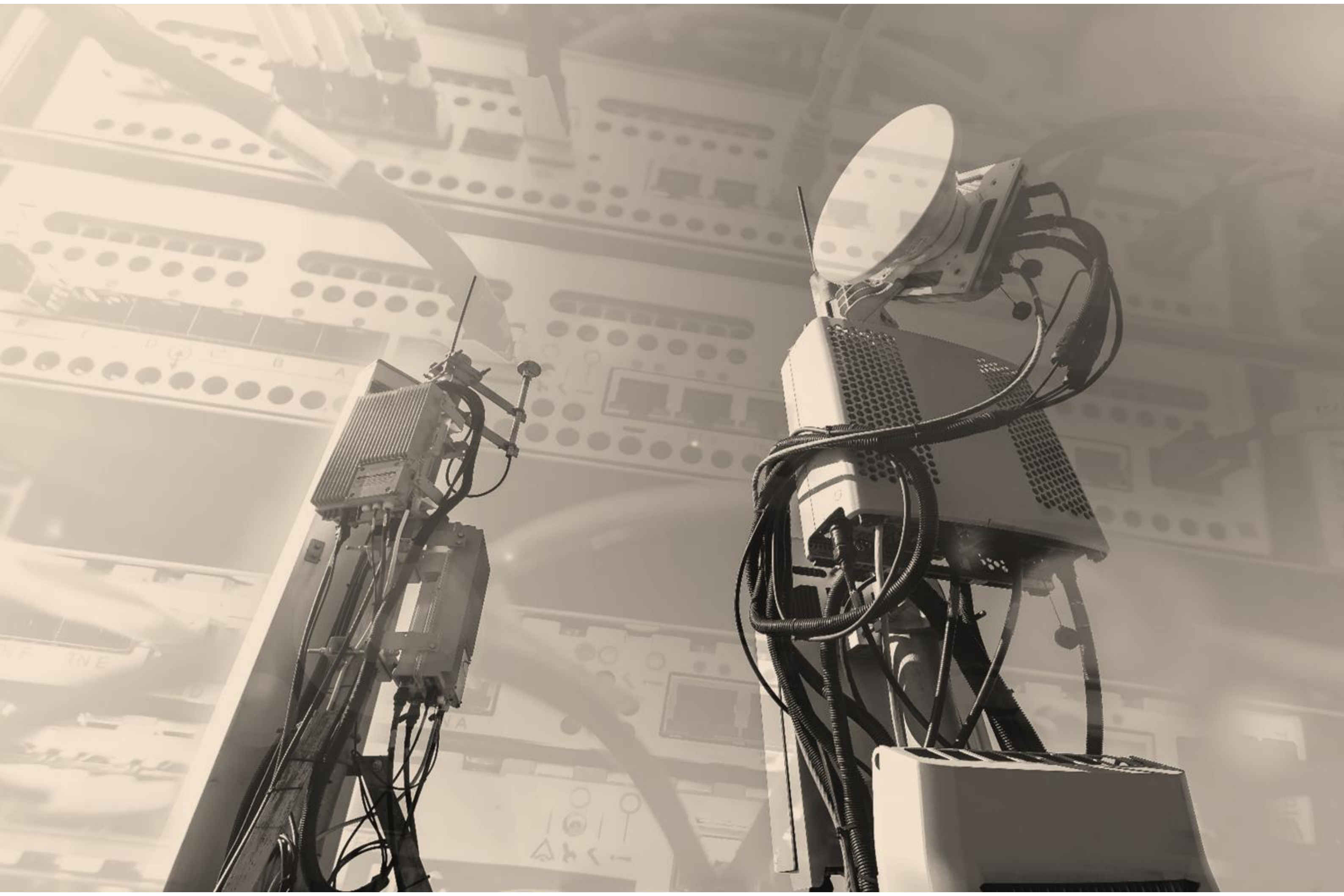

Gigabit radio:

Unlocking new opportunities with state of the art fixed and portable wireless access technology

Peira Consulting Limited

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Peira Consulting

Peira Consulting is an independent consulting firm, based in the UK, focused on the TMT and digital sectors.

We practice globally, and bring deep experience of the UK market, including with altnets, across full fibre and wireless strategy, due diligence, policy, and regulation.

Whilst we work regularly with the professional investment community, we are not financial advisors.

Our report

Fixed wireless access (FWA) or radio-based broadband internet connectivity is an important networking technology, enabling gigabit capable and IOT services, that has developed rapidly over recent years.

This report examines a number of recent developments, with focus on the UK market. Whilst our assessment is not exhaustive, our objective has been to provide a clear, definitive, authoritative, and up-to-date view on the state of the FWA industry, including review of leading edge networking products, assessment of feasible and realistic commercial models, and critical analysis of investment cases.

Throughout, our assessment is balanced and objective. We aim to present only the facts, and have no regard for industry sales messages. As the question over comparison between FWA and FTTX networks often arises, we also provide some commentary as to how these technologies compare.

Our views are based on dialogue with industry stakeholders and our own experiences in the market, covering both technical network designs and financial assessment. Focus is placed firmly on commercial reality and practical deployments for the near term, rather than R&D, long term forecasts, and hypothetical situations.

The report is likely to be of interest to investors, operators, equipment vendors, policy makers, and regulators, with interests in commercial funding deals, interventions and gap funding, and radio spectrum management.

Key areas addressed are as below:

- **Background**: the current state with FWA networks in the UK.
- **What has changed**: new leading edge FWA technologies, market developments, policies and regulations, and commercial products.
- **Deployment models**: how FWA can be and is being used commercially, and comparison with full fibre and mobile networking technologies.
- **The investment angle**: cost structures, pros and cons with FWA deployments, technology alternatives, valuations, and risk perspective.
- **Looking ahead**: how will FWA technologies and solutions develop in the future?
- **Conclusions**: summing up; does FWA present a window of opportunity, or is there potential for long term value? Where is the sweet spot with FWA investment models?

Executive summary

The technology enabling fixed wireless access (FWA) or radio-based broadband networks has developed significantly in recent years, and a review on commercial performance levels and investment potential is, we feel, very timely, especially with growing interest in gigabit and multi-gigabit capable solutions, and ongoing deployment of full fibre networks.

Our focus has been to provide an up-to-date, fully independent review of the state of the FWA market, leveraging our practical experience in investment planning and deployment of commercial gigabit capable systems. Our perspective is largely towards the UK market, though FWA is applicable and interesting for many regions around the globe.

