# FUTURE OF WIRELESS BROADBAND TECHNOLOGIES

OFCOM

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**Final report**

**Bringing Ingenuity to Life**
paconsulting.com

**Corporate Headquarters**
10 Bressenden Place
London
SW1E 5DN
+44 20 7730 9000

**paconsulting.com**

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# Executive summary

We were appointed by Ofcom to produce an independent report on wireless technology and market developments enabling broadband services, with applicability to the UK market (especially rural and hard-to-reach areas), and to address a number of related questions raised by Ofcom.

Our focus has been to assess relevant technology developments in the near term, whilst also looking forwards with an assessment on key wireless R&D initiatives such as 6G – expected to be commercialised around 2030. Our work has been time-bounded and has consisted of desk-based review of relevant documentation, leverage of our own experience, and industry dialogue with our established network of stakeholders. We cannot guarantee that we have had sight of all information that may be relevant to our purpose and we are not at liberty to disclose all sources. Throughout, we have sought to maintain balance, avoid bias, and report only on the facts as we see them.

We have not reviewed developments in related commercial models, spectrum policy, or full fibre in any detail here, but refer to these as appropriate. In order to provide context, we have included some discussion on the current state of broadband in the UK market today.

We feel that it is timely to review wireless developments. Since the Future Telecoms Infrastructure Review (FTIR) was published in 2018[1], the telecoms industry has developed significantly, with rollout of Gigabit capable full fibre ongoing, and new commercial models now enabled with spectrum sharing and stand alone 5G. We expect a busy year in the wireless sector – with Government's publication of the Wireless 2030 report[2] and the potential for further significant policy developments.

In many ways, and for good reason, the national focus is on Gigabit broadband. But where Gigabit service is not likely to arrive for some time, often the case in rural areas, and where long loop copper lines prevent access to decent broadband, there is interest to explore other options.

New wireless technologies also offer promise for non-rural areas. There is now very significant commercial interest in private and shared access 5G, with applications in both public and private sectors spanning health and social care, smart cities, and enterprises – to name but a few.

The telecoms and technology fields are complex sectors, and a significant amount of misinformation naturally abounds. Application of deep industry experience spanning both commercial and R&D domains is essential if some clarity is to be provided. Further, it is important to know where to look. We have focused particularly on market and technology developments which relate to broadband performance. This has led to us to look particularly at innovations within the radio access network (RAN) (i.e. 'the last mile'), as these are where challenges at the engineering level and with investment cases often lie.

Main findings are set out in the points below:

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[1] See: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/732496/Future_Telecoms_Infrastructure_Review.pdf

[2] See: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1127927/Wireless_2030_Report_PDF.pdf

- From a demand side perspective, within current markets, there is some evidence to show that not all users demand Gigabit services. This is particularly relevant in rural areas where, in some cases, end users may be unable to access even decent broadband, and the wait for full fibre may be excessive.

- In recent years, technology advances in wireless networking equipment have been significant, and Gigabit capable broadband services are now possible with wireless systems operating at both the mid- (C-band) and high millimetre wave bands.

- Whilst fixed wireless access (FWA) technology and operators are established in the market, these remain as niches for rural areas. However, with the commercial development of stand alone (SA) 5G and Terragraph-enabled mesh radio products, there has been a sharp rise in interest in the development of broadband wireless solutions for non-rural areas.

- The economics of the wireless industry are driven strongly by global and regional supply chains, global standards, and volume economies of scale. Whilst the mobile equipment industry is inherently global and at scale, the FWA industry has accessed this scale through leverage of chip-sets from the mobile industry, whilst developing innovative RF product front-ends (using harmonised bands) to attain greater range and capacity suited to fixed premises applications.

- Whilst our focus here is not on spectrum policy, spectrum is an essential element for all wireless systems. There is recognition in the market[3] that spectrum sharing (particularly in the low- and mid-bands) should be supported further, to ensure that finite spectrum resources are used efficiently. Continued use of ever-higher bands, to meet capacity needs, is seen as unsustainable, given the consequent impact on network density levels and associated capital investment levels. This does not mean that higher bands will not be useful, but they should not be seen as the only solution for future wireless broadband.

- Satellite-based systems including so-called new LEOs are continuing to develop. Retail pricing for services using these networks remains around double that of terrestrial broadband systems, and service quality levels can be intermittent. Any potential for price reductions will be contingent on global market take-up, which in our view remains unproven. Recent developments with direct satellite to handset systems using cellular technologies currently are focused on cellular in-fill, and do not support broadband services. HAPS solutions remain commercially unproven with a history of project closures. We continue to see these solutions as under development, not yet fully proven, with some potential for providing broadband connectivity to very hard to reach premises, where terrestrial systems are not feasible.

- The capital cost per connected premises can be significantly lower with point to multipoint (P2MP) FWA networks than full fibre connections in rural areas, but as ever, great care is needed in assessing economic performances, and individual deployment cases will invariably differ.

- There is no ‘magic sauce’ in designing advanced wireless broadband systems: challenges remain with engineering and economics, and performance levels are mainly impacted by digital radio and array antenna designs. Recent vendor reports of extended range operation with millimetre wave FWA systems should be taken cautiously. Whilst ranges can be extended with novel antenna

[3] Based on dialogue with the UK Spectrum Policy Forum, and leading UK academics involved in 6G R&D.

technologies, coverage levels may be no higher if beam widths are reduced. Coverage directly impacts cost per connected premises.

- This means that Gigabit and higher wireless capacity cannot be expected for the whole of the UK landmass, but should be targeted at key regions and vertical segments, according to focused demand and where economic and social benefits will accrue.

- Wireless technologies and issues most relevant to performance in the access network include: 5G-enabled terrestrial FWA, 5G access to new 5G harmonised bands (including low, mid, and higher bands), radio power link budgets, physical layer modulation types and orders, and array antenna processing (advanced MIMO). We expect these technology areas to hold most promise for economically efficient deployment of wireless broadband until 6G technology is launched (expected c. 2030).

- With R&D now started on 5G-Advanced and 6G wireless technologies, further developments can be expected in the above areas, though it must be noted that with additional complexity in radio systems comes additional cost: the challenge to improve on spectral efficiency and radio performance *per unit cost* is increasing. Given that work on 6G technologies remains very much in the research stage, it is premature to predict on outcomes at this stage, and 6G remains currently as more of a conceptual framework with design principles, rather than with firmly defined technologies. Post-2030, we expect that improved wireless broadband performance will be possible, using enhancements to terrestrial FWA technology with new 6G radios and further advances with MIMO antennas.

- Looking forwards, we see main challenges for policy makers and regulators in the wireless sector to include:

  – Maintenance of a technology neutral and pragmatic approach in rolling out broadband services accessible by all in the UK, commensurate with (and not necessarily exceeding) market demand;

  – Ensuring influence to global suppliers and technical standards bodies, in line with UK interests (with some caution as to how open standards may play out in industry);

  – Spectrum management particularly with the sub-6 GHz bands to ensure equitable access across a variety of industry players including satellite, mobile, and fixed wireless operators;

  – Implementation of regulatory price controls which stimulate competition, taking into account the diverse nature and needs of various players in the market;

  – Licensing of spectrum with terms and conditions (e.g. EIRP levels) appropriate to the development of innovative commercial models, efficient services for end users, and fair bets for industry;

  – Continued timely release of radio spectrum appropriate to development of wireless markets, with international harmonisation in accordance with technology standards (including 802.11, 5G, 6G).

# Contents

# 1 Scope and methodology

Our scope is on reviewing market and technology developments associated with the wireless provisioning of broadband services in the UK market.

Such services may be deployed by mobile network operators (MNOs), fixed wireless access (FWA) operators (wireless ISPs, WISPs), satellite operating companies, and others (e.g. new entrants), using a variety of different technologies and commercial models (e.g. established mobile networks, neutral host and wholesale estate, HAPS[4], TV White Space[5], 5G-enabled devices, and hybrid approaches).

We have included assessment on current commercially available and deployed wireless technologies and services, as well as those developing in the near and longer terms (inclusive of 6G – expected to be commercialised around the year 2030).

We have drawn from our own experience in working with investors, operators, and vendors, yielding insight with the current development of MNO-FWA, WISP-FWA (especially in the 3.8-4.2 GHz and 5.8 GHz bands), 5G mobile (with C-band and 26-28 GHz bands), and meshed FWA technologies with commercial deployments. In producing our report, we have augmented this with industry dialogue.

A significant part of technology and market developments lies in the private domain and, as such, we are either not at liberty to disclose at all or by name, or unable to access certain information. Whilst our report includes high quality information and assessments on terrestrial FWA deployments, 5G and 6G R&D, our ability to access detailed information on new satellite and hybrid systems has been more limited[6].

Our main focus has been to assess technology developments enabling wireless broadband services, and to address a number of related questions raised by Ofcom. We have therefore primarily reviewed developments in the wireless networking equipment supply chain (and related system deployments), especially in wireless access systems, with interests on both highly performing equipment currently commercially available in the market, and also on forward technology roadmaps (i.e. direction of R&D with wireless systems).

We have not focused here on developments in related commercial models, broadband policy, spectrum policy, or full fibre in any detail, but refer to these areas as appropriate.

[4] HAPS: High Altitude Platform Systems.
[5] TV White Space (TVWS): Use of unused digital TV bands to support broadband communications.
[6] For example, StarLink, Apple, and Google, were not available for discussion during this work.

# 2 Broadband and the market

## 2.1 Broadband today: the current state

The scale of broadband rollout in the UK is regularly tracked with Ofcom's own Connected Nations reports[7], as well as by other independent sources such as ThinkBroadband[8] – operated by NetConnex Ltd.

The UK broadband market continues to develop at pace, in the main, with significant capital supporting rollout of full fibre in areas offering good commercial returns (i.e. non-rural areas). To ensure rollout of broadband in areas without clear investment cases in the private sector, in 2021 the UK Government introduced its Project Gigabit programme – providing gap funding and vouchers supporting Gigabit broadband rollout covering around 20% of UK premises[9]. As a technology neutral programme, this was introduced to support investment in both full fibre and FWA development (and hybrid architectures), subject to certain specifications being met (see section 2.6).

According to the Connected Nations 2022 report, 16% of UK premises in rural areas are still not able to access broadband at Superfast (30 Mbps) downlink rates or better, increasing to 64% not able to access at Gigabit capable rates. That leaves some 3.8m rural UK premises (around 13% of UK total) still without Gigabit connections.

Very-hard-to reach (VHTR) premises (i.e. those unable to access 'basic' or 'decent' broadband services at 10 Mbps or better) amount to 7% of those in rural areas (around 300k, 1% of UK premises). The volume of VHTR premises in the UK with broadband installation costs exceeding the USO threshold is estimated at around 100k. Ofcom's 2022 Connected Nations Report further estimates that there are around 30,000 UK premises that cannot access a 10 Mbps broadband service, or good 4G mobile coverage (around 0.1% of UK premises).

It is worth noting that 'hard-to reach' is not all about rural consumers, local small businesses, farmers, and the like. There are other important facilities that also reside in remote areas including: nuclear and other power plants, military and security forces bases, maritime and scientific stations, and enterprise infrastructure.

[7] See: https://www.ofcom.org.uk/research-and-data/multi-sector-research/infrastructure-research
[8] See: https://www.thinkbroadband.com/
[9] See: https://www.gov.uk/government/publications/project-gigabit-phase-one-delivery-plan/project-gigabit-phase-one-delivery-plan

## 2.2 Government targets

Government's commitment was to deliver nationwide Gigabit-broadband by 2025. That target was revised in November 2020 to a minimum of 85% of premises by 2025. The Levelling Up White Paper[10] published in February 2022 set a new target: for Gigabit-broadband to be available nationwide by 2030. Nationwide coverage means 'at least 99%' of premises. Government says it remains committed to meet 85% of premises by 2025.

In the Levelling Up White Paper, Government set a target for 'majority' UK population coverage with 5G by 2027, and DCMS (now the Department of Science, Innovation and Technology, DSIT[11]) continues to develop its wireless infrastructure strategy; Government has recently published its Wireless 2030 report[12]. This sets out four alternative scenarios to support policy development: (i) with demand stimulation, (ii) with risk management, (iii) with limitations on rollout, and (iv) with balanced supply and demand. However, population targets are not the same as coverage targets; 5G cellular investment cases are likely to remain challenging in rural areas, risking delays to rollout.

The 'nationwide-by-2030' target therefore puts a timeline for connecting the remaining 15% of premises, which will mostly require public funding support. The 2030 target is considered more realistic by industry stakeholders but the delay from 2025 has been described as a 'blow to rural communities'[13]. Government says the revised targets reflect how quickly industry could build in hard to reach areas requiring public funding alongside their commercial roll-out. The Public Accounts Committee said in January 2022 that it was 'not convinced' that Government was on track to meet its targets and that its approach to Gigabit-broadband roll-out 'risks perpetuating digital inequality across the UK'[14].

## 2.3 Demand and take-up drivers

Demand for broadband varies, according to levels of connectivity in place – driven by the quality of legacy metallic path lines in the local loop; evidence on take-up shows that demand for FTTP access is highest where established broadband services are poor (i.e. propensity to switch from legacy FTTC to new FTTP is higher where legacy connections are at lower data speeds, e.g. below Superfast (30 Mbps) levels).

[10] See: https://www.gov.uk/government/publications/levelling-up-the-united-kingdom
[11] See: https://www.gov.uk/government/organisations/department-for-science-innovation-and-technology
[12] See: https://www.gov.uk/government/publications/wireless-2030
[13] See: https://www.bbc.co.uk/news/technology-55071349
[14] See: https://researchbriefings.files.parliament.uk/documents/CBP-8392/CBP-8392.pdf

Analysis of Ofcom Connected Nations data sets[15] from 2015 onwards has shown the patterns of demand for broadband over time[16]. In the past, where availability of Superfast broadband speeds was low, demand for Superfast services or better was subsequently significant.

As the market continues to move on, demand for Gigabit services and new commercial solutions is growing, driven by ongoing growth in data traffic consumption, new high data volume devices, new use cases, and continued growth in the digital economy and with online services. Video (IPTV) streaming services are a key driver for traffic growth in networks. Other drivers include remote working with digital office technologies (i.e. video conferencing and file sharing), and e-commerce. Online access with sufficient quality is a key enabler for the UK's digital economy.

## 2.4 The move to Gigabit capable services

The case for high quality digital connectivity, whether via wireless or full fibre networks, is well-established, with clear evidence available[17] showing the benefits of digital services for modern service-based economies. The need for access to digital networks and services at acceptable quality levels has been endorsed and proven further with the global pandemic (i.e. with essential home working) and with geopolitical instabilities (i.e. with robust levels of cybersecurity).

In many markets, there has been strong focus on rolling out Gigabit (per second) capable networks, as these are seen as 'future-proof', able to meet the needs of today's markets, whilst also providing good capacity headroom levels to accommodate growth through the next decade. This has been the case in the UK market, where both industry and Government have strongly supported roll-out of Gigabit networks.

However, it is important not be 'blinded' by the 'charm' of Gigabit networks. In areas where users are unable to access decent broadband (e.g. less than 10Mbps), many argue that interim solutions at around Superfast (30Mbps) or near Ultrafast (100Mbps) data speeds are preferable to long waits for Gigabit connections with full fibre. Further, some would argue that the need for Gigabit services is unproven: in residential cases, 4k UHD IPTV services only require around 30Mbps to run without service interruptions[18]. Even with four TVs running per household, that is only around 10% of the capacity of a 1Gbps connection.

As with the Victorian sewers, in building any civil infrastructure with long asset lifetimes, there is a strong case to 'build for the future'. This is important with buried ducts and cables (and sewers). However, radio

[15] See: https://www.ofcom.org.uk/research-and-data/multi-sector-research/infrastructure-research
[16] Credit: Greysky Consulting Ltd.
[17] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0025/113299/economic-broadband-oecd-countries.pdf
[18] See: https://www.cable.co.uk/broadband/guides/broadband-streaming/

equipment installations mounted on towers are more accessible (and have shorter asset lives than ducts and full fibre cables), meaning that they can be periodically upgraded – as demand develops.

## 2.5 Broadband networks

There remains, therefore, an imperative for effective rollout of modern broadband infrastructure, including in rural and hard-to-reach areas, where the investment cases with full fibre typically become very challenging (with long local loop distances and low population densities).

Throughout, we refer to access and backhaul networks, as commonly understood terms within the industry. Access networks connect end users to local network nodes (e.g. telecoms exchanges). Backhaul networks connect local nodes to national trunk networks (see Figure 2-1). Further industry terms are defined in the 'Glossary of terms' section of this report.

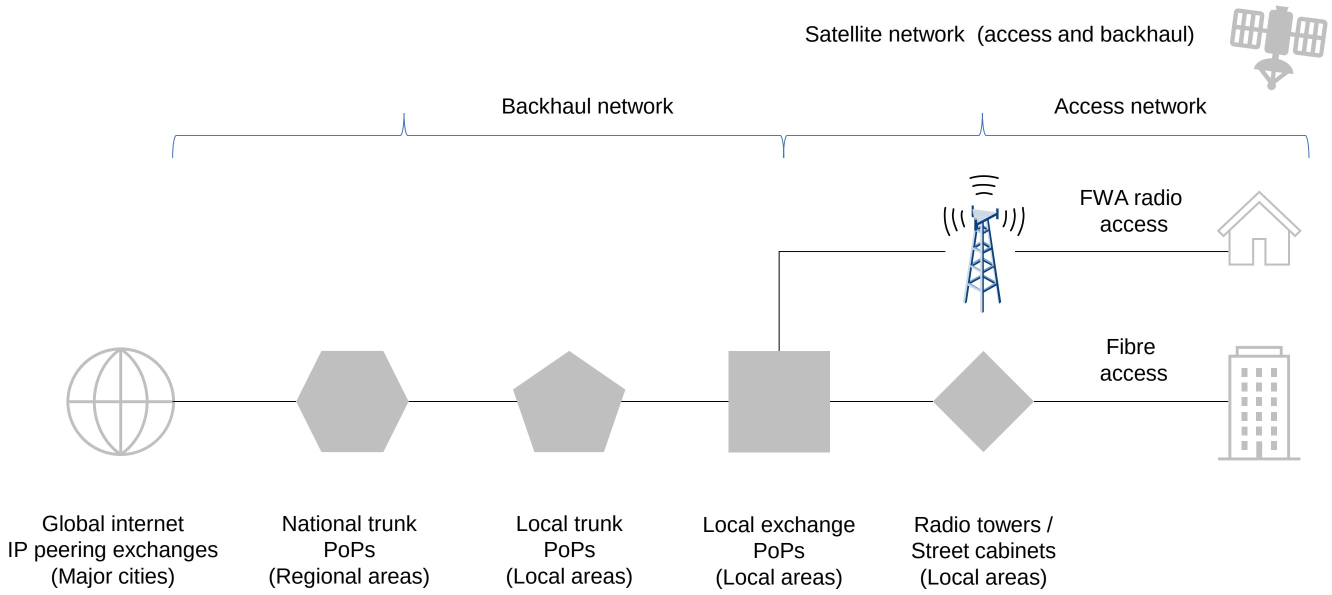


*Figure 2-1: Use of alternative access technologies (fibre and FWA) to provide broadband services.*

Wireless technologies can and are providing attractive solutions for broadband coverage across rural areas (including with gap funding), with potentially lower cost demands on both private and public sector investors.

However, it is wrong to equate full fibre and wireless technologies directly. Expert assessment on engineering designs, service performance levels, and network economics is required.

## 2.6 Broadband performance parameters

The BDUK technical specifications[19] provide a definition for Gigabit capable networks.

Key elements of the specifications include:

- Open access, wholesale requirement: infrastructure shall support all forms of the wholesale access requirements where technically and legally feasible.
- Gigabit capable performance:
  - Download line speed capable of at least 1 Gbps (i.e. peak line speed);
  - Minimum available download speed of 330 Mbps at busy hour;
  - Minimum upload speed of 200 Mbps;
  - Busy hour speed to be available for at least 95% of the busy hour.
  - Data latency: 10 ms and below for 95% of the time.
  - Jitter and packet loss: 2 ms jitter, 0.1% packet loss for 95% of the time.
- No degradation with take-up requirement: data speeds should be maintained as the number of customers connected increases[20].

We have used these specifications as a basis for technology comparisons and with a case study presented in section 4.7.

## 2.7 Recent industry developments

Various recent developments can be expected to have some impact on broadband wireless supply chains. Key developments are addressed below:

- With continued technology innovations (notably, with MU-MIMO, support for high order modulation schemes such as 256QAM, and support for higher bandwidths), FWA equipment is now available

[19] See: https://www.gov.uk/government/publications/project-gigabit-uk-subsidy-advice; dialogue with commercial operators.
[20] Addressable with site upgrades, as traffic demand increase over time.

supporting Gigabit capability[21,22,23,24,25]. We regard this recent development as significant, in that market demands can be addressed with technologies other than full fibre. These innovations are discussed in later sections.

