode fibre has two near-degenerate modes, and the de-polarisation of light through fibre means that the energy is distributed across two polarisations.

Figure 6 Direct detection in existing PON systems.



[Source: Ofcom]

[71] Enabling Technologies for Future Scalable and Flexible WDM-PON and WDM/TDM-PON Systems | IEEE Journals & Magazine | IEEE Xplore, [accessed on 6 September 2023].
[72] XR-Optics-SB-0217-RevF-0222.pdf (infinera.com), [accessed on 6 September 2023].

- Beyond current standards, i.e., 50 Gbit/s per wavelength, PON systems are expected to employ transmission and detection techniques which can allow future terminals to utilise the phase, amplitude, and polarisation information of the light to encode more bits per Hertz. Adoption of advanced transmission and coherent detection techniques, that have been matured for many decades over copper and RF (Radio Frequency) systems,[73] may enable future PON standards, termed as Coherent PON, to achieve data rates in excess of 100 Gbit/s per wavelength.
- Coherent PON with off-the-shelf advanced digital signal processing techniques may facilitate innovation at a much faster pace than PON's predecessor access technologies. Coherent optics were first introduced commercially around 2009 with 40 Gbit/s per wavelength mainly for long-haul and subsea links and since then the technology has developed rapidly. Today's technology is capable of 800 Gbit/s[74] and more recently 1.2 Tbit/s,[75] while 1.6 Tbit/s[76] is yet to emerge, targeting additional multi-haul network applications such as data centre interconnect (DCI) and metro.
- The fundamental component in coherent PON is the addition of the local oscillator, i.e., a laser source, to the ONUs which enhances the receiver sensitivity, see Figure 7. The local oscillator provides a reference to mix with the incoming optical signals and differentiate polarisation, phase, and amplitude information. Coherent detection, probabilistic shaping,[77] polarisation-time block coding (also referred to as Alamouti[78]), differential group delay predistortion, polarisation scrambling, higher modulation orders and more powerful Forward-Error-Correction schemes have all started to emerge in the access network with meaningful room for improvement. While this offers powerful performance, it comes with additional cost due to the use of multiple transmitters and detectors at the network terminals, i.e., OLT and ONU. The implementation methods for coherent PON vary in terms of how they distribute design cost and complexity between the OLT and ONU and whether they require exploiting both polarisation and phase diversities. The main methods include Single Polarisation Heterodyne

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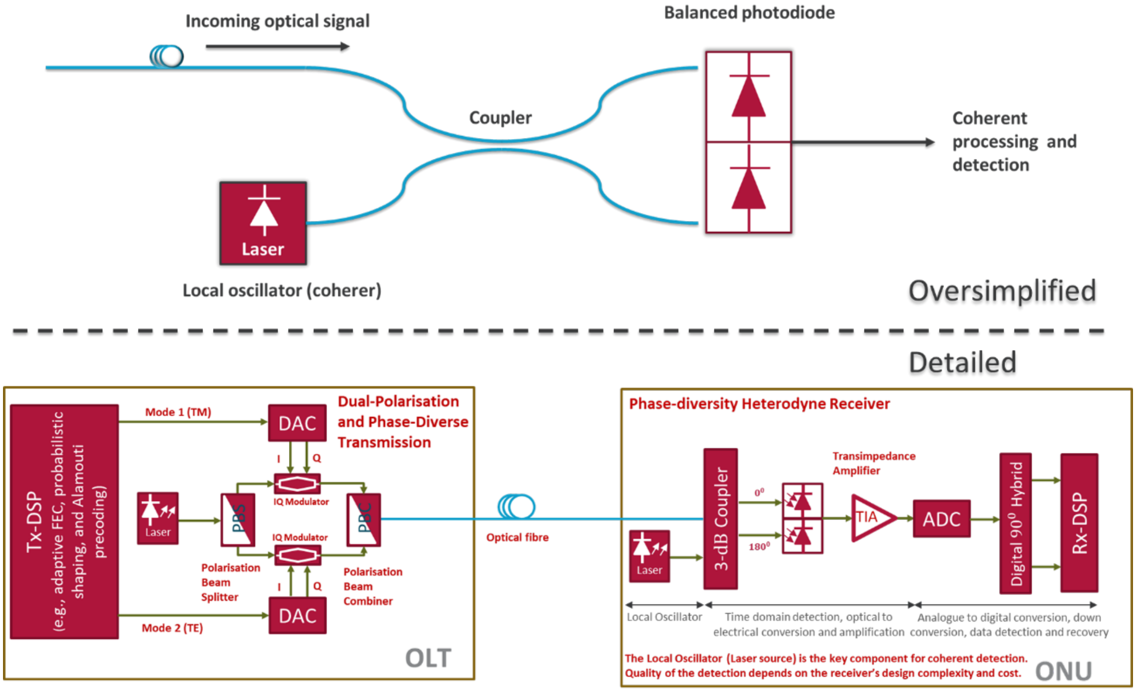
[73] Techniques to enhance data communications and to reduce interference between multiple communication channels emerged in the 1960s and 1970s. This era saw the development of many fundamental techniques, like zero forcing, decision feedback and adaptive equalisers. Originally designed for data communications over copper and RF systems, these techniques underpin transceiver design of modern copper and RF communication systems – and more recently coherent optics, [accessed on 6 September 2023].
[74] Coherent Optics at 400G, 800G, and Beyond (lightreading.com), [accessed on 6 September 2023].
[75] Acacia Ships CIM 8: Industry First 1.2T Pluggable Multi-Haul Module - Acacia Communications, Inc. (acacia-inc.com), [accessed on 6 September 2023].
[76] OFC 2023: The Terabit Era - Dell'Oro Group (delloro.com), [accessed on 6 September 2023].
[77] Probabilistic or constellation shaping can be traced back to Claude Shannon with the earliest record in 1949, [accessed on 6 September 2023].
[78] A simple transmit diversity technique for wireless communications | IEEE Journals & Magazine | IEEE Xplore, [accessed on 6 September 2023].

detection, Dual Polarisation Heterodyne detection, and Dual Polarisation Intradyne detection. [79,80,81,82,83,84,85]

Figure 7 Coherent detection.