Gigabit wireless has arrived…

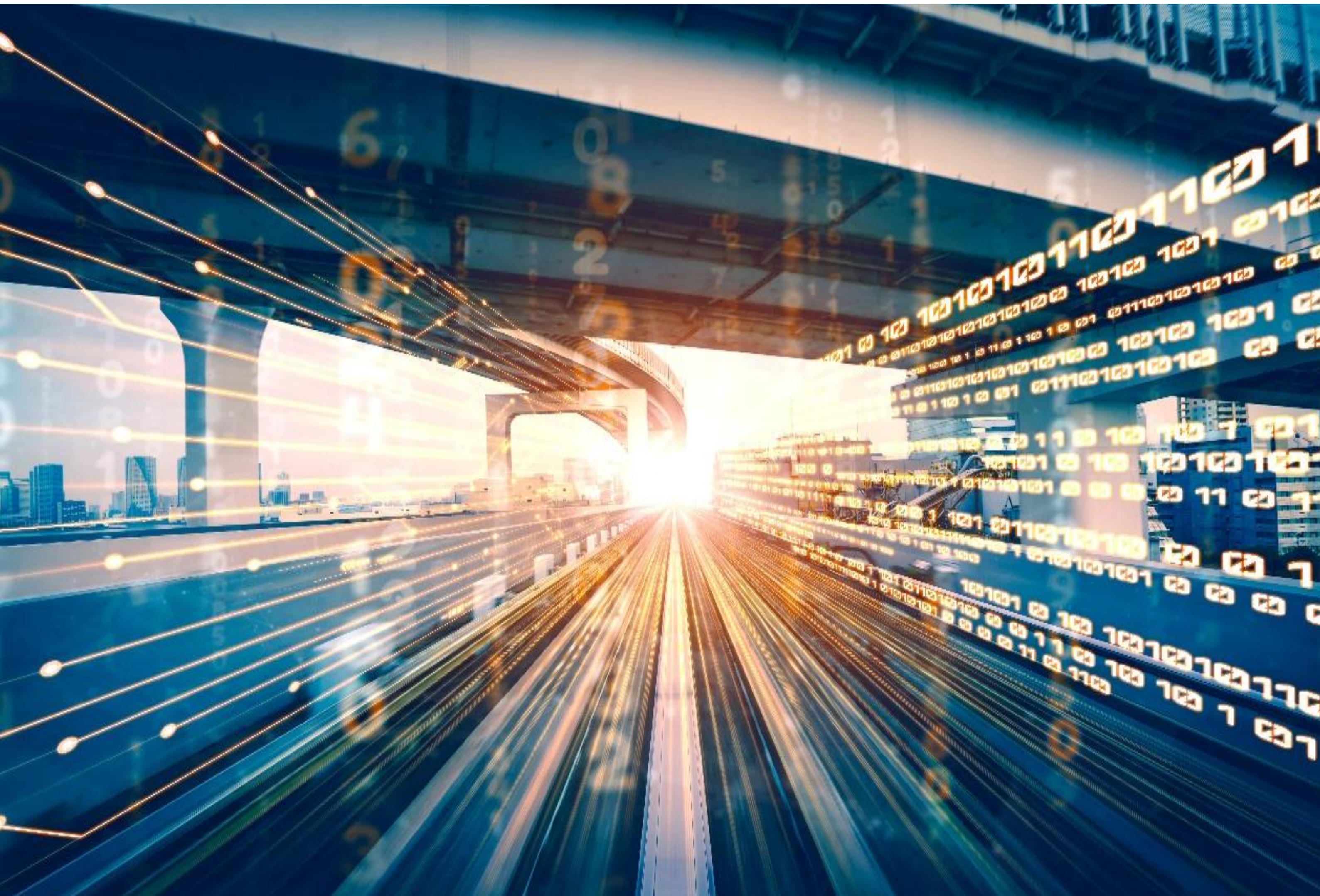
From a terminology standpoint, it is important to note that the 'wireless' industry includes 'mobile' (or cellular) networks, WiFi, public and private 4G and 5G systems, and much more.

There is more to 'wireless' than 'mobile', although often, the terms are used interchangeably, *incorrectly*. Further, 5G technology is *not only* for smartphones.

Whereas the FWA industry is well-established, especially with products supporting operation in the 5GHz radio band targeted towards providing connectivity for more rural areas, there have been some key developments of late.

***Gigabit* and *multi-gigabit* capable radios are now commercially available, supporting a range of radio bands from sub-6GHz, to the EHF 26-28GHz and 60GHz bands.**

In some respects, these solutions can offer broadband service performance levels similar to those with full fibre. But it is wrong to equate wireless systems to fibre without careful qualification, as cost structures and engineering details can vary widely.



Cost structure with gigabit capable FWA can be superior to that for full fibre networks across a range of deployment scenarios …

With equipment using the sub-6GHz radio bands, gigabit connectivity is possible with wireless links with range up to around 10km, with high gain directional antennas and high order modulation radios.

Key advantages with FWA networks over cellular systems include the ability to deploy high gain antennas to reach specific areas, and much simpler core network technology – as mobility management is not required. These factors improve cost structure significantly, and when coupled with use of lightly licensed shared access radio spectrum – available at nominal costs, allow compelling investment cases in some situations.

Capital cost per connected premises (CPCP) with gigabit capable FWA designs can be around £350 at the access network level, significantly less than with full fibre network designs.

Given this attractive cost structure, and with cost-efficient cloud-native core network designs,

EBITDA margins in excess of 50% are possible with FWA networks, along with healthy valuation multiples – supported by fast network roll-out times.

New commercial models are becoming important for non-rural areas…

In non-rural areas, interest is growing strongly in the deployment of FWA systems operating in the millimetre wave (extra high frequency, EHF) bands such as 26-28GHz and 60GHz, as these can offer multi-gigabit performance (as an alternative to full fibre), *and* address demand cases (e.g. nomadic connectivity, holiday parks, coverage at event spaces) which cannot be served using fibre.

We expect this market to offer good potential in the near future, including in the UK – with Ofcom expected to offer licensing for outdoor wireless systems in the lower 26GHz band.

Wireless mesh networks using the EHF bands can provide highly resilient multi-gigabit connectivity with node to node link ranges of hundreds of metres.

Radio meshing is an important technology for non-rural areas, as multi-gigabit capacities can be provided, and network capital costs are significantly lower than with full fibre.

In meshed FWA network designs, CPCP is around £100 with current deployments, and costs are expected to reduce further as this market continues to develop. Meshing provides good cost efficiencies with backhaul circuits and network resilience benefits across the whole access network. Meshing also enables flexible capacity development as markets develop.

Wireless solutions need not contribute more risk than with full fibre, and investment models can be very appealing…

From an investor perspective, we do not see higher risk *per se* with FWA systems over full fibre deployments (as is often the perception without a level of analysis), but neither are the two technologies directly comparable.

With well-engineered designs, FWA networks can provide resilient connectivity levels. As with many technologies, there are pros and cons with both.

FWA solutions, with attractive cost structure and time to market, become particularly compelling with the advent of gigabit capability.

FWA solutions are attractive in various cases including in:

- **rural areas,**
- **cases where semi-mobile, vehicular, or portable connectivity is required, and**
- **non-rural areas to support smart city and transport opportunities.**

Gigabit capable wireless networks now provide an important complement to FTTX networks, enabling pervasive connectivity, new services, and valuable consumer benefits.

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**.

Increased market access and competition, with regional shared spectrum access, will provide important consumer benefits and remove the innovation log-jam that has long existed with the cellular industry.

FWA and FTTX *together* will support the development of pervasive gigabit connectivity for the whole of the UK.