- With Government's Diversification initiative, there have been some developments with open standards networking (i.e. supporting multi-vendor systems), with objectives to improve resilience in vendor supply chains. For example, Vodafone has announced its intent to build open RAN networks in Europe, with a number of trials ongoing[26,27]. Related developments include the move from Dish USA with AWS[28] and Rakuten Japan[29] developing cloud-native core networks (including with partnerships with other operators), which we expect will evolve towards cloud-based RAN solutions. In the UK, Government has supported a number of new initiatives including the SONIC[30] and FRANC[31] programmes, with objectives to support development of open networking standards. However, we remain cautious as to long term developments in this area. Notably, there is presently no work in 3GPP in support of open networking, this being led primarily by the ORAN Alliance[32] and industry groups[33]. Some would argue that in the long term, any de facto open standards will ultimately close down again – if large scale vendors are able to retain control – which is currently the case in 3GPP. It is presently unclear whether open networking will lead to benefits in the wireless equipment supply chain.

- With the move to software-defined networking and stand-alone 5G technology, greater freedom in commercial models is enabled, as local networks can be deployed, and 5G offers greater modularity and flexibility in system designs. There has been significant interest and commercial development in neutral host networks (for example, with BAI Communications and TfL London supporting cellular deployments across the London Underground network[34]; Freshwave with small cell deployments across the City of London[35]; and Wireless Infrastructure Group with commercial interests in hotels and enterprises[36]) – which enable multiple commercial entities to run services over common network estate.

[21] See: Mavenir: https://www.mavenir.com/press-releases/mavenir-introduces-fixed-wireless-access-solution/
[22] See: CableFree: https://www.cablefree.net/
[23] See: Cambium Networks: https://www.cambiumnetworks.com/wp-content/uploads/2018/09/Cambium_Networks_data_sheet_5GHz_PMP_450m.pdf
[24] See: https://www.siklu.com/products/
[25] Examples only. Some product details confidential.
[26] See: https://www.vodafone.com/about-vodafone/what-we-do/technology/open-ran
[27] See: https://www.vodafone.com/news/technology/5g-open-ran-first-uk-site
[28] See: https://aws.amazon.com/blogs/industries/telco-meets-aws-cloud-deploying-dishs-5g-network-in-aws-cloud/
[29] See: https://symphony.rakuten.com/products/open-ran-5g
[30] See: https://www.gov.uk/government/case-studies/smartran-open-network-interoperability-centre-sonic-labs
[31] See: https://www.gov.uk/guidance/future-ran-diversifying-the-5g-supply-chain
[32] See: https://www.o-ran.org/about
[33] E.g. CableLabs; see: https://www.globenewswire.com/en/news-release/2022/03/02/2395563/0/en/CableLabs-named-by-the-US-Department-of-Commerce-as-Host-Lab-for-5G-Challenge.html
[34] See: https://tfl.gov.uk/info-for/business-and-advertisers/creating-a-connected-london
[35] See: https://freshwavegroup.com/case-studies/city-of-london/
[36] See: https://www.wirelessinfrastructure.co.uk/case-studies/the-savoy-hotel-london/

- Neutral hosting in rural areas, as with the mobile SRN[37], may emerge as a useful approach, providing that levels of competition and innovation in the market are not hindered. It must be mentioned that with wireless networks such as FWA, neutral hosting can bring some challenges – sufficient network capacity must be provided for all commercial players, with enough room for growth or scalability.

- Provision for open access is a requirement under Project Gigabit, such that retail competition can be enabled with provision for access over local networks. In practical terms, this requirement is being met in the market with provision for interconnect access and support for customer switching[38]. With all commercial networks (including neutral host based designs), capacity will typically be (and can be) developed according to market demand. Compliance with new regulations on the open access requirement could prove challenging for some altnets, which could mean that some end users may experience delays in accessing competitive broadband services.

## 2.8 Network security and resilience

Consideration of network security and resilience is important, and must be considered within the market as a whole.

Telecommunications networks are now regarded as critical national infrastructure (CNI); there is potential for damage to the UK economy, national security, and critical operations if networks are compromised.

Consequently, Government has taken action with the Diversification initiative and through other means to ensure that digital infrastructure meets security and resilience needs. Key facilities with oversight on security include the UK's National Cyber Security Centre (NCSC) and the newly formed National Telecoms Lab (UKTL, NTL) – operating under the National Physical Lab (NPL).

This has bearing on supply chains associated with wireless broadband network equipment. Not all equipment available in global markets will be of acceptable quality for deployment.

[37] See: https://srn.org.uk/
[38] See: https://www.ispreview.co.uk/index.php/2022/11/broadband-isps-unlikely-to-meet-ofcom-uks-switching-deadline.html

# 3 Wireless broadband networks today

## 3.1 Alternative fixed wireless models

Radio spectrum plays an essential role in the design and performance of wireless networks. Key parameters in wireless networks include the maximum allowable transmit power and carrier frequency (which have bearing on the radio link range and capacity), bandwidth (which also affects the available data capacity), and the radio technology type used (which further affects capacity and range, and hence network cost structure). As with all radio spectrum, there is a level of 'competition' across industry sectors for access to bands, which is managed by national regulators. Key systems which require radio spectrum include satellite links, mobile cellular networks, fixed wireless, and military systems.

There are various cases in which radio spectrum can be used to provide broadband services to end users:

- Mobile network operators (MNOs), as mobile spectrum licence holders, can operate MNO-FWA and mobile network systems (i.e. by using established 4G or 5G networks to provide fixed broadband services)[39,40]. Unless external antennas are used, building attenuation levels will degrade performance levels, and any fixed wireless services deployed using these approaches will share capacity levels with mobile cellular users.

- Alternative network (altnet) operators can resell MNO-FWA or mobile solutions, by purchasing mobile SIMs wholesale from MNOs and selling solutions to altnet customers, putting in place wholesale and retail billing solutions (i.e. MVNO-like model, with no need to build access network infrastructure, or procure radio spectrum licences)[41].

- Altnets and others can build wireless access networks and either procure their own radio spectrum licence (e.g. via light licensing with 5.8 GHz bands, or with shared access bands such as 3.8-4.2 GHz), sub-lease spectrum from a spectrum licence holder[42], or establish commercial infrastructure-only (infrastructure as a service, IaaS) deals with spectrum licence holders (e.g. neutral hosts)[43]. In the case of sub-leasing, operation will be subject to commercial agreements and Ofcom approvals, potentially raising barriers for new entrants. Networks can be operated using wholesale or retail models. As 5G stand alone (SA) technology has now become available commercially, there is now

[39] See: https://telecoms.com/487670/ee-rolls-out-fwa-to-compensate-for-bt-inadequacies/
[40] See: https://www.three.co.uk/store/broadband/home-broadband?intid=3blog_home-broadband-without-wires
[41] For example, see: https://wildanet.com/
[42] For example, see: https://ch4lke.co.uk/
[43] For example, see: https://www.wirelessinfrastructure.co.uk/

significant interest and activity in building 5G SA networks at the regional or enterprise level (i.e. without the need for 4G core and access networks to service network control functions)[44].

## 3.2 Radio spectrum: international situation

Radio spectrum is an essential element of all wireless networks, and there are various bands used and available for FWA systems, with some international harmonisation, either at the ITU or CEPT (and EU) level, and authorisation from Ofcom[45] in the UK, as applicable.

With both mobile and fixed wireless technologies, vendors strive to develop products in internationally harmonised bands. Without harmonisation (i.e. with development for local markets), costs will rise and investment cases will become less viable.

## 3.3 Radio spectrum used with WISP-FWA

As with any equipment supply chain, economies of scale matter; hence where radio spectrum is harmonised for FWA use internationally, cost benefits will arise. Key factors affecting the costs of FWA equipment include: use of high volume chipsets (e.g. 802.11, 4G/5G chips), and operation in harmonised bands. There is reasonable (though not uniform) international harmonisation of technical conditions of use across the bands: 3.8-4.2 GHz, 5.8 GHz, 26-28 GHz, and 60 GHz.

Without scale, business cases become less viable. The 3.8-4.2 GHz (upper n77) band, being used for deployment of private and shared access[46] 5G and FWA networks in the UK represents a smaller market than the n78 C-band which is globally harmonised for use of 5G. This has led to some concerns over supply chains and equipment costs. A recent study[47] has investigated these issues and concluded that most major 5G chip vendors are supporting the full n77 band, although operational factors could still be impacting. As interest in private 5G solutions continues to develop, these issues are expected to become less significant[48].

In the UK, the key radio bands for FWA include:

- 3.8-4.2 GHz: made available by Ofcom through its ‘Wireless Innovation’ Statement[49], of 2019, which affords regional access with the so-called ‘shared access bands’. Operators are required to apply to

[44] For example, see: https://quickline.co.uk/blog/news/uks-first-broadband-provider-to-deliver-5g-sa-cloud-native-open-ran-solution/
[45] See: https://www.ofcom.org.uk/manage-your-licence/radiocommunication-licences
[46] Note: we refer to shared access solutions as those where multiple retail or wholesale services may be operated over actively shared RAN estate; e.g. shared public and private 5G networks over one network.
[47] See: https://uk5g.org/updates/read-articles/upper-band-n77/
[48] Note: The EU has now commenced investigating harmonised technical conditions for deployment across EU and CEPT is working on this at present. This will likely result in an EU harmonisation decision in the coming years.
[49] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0033/157884/enabling-wireless-innovation-through-local-licensing.pdf

Ofcom for licences, which are awarded using a cost-based approach (i.e. nominal fee, to cover Ofcom's management costs), and are available with up to 100 MHz bandwidth and defined transmit power levels. Since licences have been offered, availability of FWA network equipment capable of operating in the band has increased. Gigabit capable links with LOS ranges up to around 10km are possible using FWA equipment operating in this band. Currently, this band is most promising for WISP-FWA deployments (see case study, section 4.7).

- 5.4-5.8 GHz: legacy FWA band, currently available under exemptions and light licensing[50] from Ofcom, and used by many UK WISP operators for deployment of FWA services, typically at Superfast quality levels. This band is not ideally suited for longer distance ranges and Gigabit capable services (due to attenuation levels caused by clutter with buildings and trees).

- 26 GHz: the lower band (24.25-26.5 GHz) is not currently licensed in the UK by Ofcom for outdoor usage, though this is expected to change during 2023. The 24.25-27.5 GHz band is identified internationally as a 5G pioneer band[51], and hence can be expected to be widely licensed in future.

- 60 GHz (57-71 GHz, EHF licences): available under light licensing[52] from Ofcom[53,54] (with nominal fees), supporting Gigabit capable wireless access links, although link ranges are limited. Interest in this band has risen sharply, with equipment becoming available from a number of suppliers (see Appendix 2), and also the Terragraph[55] technology developed by Facebook Connectivity (Meta Platforms Inc).

- 70/80 GHz: the 73.375-75.875 GHz and 83.375-85.875 GHz bands are available in the UK under a light licensed process for point to point fixed wireless applications. Applications include wireless backhaul for cellular, CCTV, and smart city services[56].

## 3.4 Radio spectrum for MNOs and satellite operators

Looking more widely, there is an expectation from MNOs that, with continued growth in traffic, access to sufficient volumes of radio spectrum (in the market as a whole) may become an issue in around 5 years time (depending on levels of growth in mobile data traffic)[57]. This is likely to be driven by greater usage with new types of devices (e.g. within vehicles, new larger screens) and a rise in consumption of digital

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[50] See: https://www.ofcom.org.uk/manage-your-licence/radiocommunication-licences/fixed-wireless-access
[51] See: https://digital-strategy.ec.europa.eu/en/news/european-commission-harmonise-last-pioneer-frequency-band-needed-5g-deployment
[52] Licensing is required in the UK, to meet EMF conditions. See: https://www.ofcom.org.uk/consultations-and-statements/category-2/licence-exemption-licensing-equipment-changes
[53] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0025/203767/spectrum-access-ehf-licence-guidance.pdf
[54] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0018/203652/IR-2106.pdf
[55] See: https://terragraph.com/
[56] See: https://videcomsecurity.co.uk/services-wireless3.php
[57] Based on dialogue with all major UK-based MNOs.

services. In its mobile markets review, Ofcom noted that mitigations could include further densification and use of mmW band spectrum[58].

To meet this increasing demand, and to ensure sustainable financial models, there is an expectation that new commercial models will be required, including: greater use of site and asset sharing. MNOs see access to spectrum bands (especially lower and mid- bands, including lower UHF, 2.3 GHz, 6 GHz) as a means to offset the cost of developing new sites. Millimetre (mmW, or mm Wave) band spectrum is generally seen as less attractive due to the limited ranges possible. To mitigate potential limitations in mobile spectrum in future, MNOs have indicated some interest in release of spectrum in the 600 MHz and 6 GHz bands. This is not to say that no alternatives are possible, but there are economic consequences of moving to ever higher bands.

There are notable challenges in spectrum management:

- National spectrum licences are used for cellular coverage, but spectrum is not used equally in all areas nationally[59]. Often, spectrum can lie unused in some areas; for example, in rural areas where some see no investment cases for the building of new estate.

- Some would argue that the constraint is not physical spectrum but access to capital: in theory, capacity can always be added with finite amounts of spectrum by reducing cell ranges, and with spatial and frequency reuse. However, there are also practical considerations: operators are not typically at liberty to deploy wireless towers freely – practical planning issues at the local level are involved[60].

Thus, economic constraints place limitations on densification of networks, and there is potential to enhance the efficiency of spectrum use in some cases.

With LEO satellite systems, the Ku (12-18 GHz) and Ka (26-40 GHz) bands are preferred, given their ability to support high bandwidths[61], and with less radio clutter on satellite links. The V band (40-75 GHz) is also being considered for use with satellite systems, and is already used in some areas, including the US and UK, for terrestrial FWA.

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[58] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0036/248769/conclusions-mobile-spectrum-demand-and-markets.pdf
[59] Note: Access to mobile bands is possible, but requires commercial agreements and Ofcom approvals.
[60] Note: Deployment of wireless towers and infrastructure typically requires local authority planning approvals, and applications can be time-consuming. See: https://commonslibrary.parliament.uk/research-briefings/cbp-9156/
[61] See: https://www.esa.int/Applications/Telecommunications_Integrated_Applications/Satellite_frequency_bands

A key ongoing issue with spectrum management will be avoidance of interference between terrestrial and satellite-based operators. Satellite spectrum is managed via national regulators and internationally via ITU filings[62].

## 3.5 Established wireless technologies

With the ongoing commercial development of 5G networks and services in many markets, 4G (LTE technology) remains as a major component with many cellular networks today. As cellular technologies have progressed, successive generations have provided improved levels of performance, principally through improvements in digital signal processing and matrix antenna technologies. However, as engineering solutions can give way to improved levels of performance (e.g. with spectral efficiency gains), it is also important to factor in costs: improvements in technical efficiency may have limited benefit if they come with much higher levels of cost. Table 3-1 shows data rate and capacity performance improvements that have been achieved with successive developments of cellular technologies, developed under 3GPP[63].

| Common reference | Technology, 3GPP standard | Functional parameters | Downlink peak channel data rate (Mbps) | Successive capacity performance improvement[64] | Cumulative capacity performance improvement |
|---|---|---|---|---|---|
| 3.5G | HSDPA, 3GPP Rel. 5 | WCDMA, 16-QAM | 14<br>(5 MHz band)[65] | x 1 | x 1 |
| 3.75G | HSPA+, 3GPP Rel. 8 | WCDMA, 64-QAM, 2 x 2 MIMO | 42<br>(5MHz band)[66] | x 3 | x 3 |
| 3.9G | LTE, 3GPP Rel. 8 | OFDM, 64-QAM, 4 x 4 MIMO[67] | 300<br>(20MHz band)[68] | x 1.79 | x 5.37 |
| 4G | LTE-A, 3GPP Rel. 10 | OFDM, 64-QAM, 8 x 8 MIMO | 3000<br>(100 MHz band)[69] | x 2 | x 10.74 |
| **Mean successive capacity performance improvement:** | | | | **x 2.26** | |
| (3G and 4G data shown based on theoretical peak performance levels) | | | | | |

[62] See: https://www.ofcom.org.uk/spectrum/information/satellites-space-science/satellite-filings
[63] See: https://www.3gpp.org/; https://www.etsi.org/committee/3gpp
[64] Provided for guidance only (bandwidth normalised to 5 MHz). Peak channel data rates represent potential maximal rates attainable by one user under 'laboratory conditions'. In practical systems, many users share capacity on a system scheduled basis. Further, practical systems introduce performance degradations, e.g. inter-cell interference, and user capacity is variable according to distance from base station. It is useful however to gain some perspective on the relative levels of performance enhancement across successive systems.
[65] See: http://www.3gpp.org/technologies/keywords-acronyms/99-hspa
[66] See: http://www.3gpp.org/technologies/keywords-acronyms/99-hspa
[67] Includes minimal multi-user (MU) MIMO capability.
[68] See: http://www.3gpp.org/technologies/keywords-acronyms/98-lte
[69] See: http://www.3gpp.org/keywords-acronyms/1612-ue-category

| Common reference | Technology, 3GPP standard | Functional parameters | Downlink peak channel data rate (Mbps) | Successive capacity performance improvement[64] | Cumulative capacity performance improvement |
|---|---|---|---|---|---|
| 5G | 5G NR, Rel. 15 | OFDM, 256-QAM, 2 x 2 MIMO | 1000 (100 MHz band)[70] | Not shown, as not directly comparable | |
| (Practical deployment configuration shown for 5G case, based on vendor data) | | | | | |

*Table 3-1: Successive capacity performance improvement across cellular radio systems (indicative)*[71]

Evolution of cellular and other mass market technologies such as WiFi[72] matters as scale economies are important with supply chains. Leverage of scale is important: standard 4G LTE, 5G NR, and 802.11 WiFi chipsets are typically used in the development of FWA CPEs and network equipment, enabling cost reductions, whilst RF designs are adapted to fit with relevant radio bands and performance needs. With CPEs, standard Internet routers may be modified to allow external antennas to be connected, or dedicated FWA (non-portable) CPE units may be developed.

## 3.6 Legacy FWA

Fixed wireless access (FWA) technology is not new, *per se*. In the UK, the FWA industry is represented by UKWISPA[73], an established industry body, and there are already many network operators using FWA technology to provide broadband Internet and voice services to users.

In many cases, FWA systems employ external antennas at both user premises and radio network hub sites, and radio designs with directional antennas, to provide directional beams and coverage areas well-matched to demand-side needs.

Fixed wireless access services are currently available and operated in the UK, with many service providers operating equipment in the 5 GHz bands (Bands B and C – see Table 3-2), under current permissions granted by Ofcom[74] (see Figure 3-1). Legacy FWA systems have typically employed point to multi-point (P2MP) links, requiring line-of-sight (LOS), or near-LOS designs.

Over one hundred wireless service providers currently offer commercial services of varying scale across the UK; these are often referred to as alternative network (altnet) operators or wireless Internet service providers (WISPs).

[70] Note: practical deployment configuration shown. Note: performance with MU-MIMO and beamforming may be higher; MIMO scales linearly with antenna order, but performance can degrade under field conditions.
[71] Source: PA Consulting analysis.
[72] See: https://standards.ieee.org/ieee/802.11/5536/
[73] See: https://www.ukwispa.org/
[74] See: https://www.ofcom.org.uk/manage-your-licence/radiocommunication-licences/fixed-wireless-access

| Band | Low (MHz) | High (MHz) | Usage | Maximum power level EIRP | Licence requirements |
|---|---|---|---|---|---|
| B<br>(Channels 100 - 140)<br>(255 MHz) | 5470 | 5725 | Indoor and outdoor permitted | 1000 mW<br>(30 dBm) | Licence exempt; compliance with IR 2006[75] required |
| C<br>(Channels 149 - 161)<br>(125 MHz) | 5725 | 5850 | Outdoor (FWA) permitted | 4000 mW<br>(36 dBm) | Licence required; compliance with IR 2007[76] required |

*Table 3-2: 5.8 GHz bands as used by many FWA WISP operators in the UK*

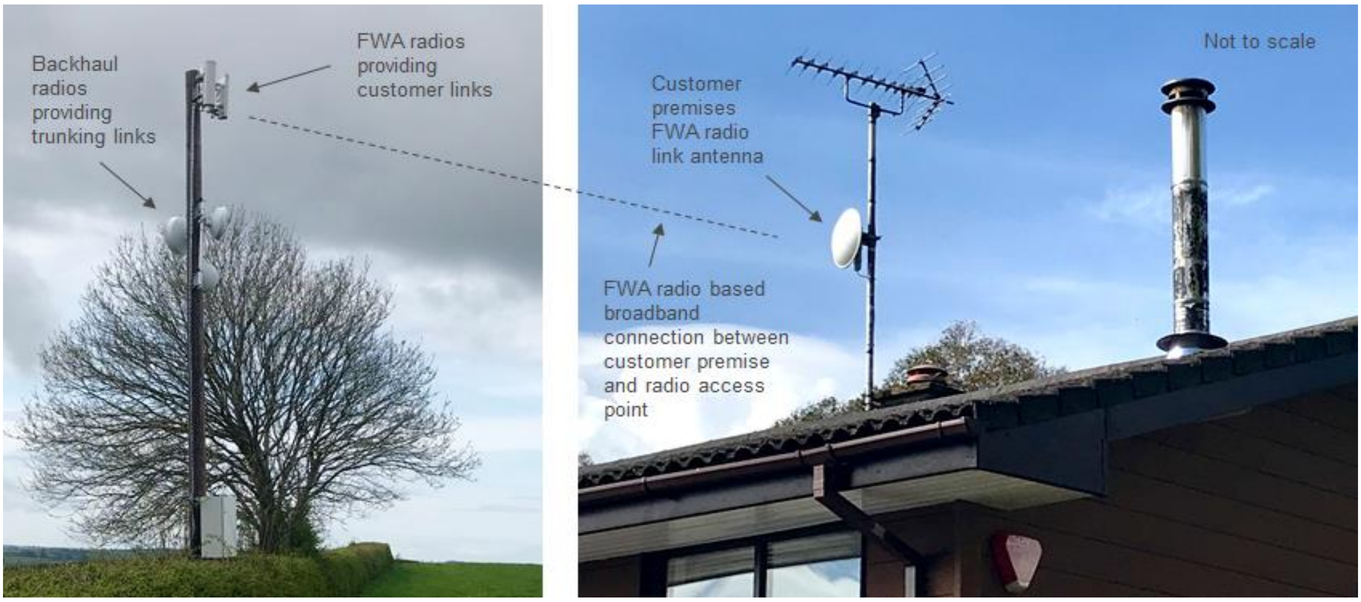


*Figure 3-1: Typical 5.8 GHz FWA installation showing radio access point and customer antenna*

## 3.7 User devices

It is notable that FWA devices are not typically developed by the large mobile device vendors (e.g. Apple, Google, Samsung, others; see Appendix 2). What matters is the cost structure within the supply chain: economies of scale in chipset supply are critical – meaning that wireless vendors tend to follow the 3GPP and IEEE standards at the baseband layer.