[Source: Ofcom – adapted from the reference in footnote 82]

- The principles of disaggregated architectures, i.e., software-defined networking (SDN) and network function virtualisation (NFV), originally adopted in data centres, are now emerging in the core[86] and access[87] of telecom networks including full-fibre networks. The disaggregation of the network can decouple the hardware and software evolution cycles and improve scalability to match varying network demands. Disaggregated architectures have

[79] Coherent Access: Status and Opportunities | IEEE Conference Publication | IEEE Xplore, [accessed on 6 September 2023].
[80] FLCS-PON – A 100 Gbit/s Flexible Passive Optical Network: Concepts and Field Trial | IEEE Journals & Magazine | IEEE Xplore, [accessed on 6 September 2023].
[81] Introduction to the JOCN special issue on future PON architectures enabled by advanced technology (optica.org), [accessed on 6 September 2023].
[82] Coherent Passive Optical Networks: Why, When, and How | IEEE Journals & Magazine | IEEE Xplore, [accessed on 6 September 2023].
[83] Real-Time DSP-Free 100 Gbit/s/λ PAM-4 Fiber Access Link Using EML and Direct Detection | IEEE Journals & Magazine | IEEE Xplore, [accessed on 6 September 2023].
[84] 100 Gbit/s PAM-4 Linear Burst-Mode Transimpedance Amplifier for Upstream Flexible Passive Optical Networks | IEEE Journals & Magazine | IEEE Xplore, [accessed on 6 September 2023].
[85] Real-Time 100 Gb/s PAM-4 for Access Links With up to 34 dB Power Budget | IEEE Journals & Magazine | IEEE Xplore, [accessed on 6 September 2023].
[86] BT Group adopts Juniper's cloud core network for global scalable services | Fibre Systems (fibre-systems.com), [accessed on 6 September 2023].
[87] ADTRAN breaks ground at Openreach | TelecomTV, [accessed on 6 September 2023].

been driven by standards, collaborative industry initiatives and academic research[88] such as Broadband Forum (BBF[89]), European Telecommunications Standards Institute (ETSI[90]), Open Networking Foundation (ONF[91]) and Telecom Infra Project (TIP[92,93,94]).

- SDN offers, in principle, centralised intelligence and provides a configurable control plane where the rules that control data flows via network routers and switches (i.e., the data plane) are controlled using software. The SDN controller is the fundamental component of the SDN control plane benefiting from an abstract view of the network topology and promising more optimised traffic engineering. In large scale networks, distributed controllers are necessary, and their placement is critical for determining network latency, performance, resilience, and cost.[95] On the other hand, NFV allows the abstraction of the network functions (e.g., firewall, routing, switching, etc) from the hardware allowing these network functions to operate on commodity hardware and remotely. Both SDN and NFV are complementary to each other and require programmable and interoperable interfaces, see Figure 8.[96]

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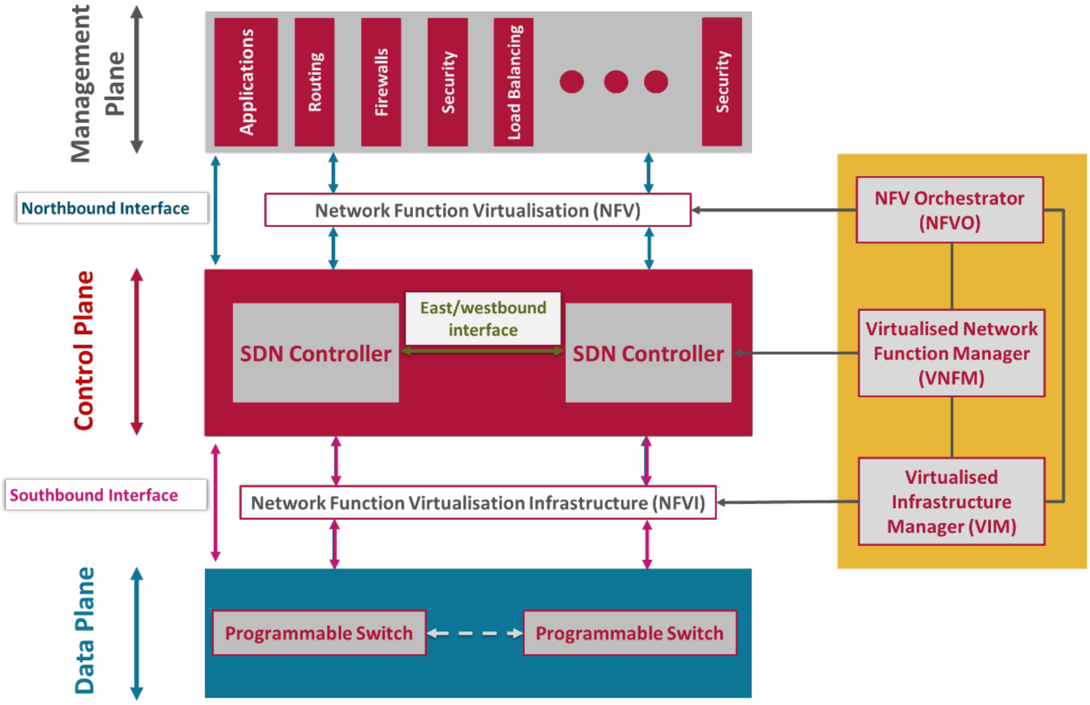
[88] The First 10 Years of Software Defined Networking - Linux Foundation, [accessed on 6 September 2023].
[89] Open Broadband - Broadband Access Abstraction (OB-BAA) - Broadband Forum (broadband-forum.org), [accessed on 6 September 2023].
[90] ETSI - Standards for NFV - Network Functions Virtualisation | NFV Solutions, [accessed on 6 September 2023].
[91] SDN Enabled Broadband Access (SEBA) ONF Reference Design - SEBAv2.0[FINAL(3)].docx (opennetworking.org), [accessed on 6 September 2023].
[92] Open-BNG-Technical-Requirements-v2-final-no-backgrounds.docx (brandfolder.io), [accessed on 6 September 2023].
[93] Open Fixed Access Networks Use Case Document (telecominfraproject.com), [accessed on 6 September 2023].
[94] Open Fixed Access Networks Technical Requirements Document- Link (telecominfraproject.com), [accessed on 6 September 2023].
[95] A Survey on Controller Placement in SDN | IEEE Journals & Magazine | IEEE Xplore, [accessed on 6 September 2023].
[96] A comprehensive survey of interface protocols for software defined networks - ScienceDirect, [accessed on 6 September 2023].