We do not see a closing window of opportunity for wireless solutions as full fibre develops, but a shifting of markets and technology supply chains – presenting new opportunities for those able to leverage key developments (i.e. changing social behaviours, new regulations, limitations with cellular mobile systems, and unique capabilities of new gigabit wireless systems).

Looking to the future, a key issue, facilitated by effective regulation, will be increased access to radio spectrum on a regional basis (spectrum sharing), at cost levels that do not present excessively high barriers to entry – as has been the case with national licensing for spectrum in the mobile bands. Key issues include maintenance of alignment between radio spectrum regulation and equipment suppliers, and international harmonisation, so that network equipment can be made available to the market in a timely way, and with economies of scale supporting efficient pricing levels.

Wireless systems are expected to evolve with particular technologies suited to selected market needs, as it is not economically efficient to design one network which meets all demands. As full fibre continues to be rolled out,

we expect that winners in the market will capitalise on the unique advantages that wireless connectivity brings, with new commercial models and services such as: neutral host networks, gigabit capable portable services, joint investments, and carrier-neutral segment-focused datacentres.

Taking into account attractiveness of scalable opportunities,

we see smart cities and solutions for portable and vehicular needs as particularly notable areas for development.

1 Background

1.1 Terminology

As with many professional fields, in telecommunications, there are quite a few acronyms, terms, and phrases that can be confusing or ambiguous. This is particularly true in the wireless domain, so as a first step, let us explain a few important terms:

- *Wireless (or radio) communications*: refers to all types of telecommunications equipment that use radio in the network, to support user services. Importantly, wireless communications therefore include mobile systems and other radio-based networks such as satellite links, machine to machine (M2M) connections, and WiFi. The field of wireless communications is much bigger than 'mobile', and yet often, and *wrongly*, the terms are used synonymously. Today, the vast majority of wireless systems are based on digital technology.
- *Mobile communications systems* then, are those that we are all familiar with today. Commercial deployment and use of mobile systems grew significantly in the 1990s with the launch of GSM (2G) which eventually became a global standard. GSM has since been followed by newer mobile technologies: 3G (UMTS or WCDMA), 4G (LTE), and now 5G (OFDMA).
- *5G* is where things start to get interesting *and* confusing, as the industry has started to use the 5G name when referring to mobile *and* other wireless networks.
- *Fixed wireless communications systems* use radio technology to provide digital network connections 'over the air' (and hence without cables or ducts) to fixed (or semi-fixed) locations. A key difference to mobile systems is that handover of calls or sessions is not supported with users in motion. Fixed wireless links may be of various types including point to point (P2P, direct links between two locations), or point to multi-point (P2MP, links from one site to many sites), and may either serve end users in so-called access networks, or form part of regional or national trunking networks. P2MP solutions are attractive at the access network level, as many end users can be served from one radio hub site.
- *Access networks* provide connectivity between end users (e.g. user premises) and local exchanges or first stage network aggregation points in the trunk network.
- *Points of presence (PoPs)* are nodes in networks where interconnection can be established (e.g. between networks operated by different commercial entities).
- *Full fibre* (or fibre to the premises, FTTP) describes broadband networks using fibre optic cable connections running from local exchange or gateway nodes, all the way to end users' premises.

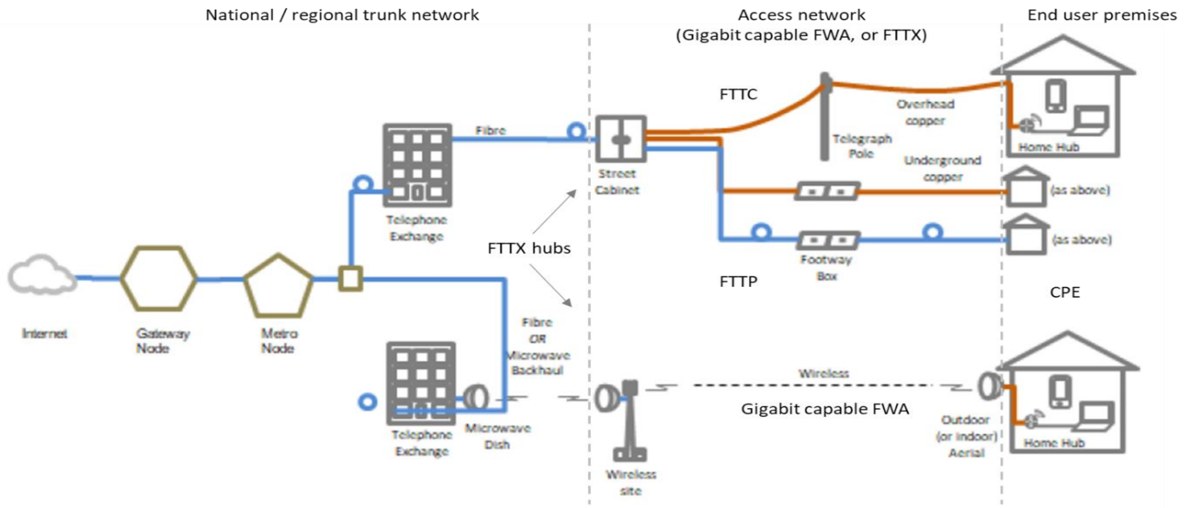
1.2 What is fixed wireless access?

- **Fixed wireless access (FWA) networks provide terrestrial wireless connections from local radio network sites to end users' premises, enabling voice and broadband internet connections at up to and beyond gigabit per second speeds.**
- FWA networks are commercially established in many countries, and are typically used where it is difficult to provide access network connectivity to end users from trunk network PoPs using cabled (i.e. fixed line) network technologies such as full fibre.
- FWA network elements typically use WiFi, 4G, or 5G *chipsets*, to leverage economies of scale from the mobile networking industry, but many use different radio bands. FWA networks do not typically include core networks as used in mobile systems (i.e. with mobility management). FWA networks are thus 'last mile' technology, typically used in combination with full fibre trunking networks, and cost structure is different than with mobile networks.
- *Hybrid* networks, are those typically built with a combination of full fibre (FTTX) and FWA technologies, to attain performance and economic compromises.
- Since FWA networks typically operate using different radio bands to mobile networks, mobile smartphones do not usually function on FWA networks. Rather, FWA networks use purpose-built customer premises equipment (CPEs), which are usually wall or roof mounted on users' premises. However, in the US market (only, currently), Apple iPhones do support the 26GHz, 28GHz, and 39GHz bands, which may also be supported by FWA equipment.

Fixed wireless access (FWA) networks then, provide a wireless alternative to cabled last mile access in telecoms networks, enabling broadband internet connectivity to end users.

Typical access network configurations for FWA and FTTX technologies are shown in the figure below.

Figure 1.1: Typical access network configurations[1]



[1] Source: UK Government, DCMS, 2021.

1.3 Why are fixed wireless access networks useful?

So why go wireless? The major issues are network economics and deployment time.

With no need for cabling, ducting, and civil works in new network projects, broadband connectivity can be provided in days and weeks with FWA solutions, rather than months and years as with fibre to the premises (FTTP) programmes, and costs per connected user can be significantly less with FWA.