Thus, development of new user devices can be expected to be driven by developments in standards from the major global bodies (i.e. 3GPP and IEEE). We expect that improvements in performance with FWA systems will be driven largely by developments in the access network equipment; increases in complexity at the user device level are likely impact investment cases negatively.

[75] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0027/84645/IR_2006.pdf
[76] See: https://www.ofcom.org.uk/manage-your-licence/radiocommunication-licences/fixed-wireless-access

# 4 Novel and emerging technologies

## 4.1 WISP-based P2MP FWA

In the past, broadband services over FWA networks have been possible mainly up to Superfast data rates (i.e. line speed at 30Mbps[77]). However, FWA network equipment performance and pricing levels have improved significantly in recent years, with Gigabit and multi-Gigabit capable services now possible at both C-band and with mmW bands (see section 4.7, and Appendix 2).

In the UK market, FWA networks have typically operated largely in the lightly licensed 5.8 GHz band, according to Ofcom regulations[78] (which stipulate a maximum radio transmit power level of 4 Watts (36 dBm) EIRP[79]). This has meant that under practical conditions, FWA links have needed to attain clear line of sight (LOS) between radio towers and user premises (i.e. without rooftops, buildings or trees obstructions), in order to ensure acceptable levels of services for users over reasonable ranges of several kilometres. With access to the 3.8-4.2 GHz band, FWA solutions can now provide higher service performance levels and higher ranges than with the 5.8 GHz band.

With no need for access cables and ducts, FWA networks are classically seen as advantageous in situations where new trenching, civil works, and cabling prove too costly. This is often the situation in rural areas, where premises' locations can be sparse, and distances between network hubs and premises are large (i.e. several kilometres). At the access network level, point to multi-point (P2MP) FWA solutions are preferable; a high volume of point to point (P2P) radio links serving many customer premises would be impractical (see Figure 4-1).

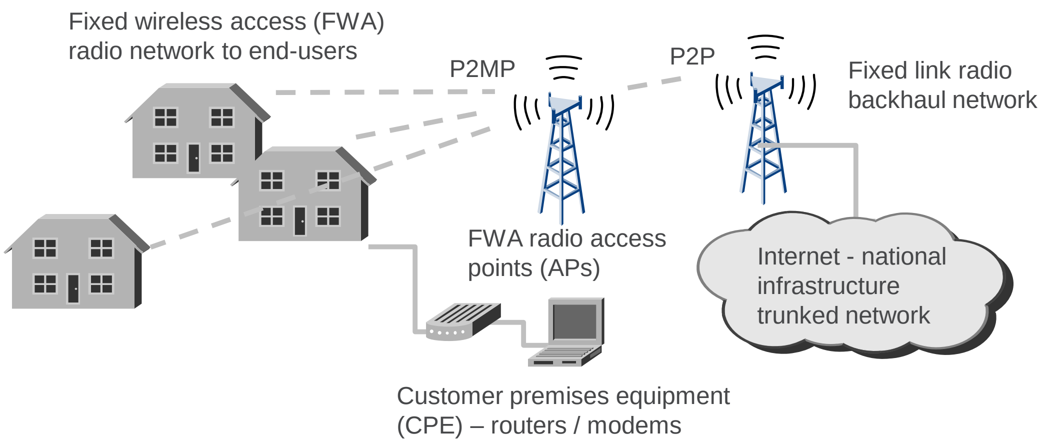


*Figure 4-1: Architecture overview showing point-to-multipoint FWA case*

[77] See: https://researchbriefings.files.parliament.uk/documents/SN06643/SN06643.pdf
[78] See: https://www.ofcom.org.uk/manage-your-licence/radiocommunication-licences/fixed-wireless-access
[79] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0031/84955/IR_2007.pdf

P2P links are relevant for backhaul network connectivity, where the market is well established. Depending on range and carrier frequency band used, P2P radio links can suffer degradation due to weather conditions, but this is mainly in 'difficult' areas (e.g. Northern Scotland, areas with high rainfall), and can be mitigated with effective radio system designs.

Broadly, the main radio bands supported in the FWA P2MP market include:

- sub-6 GHz: particularly relevant for rural areas, with relatively good area coverage capabilities, due to the physical properties of radio transmission in this band;
- 26 and 28 GHz bands: of particular interest for urban areas and mesh networking, with Gigabit requirements (subject to regulatory licences being available); and
- 60 GHz: as with the 26-28 GHz bands (although use of unlicensed bands can lead to poorer performance with inter-system interference).

A list of notable products from leading suppliers in the FWA industry is provided in Appendix 2.

A case study illustrating Gigabit capable P2MP WISP-FWA deployment using the 3.8-4.2 GHz band is provided in section 4.7. Key points drawn from the case study and industry dialogue relating to novel FWA solutions are provided below:

- Leading P2MP FWA products in the market today are capable of supporting Gigabit performance with LOS designs at up to c. 10 km range (3.8-4.2 GHz band, see section 4.7 and Appendix 2).
- Costs per connected premises with FWA network solutions can be lower than with full fibre (FTTP) network designs (see section 4.7).
- FWA networks for rural areas are more economically efficient when lower frequency radio bands (typically below 6 GHz) are used, as radio waves at lower frequencies can travel further distances (see section 4.7).
- The '5G' term is being used rather widely across industry and by the media, to refer to new radio systems. 5G mobile networks are just one type of many wireless technologies. However, 5G *chipsets* are being used in some wireless products such as fixed wireless[80,81].

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80 E.g. CableFree: https://www.cablefree.net/
81 Note: Chipsets used in FWA equipment typically with 3GPP (TS 38 series) or IEEE technologies (802 series).

- Commercial models with mobile networks are typically very different from those with FWA networks (for example, investment decisions on mobile networks will tend to be focused on areas with higher population density). This means that where some investment cases may be rejected as non-viable with mobile networks, valid investment cases could exist with FWA technologies. Note that with a shift in the market towards voice over IP (VOIP), voice calls (e.g. WiFi calling) can be supported over IP data networks.

- The FWA market is established in the UK, but is generally seen as a niche, with many investors and operators now deploying full fibre. We expect FWA deployments in the UK market to remain at a niche level, although commercial interest in private 5G systems at regional and local levels is increasing (e.g. with enterprise deployments[82] and with smart city initiatives[83]).

- However, FWA technology remains important, especially in rural areas – where investment cases with FTTP become infeasible. Capital and operational costs with FWA networks can be significantly lower than with FTTP (see section 4.7).

- FWA technology is continuing to advance, with recent important developments in Gigabit capable radios and mesh technology.

- Many operators continue to deploy FWA and full fibre together in hybrid networks (i.e. those using both fibre and wireless technologies) – to attain best coverage and network economics (e.g. Voneus[84], Boundless[85], Quickline[86], Wildanet[87]).

- Wireless backhaul can be provided either with commodity microwave P2P links, or via in-band solutions using FWA access points. Use of wireless backhaul will depend upon locations of national trunking nodes and network economics – whether leased circuit costs are considered viable in particular investment cases (i.e. case by case)[88]. Key challenges with wireless backhaul will include capacity and range, which ultimately translates to capital or leasing costs. As backhaul ranges increase, there is also likely to be some impact on network latency levels: latency will be impacted principally by technology types and numbers of backhaul legs in the system design[89].

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82 See: https://www.uktech.news/iot/bt-ericsson-private-5g-networks-20220531
83 See: https://www.riversidesunderland.com/news/our-smart-city-sunderland-5g-ready
84 See: https://www.voneus.com/
85 See: https://www.boundlessnetworks.co.uk/
86 See: https://quickline.co.uk/
87 See: https://wildanet.com/
88 Note: Decisions to use fixed or wireless backhaul solutions will involve make or buy decisions and access viabilities: in some cases national trunk circuits will be viable if costs and distances to access networks are acceptable in particular cases. In some cases, investment cases may be more viable for operators if leased circuit costs are avoided with deployments of wireless or fixed infrastructure supported by capital investments.
89 Note: latency levels will be impacted with electrical processing of signals, e.g. via IP routers, opto-electronic conversions, and with IP packet routing. Latency levels will vary by technology types, with vendors and products, and with system designs.

## 4.2 WISP-based meshed FWA

For some environments, so-called millimetre wave (mmW) or extra high frequency (EHF) bands (typically above 20 GHz) can be useful, enabling higher bandwidths and Gigabit capable data rates, but over shorter distances (around 1 km) than typically needed in rural areas. In this case, novel short hop radio networks can be developed with mesh or matrix architectures, providing improved resilience levels.

Mesh networks provide end user connectivity with a radio access design which provides connections from one end user to the next (see Figure 4-2). Backhaul is provided at a number of points across the access mesh. This approach provides enhanced resilience, and greater capacity.

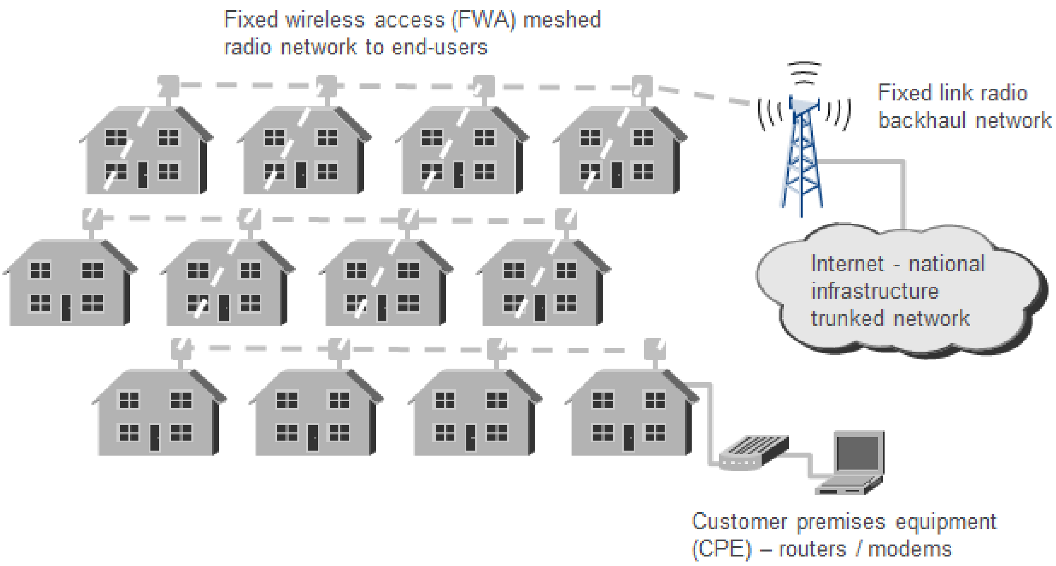


*Figure 4-2: Architecture overview for meshed FWA case*

We do not view mmW meshed Gigabit capable FWA solutions as widely applicable for rural areas, as the geographic density of premises in rural areas is typically much lower than that feasible with mmW band meshes. The radio ranges possible with highly performing mmW FWA systems are typically lower than inter-premises distances in rural areas, and hence meshing is not attractive in these cases. Any use of dense meshing will increase system deployment costs, rendering investment cases challenging. Meshed FWA solutions may be useful in some areas where premises are less sparse[90], but then in such cases FTTP becomes viable anyway.

mmW FWA systems can, however, be useful in non-rural areas. For example in smart city applications, private and shared access 5G FWA solutions can provide a variety of services which are gaining commercial interest. These include: private 5G services as direct competition with full fibre offers; portable broadband services (e.g. for events, market spaces, and students), and with vehicular

[90] For example, see: https://www.ispreview.co.uk/index.php/2023/02/isp-voneus-trial-gigabit-wireless-broadband-in-rural-durham-uk.html

applications (e.g. safety video camera uplinks via local infrastructure such as lamp-posts to local private datacentres) – with potentially lower costs and better qualities of services than with cellular 5G services.

Terragraph[91] is a wireless mesh routing technology[92], which is used in radio mesh systems. Based on the IEEE 802.11ay standard, it is being developed commercially by Facebook Connectivity (Meta Platforms Inc), and a number of equipment vendors including Cambium Networks[93], Siklu[94], and Radwin[95]. Principal innovations include data routing, designed for use with P2MP FWA radio links. Terragraph is not a complete FWA solution but a routing technology. As such it is licensed (i.e. as intellectual property) by its developers to vendors for use in FWA mesh products. Thus Terragraph technology is being developed alongside mesh radio product developments (see Appendix 2).

Fully or partially meshed local networks can be configured, providing multi-Gigabit capacity, extended range and network resilience.

Notably, mmW (26-28 GHz) band 5G and FWA deployments are being commercially deployed in some regions (e.g. US[96], China[97]). In these cases, CPE devices are typically fixed, with applications being focused on indoor and local areas – with radio ranges limited practically to several hundreds of metres per radio node site. The US is one of the most advanced markets in this regard, where mmW spectrum (including the 28 GHz and 39 GHz bands) has been deployed on a commercial scale by mobile operators such as Verizon[98] and AT&T[99]. US-based WeLink[100] is another operator which has been actively rolling out FWA mesh technologies in US markets. It is important to note however, that often what works well in one market may not work well in another: often in US markets there is little choice on Internet access, and new entrants may be welcomed. mmW-based mesh FWA solutions may be attractive in US sub-urban areas with flat terrain, much less so in rural UK locations and areas with large inter-premises distances, hills, and clutter.

## 4.3 MNO-based FWA

Some fixed wireless services are operated by mobile carriers and WISPs[101], using mobile spectrum and wholesale SIMs. Examples include BT's 'unbreakable'[102] WiFi hub (which includes 4G mobile technology

[91] See: https://terragraph.com/
[92] Terragraph is a suite of intellectual property developed by Facebook Connectivity (a division of Meta Platforms), freely licensed to equipment vendors. The technology suite includes: 60GHz radios, mesh routing, MAC & PHY layer designs, cloud management, and network planning elements.
[93] See: https://www.cambiumnetworks.com/
[94] See: https://www.siklu.com/
[95] See: https://radwin.com/
[96] See: https://about.att.com/pages/5g-plus.html
[97] See: https://www.coms-auth.hk/en/licensing/telecommunications/lwbs_private/index.html
[98] See: https://www.fiercewireless.com/5g/verizon-s-5g-mmW-crushing-it-but-for-how-long
[99] See: https://www.fiercewireless.com/5g/at-t-s-5g-strategy-a-little-like-verizon-a-little-like-t-mobile
[100] See: https://welink.com/
[101] WISP: Wireless Internet Service Provider
[102] See: https://www.bt.com/exp/halo

to provide WiFi backup), EE's 4G home broadband[103] (using an external fixed antenna), and Three's 4G/5G home broadband[104] (using an indoor non-portable CPE device).

Such options can provide wireless Internet connectivity, typically at Superfast data speeds, but service quality is compromised as they are not based on products which use radio engineering or installations optimised for fixed links; link distances are limited. Also, from a commercial standpoint, they are reliant on mobile signal coverage; if there is none, with no proven mobile network investment case in region, then no service is possible. This can result in a 'Catch 22' situation in some remote rural areas: broadband service could be accessed with mobile coverage, but mobile coverage is not available due to lack of demand.

FWA solutions using existing low and mid-band mobile networks (i.e. MNO-FWA solutions) are only viable (from a private investment perspective) where there is a valid investment case for mobile sites. In rural areas, such cases may be hard to find, meaning that public subsidy is required – as with the mobile SRN[105].

Where MNO-FWA services are viable, incremental costs to provide service may well be nominal. However, capacity levels may be limited due to mobile user loading, and with most cellular sites in rural areas using 4G or other legacy technologies, services are limited to Superfast levels. Further, with terrain often challenging in rural areas, established coverage levels may be limited. It is likely to be some time before 5G mobile coverage is available in rural areas – unless interventions are applied.

MNO-FWA solutions are not engineered optimally for rural areas (notably, beamforming technology is not easily applied with mobile networks, whereas it can be with static premises-based users). Even with directional CPE antennas, ranges will be limited[106].

It remains to be seen whether MNOs will develop novel services using mmW bands, and this will depend on availability of licences and demand. Any developments will be dependent on support for mmW bands in user devices and customer premises equipment (CPE). Whilst 5G SA network and CPE products are now available commercially from some vendors, supply chains remain under development, with unclear levels of demand and lack of regulatory alignments on band licensing across different markets.

In Europe, 26 GHz spectrum has been made available for new uses in a number of countries (including Germany, Italy and Finland), with more planned for the next few years, though commercial deployments

[103] See: https://newsroom.ee.co.uk/ee-launches-4g-home-broadband-antenna-to-connect-more-than-580000-homes-across-the-uk/
[104] See: https://www.three.co.uk/store/broadband/home-broadband
[105] See: https://srn.org.uk/
[106] With use of low and mid-band spectrum, 4G cell sites typically provide ranges to around 5 km (subject to clutter and obstructions) with reasonable performance. At cell edges, data rates may be much lower than when close to cell sites.

have been limited to date[107]. Whilst Apple iPhones support operation using the 26, 28, and 39 GHz bands in the US market, this is currently not the case in other regions[108]. Development of wireless ecosystems is important in driving take-up: with greater availability of devices comes commonality of use, which ultimately can drive demand up.

What matters for rural areas is coverage (with enough capacity to meet demand). mmW band spectrum does not currently enable reliable Gigabit capable radio link ranges much more than 1 km (even with dedicated FWA equipment, unless narrow P2P-like beams or beamforming are used), rendering investment cases challenging.

BT/EE has recently announced plans for further rollout of 5G-based services, including for rural areas, with a series of technology innovations. These include 4G backhaul via a OneWeb satellite link to a mobile core, mobile connections from HAPS platforms (via links provided by Stratospheric Platforms Ltd[109]), solar and wind powered sites, and biofuel systems. The BT/EE announcement includes a stated objective to provide 5G coverage to the whole of the UK by 2028[110]. It remains to be seen whether these plans will come to fruition; mobile coverage does not necessarily equate to high quality fixed broadband for premises, and it is important to delineate between schemes which seek to advance 4G and 5G mobile coverage, and those that will provide robust high capacity broadband. Further, national coverage objectives come with a hefty cost: BT is on record suggesting that Government gap funding will be welcomed[111]. We also note that OneWeb and HAPS platforms are not yet commercially proven.

## 4.4 Satellite-based systems

Various satellite types exist. We comment briefly on Geostationary Earth Orbit (GEO) and Medium Earth Orbit (MEO) systems, as these are well-established, and focus further below on Low Earth Orbit (LEO) systems.

**GEO systems**

GEO high throughput satellite (HTS) systems have emerged since the turn of this century. By using a large number (approximately 100) of relatively small spot beams, high gain and frequency re-use is provided across the satellite footprint. Flexible beam-steering (where available) allows the satellite capacity to be focused where needed within the field of view.

107 See: https://www.ofcom.org.uk/__data/assets/pdf_file/0027/237258/mmW-spectrum-condoc.pdf
108 See: https://www.apple.com/iphone/cellular/
109 See: https://www.stratosphericplatforms.com/
110 See: https://newsroom.bt.com/ee-announces-5g-expansion-as-part-of-fresh-drive-to-improve-rural-connectivity/
111 See: https://telecoms.com/519825/bt-pledges-cover-the-entirety-of-the-uk-in-5g-by-2028/

Key challenges are complex and costly launches, the need for a large and reasonably complex satellite payload and high power, solar capture, power amplifier, and antenna array technology.

Broadband provided by GEO satellites is available today. It can deliver higher data rate (several 100s Mbps) and is a good solution for hard-to-reach places. However, it comes at the cost of a relatively high service price and higher latencies (several hundreds of milliseconds) (due to the higher orbital altitudes required with GEO satellites).