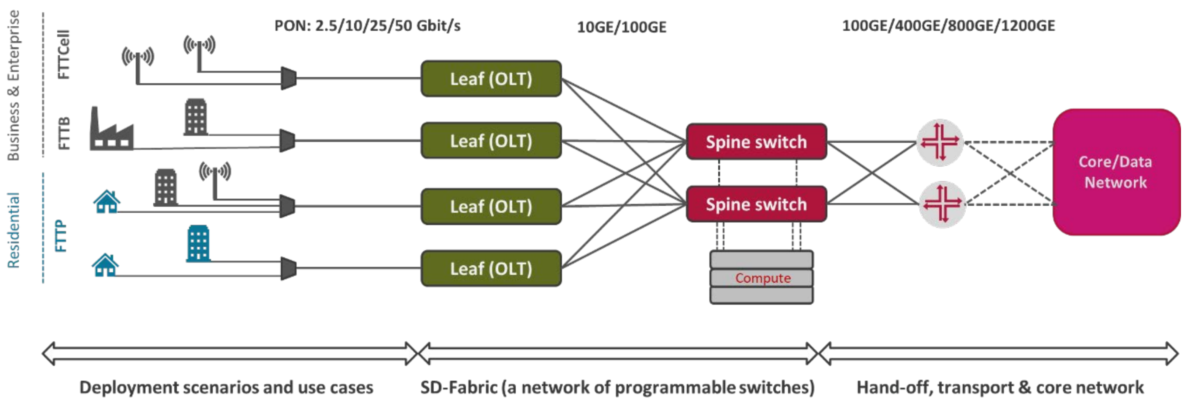
Figure 8 SDN and NFV basic architecture



[Source: Ofcom – adapted from the reference in footnote 96]

- To complement the SDN and NFV architecture principles, network topologies underpinning data centres, such as leaf-spine fabrics, started to emerge in the core and access of telecom networks. Leaf-spine fabrics can ease the scalability of the network resources, i.e., connectivity and compute, between network functions, physical or virtual, without impacting existing services. In the context of fixed access, an OLT serves as a leaf node to provide access to the network.[97] While spine nodes are connected to all leaf nodes with equal bandwidth links to form a leaf-spine fabric, as shown in Figure 9.

Figure 9 Speculative outlook of future fixed access networks



[Source: Ofcom - adapted from the ONF[98]]

[97] WT-408 - Cloud CO Migration and Coexistence (broadband-forum.org), [accessed on 6 September 2023].
[98] SEBA - Open Networking Foundation, [accessed on 6 September 2023].

Fixed wireless access and satellite broadband

- Wireless networks will continue playing an important role in delivering broadband services, especially in areas that are hard-to-reach by wireline (fixed) networks.[99] Fixed Wireless Access (FWA) networks in the UK are provided by Wireless Internet Service Providers (WISPs) and Mobile Network Operators (MNOs) and they follow a wide range of network architectures including proprietary solutions (e.g., WiMAX) and 3GPP technologies (e.g., 4G and 5G).[100,101,102,103]
- FWA benefits from stable radio conditions between the network terminals, especially with outdoor customer premise equipment (CPE) often equipped with antenna gains greater than 10 dBi.[104,105] This setup mitigates penetration losses through building materials and ensures better signal quality. The use of 5G in FWA inherits MIMO and beamforming which makes connectivity over Frequency Range 1 (FR1)[106] less dependent on LoS conditions than earlier generations of FWA technologies. Frequency Range 2 (FR2),[107] widely referred to as millimetre wave (mmWave), requires LoS conditions between network terminals. With multipath being less important for mmWave regimes,[108] the stability of radio conditions between network terminals in FWA, in theory, can be enhanced as long as LoS conditions are maintained.[109] This may enable MIMO in FWA to approach its practical limits with less computational power and less spectrum resource for channel tracking.
- In theory, FWA can offer gigabit-capable speeds, particularly when considering carrier aggregation, which allows for overall transmission bandwidths of up to 6.4 GHz, enhancing both peak speeds and coverage.[110,111] However, it has been reported that the performance of FWA is scenario-specific and therefore cannot match the reliability and scalability of full-fibre networks. [112]
- Other features, such as Integrated Access and Backhaul (IAB) developed by 3GPP, are expected to improve service delivery to hard-to-reach regions, as shown in Figure 10, where