Why then doesn't everyone deploy FWA rather than FTTP? There are, of course, pros and cons with all technologies. FTTP networks are seen as resilient, with long asset lives on fibre cabling and ducting – around 20-30 years, and are absolutely the right technology for many situations[2]. But not all. What matters is using the most appropriate technology for the situation to hand.

Modern FWA technology is capable of supporting gigabit and multi-gigabit data rates to users, and valuable 'blanket' 'immediate' coverage across wide areas. Consequently, one application of FWA networks is the direct substitution of cabled networks, such as full fibre (FTTP), or digital copper lines (FTTC).

However, in any such cases, the economics and engineering performance levels will differ across technologies; as with many things in life, the devil is very much in the detail. We address such details in a later section. It is wrong to equate FWA and FTTP technologies without some qualification.

1.3.1 FWA solutions are well-established in rural areas

Fixed wireless access technology is not new, *per se*. In the UK, the FWA industry is represented by UKWISPA[3], an established industry body, and there are already over 100 network operators using FWA technology to provide broadband internet and voice services to users.

In the past, broadband services over FWA networks have been possible up to superfast data rates (i.e. line speed at 30Mbps[4]). However, FWA network equipment performance and pricing levels have improved significantly in recent years, with gigabit and multi-gigabit capable services now possible.

All wireless technologies require radio spectrum to operate, and hence radio spectrum management and regulations are key areas. We address these in further detail below, but note here that in the UK market, FWA networks have typically operated largely in the lightly licensed 5.8GHz band, according to Ofcom regulations[5] (which also stipulate a maximum radio transmit power level of 4 Watts (36dBm) EIRP[6]). This has meant that in 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

[2] Note: asset lives on active electronic equipment are typically lower – around 5-10 years.

[3] See: https://www.ukwispa.org/

[4] See: https://www.ofcom.org.uk/phones-telecoms-and-internet/information-for-industry/codes-of-practice

[5] See: https://www.ofcom.org.uk/manage-your-licence/radiocommunication-licences/fixed-wireless-access

[6] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0031/84955/IR_2007.pdf

obstructions), in order to ensure acceptable levels of services for users over reasonable ranges of several kilometres.

With newer and developing regulations, FWA solutions can provide higher service performance levels and higher ranges.

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. In such cases, costs per connected premises run high with cabled approaches, and investment cases for full fibre tend to be challenging, typically calling for gap funding from public authorities.

Costs per connected premises with FWA network solutions can be much lower than with full fibre (FTTP) network designs, but this is too simple a viewpoint and more detail is needed to support in any commercial projects and investment decisions. Critical examination on this area is one of the key areas addressed in this report; further analysis is provided in a later section.

FWA networks for rural areas are more economically efficient when lower frequency radio bands (typically below 6GHz) are used, as radio waves at lower frequencies can travel further distances.

Commercial interest in FWA for rural deployments is thus well-established.

1.3.2 Interest in FWA is now growing to meet needs in non-rural areas

For non-rural environments, so-called millimetre wave (mmW, or mmWave) or extra high frequency (EHF) bands (typically above 20GHz) can be useful, enabling high bandwidths and data rates, but over shorter distances than in rural areas. In this case, 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. Backhaul is provided at a number of points across the access mesh. This approach provides enhanced resilience, and greater capacity – using shorter hop radio links.

Further, with no cabling used in FWA access networks in the ‘last mile’, there is some potential for a degree of ‘mobility’ from the user perspective (i.e. users with CPEs could move locations relatively easily, within coverage areas, subject to access to electrical power and antenna alignments), aside from the typical static case. As cellular handover is not usually implemented in FWA networks, and there is no guarantee of service at high user velocities, we will refer to this as ‘portable’ or ‘nomadic’ use.

The potential for portable use opens the door for FWA networks to support a number of market demands and use cases that fixed line technologies simply cannot.

There are already commercial examples of this in the market:

- in Sunderland UK, the city council is working with BAI[7], Mavenir[8], and CityFibre[9] to provide gigabit capable broadband services to users across the city in streets, event spaces, and schools, using FWA networks operating in the 60GHz band via a neutral host model;
- in Bristol UK, the city council is examining ways in which FWA technology can be used to support high speed data links to public sector vehicles (thereby bypassing costly 4/5G mobile solutions) and event spaces, leveraging the city's metropolitan fibre network and street furniture.

1.4 Is fixed wireless the same as 5G?

Yes and no. 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.

And some vendors and operators are calling things '5G', to promote marketing messages, or to access funding. Wireless mobile systems, including 5G, may not support higher gain directional antennas and gigabit capable radio channels, and require costly core networks and national spectrum licences.

Consequently, commercial models with mobile systems 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).

Thus, fixed wireless access networks can be, and are being referred to as 5G systems in some cases, but, importantly, at the technology and investment case levels, these are not the same thing as 5G mobile networks (unless 5G mobile networks are used to provide fixed wireless services).

1.5 Do satellite systems have a role to play?

Whilst the various so-called new LEO satellite initiatives (e.g. OneWeb[10], Starlink[11], Telesat[12]) have attracted some attention of late, in our view these remain commercially unproven and unsuitable to deliver gigabit services at acceptable price and quality points for the mass market.

As with many investors and independent observers, we continue to take the view that satellite-based communications systems are useful in limited niche situations including with: maritime and aeronautical cases, developing regions, areas prone to instability and theft, and war zones.

[7] See: https://www.baicommunications.com/

[8] See: https://www.mavenir.com/

[9] See: https://cityfibre.com/

[10] See: https://oneweb.net/

[11] See: https://www.starlink.com/

[12] See: https://www.telesat.com/

2 Market developments

2.1 Changes and impacts of regulation

Radio spectrum is an essential element of wireless networks, and there are various bands used and available for FWA systems, with some international harmonisation, and licensing from Ofcom[13], as applicable.

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. 4G/5G chips), and operation in harmonised bands. There is reasonable (though not uniform) international harmonisation in regulatory licensing across the bands: 3.8-4.2GHz, 5.8GHz, 26-28GHz, and 60GHz.

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

- 3.8-4.2GHz: made available by Ofcom through its 'Wireless Innovation' Statement[14], of 2019, which affords regional access with the so-called 'shared access bands'. Operators are required to apply to 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 100MHz 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.
- 5.8GHz: legacy FWA band, currently available under light licensing[15] from Ofcom, and used by many UK operators for deployment of FWA services. Not ideally suited for longer distance ranges and gigabit capable services.
- 26GHz: the lower band (24.45-27.5GHz) is not currently licensed in the UK by Ofcom for outdoor usage, though this is expected to change (shared access band). The so-called upper band is expected to be licensed as a 5G mobile band.
- 60GHz (57-71GHz, EHF licences): available under light licensing[16] from Ofcom[17,18] (with nominal fees), supporting gigabit capable wireless access links, although link ranges are limited. Interest in

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[13] See: https://www.ofcom.org.uk/manage-your-licence/radiocommunication-licences

[14] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0033/157884/enabling-wireless-innovation-through-local-licensing.pdf

[15] See: https://www.ofcom.org.uk/manage-your-licence/radiocommunication-licences/fixed-wireless-access

[16] 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

[17] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0025/203767/spectrum-access-ehf-licence-guidance.pdf

[18] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0018/203652/IR-2106.pdf

this band has risen sharply, with equipment becoming available from a number of suppliers, and also the Terragraph[19] technology developed by Facebook Connectivity (Meta Platforms Inc).