There are several main operators of interest using GEO high throughput satellite (HTS) systems. These include: UK-based Avanti[112], Eutelsat with its Konnect service[113], and US-based Viasat[114]. These currently offer broadband services via HTS satellites. Further details are provided in Appendix 4.

### MEO satellites

MEO satellites orbit the earth at an altitude above that of a low earth orbit (LEO) satellite and below that of a geostationary earth orbit (GEO) satellite. MEO systems provide a wide range of options to those deploying satellites and strike a balance between the higher costs of higher altitude constellations and the lower coverage of low orbit satellites. Some MEO systems have perfectly circular orbits while others track elliptically, but all track the same orbit continuously once it has been established.

A constellation of multiple MEO satellites is needed for continuous coverage, but the constellation will need fewer satellites than if they were in LEO; many more are needed than with GEO systems, thereby offering a 'middle road' when it comes to cost of construction and deployment. In addition, because they are at lower altitudes than GEO satellites, latency is less.

There is currently only one MEO operator with active services: SES[115]. Services from Methera Global Communications[116] and Mangata Edge Ltd[117] are expected to become available around 2025. Further details are provided in Appendix 4.

### LEO satellites

A LEO system is, as the name suggests, with an orbit that is relatively close to Earth's surface – typically at an altitude of around 1000 km, but could be as low as several hundreds of kilometres. Additional details are provided in Appendix 3.

[112] See: https://www.avanti.space/
[113] See: https://www.eutelsat.com/en/satellite-communication-services/satellite-internet-broadband.html
[114] See: https://www.viasat.com/
[115] See: https://www.ses.com/o3b-mpower
[116] See: https://www.metheraglobal.com/
[117] See: https://www.mangatanetworks.com/

Emerging new LEO satellite systems (i.e. StarLink[118], OneWeb[119] and others) with so-called mega-constellations (i.e. with high volumes of interconnected LEO satellites) have attracted attention recently in connection with broadband deployments. With global constellation coverage and relatively low latency levels, LEOs leverage a business model designed around mass connectivity to rural and developing areas with global scale. Whilst incremental costs of deployment may be low, service pricing and performance levels are ultimately what matter to end-users.

Compared with other satellite types, new LEO satellites offer most promise for broadband service to end users, with relatively low latency levels and near Ultrafast performance, and are most attractive for very hard to reach areas, with clear sky access, and where service affordability at higher levels than with terrestrial systems can be accepted.

One of the major challenges with LEO technology is the dynamic nature of the satellites' orbits, which means that ground stations must include either mechanical or electronic tracking antennas. Even with this, when satellites become obstructed by buildings or natural objects, service can be lost. Best operation is attained with clear sky access. Ofcom has recently conducted tests[120] with StarLink services indicating that on average, users experience downlink data rates at c. 100 Mbps, and uplink rates at c. 14 Mbps. As with any wireless system, actual rates will depend on system loading levels: more users, less data rate per user (unless the system is upgraded as demand increases).

Service pricing for all satellite systems will depend on their ability to attract and retain a global market of sufficient scale. Whilst this remains an open question, there is potential for user service pricing to reduce below current levels if sufficient global market scale can be attained. As with terrestrial wireless systems, once radio coverage is attained, incremental user access can be achieved quickly.

StarLink is currently most advanced in the market with capability of supporting broadband connection services at near Ultrafast or better quality levels. Latency levels with StarLink are around 20-40 ms – similar to those with terrestrial 4G mobile services.  As of December 2022, StarLink was claiming to offer commercial services in 47 countries and had reached more than one million subscribers. The StarLink service is offered 'direct-to-market'.   StarLink services are now claimed to be available across the UK including the highlands and Orkneys.      Retail service costs per user with StarLink are around £100 per month – at least double those of terrestrial wireless broadband services[121].

Unlike StarLink, the OneWeb system remains under development and service is not yet available to consumers (initial service is expected late 2023). It remains to be seen whether OneWeb services will

[118] See: https://www.starlink.com/
[119] See: https://oneweb.net/
[120] See: https://www.ofcom.org.uk/research-and-data/multi-sector-research/infrastructure-research/connected-nations-2022
[121] Any potential reductions in this cost are likely to be driven by the extent to which StarLink is able to develop its market globally.

compete effectively with those from StarLink. OneWeb is, however, expected to offer service at higher latitudes than StarLink. The OneWeb service will not be offered 'direct-to-market'. Instead, it will be retailed to subscribers via resellers or distributors.

An agreement with BT Group[122] is one of several retail distribution deals agreed by OneWeb, with partners also in Alaska[123], Canada[124], Greenland[125] and the wider Arctic area[126], with services also said to be 'coming soon' for the US[127], southern Europe[128], Australia[129] and Middle East[130, 131].

The satellite business is characterised by high capital costs (not to mention a high incidence of bankruptcies) – easily running into billions of dollars per system[132] – driven by costs associated with satellite build and launch, Earth station gateways, and user terminals. Unless large addressable global markets can be found, user service costs are likely to remain relatively high.

**Direct to device LEO satellites**

Novel direct satellite to user systems using mobile terrestrial and satellite radio bands are attracting significant industry interest, but remain at pre-commercial stages, with business models more focused on cellular coverage in-fill than fixed access broadband at Ultrafast or better data rates.

AST SpaceMobile[133] (SM) is a publicly traded satellite designer and manufacturer based in Midland, Texas, United States, founded in 2017. Its BlueWalker 3 satellite is the largest commercial communications array in low Earth orbit. The company is currently building the SpaceMobile satellite constellation, a space-based cellular network that will allow existing, unmodified smartphones to connect to satellites in areas with coverage gaps[134].

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122 See: https://oneweb.net/resources/oneweb-and-bt-sign-agreement-explore-rural-connectivity-solutions-uk-and-beyond
123 See: https://oneweb.net/resources/alaska-communications-expands-connectivity-offerings-low-earth-orbit-satellites
124 See: https://oneweb.net/resources/galaxy-broadband-secures-oneweb-capacity-canada
125 See: https://www.datacenterdynamics.com/en/news/oneweb-signs-connectivity-deal-with-greenland-telco-tusass/
126 See: https://www.worldteleport.org/news/485056/OneWeb-partners-Pacific-Dataport-for-Arctic-connectivity.htm
127 See: https://www.datacenterdynamics.com/en/news/oneweb-signs-agreement-with-att-in-the-us/
128 See: https://www.telespazio.com/en/news-and-stories-detail/-/detail/telespazio-oneweb-europe
129 See: https://oneweb.net/resources/oneweb-and-telstra-target-solving-digital-divide-australia-and-asia-pacific#:~:text=London%2C%20U.K.%2C%202%20March%202022%20-%20OneWeb%2C%20the,and%20the%20Asia%20Pacific%20region%20for%20Telstra%20customers.
130 See: https://oneweb.net/resources/oneweb-and-azyan-telecom-collaborate-provide-connectivity-sultanate-oman-and-middle-east
131 See: https://oneweb.net/resources/neom-tech-digital-holding-company-and-oneweb-sign-200m-jv-satellite-network
132 For example, StarLink costs are reported by SpaceX to be in the region of $10bn. True costs could be higher.
133 See: https://ast-science.com/
134 AST is continuing to develop its constellation of satellites, with launches ongoing; see: https://ast-science.com/2019/04/23/successful-launch-of-first-satellite/

AST's satellites are expected to support 3G, 4G, and 5G cellular communications, with downlink rates expected at around 30 Mbps and latencies at sub-100 ms levels (i.e. '4G-like' performance), not consistent with Ultrafast or higher broadband demands. The AST SM business model is primarily focused on providing cellular service continuity, outside of terrestrial cellular service coverage areas. AST's strategic partners include Vodafone, Rakuten, Telefonica, and AT&T.

The emergence of direct satellite to terrestrial mobile services has been in part driven by the development of new Non-Terrestrial Network (NTN) standards within 3GPP[135].

Historically, satellite systems have been associated with broadcasting and DVB standards. Developments with NTN mark a shift in satellite systems from use of broadcasting technology towards wireless communications.

## 4.5 Hybrid and alternative technologies

It is generally difficult, or at least economically challenging, to design engineering solutions to meet very wide sets of requirements. It is often easier and more cost-efficient to design systems with combinations of technologies to meet mixed levels of demand.

This approach is apparent in the market today, with many broadband providers using a mix of full fibre and FWA in access networks to meet service quality and coverage objectives (see Figure 2-1).

A key issue for consideration in the design of hybrid systems is cost efficiency. Where should one network start and another end? The answer to this question lies in careful design with systems engineering, taking account of network economics.

Typical rollout strategies are designed with clustered deployment of FTTP in more densely populated areas, and FWA 'extensions' to cover areas outside the main FTTP build areas. FWA solutions can also be used to quickly attain market share, with over-build using FTTP at a later date. Wireless solutions can provide wide area coverage, attractive where premises are located sparsely as in rural areas.

In all cases, relative combinations of technologies will vary according to particular operators' designs, markets, and strategic objectives.

Hybrid networks are those where multiple technologies are combined to provide a complete system. However, this definition is too broad: virtually all networks include multiple technologies. Different types of hybrid networks can be defined; we address these further below:

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[135] See: https://www.3gpp.org/news-events/partner-news/ntn-rel17

**Networks using a mix of fibre (largely in the backhaul) and wireless in the access network**

- The main hybrid technology in the market today is with WISP-FWA and full fibre. In future, we expect to see continued development of full fibre to wireless nodes, subject to economic viability.

- With 5G, fibre to mast (FTTM) technology has developed. A key benefit with this is greater freedom in system designs and commercial models. FTTM and 5G technologies enhance the potential for neutral hosted shared FWA networks (because digital backhaul over fibre can be implemented), which could be attractive for rural areas[136].

- As a general rule, with current market conditions, it is fair to summarise as: full fibre in non-rural areas, hybrid fibre-FWA in rural areas, and FWA/satellite with VHTR premises.

**Networks using alternative access technologies**

- Use of the DTT TV bands has been considered for provision of wireless services (so-called TV white space, TVWS, i.e. use of unused DTT bands). We do not regard broadband TVWS as a viable technology for broadband, coming as it does with only limited levels of bandwidth and hence capacity[137]. Further, the TVWS industry has suffered with challenges in equipment costing and competition from mainstream FWA vendors, and operational complexity is relatively high. In short, the TVWS market has failed to develop.

- High altitude platforms (HAPS) technologies have been developed within the R&D domain for decades, but no commercial ventures have succeeded. The technology consists of platforms using balloons or drones which effectively act as wireless 'base stations in the sky' or pseudo-satellites (at altitudes of around 20 km). Practical challenges arise from the movement of platforms, caused by atmospheric drifts or powered motion, which may not be in predictable paths as with space-borne satellites. One of the more notable HAPS programmes has been Google's Project Loon[138], which used balloons with solar power to create an aerial LTE 4G network, with an objective to provide Internet service to rural and developing areas. Project Loon was shut down in 2021, due to lack of commercial success. R&D with HAPS technologies continues[139,140]; it remains to be seen whether the technology will offer any commercially viable solutions.

**Networks combining different technologies for uplink and downlink services**

136 See: https://www.nokia.com/thought-leadership/articles/neutral-hosts-path-to-5G-profitability/
137 See: https://www.nominet.uk/what-is-tv-white-space/
138 See: https://x.company/projects/loon/
139 See: https://www.airbus.com/en/newsroom/press-releases/2022-10-airbus-and-salam-join-forces-for-high-altitude-platform-station
140 See: https://newsroom.bt.com/bt-group-and-spl-look-to-the-stratosphere-to-deliver-4g-and-5g-coverage-to-hard-to-reach-areas-of-the-uk/

- Some providers are developing solutions which combine technologies across uplinks and downlinks. For example, ISP start-up XtndNet[141] is offering a new broadband service with claimed data rates to 50 Mbps. The operator is using Arabsat's BADR-7 high-throughput satellite to provide services on the downlink, with uplink communications running over terrestrial broadband services. Retail products are likely to include data volume caps at around 40 GB, which is modest by today's standards with fixed broadband. It remains to be seen whether the service will be successful[142].

**Networks using channel bonding across technologies to improve service quality levels**

- Aggregation of data channels is an established method, whereby multiple bearer links can be combined to increase data rates for individual users. One such approach is with BT's 'Hybrid Speed Boost' product which combines 4G cellular links with legacy copper line links to provide data rate uplifts over what would be possible with either 4G or copper links only. We regard this very much as an interim solution: for reasons set out above, 4G cellular networks will offer only Superfast rates, and many copper lines in very rural areas are of such long length that xDSL speeds of only several Mbps can be attained. There is also the issue of the copper PSTN switch-off expected c. 2025.

**Networks using fully integrated satellite and terrestrial systems**

- With developments in NTN and 6G still firmly in the R&D domain, we do not expect to see fully integrated terrestrial and satellite technologies until beyond 2030.

## 4.6 Wireless broadband in other markets

There are some differences in the extent to which broadband services have developed with wireless technologies in different markets, but these are largely due to local variations in radio spectrum. In the main, we see a global trend in the development of 5G-enabled FWA. We examine a number of cases below:

- In Europe, there is growing interest in the use of 5G-enabled FWA to accelerate broadband rollout. For example, in Spain, Vodafone has announced plans to launch 5G FWA, although this is initially focused on city areas and leverages existing 5G mobile networks[143]. Vodafone also offers 5G FWA in Italy, Germany, and the UK[144]. This represents MNO-FWA using mobile bands, indoor 5G CPE hubs, and is unlikely to offer optimal solutions for rural areas.

[141] See: https://xtndnet.com/
[142] See: https://www.ispreview.co.uk/index.php/2022/05/xtndnet-reveal-price-of-hybrid-satellite-broadband-for-uk-rural-areas.html
[143] See: https://totaltele.com/vodafone-spain-launching-5g-fwa/
[144] See: https://www.vodafone.co.uk/gigacube/

- In Italy, EOLO[145] is a leading FWA operator (and one of the largest WISPs in Europe), which has, like many UK WISPs, built a business around FWA deployment in the 5 GHz band. The company has used network equipment from Cambium Networks, and is now deploying Intracom's WiBAS[146] P2MP products supporting operation in the mmW (10.5, 26-28, 32 GHz) bands. With high gain antennas (19 dBi hub, 43 dBi user premises), attractive ranges are claimed. However, with such design parameters, coverage areas will be narrower; there is a trade-off between range and beam width in radio systems design.

- Cambium Networks has recently released a multi- Gigabit capable FWA radio (product: ePMP4600) supporting operation in the 6 GHz band (5.925 GHz to 7.125 GHz)[147], based on 802.11ax technology. High capacity is provided by using the entire bandwidth within the radio band. In the US, the FCC is expected to make the 6 GHz frequency band fully available as standard power unlicensed spectrum in 2023.

- In the US, the FWA industry has also grown from initial use of spectrum in the 5 GHz band (with some use also in the 900 MHz, 2.4 GHz, and TVWS bands), with a wave of growth triggered by the release of the CBRS (3.55-3.7 GHz) band in 2020[148]. As with developments in other regions, there is now significant interest in deploying 5G-based FWA equipment. FWA has even caught the attention of AT&T in the US[149]. Ericsson has claims to km ranges with mmW, but this is only possible where direct line of sight (LOS) connectivity can be attained[150]. Some care is needed in the interpretation of these claims: with beamforming and high gain antennas, P2MP links become more like P2P microwave links: good range at the expense of coverage (beam) width. Solutions of this type may be applicable for very-hard-to-reach premises, but if the premises coverage level is very low per FWA site, then cost per connected user increases – essentially defeating the purpose of deployment. With operation at 26 GHz, free space path loss (FSPL) (LOS) increases by around 17dB with range extension from 1km to 7km[151]. Higher gain antennas mean less coverage. Massive MIMO means more cost. There is no 'easy' way around radio physics[152].

- In Australia, Ericsson is also deploying its 5G mmW FWA equipment, again with claims of km range. We advise some caution with these claims; we have not assessed the commercial case associated, but expect that capital cost per connected premises could be challenging. Similar results have been

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145 See: https://wholesale.eolo.it/en/index.html
146 See: https://www.intracom-telecom.com/downloads/pdf/products/wireless_access/wibas.pdf
147 See: https://www.cambiumnetworks.com/blog/cambium-networks-delivers-industrys-first-6-ghz-full-spectrum-solution-expanding-fixed-wireless-broadband-with-gbps-subscriber-speeds-to-cost-effectively-bridge-the-digital-divide/
148 See: https://www.fiercewireless.com/tech/fwa-from-big-carriers-different-than-fwa-from-wisps
149 See: https://www.fiercetelecom.com/telecom/at-t-ceo-eyes-higher-fiber-target-fwa-as-dsl-replacement
150 See: https://www.fiercetelecom.com/telecom/at-t-ceo-eyes-higher-fiber-target-fwa-as-dsl-replacement
151 See: https://www.everythingrf.com/rf-calculators/free-space-path-loss-calculator
152 See: https://www.fiercewireless.com/wireless/fwa-projected-to-grow-dramatically-but-it-still-has-problems

reported with solutions from Samsung[153] and Nokia[154]. It should be noted that if non-stand-alone 5G technology is used, then 4G coverage is required – not always available in rural areas.

## 4.7 Case example: P2MP WISP-FWA system performance

Below, we provide a case example with deployment of a novel Gigabit capable P2MP WISP-FWA network in a rural scenario. The case is based on a commercial deployment using currently available network equipment operating in the 3.8-4.2 GHz band[156]. We have selected a P2MP design as this can offer higher cost efficiency for rural areas than mesh-based radio solutions.

The case is provided to illustrate leading edge system performance levels possible with modern FWA systems. Performance levels, costs, and system dimensions are all inter-related when deploying communications networks.

Key parameters include site range and coverage area, radio beam system capacity, user data throughputs, and costs. In turn, these factors determine the volume of users within a given coverage area that can be supported.

**Case assumptions**

We assume an FWA point to multi-point radio link, with the following parameters:

- Carrier frequency: 5G NR band n77u (TDD), covering the 3.8-4.2 GHz band.
- Channel bandwidth: 100 MHz.
- Tx EIRP: 48 dBm / 100 MHz carrier, in line with Ofcom regulations157.
- 2T2R (2x2 MIMO) (using cross-polarisation via 'one' antenna).
- Receiver sensitivity: -59 dBm158.
- Receiver net front end gain (incl. 14 dBi antenna, 2 dB cable losses): 12 dB.
- Maximum allowable path loss (MAPL): 119 dB.

**System dimensioning and performance**

[153] See: https://www.computerweekly.com/news/252527039/Samsung-claims-5G-mmWave-FWA-milestone-in-Australia
[154] See: https://www.commsupdate.com/articles/2022/10/19/nbn-co-selects-nokias-5g-mmwave-fwa-technology/

With radio beam line of sight (LOS) and minimal obstructions, including design to Fresnel zone limits, between the FWA base station site and the CPE site, free space path loss (FSPL) calculations indicate a maximum available link range of around 5.5km (circular coverage area of 95km$^2$) at the acceptable MAPL[159] of 119dB. Without line of sight, range could be lower. Higher link distances can be possible with higher gain receiver antennas. For an area with c. 20 premises/km$^2$ on average, and Gigabit service penetration at around 75%, this indicates a connectivity demand side requirement at around 15 premises/km$^2$ in the rural case.

Hence, with the specifications set out, each FWA site is able to cover a demand level of 1425 premises. This level of coverage, however, would exceed the site capacity; range is only useful where premises are sparsely distributed, or distant from FWA sites. Site density must also be planned according to capacity throughput demand per user and capacity per FWA site (see below).

In the above range calculations, the receiver sensitivity is a key figure. This determines the minimal radio power level that must be available at the receiver electronics input in order to ensure acceptable link performance – for a given level of modulation order. With capacity calculations, the modulation order is another key parameter, as this determines the available data bit rate (speed) for a given radio channel bandwidth.

We use vendor data which indicates a downlink (base station to CPE) peak throughput capability of 1 Gbps using 256 QAM modulation over a 100 MHz channel bandwidth. This requires a receive signal level (RSL) of -59 dBm or better. 5G TDD operation allows some of the channel bandwidth to be used for uplink (CPE to base station) communication, which according to vendor data used gives an uplink peak speed of just under 200 Mbps (with a symmetric link design). Peak figures accord with all devices in the coverage range, per the designed link budget (peak attainable per device only with a fully unloaded system). When the FWA network becomes loaded with a number of users, the available data rate throughput (data speed) per user in either downlink or uplink is correspondingly reduced, and is dependent on a range of factors including:

- the number of connected users (N) per sector-carrier in a given FWA radio beam;
- the available data throughput as a whole, for the FWA radio beam;
- the scheduling algorithms used, according to the FWA product design and technology type;
- the level of active usage of data sessions amongst connected users;
- a capacity design safety margin factor (+40%), to ensure compliance to the 95% busy hour target[160];

- any oversubscription that is applied in traffic aggregation at the local backhaul level (i.e. to regional or national trunks, via fibre or P2P microwave links);

- the scale of the MIMO / MU-MIMO antenna designs applied in the link design.

With an available FWA sector-carrier link capable of 1 Gbps peak throughout, with the parameters noted, we estimate that N = 20-25 users can be supported per FWA site, with per-user activity at 10% of the time during busy hour ( N = 1000 Mbps / (330 Mbps * 10%) / (1+40%) = 22 connected users ).