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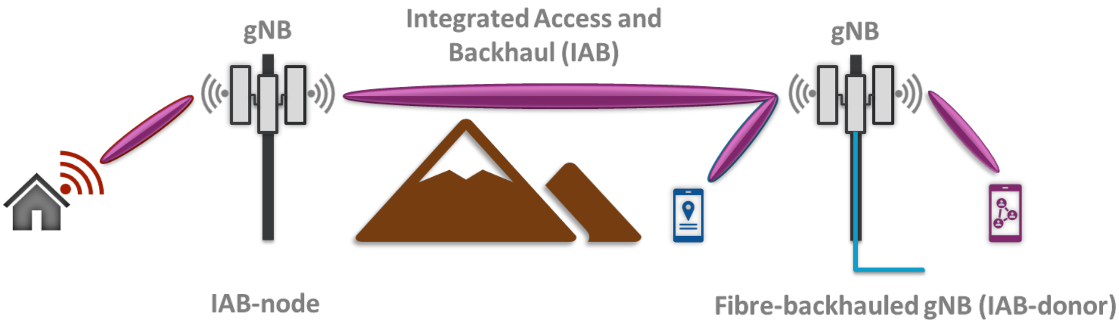
[99] Since Marconi's first wireless station and trans-Atlantic transmission in history, in Poldhu, Cornwall 1901– wireless communication continues to be the primary means for reaching distant lands, 168-4284.indd (nature.com), [accessed on 6 September 2023].
[100] 5G Fixed Wireless Access: a world of opportunities - Ericsson, [accessed on 6 September 2023].
[101] Connect more people with 5G fixed wireless access | Nokia, [accessed on 6 September 2023].
[102] FWA on mobile networks is offered on licensed 4G and 5G networks. Since network capacity is shared with mobile users, the capacity of the network must be carefully managed between the demands of FWA customers and existing mobile subscribers. There may be areas of high mobile demand where a reliable FWA service cannot be offered.
[103] FWA from WISPs mostly use license exempt or lightly licensed spectrum. Unlike 3GPP technologies such as 4G and 5G, these proprietary FWA solutions require Line of Sight (LoS) between the base station and receiver; therefore, an outdoor antenna and an indoor customer premises equipment are required to receive service at the premises.
[104] Connect more people with 5G fixed wireless access | Nokia, [accessed on 6 September 2023].
[105] 5G Fixed Wireless Access: a world of opportunities - Ericsson, [accessed on 6 September 2023].
[106] Frequency Range 1 (FR1) refers to sub-6GHz frequencies although the maximum is 7.125 GHz.
[107] Frequency Range 2 (FR2) spans frequencies from 24.25 GHz to 52.6 GHz.
[108] What Is mmWave? - MATLAB & Simulink (mathworks.com), [accessed on 6 September 2023].
[109] Downlink Cell-Free Fixed Wireless Access: Architectures, Physical Realities, and Research Opportunities | IEEE Journals & Magazine | IEEE Xplore, [accessed on 6 September 2023].
[110] Carrier Aggregation on Mobile Networks (3gpp.org), [accessed on 6 September 2023].
[111] 5G Fixed Wireless Access: a world of opportunities - Ericsson, [accessed on 6 September 2023].
[112] Uncovering the Secret to Fixed Wireless Access | BCG, [accessed on 6 September 2023].

a fibre-backhauled gNB[113] provides both access and backhaul links simultaneously.[114,115] IAB can extend wireless coverage without having to lay fibre or, at least, delaying the large and difficult investment of laying fibre for backhaul as long as electricity is available.[116,117] IAB can provide flexible, scalable, and multi-hop backhauling, using the same or different frequency bands for access and backhaul.[118] 3GPP Release 18 extends IAB capabilities to support mobile base station relays using the IAB architecture also referred to as Vehicle-Mounted Relays (VMRs).[119,120] Some of the key assumptions in this release limit a VMR node to a single hop from its IAB-donor node and also exclude satellite access at this stage.

Figure 10 Integrated and Access Backhaul (oversimplified)



[Source: Ofcom - adapted from 5G Americas]

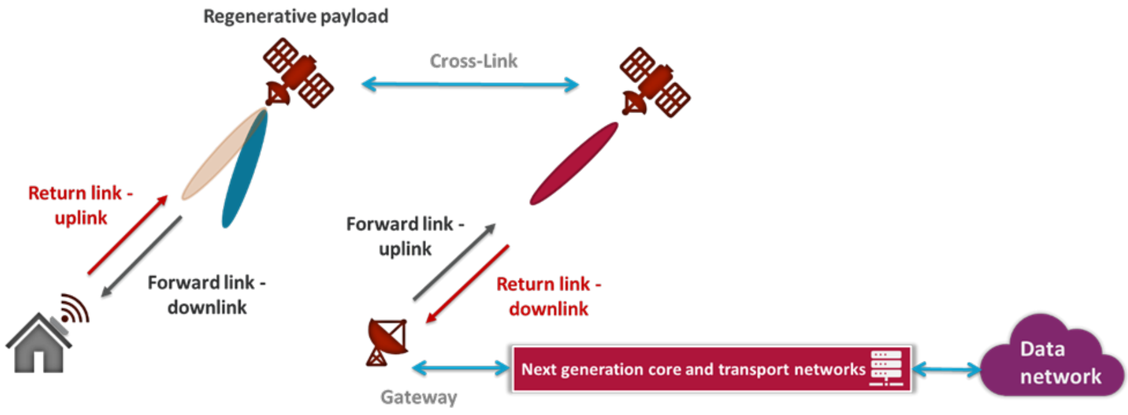
- Low Earth Orbit (LEO) satellite[121] constellations are currently growing in numbers and can, in theory, deliver download speeds of few to several hundred Mbit/s per connection[122] with sub 50 msec latency[123] in remote areas where terrestrial systems are unavailable.[124]
- State-of-the-art satellites mostly use proprietary technology with either transparent[125] or regenerative[126] payloads without cross-links. Next generation of satellite systems with regenerative payloads as showed in Figure 11, that have optical/RF cross-links, have the potential to increase data rates and reduce overall network latency by routing traffic in orbit