- 70/80GHz: the 73.375-75.875GHz and 83.375-85.875GHz bands are available in the UK under a light licensed process for point to point fixed wireless applications.

The physics of radio wave transmission vary significantly according to the frequency used, and atmospheric effects (such as rain, mist, and air oxygen levels) can also affect transmissions significantly in the EHF bands.

Most spectrum licences issued by Ofcom include a condition (the EMF licence condition) requiring licensees to ensure compliance with the limits in the ICNIRP Guidelines on EMF exposure for the protection of the general public from potentially harmful electromagnetic radiation[20].

Looking forwards, Ofcom has recently published two *discussion papers*, which set out potential further developments in spectrum management:

- In the first paper[21], Ofcom sets out views on potential developments for the mobile market, concluding that it will continue to monitor competition and service quality levels.
- In the second[22], further views are set out, inclusive of planning for the mmW bands, with a view to regional shared access.

Ofcom has also recently published its Spectrum Roadmap[23] which sets out plans for development of spectrum management. Key themes include: developing convergence across satellite and terrestrial radio systems, further regional access and spectrum sharing, and more effective use of data in spectrum management (providing a pathway to dynamic spectrum access - DSA).

We also note that some fixed wireless services are operated by mobile carriers and WISPs[24], using mobile spectrum and wholesale SIMs. Examples include BT's 'unbreakable'[25] WiFi hub (which includes 4G mobile technology to provide WiFi backup), EE's 4G home broadband[26] (using an external fixed antenna), and Three's 4G/5G home broadband[27] (using an indoor mobile fixed terminal). We refer to these as 'fixed mobile' solutions. Such options can provide wireless internet connectivity, typically at superfast data speeds, but service quality is compromised as they are not based on CPE products which use optimised radio engineering or installations; hence link distances

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[19] See: https://terragraph.com/

[20] See: https://www.ofcom.org.uk/manage-your-licence/emf/policy

[21] See: https://www.ofcom.org.uk/consultations-and-statements/category-3/ofcoms-future-approach-to-mobile-markets

[22] See: https://www.ofcom.org.uk/consultations-and-statements/category-3/discussion-paper-meeting-future-demand-for-mobile-data

[23] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0021/234633/spectrum-roadmap.pdf

[24] WISP: Wireless Internet Service Provider

[25] See: https://www.bt.com/exp/halo

[26] See: https://newsroom.ee.co.uk/ee-launches-4g-home-broadband-antenna-to-connect-more-than-580000-homes-across-the-uk/

[27] See: https://www.three.co.uk/store/broadband/home-broadband

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.

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

- Mobile network operators (MNOs), as mobile spectrum licence holders, can operate fixed mobile or mobile network systems.
- Alternative network (altnet) operators can resell fixed mobile 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. with no need to build access network infrastructure, or procure radio spectrum licences).
- Altnets can build wireless access networks and either procure their own radio spectrum licence, sub-lease spectrum from a spectrum licence holder, or establish commercial infrastructure-only deals with spectrum licence holders (e.g. neutral hosts). 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.

Radio spectrum allocation, then, 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 determine the radio link range), bandwidth (which affects the available data capacity), and the radio technology type used (which further affects capacity and range, and 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. Other key systems which require radio spectrum include: satellite links, mobile cellular networks, and military systems.

As FWA systems are typically static and regional, there has been strong interest in ensuring access to radio spectrum on a regional basis. This ensures efficient use of limited, finite radio spectrum, whilst also enabling access to markets, thus promoting good levels of market competition and innovation.

2.2 New high performance fixed wireless products and technologies

2.2.1 Point to multipoint and point to point wireless solutions

At the access network (last mile) level, P2MP FWA solutions are preferable; a high volume of P2P radio links serving many customer premises from hub sites would be impractical.

P2P links are relevant for local backhaul (middle mile) 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-6GHz: particularly relevant for rural areas, with relatively good area coverage capabilities, due to the physical properties of radio transmission in this band;
- 26-28GHz: of particular interest for urban areas and mesh networking, with gigabit requirements (subject to regulatory licences being available); and
- 60GHz: as with the 26-28GHz bands.

2.2.2 Gigabit capable wireless systems are now commercially available in the market

The availability and capability of FWA network equipment has improved significantly over recent years, with a number of vendors now providing high performance solutions capable of gigabit or higher throughput levels.

Below, we list some of the leading suppliers active in the FWA industry, with a short summary on notable products in each case (non-exhaustive list):

- **Cambium Networks Ltd**[28] is a leading provider of FWA networking equipment: with operations in the US, UK, and India, the company provides a number of P2MP FWA products covering the sub-6GHz, 28GHz, and 60GHz bands.
    - The PMP450™ product is a high capacity P2MP platform, featuring massive MU-MIMO and beamforming (cnMedusa™) technologies that can provide enhanced capacity and range. Products are available covering both 3GHz and 5GHz bands.
    - The cnWave™ product supports in excess of one gigabit throughput, with operation over the 24.25-29.5GHz band, also using MU-MIMO technology.
    - The cnWave™ V5000 product supports multi-gigabit throughput, with operation over the 57-66GHz band.
- **Siklu Communication Ltd**[29] is another leading provider of FWA equipment with more than 200k links deployed globally, with a focus on multi-gigabit wireless solutions for smart cities and other verticals. The company has operations including in the US, Israel, and the UK, and has created the world's largest portfolio of mmWave products and the first mass produced mmWave radio, the EtherHaul™ 1200, which is still widely deployed. A range of P2P, P2MP, and MP2MP (wireless mesh) FWA products are offered, covering the 60GHz and 70/80GHz bands.
    - The MultiHaul™ TG series of products provides multi-gigabit meshed connectivity, supporting operations in the 60GHz V-Band (802.11ay, Terragraph certified; see below) with multiple form factors and configurations suitable to roof, street or wall deployments.
    - The EtherHaul™ 8010FX product provides multi-gigabit P2P connectivity, operating in the 70/80GHz band.

[28] See: https://www.cambiumnetworks.com/

[29] See: https://www.siklu.com/

- Siklu has recently announced a strategic partnership agreement with Signify to add Siklu's MultiHaul™ TG multi-gigabit wireless connectivity technology to Signify's BrightSites portfolio and has already announced several deployments.
- Siklu also offers its SmartHaul™ solutions that cover the complete life cycle from network designs to hands-off SON operations.

- **Wireless Coverage Ltd**[30] provides one of the FWA industry's leading cloud-based radio planning software tools, enabling fast and efficient deployment of fixed wireless networks.
    - The WISDM™ product represents a new disruptive 'breed' of radio planning software – providing highly accurate and practically useful analysis results, and efficient user-friendly access.
    - WISDM™ uses high efficiency fast processing algorithms to compute radio propagation paths in combination with highly detailed 3D terrain maps and property profiling. WISDM has a distinct advantage over other modelling tools by utilising 25cm LIDAR terrain mapping and rendering from tree growth databases.
    - The company also offers consulting services, to support on development of radio plans and commercial system deployment strategies.