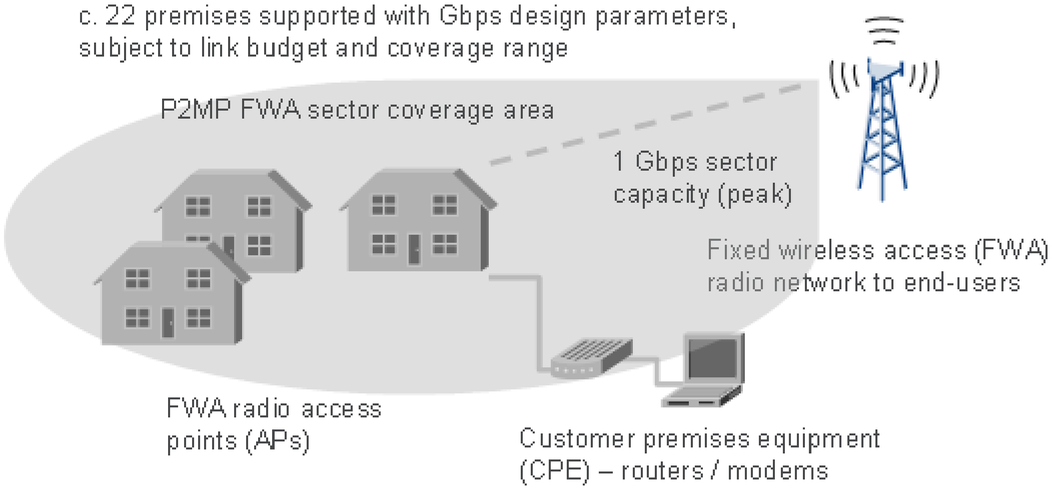


*Figure 4-3: P2MP WISP-FWA architecture showing capacity levels*

With 2 sector-carriers per FWA site (e.g. 180 degrees apart), then 40-50 connected users per site are feasible with this design (subject to available backhaul capacity). This is in line with typical FWA commercial designs (i.e. around 50 customers supported per FWA tower site)[161].

Assuming an available system throughput of 1 Gbps per sector-carrier over a 100 MHz spectrum bandwidth, spectrum efficiency is around 10 bps/Hz[162]. Higher peak throughputs and spectral efficiencies could be possible with shorter ranges between the FWA base station and CPE. Calculations are shown here effectively for 'cell edge' situations (i.e. maximal range for required performance levels).

**Commercial assessment**

Based on dialogue with sub-6 GHz FWA operators, we assume costs as: £250 per CPE unit, and £2.5k per P2MP FWA radio unit (per sector). Hence, with the design parameters as above, capital cost per connected premises (CPCP) is around £100 (radios only, excluding site hardware).

If a complete P2MP FWA site is considered, supporting 2 sectors, additional hardware costs will include: electrical cabling, fibre or P2P radio backhaul, electrical power units and batteries, metal cabinets, mast or pole and fixings, and capitalised installation costs. All of these typically amount to around £15k per FWA site. Hence, CPCP is around £300 (complete FWA site).

CPCP costs for full fibre FTTP installations in rural areas can run into thousands of pounds[163]. Hence, P2MP FWA networks can present commercially attractive solutions in certain cases.

If higher data rates or activity levels are required, then less user premises would be supportable per FWA site. This would drive CPCP costs up. Hence density of premises will be a key factor in driving costs per connected user premises.

Clearly, individual cases will differ. Costs and solution architectures will vary according to technologies deployed and market conditions. The case example is provided to show what is typically possible with rollout using FWA broadband in rural areas. The case shown illustrates cost data for one P2MP FWA Gigabit capable radio site, with 50 premises connected assumed. If additional premises are required to be served, then per-user service levels would be degraded, or additional equipment would need to be installed. For illustration on scale, with the modelled (capacity rather than coverage limited) case, with a rural village with connected premises at 15/km$^2$, over an area of 10km$^2$, at least 3 FWA radio sites would be required (150 premises, 50 per FWA site supported).

# 5 Wireless broadband performance

## 5.1 Performance capabilities

Technology performance levels, including latency, are a function of the technology design including the physical and higher layers in the network. However, data latency in networks is also impacted with conveyance across transport and core networks.

**Data rates** will be affected primarily by radio link budgets, modulation orders, antenna array scale, system loading, contention levels, and digital baseband processing technologies (see below and also section 6).

**Latency** levels are expected to be reduced to sub-10 ms levels with use of 5G New Radio chipsets and also with edge-driven architectures[155,156]. To ensure such low latency levels, edge-based architectures place digital computing and storage functions at the access network level. Non-critical functions can be placed separately, in core and cloud networks which may be physically and logically remote from the edge. Latency is impacted by the physical radio technology and also the network design, with edge (access network) processing being an important driver.

The fastest rate at which humans appear to be able to process incoming visual stimuli is about 13 ms. Human physical responses can be slower than this; for example, in a duel, 100 ms can make all the difference. Hence, 10 ms is a good design threshold; higher levels risk user detection, especially when using streaming, gaming, or other interactive services (see also section 2.6).

Both data rates and latency can be affected by network conditions. With high loading levels, data rates will tend to degrade, and with low quality channels latency may be increased. There is some correlation between these two factors, but not necessarily a causal relationship[157].

**Jitter** is also important in network design – defined as the fluctuation level in packet delays. For acceptable quality in streaming services, jitter should be below 10 ms.

**Packet loss** is another key parameter affecting quality of service, and levels of 2% or higher can cause noticeable impacts with streaming services[158]. Packet loss is driven largely by network congestion, meaning that prevention is with adequate design and dimensioning of networks at a systems architecture

[155] See: https://www.ericsson.com/en/blog/2022/8/who-cares-about-latency-in-5g
[156] See: https://www.t-mobile.com/business/trends-insights/5g/approaching-zero-latency-5g
[157] See: https://www.ericsson.com/en/blog/2022/8/who-cares-about-latency-in-5g
[158] Note: service level impacts with packet loss will vary by service types.

level (including design on contention or over-subscription ratios). Packet loss should be around the 1% level or lower.

## 5.2 Performance comparisons

The table below charts performance with various wireless technologies against baseline performance requirements for Gigabit service. Note: tabulations of technologies and performance levels must always be used with care; performance levels can vary considerably case by case, and according to system designs.

Potential developments with performance are addressed further below and in section 6.

| Performance attribute[159] | Sub-attribute | 5G-based P2MP WISP-FWA[160] | 5G-based Mesh WISP-FWA[161] | 4G-based MNO-FWA[162] | LEO satellite[163] | Baseline Gigabit requirement[164] |
|---|---|---|---|---|---|---|
| Summary (meets Gigabit specification in the main?) | | Yes, but quality may vary[165] | Yes | No | No | -- |
| Data rate | Peak downlink (line speed, uncontended)[166] | 1 Gbps | >=1 Gbps[167] | 300 Mbps[168] | 200 Mbps[169] | 1 Gbps |
| | Downlink rate[170] | 330 Mbps | 330 Mbps | 20 Mbps | 100 Mbps | 330 Mbps |
| | Uplink rate | 200 Mbps | 200 Mbps | 10 Mbps | 14 Mbps | 200 Mbps |
| Latency[171] | | c. 10ms | c. 10ms | c. 30ms | c. 50ms | <10ms |
| Jitter | | c. 5ms | c. 5ms | c. 10ms | c. 30ms | <2ms[172] |
| Packet loss | | c. 1% | c. 1% | c. 3% | c. 1% | 0.1%[173] |

159 Based on figures typically attainable with commercially deployed systems.
160 Based on modern Gigabit capable (5G chipset based) FWA equipment, operating in 3.8-4.2 GHz band.
161 Based on modern Gigabit capable (5G chipset based) FWA equipment, operating in 60 GHz band.
162 Based on 4G LTE-A (Rel. 10) FWA provided by MNOs in areas with existing cellular coverage (with carrier aggregation). (5G mobile coverage is currently not available in many rural areas).
163 Based on StarLink satellite services, currently available.
164 See: Project Gigabit Technical Specifications, and BEREC guidelines on VHCN.
165 Depending on radio design (see case example, section 4.7).
166 Peak rates will vary according to technology and system designs. We quote peak system capacity (i.e. unloaded).
167 Multi-Gigabit data rates possible with mmW bands at bandwidths over 100 MHz.
168 See: https://www.cablefree.net/wirelesstechnology/4glte/lte-ue-category-class-definitions/
169 Based on reported figures.
170 Downlink and uplink rates based on typical commercial system designs, and experienced performance levels.
171 Note: Latency and jitter times will be affected by overall system design, not merely radio or access types.
172 Note: Typical industry target design figures on jitter are around 10 ms.
173 Note: Typical industry target design figures on packet loss are around 1%.

| Performance attribute[159] | Sub-attribute | 5G-based P2MP WISP-FWA[160] | 5G-based Mesh WISP-FWA[161] | 4G-based MNO-FWA[162] | LEO satellite[163] | Baseline Gigabit requirement [164] |
|---|---|---|---|---|---|---|
| Open access support | | Yes | Yes | No | Yes | Yes |
| Range[174] (coverage) | | c. <10 km per radio site | c. <1 km per radio site | N/a | N/a | Not stated |
| Most suitable market application | | Rural | Non-rural | Rural | Rural | Not stated |
| Spectral efficiency (downlink, system level mean, bps/Hz) | | c. 10 bps/Hz | c. 10 bps/Hz | c. 1.5 bps/Hz | c. 4 bps/Hz | Not stated |
| Deployment cost (typical capital cost per connected premises (CPCP) for access network in rural areas) | | Lower than FTTP | N/a | Variable (depends on incremental / new build) | Variable (depending on global business models) | Not stated |
| Energy efficiency[175] | | Variable (potentially higher than with FTTP)[176] | | | | Not stated |
| Sustainability (asset life[177]) | | Lower than with FTTP | | | | Not stated |

*Table 5-1: Typical performance attributes for key technologies, compared with Gigabit requirements.*

## 5.3 Factors affecting performance

Wireless systems are inherently prone to impacts from the environment, with issues such as rain fading, clutter, terrain, and atmospherics being common obstacles. With adequate design using modern software-based radio planning tools[178], designs can be developed which overcome these challenges – at a cost. Radio links are commonly designed by taking into account radio link power budgets, system capacity levels, network contention levels, and transmit-receive Fresnel zones.

Weather-induced fading with radio systems varies by frequency, and starts to become significant with carrier frequencies above 10 GHz[179]. This means that the low (sub-1 GHz) and mid radio bands (Sub-6 GHz) are preferable for rural FWA applications.

[174] Note: Coverage will vary with cost. Data is indicative for Gigabit coverage in rural areas.
[175] See: https://www.prysmiangroup.com/en/insight/telecoms/nexst/new-whitepaper-fibre-the-most-energy-efficient-solution-for-europe-s-bandwidth-needs
[176] See: https://www.ispreview.co.uk/index.php/2020/11/study-finds-full-fibre-is-the-most-energy-efficient-broadband.html
[177] Note: asset life on FTTP solutions typically 20-30 years, vs c. 5 year upgrade paths with FWA.
[178] For example, the WISDM$^{TM}$ software tool, developed by Wireless Coverage Ltd.
[179] See: https://www.cablefree.net/wirelesstechnology/microwave/rain-fade-on-microwave-links/

## 5.4 Technologies for performance improvement

Modern FWA network systems include MU-MIMO[180] technology, which exploits the radio environment to overcoming fading due to natural phenomena[181]. The term 'massive MIMO' is also often used; this generally refers to the use of MU-MIMO technology with a large number of antenna array elements at the radio network node (e.g. 32 elements or more)[182]. With radio system design, technology-enabled gains are offset against radio fades caused by the physical environment. MU-MIMO with OFDM can provide both capacity and coverage enhancements (by virtue of beamforming gain and diversity across time, frequency, and spatial components of the channel), although inclusion of the technology can drive up equipment and operating costs.

The large spectral efficiencies associated with MIMO channels are based on the premise that a rich radio scattering environment provides independent transmission paths from each transmit antenna to each receive antenna[183]. Therefore, for single-user (SU) MIMO systems, a transmission and reception strategy that exploits this structure achieves capacity on approximately min{M,N} separate channels, where M is the number of transmit antennas and N is the number of receive antennas. Thus, theoretically, MIMO capacity scales linearly with min{M,N} relative to a system with just one transmit and one receive antenna. In practice, MIMO systems are designed according to the number of information streams or layers that may be effectively conveyed over the scattering environment; this in turn depends on the correlation properties associated with the system design and the channel matrix.

Multi-user (MU) MIMO technology uses a combination of spatial beamforming and established SU-MIMO techniques to enable spectrally efficient communications at the system level. Under the assumption that the transmitter has perfect CSIT (channel state information at the transmitter), the sum capacity of a MU-MIMO system is scaled by min{M, Nn}, where n is the number of users multiplexed into the MU-MIMO transmission, so that M-fold increase in the sum rate can be obtained as long as Nn is larger than M[184]. For example, in a system with n=5 users co-scheduled, M=16 transmit antennas and N=4 antennas per user device, capacity gain over SISO of 16 is theoretically possible.

However, in practical situations, the benefits are less clear. With directional antenna gain, achieved through beamforming, MU-MIMO systems bring the potential of increased inter-cell interference at cell edges, diminishing overall spectral efficiency gains. Further, MU-MIMO systems require closed loop feedback, meaning that significant control plane capacity resource can be required to enable the MU-

180 Multi-user multi-input multi-output (array antenna systems)
181 E.g. Cambium Networks cnMedusa™ products; See: https://www.cambiumnetworks.com/products/pmp-distribution/5-ghz-pmp-450m-fixed-wireless-access-point/
182 Note: MU-MIMO technology can be used with asymmetric antenna matrices (e.g. 2x2 at CPE, 32x32 at radio network sites).
183 See: Goldsmith, A. et al. 'Capacity Limits of MIMO Channels'. IEEE Journal on Selected Areas in Communications, Vol. 21, No. 5, June 2003.
184 See: Lim, C. et al. 'Recent Trend of Multiuser MIMO in LTE-Advanced'. IEEE Communications Magazine, Volume 51, Issue 3. March 2013.

MIMO system to operate; the performance of MU-MIMO systems is much more sensitive to channel state information (CSI).

The summary point to note is that weather can affect radio systems, and is mostly an issue with microwave P2P links and satellite systems running over km link distances. With sub-6 GHz bands, weather-induced attenuation is relatively low and systems can be effectively designed with adequate fade margin without excessive impacts on costs.

## 5.5 Case example: P2MP FWA link budget

We examine a typical P2MP FWA link budget below, to illustrate the sensitivity in radio designs to fading and link ranges. This example is drawn from current commercial designs, and assumes a deployment with the 3.8-4.2 GHz band.

Fading can occur due to a number of factors, including attenuation with link obstructions such as buildings and trees. Attenuation levels of 10-20 dB per object can result in practical situations, meaning that free space line of sight (LOS) propagation is preferable, with direct impact to network designs and costs.

| FWA link budget | | |
|---|---|---|
| **TX: FWA site** | | |
| TX EIRP | 48 | dBm |
| **RX: user premises and radio link** | | |
| Receiver sensitivity | -59 | dBm |
| **Link gains and losses** | | |
| Scheduler / coding gain | 0 | dB |
| Antenna diversity gain | 0 | dB |
| RX cable losses | 2 | dB |
| RX antenna gain | 14 | dBi |
| RX LNA gain | 0 | dB |
| **Fade margin** | **0** | **dB** |
| **Indoor penetration margin** | **0** | **dB** |
| Net margins | 12 | dB |
| Link allowable path loss | 119 | dB |
| Maximum allowable path loss (MAPL) | 119 | dB |
| Radio link carrier frequency | 3.8 | GHz |
| **Maximum range for radio link** | **5.59** | **km** |

| FWA link budget | | |
|---|---|---|
| **TX: FWA site** | | |
| TX EIRP | 48 | dBm |
| **RX: user premises and radio link** | | |
| Receiver sensitivity | -59 | dBm |
| **Link gains and losses** | | |
| Scheduler / coding gain | 0 | dB |
| Antenna diversity gain | 0 | dB |
| RX cable losses | 2 | dB |
| RX antenna gain | 14 | dBi |
| RX LNA gain | 0 | dB |
| **Fade margin** | **10** | **dB** |
| **Indoor penetration margin** | **0** | **dB** |
| Net margins | 2 | dB |
| Link allowable path loss | 109 | dB |
| Maximum allowable path loss (MAPL) | 109 | dB |
| Radio link carrier frequency | 3.8 | GHz |
| **Maximum range for radio link** | **1.77** | **km** |

*Figure 5-1: FWA radio link budget, based on typical commercial design, showing impact of 10dB fade on range*[185]

The example shows that significant impact to maximum range can result (i.e. several km, in this case reducing range from 5.59 km down to 1.77 km) with fade levels of even several decibels (radio link power, dB).

[185] Corresponding design assumptions: 1 Gbps downlink service, 100 MHz carrier bandwidth; Rx sensitivity neg 59dBm at 256QAM, 2x2 MIMO. Some data vendor confidential.

# 6 Looking ahead: the road to 6G

## 6.1 Drivers and challenges

R&D with 6G technology has now started globally, with significant funding being made available, and technical and commercial drivers are being examined carefully within industry.

It should be noted that 6G development remains at an early stage; no use cases or key features are yet established. Primary focus with 6G is currently around high level design principles, drivers and challenges, and reference architectures.

Below, we list below a number of drivers and challenges associated with rollout of broadband services in rural areas; these represent one area which can be expected to influence development of 6G technologies:

**Technical and commercial factors**

- The UK broadband market has developed as a ‘patchwork’ of full fibre and WISP providers with around 100 players in each camp. At a national level, there are three main players: BT/Openreach, Virgin Media O2, and CityFibre. Some M&A is expected as the market matures. Good levels of innovation exist at the local level, and commercial build is continuing in many rural areas, using hybrid fibre and wireless networks. Regional operation has developed in the market.

- There is clear demand in rural areas for good quality broadband (i.e. Superfast or better) (especially where broadband service is poor – i.e. at USO levels or below), but the demand for Gigabit service is less clear.

- Rollout of both cellular mobile 5G and full fibre to many rural areas is expected to take some time, with challenging investment cases on commercial build, and may not be realised for some years, potentially missing Government targets.

- Commercial development of 5G-enabled private and shared access stand alone networks is increasing at the local level, enabled by availability of licences in the 3.8-4.2 GHz band, and continued developments of equipment in the supply chain.

- mmW solutions are less attractive for rural areas than systems using the sub-6 GHz bands.

- Quality of service and link resilience is invariably higher with use of licensed spectrum. Unlicensed bands are prone to interference.

- Many operators at the local level are small and medium sized businesses, meaning that high costs for access to spectrum do not accord with feasible investment cases.

- The 4G-based SRN and present 4G-based MNO FWA solutions will not provide anything above Superfast broadband for some and not all rural areas.

- Satellite-based broadband solutions are developing, but quality levels remain variable, and retail service pricing is at least around twice that found with WISP-FWA and full fibre solutions (see section 4.4).

**Regulatory issues**

- Uneven use of radio spectrum can lead to market inefficiencies; if radio spectrum is not used by licence holders in local areas, it prevents market access for others who may provide innovative uses. The value of spectrum varies by frequency, geography, and application.

- Access to the mobile bands (under local access licensing) is subject to commercial deals and Ofcom approvals.

- The mmW 5G bands (26-28 GHz) have already been licensed in some countries (e.g. China, Italy) for outdoor use. Equipment for operation in these bands is already commercially available (see Appendix 2).

- Affordable and efficient access, at the local level, to sub-6 GHz spectrum in the mobile or near-mobile bands is key, enabling economies of scale in equipment supply chains to be accessed, and operators to deploy wireless coverage and capacity with reasonable investment cases.

- Continued innovation in the regulation and management of radio spectrum will be crucial, especially in the sub-6 GHz bands, with continued support for spectrum sharing and local access, and development of dynamic shared access (DSA)[186]. Progressive developments to use of ever-higher bands for new wireless systems will not be attractive as a singular solution, as this will lead to the need for increased network density levels, and hence poorer investment cases.

[186] DSA: dynamic allocation of radio spectrum according to dynamic demand requirements.

## 6.2 Developments in technical standards

3GPP and IEEE remain as the major standards developments groups globally, with publications of standards developed at regional levels (e.g. via ETSI In Europe).

Technical standards are an important area in the telecoms and technology sectors, enabling competition to thrive within global and regional markets. Without global or regional scale, costs rise and firms find it difficult to access markets. Thus, proprietary standards tend not to work well within the industry. That said, engineered solutions, with optimised designs using standardised components can work well[187].

The 3GPP technical standards group is continuing its work on 5G[188]; new product developments stemming from Releases 16 and beyond are likely to include: vehicle and transport communications (V2X), 5G-based IOT, support for unlicensed and shared spectrum bands, efficiency improvements, indoor location sensing, carrier aggregation, meshing, private networking, and array antenna enhancements. These all essentially render a more pervasive, flexible, and feature-rich 5G experience for users. Of most relevance for FWA broadband are developments in array antennas.