[113] Next generation base station which supports 5G New Radio (NR).
[114] Integrated access and backhaul: Why it is essential for mmWave deployments | Nokia, [accessed on 6 September 2023].
[115] Integrated access and backhaul: new option for 5G - Ericsson, [accessed on 6 September 2023].
[116] Verizon eyes IAB for mmWave expansion | Light Reading, [accessed on 6 September 2023].
[117] Innovations-in-5G-Backhaul-Technologies-WP-PDF.pdf (5gamericas.org), [accessed on 6 September 2023].
[118] Ref: Specification # 38.300 (3gpp.org), Specification # 38.401 (3gpp.org), [accessed on 6 September 2023].
[119] Becoming-5G-Advanced-the-3GPP-2025-Roadmap-InDesign.pdf (5gamericas.org), [accessed on 6 September 2023].
[120] Ref: Specification # 23.700-05 (3gpp.org), [accessed on 6 September 2023].
[121] In 1945, Arthur C. Clarke was the first to speculate Extra-Terrestrial Relays, i.e., satellite systems, stating that "*It is the only way in which true world coverage can be achieved for all possible types of service*". Wireless-World-1945-10.pdf (worldradiohistory.com), [accessed on 6 September 2023].
[122] Here's your first look at Project Kuiper's low-cost customer terminals (aboutamazon.com), [accessed on 6 September 2023].
[123] Measured performance report - Ofcom, [accessed on 6 September 2023].
[124] Starlink Specifications - Starlink, [accessed on 6 September 2023].
[125] Transparent payloads can only amplify and switch the frequency bands of the incoming signals without digitisation, advanced detection, and transmission techniques.
[126] Regenerative payload regenerates incoming signals with digital signal processing techniques such as demodulation, decoding, switching, encoding, and modulation.

rather than offloading to and routing over terrestrial networks. The latter may free up resources to allow satellite networks to deliver higher data rates.

- SDN[127] started to emerge in satellite communications, however Cloud-native solutions are also expected to emerge especially in the Gateways which are expected to be deployed in closer proximity to data centres to reduce the end-to-end network latency. SDN may provide payloads programmability[128] to enable new standard features and enhance system performance while in orbit. In Satellite networks, Artificial Intelligence (AI) and Machine Learning (ML) may become instrumental in orchestrating network resources including spectrum allocation, beam shaping, interference management and traffic routing to deliver higher satellite broadband speeds.[129]

Figure 11 Future NTN: regenerative and cross-linked



[Source: Ofcom]

- Satellite broadband services are also emerging as a part of 5G services within 3GPP standards. 3GPP Release 17[130] has now well-defined support to non-terrestrial networks, namely LEO and GEO (Geostationary Orbit) to provide service continuity and ubiquity which can potentially benefit mobile access in hard-to-reach areas. The services included within current 3GPP standards can be grouped into two categories: direct-to-device[131] and satellite backhaul to mobile masts. The current version of the standard only focusses on mobile broadband and IoT connectivity and support is limited to transparent satellite payloads operating below 6 GHz with Frequency Division Duplex (FDD). Future releases, especially including support for New Radio (NR) based satellite access above 10 GHz and regenerative payload using optical/RF cross-links as in Figure 11, are expected to include direct-to-terminal[132] services, which may enable broadband services to building mounted or mobile terminals. In this way, 3GPP

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[127] ESA - Software-defined satellite enters commercial service, [accessed on 6 September 2023].
[128] Software-defined payload may allow operators to reconfigure the network (e.g., modifying beams, waveform, capacity, and power distribution dynamically) based on demand.
[129] ESA - Artificial intelligence in space, [accessed on 11 September 2023].
[130] Specification # 21.917 (3gpp.org), [accessed on 6 September 2023].
[131] Direct-to-device refers to connectivity services provided from a satellite directly to a mobile handset or an IoT node.
[132] Terminal refers to a user equipped with a dedicated satellite terminal with a directional antenna capable of higher power levels which may be a flat panel antenna or a parabolic dish (with mechanical steering if it is used with low or medium earth orbit satellites).

compliant satellite broadband services can be provided as well via non-terrestrial networks offering new opportunities to serve the hardest to reach network regions.[133]

[133] NTN & Satellite in Rel-17 & 18 (3gpp.org), [accessed on 6 September 2023].

Other considerations

- The drive for adopting the virtualisation or cloud-native technologies and disaggregated architecture of the data centres in access networks may require new thinking about the implications and nature of vendor mix when common and commodity hardware solutions (e.g., Whitebox[134]) and proprietary software solutions are deployed in the network.
- As a result of disaggregation, networks are expected to become more software based than traditional network elements, i.e., monolithic. [135] Virtualised Network Functions (VNFs)[136] of different networks may share the same hardware platform. This is expected to give rise for convergence in network infrastructure, e.g., core and access,[137,138] wireline and wireless,[139] terrestrial and non-terrestrial, [140] and RAN (Radio Access Network) and Wi-Fi.[141,142] In theory, this may simplify the network and optimise it operations through automation.[143] The key technical challenge lies in handling traffic, i.e., splitting, aggregation, and steering, over different networks with different Quality of Service (QoS) requirements and latencies. These solutions exist already, however demand for such architectures has not yet matured to test and stabilise their development.
- The hardware supporting disaggregation is an area of active development, as a wide range of programmable Application Specific Integrated Circuits (ASICs) started to emerge in the last decade.[144] This has driven disaggregated solutions using whitebox solutions, which are often certified by the Open Compute Project (OCP[145]). These solutions are being trialled around the world for both fixed and radio access networks.
- Adopting disaggregation is a fundamental change which may involve organisational changes and skill set upgrades.[146] While software solutions can offer greater flexibility, there is often a trade-off between flexibility and efficiency where increased flexibility with software solutions may potentially impair performance and subsequently reliability. This challenge, identified early in the development of NFV, has not been entirely resolved.[147] Migration from legacy to

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[134] Whitebox refers to the ability to use a commercial off-the-shelf (COTS) switching and routing hardware.

[135] In traditional hardware based physical network functions, hardware and software are tightly integrated (hence they are referred to as 'monolithic').

[136] The concept of virtualising network functions refers to migrating network functions (mostly in the form of software) from dedicated (sometimes proprietary) hardware appliances to network functions (in software form) run on a Commercial Off-The-Shelf (COTS) hardware.

[137] SEBA - Open Networking Foundation, [accessed on 6 September 2023].

[138] COMAC - Open Networking Foundation, [accessed on 6 September 2023].

[139] Wireless-Wireline Convergence - BBF Wiki - BBF Wiki (broadband-forum.org), [accessed on 6 September 2023].

[140] NTN & Satellite in Rel-17 & 18 (3gpp.org), [accessed on 6 September 2023].