Other network equipment providers offering FWA products include:

- **Radwin Ltd**[31], an established FWA equipment vendor, with office locations including in Israel, and the US. The company produces P2MP and mesh products supporting the sub-6GHz and 60GHz bands.
- **Mimosa Networks**[32] (acquired by Airspan Networks Inc in 2018), a US-based vendor offering a range of gigabit capable FWA products covering the sub-6GHz bands. In 2021, the company launched its A6 WiFi 6E, 802.11ax gigabit capable P2MP access point, using 1024 QAM, OFDMA, channel bonding, MU-MIMO and beamforming technologies, operating in the 5.150-6.425GHz band.
- **Wireless Excellence Limited**[33] (CableFree™), a UK-based firm, offering a variety of radio networking products including sub-6GHz P2MP MIMO OFDM radios, and 60GHz & 70/80GHz P2P links, as well as P2MP 4G LTE MIMO equipment capable of operating in the 3.8-4.2GHz band.
- **Cambridge Broadband Networks Group Ltd**[34] (CBNG), another UK-based firm, offering P2MP licensed band microwave radios for middle mile access with its VectaStar™ product range.

[30] See: https://www.wirelesscoverage.com/

[31] See: https://www.radwin.com/

[32] See: https://mimosa.co/

[33] See: https://www.cablefree.net/

[34] See: https://www.cbng.co.uk/

- **Ubiquiti Inc**[35], a US-based equipment vendor which offers a range of networking products including its LTU P2MP gigabit capable product, which operates in the 5GHz band.
- **Redline Communications Inc**[36], an established Canadian developer of FWA equipment, with an interest in providing digital infrastructure for remote and harsh environments. The company's Ellipse™ series of products offer OFDM MIMO capability in the sub-6GHz bands.
- **Intracom Telecom** (division of Intracom SA Holdings), which develops a range of FWA network equipment, with its main office in Greece, including P2MP solutions supporting the 24.25-29.50GHz band.
- **WeLink Communications Inc**[37], a US-based equipment vendor and wireless ISP operator. The company uses 60GHz mesh radio products and gigabit routers to provide gigabit capable broadband last mile connectivity. WeLink has interests in the UK market via its WeLink Communications (UK) Ltd entity, based in Harrogate.
- **MikroTik SIA**[38], a Latvian network equipment manufacturer, founded in 1996 with the focus of selling equipment in emerging markets. There have been reports of cybersecurity vulnerabilities in the company's products. The company provides products for the sub-6GHz and 60GHz bands.
- **IgniteNet**[39] (subsidiary of Accton Technology Corporation[40], Taiwan), which offers a range of gigabit capable FWA products supporting P2P, P2MP, and meshed operation in the 60GHz band.
- **Adtran Inc**[41], a US-based provider of networking equipment with a history of developing products to serve the fixed line and full fibre industry. The company has recently entered the wireless mesh FWA market, with introduction of its 60GHz gigabit capable Metnet™ product line.
- **SIAE Microelettronica SPA**[42], an Italian provider of networking equipment. The company provides a range of products focused on wireless backhauling (i.e. middle mile) solutions.
- **Curvalux UK Limited**[43] (subsidiary of US-based Airspace Internet Exchange Inc[44]), a relatively new company, with a focus on multi-beam phased array wireless broadband (WiFi) access technology, operating in the 5GHz band.

[35] See: https://www.ui.com/

[36] See: https://rdlcom.com/

[37] See: https://welink.com/

[38] See: https://mikrotik.com/

[39] See: https://www.ignitenet.com/

[40] See: https://www.accton.com/

[41] See: https://www.adtran.com/

[42] See: https://www.siaemic.com/

[43] See: https://curvalux.com/

[44] See: https://airspaceix.com/

- **Aviat Networks Inc**[45], a US-based firm focused on the wireless transport (P2P, middle mile) sector.

2.2.3 Terragraph technology

Terragraph is a wireless mesh technology[46], based on the IEEE 802.11ay standard, developed by Facebook Connectivity (Meta Platforms Inc), and a number of equipment vendors including Cambium Networks, Siklu, and Radwin.

Designed for operation in the 60GHz V-band, fully or partially meshed local networks can be configured, providing multi-gigabit capacity, extended range and network resilience.

In some respects, Terragraph can be viewed as a type of wireless Ethernet, enabling local radio-based access networks across neighbourhood rooftops or street furniture.

We note that use of the term ‘5G’ here, again, can be misleading: some vendors and operators refer to Terragraph products as 5G FWA. Strictly, this is not correct, as 5G New Radio (NR) chipsets and radio physical layer specifications are not included. A better term covering both 5G-based FWA and Terragraph is ‘gigabit capable wireless’.

2.3 What drives market demand?

As the equipment supply chain has continued to mature in the FWA sector, so has market interest – driven by demand for broadband and gigabit capable internet access.

Demand for gigabit 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 (30Mbps) levels).

Our own analysis of Ofcom Connected Nations data sets[47] from 2015 onwards has shown the patterns of adoption of superfast broadband over time. Comparing with other factors, the only meaningful relationship identified is the previously available broadband speed. In the past, where users had speeds previously below a certain level: 5Mbps, adoption was very strong – 97% adopted superfast as it became available. In the same analysis, some adoption was noted for <10Mbps, but above 10Mbps there was lower observed churn to new services. In addition, in areas where ultrafast

[45] See: https://aviatnetworks.com/

[46] 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.

[47] See: https://www.ofcom.org.uk/research-and-data/multi-sector-research/infrastructure-research

was available, only 11% of users chose it – the majority simply went with mainstream products and default infrastructure.

This dynamic is typical and well-known: adoption of new technologies takes time, as users 'discover' new benefits, and migrate from old ways, and old technologies.

As time moves on, so do broadband requirements. The reference points at 5Mbps and 10Mbps, described above, are now of course dated, but the behavioural characteristics still stand. In today's market, demand for new broadband services at superfast and ultrafast quality levels is high in areas without these, but lower in areas with good quality FTTC services in place.

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 and services, new use cases, and continued growth in the digital economy and with online services.

It is notable that in some countries, demand has moved beyond gigabit levels. For example, in the Swiss market, 10Gbps services are now regarded as the desirable quality level in broadband access.

In the UK, roll-out of 10Gbps capable XGS-PON technology is becoming established.

3 Gigabit wireless in the marketplace

3.1 Demand for gigabit services is growing

The case for high quality digital connectivity, whether via wireless or full fibre networks, is well-established, with clear evidence available[48] showing the benefits of digital services for modern service-based economies. The need for access to digital networks and services at high quality levels has only been endorsed and proven further with the global pandemic and geopolitical instabilities across the world.

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, with one key initiative being the UK Government's Project Gigabit, which is providing an initial £1.2bn of public gap funding to support gigabit connectivity in areas lacking in commercial investments.