The 5G system is described in over one thousand 3GPP Technical Reports (TRs) and Technical Specifications (TSs)[189]. 3GPP standards and reports are listed by series on the 3GPP website[190].

The next wave of 3GPP Releases 17 and 18 can be expected to drive 5G product releases through 2025. Within 3GPP, key standards associated with the 5G radio access network and physical layer (i.e. with chipsets) include those developed under the TSG RAN group (i.e. including the 38 series[191]). Within Europe, 5G specifications produced by 3GPP are published by ETSI[192]. 5G RAN standards and technologies have essential bearing on radio performance levels with 5G mobile and FWA systems.

With Releases 17 and 18[193], 3GPP RAN and SA working groups are working on non-terrestrial networks (NTNs), towards support for both terrestrial and satellite-based technologies in user handsets, together with integrated core network architectures[194]. We see this as a significant development, as terrestrial-satellite based communications systems integration is being seen as a major component of 6G.

[187] Note: in some cases this may lead to proprietary designs, but the important point is that standardised elements are vital in the supply chain.
[188] See: https://www.3gpp.org/news-events/partner-news/5ga-5g-advanced
[189] See: https://www.3gpp.org/technologies/5g-system-overview
[190] See: https://www.3gpp.org/specifications-technologies/specifications-by-series
[191] See: https://www.3gpp.org/dynareport?code=38-series.htm
[192] See: https://www.etsi.org/technologies/mobile/5g
[193] See: https://www.3gpp.org/specifications-technologies/releases
[194] See: https://www.3gpp.org/news-events/partner-news/ntn-rel17

Key developments with Releases 17 include spectrum expansion, IOT support, device enhancements, NTN, and topology expansion (incl. V2X, repeaters)[195]. 3GPP Release 17 also includes enhancements relating to higher power use for user devices[196], and enhancements for mmW operation – including 5G operation in the 60 GHz band.

With Release 18 (5G-Advanced) comes work on advanced MIMO, improved mobility management, smart repeaters, TDD duplexing, AI, and energy saving[197]. Key to wireless broadband performance will be developments in MIMO technology[198].

A technology roadmap illustrating key developments expected with 3GPP technical standards is shown in Figure 6-1. Once standards become 'frozen', commercial development of products in industry typically follows in around 12-18 months.

Given the global scale of the telecoms industry, we do not expect 'splinter' standards groups to emerge. It is likely that wireless vendors will continue to leverage 3GPP, IEEE, and possibly emerging open standards.

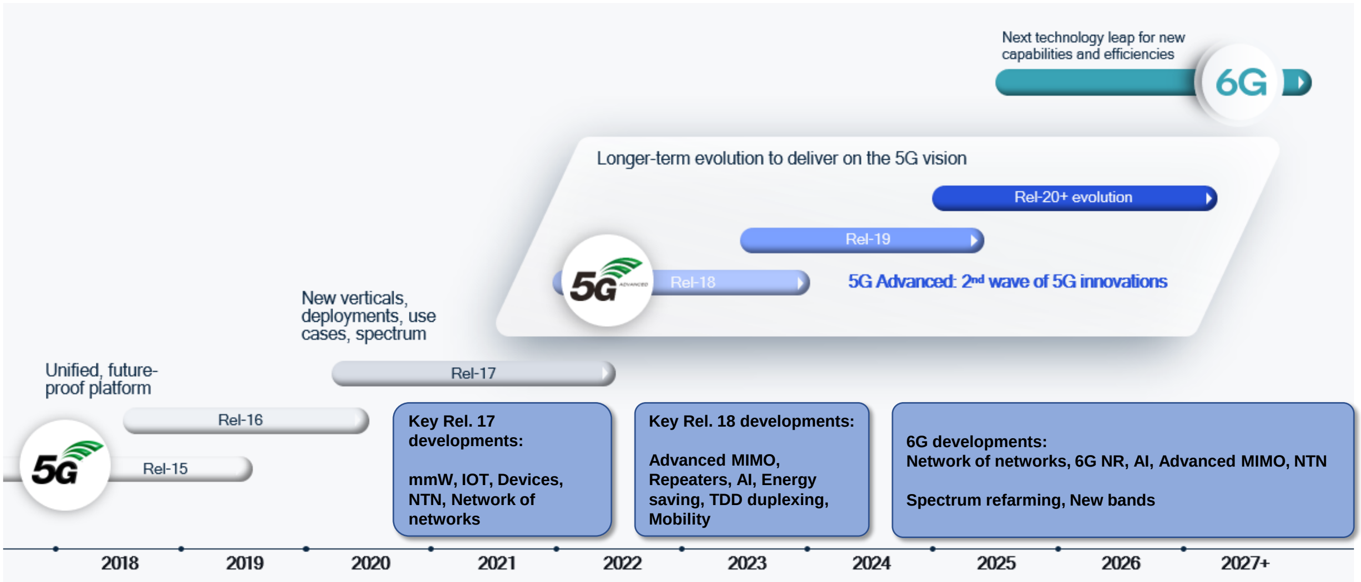


*Figure 6-1: Technology roadmap showing key 5G and 6G developments expected[199]*

195 See: See: https://www.qualcomm.com/news/onq/2022/04/5-key-technology-inventions-5g-nr-release-17
196 See: https://www.3gpp.org/technologies/high-power-ues
197 See: https://www.qualcomm.com/news/onq/2021/12/setting-5g-advanced-evolution
198 See: https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/5g-evolution-toward-5g-advanced; https://www.qualcomm.com/content/dam/qcomm-martech/dm-assets/documents/setting-off-the-5g-advanced-evolution-with-3gpp-release-18.pdf; https://www.3gpp.org/images/PDF/Release_18_features_tsg95_v03.pdf; https://www.nokia.com/about-us/newsroom/articles/5g-advanced-explained/
199 Sources: https://www.3gpp.org/specifications-technologies/releases; https://www.qualcomm.com/news/onq/2022/11/its-2022-and-were-already-thinking-about-the-evolution-of-5g-advanced-to-6g; PA Consulting analysis.

We note also that there is work ongoing within the Broadband Forum (BBF)[200] (industry group) referred to as wireless wireline convergence[201]. This relates to fixed-mobile convergence (FMC) across core networks: an established line of research that has not yet yielded significant impacts, but is relevant to work on 6G. This is not directly relevant to performance levels with wireless access networks. FMC, if it matures, is likely to yield economy of scale benefits with core networks and also provide greater levels of service integration.

3GPP, the Broadband Forum (BBF) and CableLabs have united to create technical reports and specifications defining the services and systems required to support 5G wireless and wireline convergence (5G WWC) architectures. Their resulting work is detailed within BBF's TR-456 (Fixed Mobile Convergence / FMC) and CableLabs WR-TR-5WWC-ARCH and rolled-up within 3GPP Release 16 Technical Specification TS 23.316[202].

Development of WiFi 802.11 technology continues under the IEEE Standards Association[203]. 802.11 technology is being used in current WISP-FWA products, and the technology continues to develop – with recent notable advances with WiFi6 using improved diversity (thus enabling improved performance through reduced intra-system interference)[204]. This is typically beneficial in environments with dense usage and where network orchestration can be managed within a single enterprise.

Work on 6G remains firmly in the R&D domain at present, with no work yet started in the main standards group – 3GPP (expected around 2025).

Reflecting on the these technology developments, most significant areas, in our view, supporting Superfast and higher quality wireless broadband include: continued development of terrestrial FWA within the sub-6 GHz bands (with regional spectrum sharing), increased deployment of 5G and 5G-Advanced systems in existing and new bands (aligned with 3GPP standards, including 26-28 GHz, 60 GHz bands), continued development of 5G-enabled FWA equipment, and advanced MIMO.

## 6.3 Technology performance enablers

Radio performance improvements possible with 5G New Radio technology (relative to a baseline with 4G LTE Release 10) are driven principally by improvements at the physical layer and with antenna scale enhancements. However, as more complex technology is applied to realise technical efficiency gains, cost efficiency levels may be compromised; both must be considered carefully.

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[200] See: https://www.broadband-forum.org/
[201] See: https://wiki.broadband-forum.org/display/BBF/Wireless-Wireline+Convergence
[202] See: https://www.metaswitch.com/knowledge-center/reference/what-is-5g-wireless-wireline-convergence-wwc
[203] See: https://standards.ieee.org/access-standards/
[204] See: https://www.cisco.com/c/en/us/td/docs/wireless/controller/9800/17-7/config-guide/b_wl_17_7_cg/m_bss_coloring_ewlc.pdf

**5G New Radio (NR) Physical layer (PHY)**

The 5G New Radio physical layer improves on the 4G LTE design, essentially with greater flexibility in bandwidth (i.e. from 20 MHz to 100 MHz in low and mid- bands) and support for new radio bands. Significantly, OFDMA technology as deployed in LTE-A is mature in spectral efficiency terms relative to theoretical limits. Spectral efficiency gains possible at the physical modulation level from LTE-A with 5G can be enabled with higher order modulation schemes such as 256-QAM, cell edge performance enhancements, and coding and pulse shaping technologies, though these will not be accessible at all times. Spectral efficiency gains of around 30% are possible with these methods (i.e. with higher modulation order, a higher volume of bits per symbol can be conveyed).

**MIMO antenna systems**

Massive user (MU) MIMO technology advances the MIMO concept still further by adding beamforming, but this adds complexity (i.e. cost). Whilst large scale (e.g. 32x32 elements) MU-MIMO arrays have been deployed, there can be practical problems – including antenna weight and size, cost, and operational complexity. Further, theoretical capacity and coverage gains are often reduced in field deployments, due to practical engineering challenges (e.g. channel state estimation). Spectral efficiency gains of around +70% are typical with 5G NR massive MIMO systems, compared with maximally configured LTE-A solutions.

**Spectral efficiency gains of 5G NR over 4G LTE-Advanced (3GPP Release 10)**

Following from the above (i.e. +30% and +70%, taken together), with higher modulation orders and massive MU-MIMO technology, spectral efficiency gains of around 2-3 times are possible practically when using 5G NR technology over 4G LTE-Advanced Release 10 (at a system (radio cell) averaged level). Higher spectral efficiency levels may be attainable with greater use of directional beamforming.

## 6.4 Developments with 6G

New generations of wireless technology have appeared roughly every ten years since the development of GSM technology in the 1990s. With each new generation, there is a push for higher data rates, which means more spectrum. More spectrum means higher bands, which means less coverage for given cost. Also, the need for mobility varies; users now consume wireless services across a variety of spaces: from indoors, to high speed vehicles. Development on 5G and 6G wireless technology is continuing with recognition that the economics of radio networks are reaching a point of inflexion where new approaches are required[205].

[205] See: https://www.techuk.org/resource/uk-spf-reports-a-key-insight-into-future-spectrum-policy.html

The engineering challenge in designing any one system such as 5G to serve all market segments is increasing: improving spectrum efficiency and coverage without affecting unit costs is getting more difficult. Engineering difficulties also lie in seeking greater spectrum efficiency with wireless systems, especially if the definition includes capital costs, as it should do (i.e. bps/Hz/£).

Therefore, as 5G and 6G continue to develop, a systems approach will be required: wireless capacity levels will need to be related to environments served, radio bands used, and market demands. Practically, this can be expected to evolve with network coverage 'layers' with separate focus on body-worn and indoor areas, urban markets, and wide area non-urban coverage, with very high capacity wireless services increasingly carried over millimetre radio bands such as those at the 26-28 GHz and 60 GHz carrier frequencies. This means that Gigabit and higher wireless capacity cannot be expected for the whole of the UK landmass, but should be targeted at key regions and vertical segments, according to focused demand and where economic and social benefits will accrue.

Increased roll-out of FTTX networks will enable greater deployment of FWA 'last mile' solutions. We see this as an important development, where Gigabit and multi-Gigabit wireless access networks will provide valuable new solutions supporting a range of new market needs such as nomadic and semi-portable access. FWA and FTTX *together* will support the development of pervasive Gigabit connectivity for the whole of the UK.

Consequently, 6G is being developed around a 'network of networks' concept with recognition of the economics and design challenges. This means that different access network technologies may be combined, to provide more seamless connectivity for end users.

With 6G still very much in the R&D phase, it is too early to say how performance levels will differ from those with 5G, or comment on operators' intentions. However, with leverage from industry experience, we comment below on key technologies which can be expected to be relevant for wireless broadband and regulation:

**Spectrum sharing and dynamic access across key bands including: sub-6 GHz, 6-7 GHz[206], 7-15 GHz, 26-28 GHz:**

- Again, the importance of global supply chains and economies of scale must be noted. With the 6-7 GHz band (5.925 GHz – 7.125 GHz), there is currently industry debate as to whether this is allocated to WiFi or 5G technologies. This is essentially a question as to whether the band is further allocated for licensed or unlicensed use[207], which relates to radio resilience. Developments are expected with the next World Radiocommunications Conference WRC-23 in late 2023.

[206] See: https://www.gsma.com/spectrum/resources/6-ghz-for-5g/
[207] See: https://www.ofcom.org.uk/spectrum/spectrum-management/6-ghz

- The 7-15 GHz band is presently used in the UK by a mix of various stakeholders including the Ministry of Defence (MoD), civil radar operators, satellite operators, and others, and is currently subject to debate as to whether it may be reallocated as a 5G extension or 6G band[208]. Additional spectrum at mid-band could be valuable for FWA broadband applications, depending on power levels (attenuation will be significant with radio clutter, as with the 5.8 GHz FWA band).

- The 26-28 GHz band is a 5G harmonised band. Hence, appropriate approaches to authorisation and license conditions are seen as essential.

**Advanced MIMO:**

- To attain greater coverage and capacity levels, MIMO array orders can be increased. With 5G technologies, base station arrays of 32x32 and 64x64 have been developed, but these have proven costly, large, and heavy (with low and mid- bands)[209].

- With MU-MIMO technology, asymmetric arrays can be used, meaning that performance gains can be attained without needing high order arrays at the user device.

- It is presently difficult to see how MIMO technology can be evolved further, without encountering further complexity and cost challenges.

- With FWA and wireless broadband, there is likely to be a 'sweet spot' with each technology generation where performance is optimised when taking into account product costs. With current WISP-FWA technology supporting operation in the sub-6 GHz bands, the MIMO optimum appears currently to be with around 7 radio beams per FWA radio[210].

- Despite industry claims for link ranges at several km with mmW radios[211] (which will be limited by radio power regulations), the benefits of MIMO technology can be questioned with mmW bands, as spatial diversity in the radio channel is more difficult to achieve with attenuation of reflected channels driven by environmental clutter. We have not seen clear evidence that extended ranges of several km are possible practically and commercially with mmW FWA equipment using MIMO and beamforming technology.

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208 See: https://www.ofcom.org.uk/__data/assets/pdf_file/0036/248769/conclusions-mobile-spectrum-demand-and-markets.pdf
209 See: https://futurenetworks.ieee.org/topics/massive-mimo
210 See: https://www.cambiumnetworks.com/wp-content/uploads/2018/06/SP_MU-MIMO_MEDUSA_04042019.pdf
211 See: https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/closing-the-digital-divide-with-mmwave-extended-range-for-fwa

- MIMO technology is generally more attractive when used with lower and mid bands, and hence is relevant for FWA broadband in rural areas, subject to costs and efficiency levels.

**6G new radios**

- 6G new radio: Technology which may be applicable for 6G radios (i.e. physical layer) remains under development. There is even some debate as to whether 6G radios will differ significantly from 5G NR (i.e. using OFDMA). Promising areas of research with potential 6G application include rate splitting and Non-Orthogonal Multiple Access (NOMA)[212]. As these remain under R&D, it is too early to say to what extent they will have impact to commercial deployments and products.

- Non-Orthogonal Multiple Access (NOMA)[213]: Since the development of OFDMA technology, used in 4G and 5G physical layers, and regarded as an attractive technology – due to its ability to mitigate the effects of multipath fading, R&D has continued on new physical layer technologies. NOMA uses advanced channel interference cancelling techniques to 'distil' wanted signals from a non-orthogonal multiplex of transmitted wanted signals. This can yield improved spectral efficiency levels over 5G NR, whilst also meeting low (sub- 10 ms) latency objectives.

- Rate-Splitting Multiple Access (RSMA)[214]: This is another digital technology applicable at the physical layer, seen as promising for 6G radios. RSMA relies on splitting data streams into multiple parts, which are then transmitted over common time-frequency blocks using superposition coding. Receiver decoding is implemented using advanced interference cancelling techniques. Rate splitting combines both NOMA and spatial division multiple access (SDMA).

- Software-Defined Radio (SDR): SDRs are not a new concept[215], and have been in the R&D domain for some decades. Modern radio systems typically employ digital signal processing (DSP) at the baseband level and network products and user devices use digital chipsets to process signals. A key challenge with SDR technology is the move from fixed silicon devices to programmable DSP devices and software – which tend to consume more power and can be slower. Hence, battery life with devices can be a challenge. Once SDR technology becomes mature, it will enable radio spectrum bands to be used more flexibly (e.g. with time variant physical layer technologies).

**Reflective RF surfaces**

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[212] See: https://www.researchgate.net/profile/Jihun-Han-3/publication/339629540_Multiple_Access_Techniques_for_5G_Wireless_Networks_and_Beyond_by_Mojtaba_Vaezi_Zhiguo_Ding_H_Vincent_Poor_z-liborg/links/5e5d3e794585152ce8010115/Multiple-Access-Techniques-for-5G-Wireless-Networks-and-Beyond-by-Mojtaba-Vaezi-Zhiguo-Ding-H-Vincent-Poor-z-liborg.pdf
[213] See: https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9512046
[214] See: https://arxiv.org/pdf/2205.02548.pdf
[215] See: Markus Dillinger, Kambiz Madani, Nancy Alonistioti (2003). Software Defined Radio: Architectures, Systems and Functions. Wiley & Sons. p. xxxiii. ISBN 0-470-85164-3.

- Intelligent Reflecting Surfaces (IRS)[216]: Electrically programmable RF reflectors remain as the subject of much R&D, and can be used to alter the reflection of radio beams, via electrical 'programming', with operation similar to that of a Fresnel lens. IRS technology is not yet proven, and may have limited application in sparse rural environments. Greater application is likely for urban areas where IRS panels can be mounted on buildings (e.g. with urban canyons).

With current research directions, 6G will provide advanced services through combinations of ultra-high definition sensors and devices, edge processing at the local level for very low latency, and high accuracy timing and geolocation functions, with core processing to be taken to new levels of machine intelligence. Over the next decade, network architectures are likely to shift to a mix of FTTX, wireless and satellite links, and cloud-native networking – supported by edge and core datacentres.

## 6.5 International developments in 6G R&D

International harmonisation across technical standards and radio bands is crucial to ensure scale economies. It is also worth noting that given the global scale, UK suppliers will be effective where they are able to influence global standards and R&D (rather than competing directly). With these principles established, they continue to be important in the development of 6G technology.

With 6G R&D, there is a strong level of alignment across key R&D hubs internationally (e.g. UK[217], Finland[218], Japan[219]). We summarise some of the key developments below:

**University of Tokyo, Japan: Professor Akihiro Nakao Labs**

In Japan, the National Institute of Information and Communications Technology (NICT) continues to publish updates on 6G R&D with its series of white papers[220]. The Japanese vision for 6G, supported by Professor Akihiro Nakao of the University of Tokyo[221], and international collaboration (including with Finland and UK universities) sets out a number of R&D areas for 6G, as below.

[216] See: https://www.comsoc.org/publications/best-readings/reconfigurable-intelligent-surfaces
[217] See: https://www.surrey.ac.uk/institute-communication-systems/5g-6g-innovation-centre
[218] See: https://www.6gflagship.com/
[219] See: https://www.nakao-lab.org/
[220] See: https://beyond5g.nict.go.jp/images/download/NICT_B5G6G_WhitePaperEN_v2_0.pdf
[221] See: https://www.nakao-lab.org/

| | |
|---|---|
| T1. Ultra-high-speed and high-capacity wireless communication | |
| T1.1 | Terahertz wave |
| T1.2 | All-optical network (high-capacity optical fiber communication) |
| T1.3 | All-optical network (optical and radio convergence technology) |
| T2. Ultra-low latency and ultra-multi-source connection | |
| T2.1 | Edge computing technology |
| T2.2 | Adaptive wireless network construction technology |
| T2.3 | Adaptive wireless network application technology |
| T2.4 | Autonomous localization, tracking and reservation technologies for radio wave radiation space |
| T2.5 | Autonomous M2M network construction technology with super multi-connection |
| T3. Wired and wireless communication and network control technology | |
| T3.1 | Network control technology (Zero-touch automation) |
| T3.2 | Frequency allocation and sharing management |
| T3.3 | Private wireless system management (Local Beyond 5G) |
| T3.4 | Advanced wireless emulator |
| T4. Multi-Layer wireless systems - NTN | |
| T4.1 | Satellite and non-terrestrial communication platform |
| T4.2 | Optical satellite communication |
| T4.3 | Maritime communication |
| T4.4 | Underwater and submarine communication |
| T4.5 | Cooperative control of multi-layered networks |

| | |
|---|---|
| T5. Space-time synchronization | |
| T5.1 | Wireless Space-Time Synchronization |
| T5.2 | Chip-Scale Atomic Clock |
| T5.3 | Generation and sharing technology for reference time |
| T6. Ultra-security and reliability | |
| T6.1 | Emerging security technology |
| T6.2 | Cyber security technology based on real attack data |
| T6.3 | Quantum cryptography |
| T6.4 | Electromagnetic environmental technology |
| T6.5 | Resilient ICT |
| T6.6 | Sensing |
| T7. Ultra-realistic and Innovative Applications | |
| T7.1 | Brain information reading, visualization, and BMI technology |
| T7.2 | Intuition measurement, transmission and assurance technologies |
| T7.3 | Real 3D avatars, multisensory communication and XR technology |
| T7.4 | AI analytics and dialogue technology using language and extra-linguistic information |
| T7.5 | Edge AI behavioral support |
| T7.6 | Simultaneous multi-lingual interpretation, paraphrase and summarization technology |
| T7.7 | Automated driving |
| T7.8 | Drones |

*Table 6-1: NICT Japan 6G R&D roadmap (source NICT, Japan)*

**University of Oulu, Finland: 6G Flagship**

The 6G Flagship is an initiative driven by the University of Oulu to develop technologies and supporting initiatives relevant to 6G wireless systems.