[141] 5G and Wi-Fi RAN Convergence Whitepaper - Executive Summary - Wireless Broadband Alliance (wballiance.com), [accessed on 6 September 2023].

[142] Of note, convergence in certain scenarios, e.g., Wireless-Wireline Convergence, can provide network operators higher resilience via alternative service routing over 3GPP networks when fixed broadband is unavailable.

[143] ADLittle Report - Open Networking Foundation, [accessed on 6 September 2023].

[144] A summary of High Speed Ethernet ASICs | by Justin Pietsch | The Elegant Network | Medium, [accessed on 6 September 2023].

[145] About » Open Compute Project, [accessed on 6 September 2023].

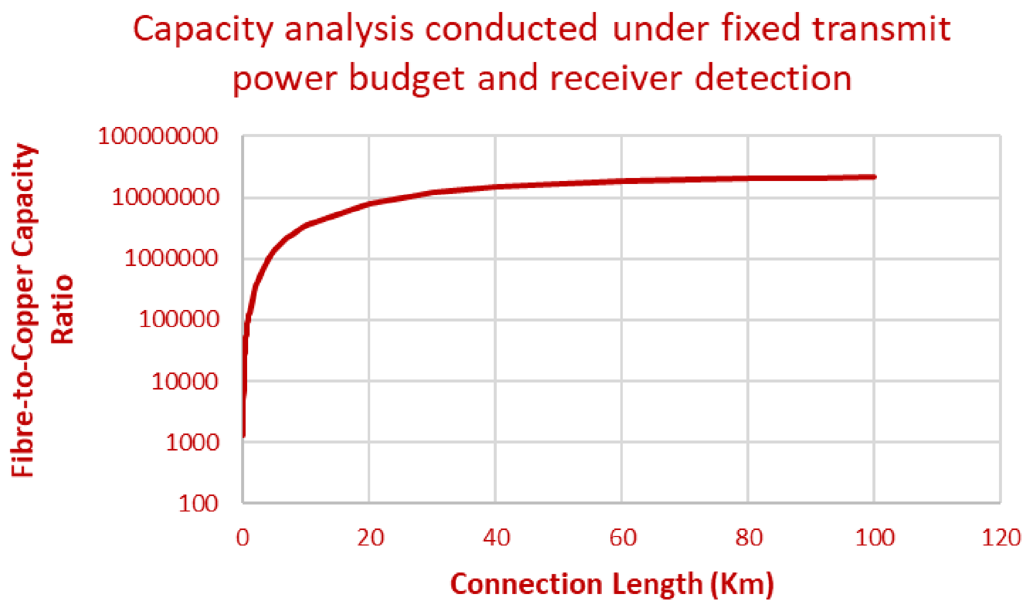
[146] How Your Business and SDN/NFV Can Evolve Together (vodafone.com), [accessed on 6 September 2023].

[147] ETSI-WP-53-In-the-Light-of-Ten-ears-from-the-NFV-Introductory-Whitepaper.pdf, [accessed on 6 September 2023].

disaggregated architectures can present interim challenges. These challenges arise from technical complexities associated with system maturity, integration, and interoperability. Additionally, the coexistence of these new architectures with legacy systems can introduce issues that impact network reliability, resilience, and security.[148,149,150,151]

- Single mode fibre is now being rapidly deployed, and it is here to stay and dominate access networks for many decades to come. It has the potential to drive sustainability due to its low losses (~0.2 dB/km), making communications less distance dependent in comparison to legacy copper, as shown in Figure 12, while future-proofing investments in fixed broadband infrastructure.[152]

Figure 12 Fibre vs copper theoretical capacity limits.



[Source: Ofcom in collaboration with the Cavendish Lab of Cambridge University.]

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[148] Implications of the emerging technologies Software-Defined Networking and Network Function Virtualisation on the future Telecommunications Landscape | Shaping Europe's digital future (europa.eu), [accessed on 6 September 2023].

[149] NFV Security in 5G - Challenges and Best Practices — ENISA (europa.eu), [accessed on 6 September 2023].

[150] GSMA | Migration from Physical to Virtual Network Functions: Best Practices and Lessons Learned - Future Networks, [accessed on 6 September 2023].

[151] Maintaining reliability in telco cloud transformation, ITP | Volume 17 Part 2 (theitp.org), [accessed on 6 September 2023].

[152] In collaboration with the Cavendish Lab of Cambridge University, we have conducted a 'theoretical' capacity comparison between single mode fibre and single twisted pair copper under fixed transmit power budget of 30 dBm and receiver detection of -140 dBm/Hz. The single mode fibre capacity is estimated over the spectrum spanning from O to L band (1270 - 1610 nm) in an ODN with 35 dB loss while copper is modelled as a single pair transmission line. The analysis shows that fibre-to-copper capacity grows exponentially with the connection's length. It suggests that fibre is approximately 100000 times better than copper for about 1km connection length, it rapidly grows to become millions of times better for 10s of km. The modelling does not take into account the powering requirement of the electronics or the practical implementation aspects of these systems. For specific technology comparisons, see EU Code of Conduct on Energy Consumption of Broadband Equipment: Version 8.1 (current version valid from 1.1.2023) | E3P (europa.eu) , [accessed on 6 September 2023].