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 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. Even with four TVs running per household, that is only around 10% of the capacity of a 1Gbps connection. The counter argument is that download time matters: gigabit connections provide fast user access to high data volume services, and again – 'we are building for the future'. There is also a need for capacity headroom where wholesale access networks are built, and there is a requirement for these in the Project Gigabit technical specifications.

But then, if gigabit capability *and* fast and economically attractive roll-out is possible, commercial cases start to become very interesting.

Gigabit performance with FWA networks is explored further below.

3.2 Gigabit capable FWA deployment scenarios

Gigabit capable FWA networks are attractive in a number of market situations:

- In rural areas, where the cost structure associated with network deployment is more attractive than with FTTP networks.

[48] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0025/113299/economic-broadband-oecd-countries.pdf

- As a direct alternative to full fibre FTTP networks, with potentially lower network-related costs – depending on design characteristics (e.g. gigabit capable FWA to city high streets, with FWA hubs associated with street furniture). Such deployments can open up new routes to market, increasing competition – to the advantage of end users.
- For nomadic and vehicular[49] applications, such as with public and private sector vehicles in urban areas, and for provision of gigabit connectivity to areas such as event spaces.
    - Bypassing of cellular networks can enable reduced costs for public authorities and private operators, and provide higher data throughputs than possible with 5G mobile systems operating over sub-6GHz bands.
    - Various use cases are of interest to public authorities and private network operators, including: internet and IOT connectivity to monitor buildings and assets (smart cities), security camera video uploads from vehicles, traffic management applications, digital connections for social care situations, internet for users in the community, and educational and healthcare support services.

3.3 FWA network architectures

Network architecture designs will vary according to a number of factors including: geography and terrain types, population density and sparsity levels, access to backhaul (trunking) networks, and access technology types used. Other important factors include network contention (service overbooking) levels, traffic growth levels, and network resilience and redundancy requirements.

We consider two main deployment scenarios below, with focus on last mile access:

- Use of sub-6GHz FWA networks at the local level in rural areas; and
- Use of 60GHz FWA networks in non-rural areas.

In both cases, we assume that FWA radio hub sites are supported by full fibre (FTTX, fibre to the mast, local backhaul). Access to full fibre at the regional trunking level is readily available in many areas (e.g. via leased full fibre bitstream services, such as Openreach EAD10000 circuits in the UK market), and typically the main challenge is last mile access.

In all cases, to ensure full independence in our reporting, we use FWA equipment specifications and network designs based on practical commercial situations in today's markets, whilst maintaining anonymity on equipment suppliers, products, and operator networks. Our assessments are based on years of experience in working with FWA equipment vendors, operators, and investors in design and deployment of networks in commercial situations, not hypothetical scenarios.

[49] Vehicular applications can be supported using FWA technology in static and nomadic situations, e.g. with parked vehicles near to street furniture – where radio connections can be established. This type of application has good potential to reduce costs and improve performance over cellular alternatives.

Main internet backbone peering (colocation) sites are typically located in major cities. Therefore, backhaul costs are usually driven significantly by geographic distances from access networks to backbone city hubs.

Redundancy in local backhaul networks is preferable (albeit with increased costs), to avoid single points of failure and major incidents affecting many end user premises at any one time. With packet networks and redundant network designs, data packets can be routed via available network paths to maintain customer services, even when some network links may be damaged or impaired.

3.4 FWA network dimensioning and performance

Radio network dimensioning at the access level is governed principally by coverage and data capacity requirements. Both of these are tied to market requirements, as well as radio technology types and performance levels.

Coverage (and hence range to user premises) per FWA radio hub site is dependent on a number of factors, including terrain types, radio clutter levels, radio band, antenna types, radio transmitter power levels, and receiver sensitivity (i.e. radio ‘quality’; read ‘cost’). Essentially, radio link designs must provide enough radio power at a receiver, relative to radio noise levels, to ensure adequate performance. To design links with adequate performance levels, radio engineers use a technique called radio power link budget analysis (i.e. the radio power ‘books’ must be ‘balanced’).

Data capacity in FWA systems is dependent on the type of radio technology and modulation order used, use of array antenna MIMO methods, available radio spectrum bandwidth, and radio link power levels. Data capacity per user is a function of the FWA hub site loading level (i.e. number of users per hub site).

With FWA systems, the quality of radio transmission paths plays a critical part in ensuring that services meet required quality levels. Line of sight (LOS) measurements and Fresnel zone calculations[50] are used in radio planning, to ensure that links are properly designed to meet needs.

3.5 Cost structure in FWA networks

Cost structure in FWA networks is dependent on unit costs and volumes used (i.e. ‘P*Q’ approach, unit equipment pricing and quantities used).

In typical deployment projects, build-out and release of capital from investors is indexed to volumes of customers (i.e. premises) passed and connected.

Annual network-related operations costs are typically a function of the cumulative volume of network equipment deployed in any one accounting period.

[50] When designing LOS radio links, calculation of the Fresnel zones ensures that path degradation is effectively controlled, by minimising radio clutter objects inside the zone, which can cause destructive interference.

In practical network operations businesses, there will be additional non-network-related costs (e.g. taxes, sales and marketing costs, staff salaries, overheads).

In developing investment cases, it is essential to develop an accurate view of cost structure and revenues, which is only possible with robust underpinning analysis at the technology and market levels.

3.6 FWA rural scenario, using 3.8-4.2GHz band products

We consider a rural coverage scenario, with a new greenfield FWA network deployment. We include backhaul to internet backbone peering in a major city. Our assessment is based on the UK market.

Rural areas in the UK are classified according to UK Government categorisations[51].

According to UK Government data, around 18% of residents in England live in areas classified as rural, and rural areas make up 85% of the land area. With a total of 24.7m dwellings in England (March 2020 data), and total land area at 130,279 km^2, average density of premises in rural areas in England is around 40 premises/km^2.

Top-down analysis on market areas in the UK can be developed using Local Authority District (LAD) classifications. There are over 300 LADs across the UK (approximately equivalent to ceremonial county or sub-county scale)[52]. For our analysis, we take the LAD of Ryedale in North Yorkshire, largely rural[53], which has a relatively high number of premises unable to access broadband internet at speeds above 30Mbps. Ryedale covers an area of 1507km^2, with c. 30k premises in region. Average density is 20 premises/km^2.

Subscriber take-up levels will be affected by market factors including: service pricing, quality of legacy services, competition, and marketing campaigns. Whereas long-term take-up levels on gigabit services in the UK market are somewhat unproven, given the developing state of the market, current market data[54] indicates take-up levels on gigabit services at around 25%. We expect churn levels to remain at nominal levels, until the gigabit market matures (with increased retail and wholesale level competition).

In our experience of working with UK network operators, market penetrations of around 50% are expected at around five years into build programmes. This is based on evidence of market development with FTTC roll-out, with FTTC penetration at around 75% in mature areas. As the

[51] See: https://www.gov.uk/government/collections/rural-urban-classification

[52] See: https://geoportal.statistics.gov.uk/documents/local-authority-districts-counties-and-unitary-authorities-april-2021-map-in-united-kingdom-/explore

[53] See: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/591466/Local_Authority_Districts_ranked_by_rural_and_rural-related_populations_with_Rural_Urban_Classification.pdf

[54] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0035/229688/connected-nations-2021-uk.pdf

market 'settles' it would not be unreasonable to expect the FTTP and FWA penetration level to increase, in line with that for FTTC. These figures are consistent with other UK gigabit programmes that we are aware of; conservatively, we have seen 45% penetration used in other similar investment cases at the 5 year point, with this increasing to around 75% at 10 years.