The 6G Flagship vision[222] for wireless broadband includes ultra high speed networking (up to 1000 Gbps, 1 Tbps) and capability for access at high vehicular speeds.

Key enablers considered include: ultra massive MIMO, active RF reflecting surfaces, cell-free networking (i.e. with active radio beams replacing radio cells), novel baseband processing (including rate splitting and non-orthogonal multiple access (NOMA))[223], and integrated terrestrial and satellite networks.

Open areas of R&D cited within the vision are summarised as below:

[222] See: http://jultika.oulu.fi/files/isbn9789526226798.pdf
[223] See: https://ieeexplore.ieee.org/abstract/document/9348672

| Summary of key open problems | | |
|---|---|---|
| **Challenges** | **Potential 6G solutions** | **Open research topics** |
| Stable service quality in coverage area | User-centric cell-free massive MIMO | Scalable synchronization, control, and resource allocation |
| Coverage improvements | Integration of a spaceborne layer, ultra-massive MIMO from tall towers, intelligent reflecting surfaces | Joint control of space and ground-based APs, real-time control of IRS |
| Extremely wide bandwidths | Sub-THz, VLC | Hardware development and mitigation of impairments |
| Reduced latency | Faster forward error correcting schemes, wider bandwidths | Efficient encoding and decoding algorithms |
| Efficient spectrum utilization | Ultra-massive MIMO, waveform adaptation, interference cancellation | Holographic radio, use-case-based waveforms, full-duplex, rate-splitting |
| Efficient backhaul infrastructure | Integrated access and backhauling | Dynamic resource allocation framework using space and frequency domains |
| Smart radio environment | Intelligent reflecting surfaces | Channel estimation, hardware development, remote control |
| Energy efficiency | Cell-free massive MIMO, suitable modulation techniques | Novel modulation methods with limited hardware complexity |
| Modeling or algorithmic deficiencies in complex and dynamic scenarios | ML-/AI-based model-free, data-driven learning and optimization techniques | End-to-end learning/joint optimization, unsupervised learning for radio resource management |

*Table 6-1: 6G Flagship: 6G R&D roadmap (source: 6G Flagship, Finland)*

## 6.6 UK developments in 6G R&D

Within the UK, leaders in 6G R&D include: University of Surrey, University of Bristol, and University of Strathclyde.

**University of Surrey, UK: 5/6GIC and Project TUDOR**

The University of Surrey (5/6GIC)[224] published its 6G vision in 2021[225], and continues to actively develop 6G R&D with strong levels of industry collaboration. The vision set out a number of key themes for 6G R&D, including: ultra high definition communications, sensing and holistic communications, network integration, satellite and terrestrial systems integration, advanced MIMO, high accuracy timing, and electrically programmable RF reflectors; see below:

[224] See: https://www.surrey.ac.uk/institute-communication-systems/5g-6g-innovation-centre
[225] See: https://www.surrey.ac.uk/sites/default/files/2020-11/6g-wireless-a-new-strategic-vision-paper.pdf

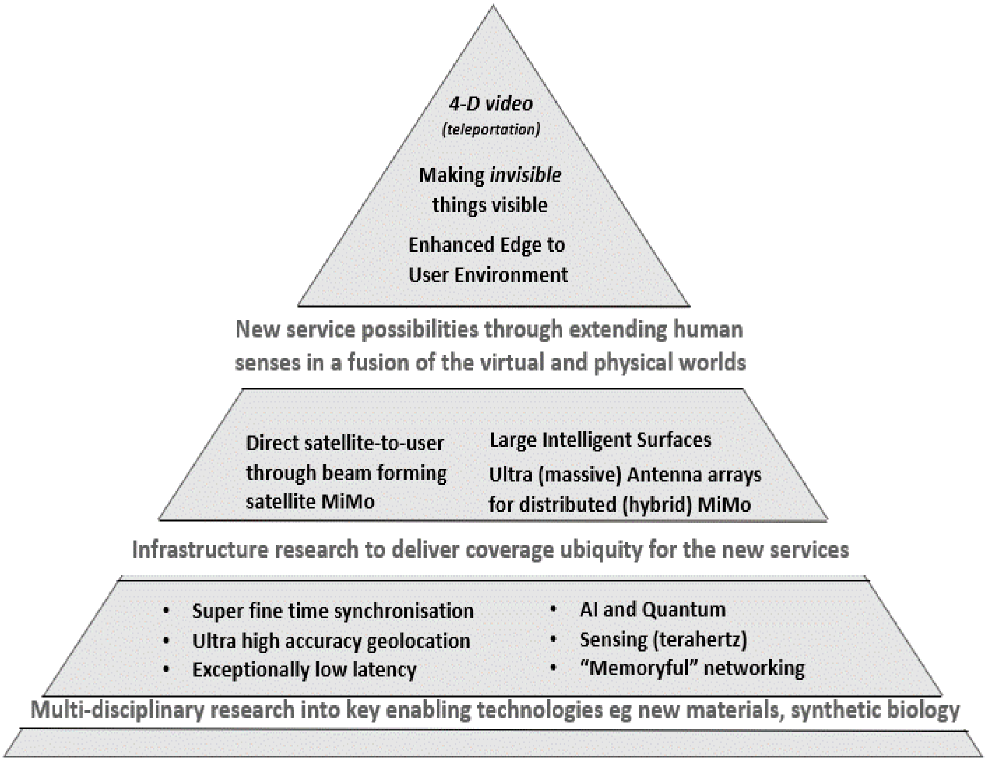


*Table 6-2: 5/6GIC 6G R&D roadmap (source University of Surrey, UK)*

In 2022, The University was successful in securing £12m of additional funding, supported by the UK Government and numerous industry partners, to embark on Project TUDOR[226]. The project includes a number of R&D work areas relevant to 6G. These include: advanced networking and services, 6G radio physical layer, radio resource management, AI for wireless systems, theory and practice with advanced wireless communications, antenna and signal processing, and wireless network security.

## 6.7 International developments in policy and regulation

Below, we review a number of notable developments in policy and regulation at the international level.

- It is worth noting the established German and French models with policy and regulation. In Germany, a part of the 5G C-band has been allocated to allow new entrants to develop services (e.g. private 5G) at the local level[227,228]. This approach was explored within the UK, but dismissed on grounds of ensuring sufficient spectrum for mobile operators[229], with a preferred option for use of the 3.8-4.2 GHz band. Separately, in France, with a different political model, public subsidies are increased within rural areas – allowing infrastructure to be built out somewhat uniformly[230,231].

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[226] See: https://www.surrey.ac.uk/news/surrey-secures-ps12m-research-grant-make-future-telecommunications-network-greener-more-resilient
[227] See: https://digitalregulation.org/spectrum-licensing-local-and-private-networks-in-germany/
[228] See: https://www.gsma.com/spectrum/private-fashion-vertical-set-asides-versus-spectrum-capacity-for-operators/
[229] See: https://www.theiet.org/media/2589/5gff-main.pdf
[230] See: https://digital-strategy.ec.europa.eu/en/policies/broadband-france
[231] See: https://5gobservatory.eu/france-awards-13-private-5g-network-licences-in-3-8-4-0-ghz-band/

- With Neom[232], in Saudi Arabia, provision for dynamic spectrum access (DSA) has been written into the founding telecoms regulations, as a mechanism to strive for innovation and global market leadership. DSA has not, however, been developed commercially as yet.

- In China, local area (i.e. city level) licences have been awarded for local use of the 26-28 GHz mmW and C-band 5G bands, and commercial systems using them are already in operation[233].

- In the USA, the FCC has developed new regulations to support industry in fast-tracked development of new LEO systems[234].

- In Australia, the government-led publicly funded NBN programme is widely regarded as a failure, with budget overruns, delivery dates missed, and billions of dollars now written off. Problems are widely attributed to lack of effective engagement with the market and overly ambitious use of public sector funds without clear accountability[235]. Notably, it was announced late last year that NBN stakeholders are working with Ericsson to extend the footprint of their fixed wireless networks using 5G technology[236], which may be a move to develop connectivity at reduced costs.

## 6.8 Implications for the market

The following potential key developments for the wireless industry are expected over the next decade[237]:

- Increased use of spectrum sharing and local access, enabling new entrants and innovation, leading to enhanced levels of market competition – beneficial for consumers and industry alike[238].

- Development of 5G technology-enabled regional stand alone and neutral host networks (i.e. with active asset sharing, spectrum sharing[239], open access, wholesale, FWA, mobile) networks, enabling new services and revenues, cost synergies, and margin improvements for operators[240].

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232 See: https://www.neom.com/en-us
233 See: https://www.ofca.gov.hk/en/home/index.html
234 See: https://www.federalregister.gov/documents/2020/07/20/2020-12013/streamlining-licensing-procedures-for-small-satellites
235 See: https://www.pc.gov.au/competitive-neutrality/investigations/nbn-co/nbn-co-report18.pdf
236 See: https://www.ericsson.com/en/press-releases/2022/11/major-boost-for-australias-digital-backbone-as-nbn-co-selects-ericsson-for-fixed-wireless-access-network-upgrade
237 Note: many of these areas remain under R&D, or early stage commercial development.
238 For example, see: https://scotland5gcentre.org/rural-5g-solutions-increase-opportunity-for-everyone/
239 Note: dynamic spectrum sharing (DSA) technology is not yet operationally mature.
240 Note: With development of 5G SA technology, there is growing and significant interest in private and shared access 5G networks. Companies active in this field include BAI Communications, Nokia, Ericsson, Wireless Infrastructure Group, and Freshwave. We expect significant growth in this area.

- Development, in the longer term, of DSA[241] supported by AI and database technologies in the core network[242]. DSA technology is available, but has not been implemented widely in practice due to complexity of operations.

- M&A, consolidation, and wastage within the altnet and WISP markets, leading to a smaller number of more significant players, retaining regional interests.

- Development (with 6G) of a 'network of networks' approach, with seamless integration across WiFi, local access, IOT, V2X, 4G, 5G, 6G and satellite-supported services. Any such developments will depend on industry factions' commercial interests and whether technical standards bodies move to increase collaboration and joint working. This concept is not new, but has been held back thus far by competitive interests within industry. It remains to be seen whether it can succeed.

- Reductions in vertical integration in the wireless value system, with potential development of open standards, and increased use of software-defined and cloud-native networking[243] – enabling development of functionally specialised operators (e.g. cloud-based billing operators, RAN only operators[244], and others).

In terms of impact at the local level (e.g. with local FWA models), we view the development of shared asset and shared spectrum models (e.g. with private and shared access regional 5G deployments) as having particular importance in the development of the market.

## 6.9 Implications for regulation

With 5G, and 6G and R&D developments in new radio, there has been considerable interest in the mmW and higher bands. Whilst these bands can offer high bandwidth and therefore capacity, they come 'at a price': with shorter range, cost density is inherently driven up. Terahertz bands will only be useful for very short range communication (e.g. with body-worn devices).

Management of the sub-6 GHz bands will be important, to enable shared access according to local demand levels, with linkage to higher bands via continued support for integrated systems (i.e. 'network of networks' concept). Use of the mmW bands is unlikely to provide an economically effective and affordable solution for pervasive gigabit coverage and as demand develops. This is an important regulatory point: rather than address regional demand via allocation of progressively ever higher bands

241 Note: Nominet Group has been involved in developments in DSA.
242 See: https://www.techuk.org/who-we-are/our-partners/uk-spectrum-policy-forum/uk-spf-cluster-2-spectrum-access-and-sharing.html
243 E.g. as with Rakuten (https://corp.mobile.rakuten.co.jp/english/ ) and Dish / AWS (https://www.dishwireless.com/home ) models.
244 For example, Telnet: https://teletresearch.com/

(leading to economic challenges in the market), with our dialogue with industry stakeholders[245], there is a view that equitable access to the sub-6 GHz bands should be afforded, preserving economic and commercial efficiencies for operators – according to local demand levels.

Looking ahead, ongoing development with the 5G extension and shared access bands (3.8-4.2, 6-7, 7-15 GHz) will also be important. Key issues for regulation in spectrum management include: ensuring fair access to spectrum for all players, and ensuring that spectrum is used efficiently in all areas.

Other changes will arise due to novel technologies including software defined networks, cluster and edge computing, data centre developments, and new 6G technologies.

The UK Spectrum Policy Forum (SPF) has recently reviewed market mechanisms in a key report[246], with a view to establishing a new effective approach to spectrum management. This follows earlier work led by Professor Martin Cave in 2002[247] ('The Cave Report'), which led the industry in setting up spectrum auctions, trading, and incentive pricing. Major recommendations from the new report include: increased use of spectrum sharing – especially in cases where spectrum has potential to be used innovatively; and dynamic spectrum access – supported by database management and new technologies such as AI.

With developments in terrestrial and satellite systems integration, key regulatory issues will include management of bands in both domains to mitigate interference whilst supporting band harmonisation and progressive levels of coexistence.

[245] PA Consulting dialogue with Regius Prof. Rahim Tafazolli.
[246] See: https://www.techuk.org/resource/uk-spf-reports-a-key-insight-into-future-spectrum-policy.html
[247] See: https://publications.parliament.uk/pa/cm200203/cmselect/cmtrdind/128/12802.htm

# Appendix 1: List of industry stakeholders

✂

# Appendix 2: FWA network & CPE suppliers

✂

# Appendix 3: LEO satellite systems

There are currently two LEO operators: StarLink and OneWeb with launched satellites, and two, namely: Kuiper Systems and Telesat, with launches planned.

B2C services are currently only provided by StarLink, though retail partnerships are emerging with other providers.

Summary details are provided below.

**SpaceX StarLink**

StarLink is a LEO satellite Internet constellation operated by the US based SpaceX. As of December 2022, StarLink claimed to have more than 1 million active subscribers receiving satellite Internet access coverage in 45 countries. Current focus is on providing services directly to residential consumers as well as to business and governments, i.e. B2C and B2B service models.

StarLink currently operates over 3000 LEO satellites. These are configured in two phases with a third phase planned for launch starting in 2028. The constellation uses both Ku and Ka spectrum. The Phase 1 constellation comprises 1st generation satellites orbiting at circa 550 km above ground in 4 orbital planes (with 5 inclinations).  Further 1st generation satellites are planned for launch between November 2024 and November 2027.

There are also limited numbers of second generation satellites currently in orbit in three orbital planes.  A further tranche of second generation LEO satellites is planned for launch between December 2028 and December 2031.

The company claims that the current constellation provides near-global reach at latitudes below approximately 60° (the UK Latitude is between 50° (Isle of Scilly/Lands' End and 59° (Orkney Islands)). Based on this, the Shetland Islands would not be fully served as most of the islands lie above 60°. Additional coverage is expected at later dates[248].

StarLink has a unique advantage over other satellite operators in that it has access to the SpaceX Falcon 9 launch rocket. This allows it to subsidise the launch costs by sharing the launch with other organisations and agencies.

[248] See: https://www.starlink.com/map

Between 1970 and 2000, the cost to launch a kilogram to space was estimated to be in the order of $18,500 per kilogram.  In 2019, by using the SpaceX Falcon 9 rocket the cost was just $2,720 per kilogram.

**OneWeb**

OneWeb is a LEO satellite Internet constellation operated by the London-based company OneWeb. OneWeb was originally formed by the staff from O3B Networks in 2012. Since formation it has gone through a number of changes in ownership.

OneWeb Global Limited filed for bankruptcy in March 2020. In July 2020, a consortium led by Bharti Global and the Government of the United Kingdom won the auction to purchase the bankrupt company allowing the company to exit Chapter 11 bankruptcy.

In December 2020, OneWeb resumed launching satellites including planned launches aboard the Soyuz rocket. These launches were rescheduled to use SpaceX and New Space India following the Russian invasion of Ukraine and the resulting sanctions.

On 26 July 2022, Eutelsat announced a merger with LEO satellite internet operator OneWeb[249].

As of November 2022, the OneWeb constellation comprised over 500 satellites. OneWeb does not offer services directly to residential consumers. Instead the company is focused on a B2B service model providing services to key market sectors as: Land Mobility, Carrier and Enterprise, Government, Maritime, Aviation.

**Kuiper Systems**

Kuiper Systems LLC is a US-based subsidiary of Amazon that was set up in 2019 to deploy a large broadband satellite Internet constellation to provide broadband Internet connectivity.

The deployment is also referred to by its project name ‘Project Kuiper’.

Amazon has signed launch contracts with three launch service providers for a total of 91 launches over the next decade in order to build out a constellation of up to 3,276 satellites.

Two initial prototype satellites ‘KuiperSat-1’ and ‘KuiperSat-2’ are expected to be launched in 2023. The constellation, expected to comprise Ka band satellites, will operate in 98 orbital planes in three orbital

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[249] See: https://www.eutelsat.com/en/news/press.html#/pressreleases/eutelsat-and-oneweb-to-combine-a-leap-forward-in-satellite-connectivity-3195697

shells, one each at 590 km, 610 km, and 630 km, and is expected to be served by a network of 12 satellite ground stations.

Although Amazon claims that the Kuiper satellite constellation will be ‘capable of providing reliable, affordable broadband service to unserved and underserved communities’ around the world, is it presently not clear if retail services will be provided.

**Telesat**

Telesat is a Canadian-based satellite operator with an existing fleet of 13 GEO satellites. The firm is understood to be developing both high throughput GEO satellites and a new LEO constellation: Telesat Lightspeed.

The first demonstration LEO satellite was launched January 2018, and this has been used to support live demonstrations across a variety of markets and applications. This included a demonstration of 5G backhaul over LEO satellites in partnership with Vodafone UK.

Telesat received approval for an initial 100 plus satellites but have advised that the Telesat business plan is largely based around 300 satellites with the system designed to scale to c. 500.

**AST SpaceMobile**

The company launched a small test satellite called BlueWalker 1 in 2019 to validate its satellite-to-cellular architecture. The company advised that the spacecraft successfully managed communications delays from low Earth orbit and the effects of doppler in a satellite-to-ground cellular environment using the 4G-LTE protocol.

In 2022, AST SpaceMobile successfully launched its BlueWalker 3 satellite, the largest commercial communications array in low Earth orbit at an altitude of between 508 and 527 km. BlueWalker 3’s 693-square-foot antenna array of was successfully deployed to support a view of over 300,000 square miles.

**Lynk**

Lynk Global is a company developing a satellite-to-mobile-phone satellite constellation that aims to provide a "cell tower in space" capability for global mobile phone service coverage, including in underserved rural areas without cellular coverage.

Lynk has requested a license from the US Federal Communications Commission to launch up to ten test satellites, with the goal to begin continuous global coverage in 2025 using a constellation of several thousand satellites.

According to the company their satellite mobile technology is capable of connecting to standard mobile phone terminals from satellites in orbit at 500 km altitude using software-designed radios that can move between slower, but still viable, 2G and 4G speeds for the mobile network operators it is trying to attract as customers.

Lynk technology connects to mobile phones on the ground in a way similar to roaming networks, where the satellite mobile service will connect to another available cellular network when outside the range of its home network. To accomplish this, Lynk needs to work through the various geographically dispersed, and often country-specific, mobile network operators in any area of the world in which the service is to be available.

# Appendix 4: GEO and MEO satellite systems

**Avanti**

Avanti is a UK-based satellite operator, selling wholesale satellite broadband and satellite connectivity services to Internet service providers, mobile network operators, enterprises, governments and other satellite operators.

The company does not offer services directly to residential consumers. Services to this market sector are offered via resellers hence maintaining a B2B service model.

Avanti operates a constellation of 5 high-throughput geostationary satellites (HTGS) covering EMEA. These satellites use a range of fixed and steerable beams in the Ka band. The latest satellite HYLAS 4 was launched in April 2018 to double capacity over EMEA. It has 64 fixed beams serving Africa and Europe, as well as four independent steerable beams. The constellation is supported by a resilient and secure ground network comprising 7 earth stations strategically located across EMEA, an international fibre ring and a cross-connected fibre network. Close to being bankrupt in 2018, Avanti restructured its debt, changed focus towards larger customers, and focused on three key markets:

- Carriers. Mobile backhaul solutions to carriers.
- Government. Provision of satellite communications services to US and global government agencies. This includes a wide range of defence and security applications.
- Satellite industry. Provision of wholesale capacity to other satellite operators and service providers.