- The rich capacity of full-fibre networks has the potential to not only support greater volumes of data, but also many different kinds of users, content and use cases; for example, fibre sharing in a multi-tenancy fashion[153] (i.e., beyond duct and pole sharing) may become important.
- Service reliability and quality are likely to improve with full-fibre networks.[154] Hybrid networks, with their reliance on copper segments, necessitate a higher density of active electronics due to greater losses over copper. Cumulatively, the failure rate of these many individual components could make hybrid networks less reliable than Passive Optical Network (PON) based full-fibre networks. Unlike copper systems which are distance-dependent, full-fibre networks are less distant-dependent due to the lower losses of single mode fibre as highlighted earlier. As a result, PON networks primarily contain passive components, with active electronics mostly limited to terminals at the customer and network ends.
- Copper connections are often crimped, which can suffer from oxidisation when exposed to wet weather conditions which may become less reliable than spliced and connectorised fibre connections. In addition, copper networks are susceptible to noise from various sources both intrinsic and extrinsic, especially during peak network traffic. These can originate at various points in the network and propagate to the customer equipment and become interference which eventually hinders performance and yields variable performance when exceeding the signal margin. This does not apply to full-fibre networks.
- Further development in hybrid networks is often viewed as an interim solution since it is expected that providers will eventually transition to full-fibre networks, especially when considering the energy efficiency of these solutions and the rising cost of maintenance and energy. This may raise questions about the reliability of a technology that might ultimately be deemed to be decommissioned. Technology development, expertise, and supply chain may decline which may subsequently make the technology less reliable in the future. In contrast, fibre technology is an area of active development with more advanced fault detection and management techniques.
- While full-fibre networks could alleviate bottlenecks in the access networks, this could also expose bottlenecks in other areas, such as transport and core network segments. These segments may then require further investment to keep up with growing user demand.
- In the upcoming phase, resilience could perhaps impose greater challenges and take on more significance than ever due to major network transitions. We may not only see transitioning from copper to fibre but also, potentially, a shift from traditional monolithic telecom architectures to disaggregated ones. In addition, the phasing out of the Public Switched Telephone Network (PSTN) in favour of all-IP-based services marks another significant shift. These challenges are further heightened by growing concerns about climate change and the rising costs and complexities of the energy supply chain.
- In principle the bottleneck removal enabled by fibre in access networks allows for greater resilience, especially with fibre-rich deployments given the low material cost of fibre. However, to further enhance the reliability and resilience of full-fibre networks, there are

[153] A multi-tenancy model may allow different service classes to coexist on the same fibre connection, for instance home broadband and 5G transport for a small cell. Although this subject has been an area of active research and standardisation, it faces a number of implementation challenges.
[154] Copper switch-off - White Paper (wik.org), [accessed on 6 September 2023].

several strategies that could be pursued. One key strategy is 'dual parenting', which might involve end-to-end protection using diverse fibre routes and network terminals. This approach ensures full redundancy and fall-back options for Optical Network Units (ONUs), Optical Line Terminals (OLTs), and the Optical Distribution Network (ODN). On the other hand, simpler protection measures may focus on redundancy at the exchange level providing only OLT protection. Nevertheless, the degree of resilience that can be achieved in practice will often depend on specific use cases and the Service Level Agreement in place. For instance, in business scenarios where a Passive Optical Network (PON) is deployed for radio cell backhaul or fronthaul, a higher level of protection and resilience would be expected.

- The shift towards disaggregated architectures, coupled with the adoption of leaf-spine designs, naturally enhances resilience. In these configurations, redundancy in spine nodes is standard, with each leaf node (e.g., OLT in the context of fixed access) maintaining diverse connections to all spine nodes. These spine nodes, in turn, offer Layer 3 or Layer 2 switching capabilities, ensuring fall-back options with equal multipath routing. This setup improves network resilience between leaf nodes, i.e., the OLTs, and Broadband Network Gateways (BNGs). However, while disaggregation can improve network programmability and modularity, it might also weave in intricate dependencies. Such complexity could lead to more demanding and challenging upgrades driven by continuous integration and development, potentially exposing vulnerabilities and risks, when system maturity is not fully achieved and stabilised.
- Transitioning to a fully IP-based system brings its own set of challenges. Traditional telephones, which were powered by copper networks, are not compatible with fibre because of its inability to forward power to premises. This saves energy[155] but in times of power outages, the need for alternative solutions, like battery backup systems, becomes essential, especially in the hardest to reach regions.
- PON networks are expected to dominate access networks throughout this decade and into the next. Their use cases are also expanding, notably into business applications and multi-tenancy. PON intrinsically broadcasts to other ONUs in the network and hence the use of encryption can be appropriate. Generally, there is likely to be a growing focus on Post-Quantum Cryptography (PQC) techniques.[156]
- As with any link there is a transmission latency (delay) -this is due to speed of light in glass, which is about 2/3 of the speed in vacuum, and the resulting latency can be sensitive to temperature and other proximity effects. Although latency is increasingly significant for new services, the fibre transmission latency is normally not yet significant compared with latencies elsewhere in the network or through network elements, e.g., switches and routers. But there are some ‘access’ instances, for example the back-haul and front-haul for some RF base stations where it matters.[157,158,159] Hollow Core Fibre (HCF) improves this as it offers several advantages, including improved propagation speed that is close to the speed of light, as well as enhanced thermal and polarisation stability.

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[155] How BT Group is making our networks more energy efficient, [accessed on 6 September 2023].
[156] National Quantum Strategy (publishing.service.gov.uk), [accessed on 6 September 2023].
[157] G.Sup66 : 5G wireless fronthaul requirements in a passive optical network context (itu.int), [accessed on 6 September 2023].
[158] G.Sup75 : 5G small cell backhaul/midhaul over TDM-PON (itu.int), [accessed on 6 September 2023].
[159] G.8271 : Time and phase synchronization aspects of telecommunication networks (itu.int), [accessed on 6 September 2023].