Avanti have identified rural connectivity as a growth market as described in their rural connectivity white paper[250]. This states that: it is common for areas with isolated and sparse populations, with low levels of traffic, to be ignored because of the heavy investment involved in deploying terrestrial infrastructure. Avanti claims that by working with mobile network operators (MNO) across Europe, Middle East and Africa they can deploy cost-effective solutions to provide reliable Internet access to under-served populations.

Working with mobile network operators also saw Avanti provide a satellite backhaul solution to approximately 1000 fixed and portable EE base stations across the UK.

[250] See: https://www.avanti.space/wp-content/uploads/2020/09/Rural-Connectivity_White-Paper_Avanti-Communications.pdf

The reseller Freedomsat uses the Avanti Satellite Broadband service to deliver fast rural broadband Internet across the UK, Ireland, and Europe. Typical retail pricing for the Avanti-based broadband services are detailed below.

| Internet plan | Price (GBP per month) | Download speed (Mbps) | Data limit (GB per month) |
|---|---|---|---|
| Consumer | £ 17.50 | <= 15 | 5 |
| Consumer | £ 22.50 | <= 15 | 10 |
| Consumer | £ 29.50 | <= 15 | 20 |
| Consumer | £ 41.00 | <= 15 | 30 |
| Consumer | £ 56.50 | <= 15 | 50 |
| Consumer | £ 94.50 | <= 15 | 100 |
| Consumer | £ 139.50 | <= 15 | 150 |
| Superfast Broadband | £ 29.50 | <= 30 | 10 |
| Superfast Broadband | £ 43.95 | <= 30 | 25 |
| Superfast Broadband | £ 59.00 | <= 30 | 40 |
| Superfast Broadband | £ 82.00 | <= 30 | 60 |
| Superfast Broadband | £ 113.00 | <= 30 | 100 |
| Superfast Broadband | £ 169.00 | <= 30 | 150 |

*Freedomsat Avanti-based broadband retail service pricing.*

**Viasat HTGS**

Viasat is a US-based satellite operator with a fleet of high throughput geostationary satellites (HTGS). Viasat's stated strategy is based on two key principles:

- Design and operate unique data-centric satellites that have the lowest cost per unit bandwidth aimed at dynamically varying, high-demand geographic areas.

- Deliver broadband services, in packages tailored to a wide range of vertical markets, within those geographic areas.

Viasat do offer services directly to residential consumers as well as to businesses, i.e. B2C and B2B service models. The Viasat constellation operates in the Ka band and the existing satellites can support data rates of up to 100 Mbps in downlink and 20 Mbps in uplink, using a dish diameter of c. 0.75m. ViaSat-1, which entered service in 2012, serves residential US markets with additional coverage in Hawaii, Canada and Alaska. ViaSat-1 runs on fixed beams trained on certain geographic areas and has a claimed total throughput capacity of 140 Gbps.

ViaSat-2 entered service in 2018 and expanded the geographic range covered by ViaSat-1 to include Mexico, Central America, the Caribbean, parts of northern South America and aeronautical and maritime routes across the Atlantic Ocean. It is claimed to be the highest ever capacity satellite with a total throughput of 260 Gbps and the ability to shift capacity flexibly with beam-switching.

Viasat plans to launch 3 new Viasat-3 satellites with launch scheduled for 2023. The first is planned to cover the Americas. The second is set to cover Europe, the Middle East, and Africa (EMEA) and the third is planned to cover Asia-Pacific (APAC). Once in place, the three satellites are expected to provide near global coverage for land, air, and sea. They are also expected to enable space relays between satellites in different orbits, enhancing the ability of Earth-observation satellites and others to download data much more quickly.

Each Viasat-3 is claimed to be able to support over 1000 Gbps total throughput, with a peak downlink data rate to an individual terminal of 1 Gbps. Viasat claim that each Viasat-3 will be able to support more capacity than the rest of the satellites in the world combined.

In the current US residential market Viasat offer consumers (nominally) unlimited broadband services. Though nominally unlimited, the data rate available is reduced after the data-cap is met. The plans and prices vary by location, though 'introductory' plans and prices are listed below. There is no indication of the packages and pricing that will be offered for services to the UK once the second of the Viasat-3 satellites is launched.

| Internet plan | Price (US$ per month)[251] | Download speed (Mbps) | Data Limit (GB per month) |
|---|---|---|---|
| Basic 12 | $ 50 | <= 12 | 15 |
| Liberty 12 | $ 50 | <= 12 | 12 |
| Liberty 25 | $ 75 | <= 12 | 25 |
| Liberty 50 | $ 100 | <= 12 | 50 |
| Unlimited Bronze 12 | $ 69.99 | <= 12 | 80 |
| Unlimited Silver 12 | $ 150 | <= 12 | 45 |
| Unlimited Gold 12 | $ 200 | <= 12 | 65 |
| Unlimited Silver 25 | $ 99.99 | <= 25 | 120 |
| Unlimited Gold 30 | $ 149.99 | <= 30 | 100 |
| Unlimited Gold 50 | $ 149.99 | <= 50 | 200 |
| Unlimited Platinum 100 | $ 199.99 | <= 100 | 300 |

*Viasat broadband service pricing (US market).*

[251] There is an initial 3-month promotional discount price & thereafter the price reverts to these prices.

There is currently one MEO operator, namely SES, although Methera Global Communications plans to launch a constellation starting in 2024. Summary details on these operators are provided below.

**SES**

SES is a Luxemburg based satellite operator operating the O3B MEO system. ‘O3B’ originally referred to ‘other three billion’, referring to those globally without stable Internet access. The constellation was initially built, owned and operated by O3B Networks. The O3B MEO constellation began offering service in March 2014. SES O3B does not offer services directly to residential consumers. Services to this market sector are offered via resellers through a B2B service model.

The SES O3B MEO constellation comprises 20 satellites, spaced along in a single medium height orbit directly above the equator and is supported by 9 Teleports and 13 POPs. Each satellite is equipped with twelve fully steerable Ka-band antennas (two beams for gateways, ten beams for remotes) that use 4.3 GHz bandwidth (2 × 216 MHz per beam) with a proposed throughput of 1.6 Gbit/s per beam (800 Mbit/s per direction), resulting in a total capacity of 16 Gbit/s per satellite. Each beam's footprint measures 700 km in diameter. O3B claims a one-way latency of 179 milliseconds for voice communication, and an end-to-end round-trip latency of 140 ms for data services. The maximum throughput per TCP connection is 2.1 Mbit/s.

The O3B MEO service footprint only provides standard service up to a latitude of 50° with a reduced service between 50° and 62° latitude. This means that the UK is not within the coverage of the standard service. It is often referred to as O3B MEO to distinguish these satellites from SES's forthcoming O3B mPOWER constellation.

In 2022, the first two of SES's next generation 11 satellite MEO constellation, O3B mPOWER, were launched. The O3B mPOWER service is expected to begin operations alongside the existing O3B constellation in Q3 2023. The new O3B mPOWER satellites are expected to be able to deliver tens of Mbps to multiple Gbps through thousands of electrically generated spot beams. At the time of writing, it was not clear if the O3B mPOWER service would be able to provide standard service above 50°, and hence provide any coverage to the UK.

**Methera Global Communications**

Methera Global Communications is a UK based start-up planning to launch a constellation of up to 16 satellites, starting in 2024/2025, each equipped with 40 Gbps of Ka band connectivity capacity.

The Methera vision is to enable governments, telecom companies and Internet service providers to deliver digital applications with fibre-like speeds to areas of the world where it is uneconomic or impracticable to build fibre networks.

The proposed MEO constellation is planned to provide a competitive global communications network for areas under-served and unserved by terrestrial networks, capable of serving complete nations as the primary solution.  The approach plans low-cost user terminals that are simple to install needing only a view of the sky, a firm base and a power supply (either plugin to the local electricity or a solar panel plus battery).

The initial service offerings are expected to include:

- Superfast and Ultrafast Internet services direct to customer premises using a small, low cost, high throughput terminal.

- Fixed and mobile network backhaul and trunks serving a single POP or multiple 4G or 5G cell towers / BTS with multiple Gbps with primary, back-up or additional bandwidth connectivity.

- Network edge and core Ultrafast multi-Gbps connections for swift delivery of content to the network edge.

Based on the above, it is assumed that Methera will not offer services directly to residential consumers. Services to this market sector are expected to be delivered via resellers through a B2B service model.

**Eutelsat SA**

Eutelsat S.A. is a French satellite operator. Providing coverage over the entire European continent, the Middle East, Africa, Asia and the Americas, it is one of the world's largest satellite operators in terms of revenues.

Eutelsat's satellites are used for broadcasting around 7,000 television stations, of which 1,400 are in high-definition television, and 1,100 radio stations to over 274 million cable and satellite homes. They also serve requirements for TV contribution services, corporate networks, mobile communications, Internet backbone connectivity and broadband access for terrestrial, maritime and in-flight applications. EUTELSAT is headquartered in Paris, France.

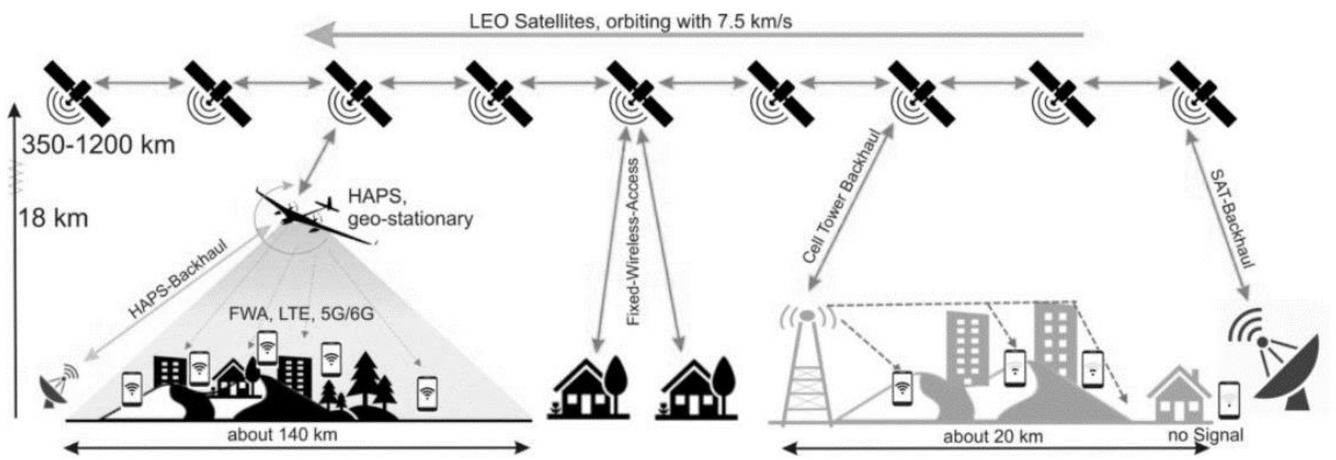
In October 2017, Eutelsat acquired Noorsat, one of the leading satellite service providers in the Middle East, from Bahrain's Orbit Holding Group. Noorsat is the premier distributor of Eutelsat capacity in the Middle East, serving blue-chip customers and providing services for over 300 TV channels almost exclusively from Eutelsat's market-leading the Middle East and North Africa neighbourhoods at 7/8° West and 25.5° East.

On 26 July 2022, Eutelsat announced a merger with LEO satellite internet operator OneWeb[252].

[252] See: https://www.eutelsat.com/en/news/press.html#/pressreleases/eutelsat-and-oneweb-to-combine-a-leap-forward-in-satellite-connectivity-3195697

# Appendix 5: High Altitude Platforms

For decades, high-altitude pseudo-satellites (HAPS, also known as high altitude platforms), have interested scientists and the industry, though early focus was mainly on the military applications of these aircrafts and balloons (see diagram below). Civilian applications include aerial imaging, environmental monitoring, and Internet services. HAPS involves lighter-than-air vehicles that operate in the stratosphere (17-22 km of altitude). They offer an efficient, non-pollutant and cost-effective alternative to satellites, with lower latency and far less path loss. HAPS can also overcome the environmental constraints which affect the propagation of terrestrial radio waves.




*HAPS concept and systems architecture*[253]

This means HAPS can be seen as an intermediate solution between satellites and terrestrial networks, exploiting the benefits of intermediate altitudes. When used in conjunction with satellites, HAPS improves the ability of conventional satellite infrastructure to offer personal telecoms services affordably. Several projects, described below, have emerged with backing from large Internet businesses. These are not commercial solutions but rather research orientated initiatives. It is difficult to predict how these solutions will develop as commercially viable solutions in forecast timelines of this report.

**Google Loon**

Google Loon[254], is a good example of HAPS. It used 'high-altitude balloons' to operate at an altitude of about 18 km to create an aerial LTE network. Balloons wirelessly interconnect with each other and with Loon ground stations, providing service to users on the ground below. The system aimed to bring Internet access to remote and rural areas poorly served by existing provisions, and to improve communication during natural disasters to affected regions.  Each balloon carried a small LTE base

[253] Source: https://haps-broadband.org/general-topic/
[254] See: https://x.company/projects/loon/

station, antenna system and solar power array to power the system and charge batteries. Google announced the closure of the Loon project in 2021 citing challenges with the commercial viability of the solution[255] .

**Aquila**

Aquila[256] was a solar-powered unpiloted aircraft (a drone) plane developed by Facebook to deliver Internet to remote parts of the world. It had a wingspan comparable with Boeing 737 but only weighed 400 kg (a Boeing 737 weighs circa 50,000 kg). The surface of the Aquila wing was covered in solar cells to power the aircraft's four electric motors; batteries, composing half the aircraft's weight, provide power storage for night flight. Aquila was intended to fly at altitudes of up to 27,000 m during the day, dropping to 18,000 m at night, with an endurance of up to three months. It would provide Internet services to an 80 km radius area below its flight path. The technology, which used high-bandwidth lasers to beam the Internet to remote locations, was intended to provide access to 4 billion users, particularly in sub-Saharan Africa. Facebook closed the Aquila program in 2018[257].

**Zepher**

Zepher[258] is another solar-powered unpiloted aircraft (drone) developed by Airbus´ HAPS Connectivity Business to deliver Internet to remote parts of the world. It also hosts an Earth Observation system. The Airbus Zepher program is still active and there were a number of commercial agreements press-released in 2022 including agreement with Space Compass Corporation of Japan to service the Japanese market with mobile connectivity and earth observation services[259], and a partnership agreement with the Saudi based Mawarid Media & Communications Group (MMCG), to progress the development of private networks, IoT applications, disaster management solutions and other connectivity[260].

**HAPS Mobile**

HAPS Mobile[261] is a subsidiary of Softbank planning to operate High Altitude Platform Station (HAPS) networks using a solar-powered unpiloted aircraft (drone). The Sunglider aircraft has a wingspan of 78m and can stay airborne, at a height of circa 20km (the stratosphere) for several months. The payload, which was co-developed with Google Loon, can provide direct to device mobile services across a circa 200 km diameter service area.

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[255] See: https://www.bbc.co.uk/news/business-55761172
[256] See: https://engineering.fb.com/2015/07/30/connectivity/building-communications-networks-in-the-stratosphere/
[257] See: https://www.bbc.co.uk/news/technology-44624702
[258] See: https://www.airbus.com/en/products-services/defence/uas/uas-solutions/zephyr
[259] See: https://www.airbus.com/en/newsroom/press-releases/2022-11-airbus-partners-with-space-compass-to-serve-the-japanese-market
[260] See: https://www.airbus.com/en/newsroom/press-releases/2022-10-airbus-and-salam-join-forces-for-high-altitude-platform-station
[261] See: https://www.hapsmobile.com/en/

# Appendix 6: Key references

Various studies have examined the developing state of broadband technologies, with particular relevance to rural and hard-to-reach areas.

We list notable reports below.

| Reference | Source | Date published | Key subject areas covered |
|---|---|---|---|
| Connected Nations Reports[262] | Ofcom | December 2022 | Market data, broadband availability |
| ThinkBroadband data[263] | NetConnex Ltd | Monthly updates | Market data, broadband availability (independent) |
| Market Mechanisms Review | techUK, SPF | November 2022 | UK spectrum policy futures |
| Project Gigabit Delivery Plan – 2022 update[264] | DCMS | November 2022 | Market updates on Project Gigabit programme |
| Research on VHTR Premises[265] | BSG | August 2021 | Technical and commercial review |
| Internet Futures[266] | Ofcom, Saunders | July 2021 | Internet R&D review |
| Technology Futures[267] | Ofcom, Saunders | January 2021 | Technology R&D review |
| 5G Rural First report[268] | 5GRF, Corden | October 2019 | UK rural economy, DCMS 5GRF programme |

*Selected key reports relevant to broadband coverage in rural areas.*

[262] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0034/249289/connected-nations-uk-report.pdf
[263] See: https://www.thinkbroadband.com/
[264] See: https://www.techuk.org/resource/uk-spf-reports-a-key-insight-into-future-spectrum-policy.html
[265] See: https://www.connectivityuk.org/2021/08/16/bsg-report-research-on-very-hard-to-reach-premises-technical-and-commercial-analysis/
[266] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0013/222205/Internet-futures.pdf
[267] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0011/211115/report-emerging-technologies.pdf
[268] See: https://www.5gruralfirst.org/wp-content/uploads/2019/10/5G-RuralFirst-New-Thinking-Applied-to-Rural-Connectivity-1.pdf

# Glossary of terms

A non-exhaustive glossary of terms is provided below:

| Term | Expansion |
|---|---|
| AV | Autonomous Vehicle |
| CBRS | Citizens Broadband Radio Service (USA) |
| CNI | Critical National Infrastructure |
| CPCP | Capital cost Per Connected Premises |
| CPE | Customer Premises Equipment (i.e. user terminals) |
| DSA | Dynamic Spectrum Access |
| DSP | Digital Signal Processing |
| DTT | Digital Terrestrial Television (radio spectrum) |
| DVB | Digital Video Broadcasting |
| EHF | Extra High Frequency (radio bands) |
| EIRP | Effective Isotropic Radiated Power (with radio systems) (dBm) |
| FMC | Fixed Mobile Convergence |
| FTTC | Fibre To The (street) Cabinet |
| FTTM | Fibre To The (radio) Mast |
| FTTX / P | Fibre To The node / premises (full fibre) |
| FWA | Fixed Wireless Access (networks) |
| GEO | Geostationary Earth Orbit (satellites) |
| Gigabit | Broadband service at 1000 Mbps or better (downlink) |
| HAPS | High Altitude Platforms Systems |
| IOT | Internet Of Things (also, machine to machine communications – M2M) |
| IPTV | IP Television (video over IP) |
| LEO | Low Earth Orbit (satellites) |
| LOS | Line Of Sight (in radio systems deployment and planning) |
| M&A | Mergers and Acquisitions |
| MEO | Medium Earth Orbit (satellites) |
| Mesh (network) | Network architecture with many end users connected together |
| mmW | Millimetre Wave (radio bands) |

| | |
|---|---|
| MNO | Mobile Network Operator |
| MOCN | Multi-Operator Core Network (RAN capacity sharing) |
| MORAN | Multi-Operator RAN (spectrum sharing) |
| MU-MIMO | Multi-User Multi-Input Multi-Output (array antenna systems) |
| MVNO | Mobile Virtual Network Operator |
| mW | Milliwatts (radio power) |
| NLOS | Non- (or Near) LOS |
| NOMA | Non-Orthogonal Multiple Access |
| NSA | Non-stand-alone (5G technology) |
| NTN | Non-Terrestrial Networks (i.e. satellite-based systems) |
| OFDMA | Orthogonal Frequency Division Multiple Access |
| P2MP | Point to Multi-Point (radio links) |
| P2P | Point to Point (radio links) |
| PHY | Physical layer (digital radio) |
| POP | Point of Presence (networks) |
| PSTN | Public Switched Telecoms Network (legacy copper network) |
| QAM | Quadrature Amplitude Modulation |
| QOS | Quality of Service |
| R&D | Research and Development |
| RAN | Radio Access Network |
| RSL | Received Signal Level (dBm) |
| RSMA | Rate Splitting Multiple Access |
| SA | Stand-alone (5G technology) |
| SDMA | Spatial Division Multiple Access |
| SDN | Software-Defined Networks |
| SDR | Software-Defined Radio |
| SLA | Service Level Agreement |
| SRN | Shared Rural Network |
| Superfast | Broadband service at 30 Mbps or better (downlink) |
| TDD | Time Division Duplex |
| TRP | Total Radiated Power (dBm) |
| TVWS | TV White Space (DTT radio spectrum) |

| | |
|---|---|
| UAV | Unmanned Aerial Vehicle |
| Ultrafast | Broadband service at 300 Mbps or better (downlink) |
| USO | Universal Service Obligation (broadband) |
| V2X | Vehicle to X (node) |
| VHCN | Very High Capacity Networks (see BEREC guidelines) |
| VHTR | Very Hard To Reach (premises) |
| VOIP | Voice Over IP |
| WISP | Wireless Internet Service Provider |

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