- While single mode fibre, with more than 50 THz of spectrum, is far from its capacity limit and is expected to remain in access networks for a considerable time (possibly many decades), HCF offers unique characteristics such as lower latency in comparison to standard silica glass fibre (by a factor 1/3) which is vital for transport networks, and low latency applications.[160] Losses of 0.22 dB/km at 1310 nm and 0.18 dB/Km at 1550 nm have been achieved on HCF enabling much lower losses in the O band.[161] Even given the benefits of HCF over single mode fibre, which is the dominant fibre type in access networks, in terms of lower losses, lower chromatic dispersion, better thermal stability, enabling larger bandwidths (i.e., more capacity) and less demands on DSP (and thus less costly terminals), it still has potential for further improvement while the insertion loss of single mode fibre is operating close to its theoretical limits. Key challenges facing the adoption of HCF concern production scalability, durability, splicing/repair mechanism, and overall associated cost.
- Other challenges may emerge from operating networks comprising mixed fibre types despite the benefits that it may offer to operators. Each type of fibre exhibits distinct characteristics, which can impact compatibility with passive and active network elements as well as test and measurement processes for fault diagnosis. For instance, using an OTDR (Optical Time Domain Reflectometer) to analyse reflections and identify the nature of fibre faults can be impacted by these variations. Hence, operators need to be aware of issues related to records management, spares management and necessary skills required to handle different fibre types in their networks.
- Although less dramatic, improvements in rapid installation techniques, especially the civil engineering is also important. The costs associated with civil engineering (or 'civil work' required to dig trenches for laying ducts followed by re-filling) remain by far the dominant factor in full-fibre networks deployment. Analysys Mason[162] suggests that labour costs can account for well over 80% of the total deployment cost. Since the fibre itself is both compact and cheap, including extra fibres in any installed cable with technologies such as Ribbonised fibres is being widely adopted as it is one of the simplest cost-reduction approaches for future-proofing and for ensuring network scalability.[163,164]
- Instead of digging trenches, Trenchless (No-dig) methods like Micro-trenching (or Slot-cutting), Mole ploughing, Directional Drilling and Impact Moling are increasingly becoming cost-effective methods of laying ducts and cables underground for longer as well as shorter distances particularly in rural deployments within the UK. Nevertheless, network reliability issues have been discussed for some of these techniques since the micro-ducts (which have a much smaller outer diameter than the traditional duct) could be positioned very close to the

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[162] Full-fibre access as strategic infrastructure: strengthening public policy for Europe (analysysmason.com), [accessed on 6 September 2023].

[163] Openreach UK Deploys New Air-Blown Ribbon Fibre Optic Cable - ISPreview UK, [accessed on 6 September 2023].

[164] Novel cable designs like Ribbon Fibre Cables allow very high fibre density (hundreds of fibres) in a given cable which combined with the ability to mass-fusion splice up to 12 fibres simultaneously translates into less time spent on installation compared with traditional loose tube fibre cables that require fibres to be spliced individually.

surface, and therefore be much more susceptible to damage during street works compared to the traditional ducts, which are installed at a much deeper level.

- Provisioning of optical systems can benefit from using OTDR based testing methods. This method has become vital when building, qualifying, maintaining, and monitoring full-fibre networks. As operators progress with the build of full-fibre networks, they can use the OTDR based technology platforms to certify new constructions, perform pre-provisioning checks, and monitor ongoing service remotely, therefore minimising the need for costly return visits from field engineers.[165,166]
- Enabling technologies for robotics[167] and automated systems are emerging such as geo-spatial data for underground infrastructure (NUAR: National Underground Asset Register)[168] and digital twins, that may help improve the efficiency of network maintenance, planning, and deployment.
- We note that full fibre and gigabit capable broadband solutions may enable faster growth in average broadband speeds than the last decade. This, in turn, may accelerate the evolution of in-home networking. User devices are increasingly featuring technologies such as Wi-Fi 6, Wi-Fi 6E, Wi-Fi EasyMesh[169,170] and in the near future Wi-Fi 7[171,172] - all of which have the potential to improve users' experience and meet their demands.[173,174] While this report does not consider in detail the emergence of new services, we note that immersive applications, e.g., in education, transport, healthcare and telework, rely on faster broadband and in-home networks.[175] Wide adoption of such applications may play a role in driving up future demands for faster broadband and in-home connectivity.[176] We also note that there is considerable work on free space optical communications, both in terms of development and standardisation,[177,178] which may become important especially for short-range communications and indoor communications, e.g., Fibre-To-The-Room (FTTR).[179,180]
- We note that the performance of video compression standards has improved considerably over the past three decades, showing great success in improving on the compression efficiency without significant degradation of picture quality, and usable for a wide range of

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[165] Full Fibre UK ISP Hyperoptic Improves Network Testing Tech - ISPreview UK, [accessed on 6 September 2023].

[166] Openreach taps VIAVI to ensure network quality for UK full-fibre build-out | Computer Weekly, [accessed on 6 September 2023].

[167] BT's new lab in Suffolk to work on mole-inspired robots - BBC News, [accessed on 6 September 2023].

[168] National Underground Asset Register (NUAR) - GOV.UK (www.gov.uk), [accessed on 6 September 2023].

[169] Wi-Fi EasyMesh | Wi-Fi Alliance, [accessed on 6 September 2023].

[170] In-Home Wi-Fi Multi-AP Solutions Trial Report - Wireless Broadband Alliance (wballiance.com) , [accessed on 6 September 2023].

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digital applications. There is a balance to be struck between more processing and compression and higher-capacity communications, a balance that will shift as technology advances. Compression standards, led jointly by expert video teams from the International Organisation for Standardisation (ISO) and ITU, have traditionally relied on the same block-based transform coding approach, starting from MPEG-1 (1991) and through to Versatile Video Coding (also called H.266 or MPEG-I Part 3, 2020). Numerous refinements have been applied to the core codec building blocks, where the compression efficiency doubled on average between key standards (e.g., H.264/AVC and HEVC).[181] However, the compression efficiency improvements currently show a slowing trend and further refinement using the traditional hybrid video coding framework based on image and video local correlations, has limited headroom for further improvements.[182] For instance, the test model of the latest standard VVC performed 27% better than the HEVC model (previous generation) for HD sequences and 35% for Ultra-HD sequences, less than the 50% figure.[183] Considering the complexity and growing size of emerging multimedia formats (such as immersive video, point-clouds, light-field video), increased reliance on the infrastructures may be expected and thus more capacity, both in terms of compute and connectivity, will be needed to accommodate future demands.

[181] J-R Ohm, et. al., "Comparison of the Coding Efficiency of Video Coding Standards—Including High Efficiency Video Coding (HEVC)", IEEE Transactions on Circuits and Systems for Video Technology, vol.22, no. 12, December 2012. [accessed on 6 September 2023].
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