We assume that modern P2MP FWA equipment is deployed in the access network, in accordance with Ofcom regulations[55,56] for the band, for the medium power 3.8-4.2GHz licence:

- Maximum of 100MHz bandwidth;
- Unlimited antenna height (subject to local planning regulations);
- Maximum base station power (EIRP) per sector: 42dBm/carrier for carriers ≤20 MHz; or 36dBm/5MHz for carriers > 20 MHz;
- Maximum terminal CPE station (TRP[57] for mobile/nomadic[58] or EIRP for fixed/installed): 28dBm TRP or 35dBm/5MHz EIRP.

3.7 FWA non-rural scenario, using 60GHz band products

We further consider a non-rural coverage scenario, also with a new greenfield FWA network deployment. We include backhaul to internet backbone peering in a major city. Our assessment is again based on the UK market.

In line with the above, around 82% of residents in @wirelEngland live in areas classified as non-rural, and non-rural areas make up 15% of the land area. With a total of 24.7m dwellings in England (March 2020 data), and total land area at 130,279 km^2, average density of premises in non-rural areas in England is around 1036 premises/km^2.

For our analysis, we take the LAD of Wakefield in West Yorkshire, classified as 'urban with city and town'. Wakefield covers an area of 339km^2, with c. 160.3k premises in region. Average density is 472 premises/km^2.

We assume subscriber take-up levels as above, though these can be varied in our model.

[55] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0033/157884/enabling-wireless-innovation-through-local-licensing.pdf

[56] See also: https://www.ofcom.org.uk/__data/assets/pdf_file/0035/157886/shared-access-licence-guidance.pdf

[57] TRP: Total Radiated Power from an antenna. Typically, TRP is lower than the Transmitter Power Output (TPO) which is usually measured at the input to a transmit antenna, after the final amplification stage (i.e. TRP = TPO less some physical losses due to the antenna itself).

[58] i.e. isotropic.

In this case, we assume that modern meshed FWA equipment is deployed in the access network, in accordance with Ofcom regulations[59,60] for the 60GHz band:

- Unlimited antenna height (subject to local planning regulations); and
- 55dBm EIRP, 38dBm/MHz EIRP density and a transmit antenna gain ≥ 30dBi.

[59] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0023/218129/2021-LE-exemption-statement-final.pdf

[60] See: https://www.ofcom.org.uk/__data/assets/pdf_file/0025/203767/spectrum-access-ehf-licence-guidance.pdf

4 Investment cases and key financial metrics

We present an investment case and key financial metrics for practical commercial deployments of FWA networks in rural and non-rural situations.

Performance and cost data will of course vary across different FWA product vendors, and with system designs. Our assessments are based on current commercially available equipment, with reasonable practical design assumptions applied.

4.1 Investment case approach

Our analysis is focused towards the access network, though we include local backhaul costs (with full fibre to the FWA site (FTTX)). We exclude regional backhaul costs, internet backbone colocation costs, non-network related costs, and CPE costs[61].

This approach ensures focus on key cost drivers, enabling a level of comparison between gigabit capable fixed wireless access solutions and full fibre (FTTP).

We adopt product specifications and costs from selected FWA network equipment data sheets and supplier information, maintaining vendor anonymity to preserve independence.

Assumptions on network architecture designs are derived from discussions with commercial operators. In addition, we apply our own knowledge of the FWA and telecoms industry to sense-check and qualify data, and develop designs.

4.2 Project Gigabit technical specifications

The UK Government Project Gigabit technical specifications[62] provide a useful baseline on the 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 feasible and legally feasible*.
- Gigabit data speed requirements:
    - Download line speed capable of at least 1Gbps (i.e. peak line speed);
    - Minimum available download speed of 330Mbps at busy hour;
    - Minimum upload speed of 200Mbps;

[61] CPE costs and customer site installations may be charged to customers in some cases (i.e. no subsidies applied).

[62] See: BDUK Supplier Briefing Session, January 2021 and revisions.

  - Busy hour speed to be available for at least 95% of the busy hour (see Appendix).
- No degradation with take-up requirement: data speeds should be maintained as the number of customers connected increases[63].

There remain some ambiguities in these specifications, meaning that the market is free to decide on full design details.

4.3 FWA for gigabit capable connectivity in rural areas

4.3.1 Gigabit capable FWA link range and coverage

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

- Carrier frequency: 5G NR band n77u (TDD), covering the 3.8-4.2GHz band.
- Channel bandwidth: 100MHz.
- Tx EIRP: 48dBm / 100MHz carrier, in line with Ofcom regulations.
- 2T2R (2x2 MIMO) (using cross-polarisation via 'one' antenna).
- Receiver sensitivity: -59dBm[64].
- Receiver net front end gain (incl. 14dBi antenna, 2dB cable losses): 12dB.
- Maximum allowable path loss (MAPL): 119dB.

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 of 119dB. Without line of sight, range could be lower.

For the Ryedale 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).

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[63] Addressable with site upgrades, as traffic demand increase over time.

[64] i.e. Received Signal Level (RSL) of -59dBm or better required.

4.3.2 Link capacity performance (peak)

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 1Gbps using 256QAM modulation over a 100MHz channel bandwidth. This requires a receive signal level (RSL) of -59dBm 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 200Mbps (with a symmetric link design).

4.3.3 Link capacity performance (mean under load at busy hour)

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;
- any oversubscription that is applied in traffic aggregation at the local backhaul level;
- the scale of the MIMO / MU-MIMO antenna designs applied in the link design.

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

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).

Assuming an available system throughput of 1Gbps per sector-carrier over a 100MHz spectrum bandwidth, spectrum efficiency is around 10bps/Hz[65]. 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).

4.3.4 Capital cost per FWA site

Based on dialogue with sub-6GHz 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 £350 (complete FWA site).

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

4.3.5 Investment case for gigabit capable FWA for a UK rural area

With the above design parameters, we have modelled a full commercial deployment of a gigabit capable FWA network for a rural area of the UK, such as Ryedale, with total market scale at around 15k connected premises.

Our model uses commercial and technical data reflective of market conditions, based on dialogue with vendors, operators, and our own extensive analysis of the UK FWA and FTTP market.

For local backhaul, we assume an FTTX (fibre to the FWA site) mesh model, with aggregation to single hop regional 10Gbps backhaul links leased at open market prices (Openreach EAD10000 circuits, including FTTP pricing supplements[66]).

Internet backbone peering is assumed via the regional backhaul links to a colocation datacentre located in a main city (e.g. Leeds).

IT (BSS/OSS) systems are included, based on cloud-native applications, as is now typical in the market.

Revenues, plus capital and operational costs are included, plus 10% cost contingency.

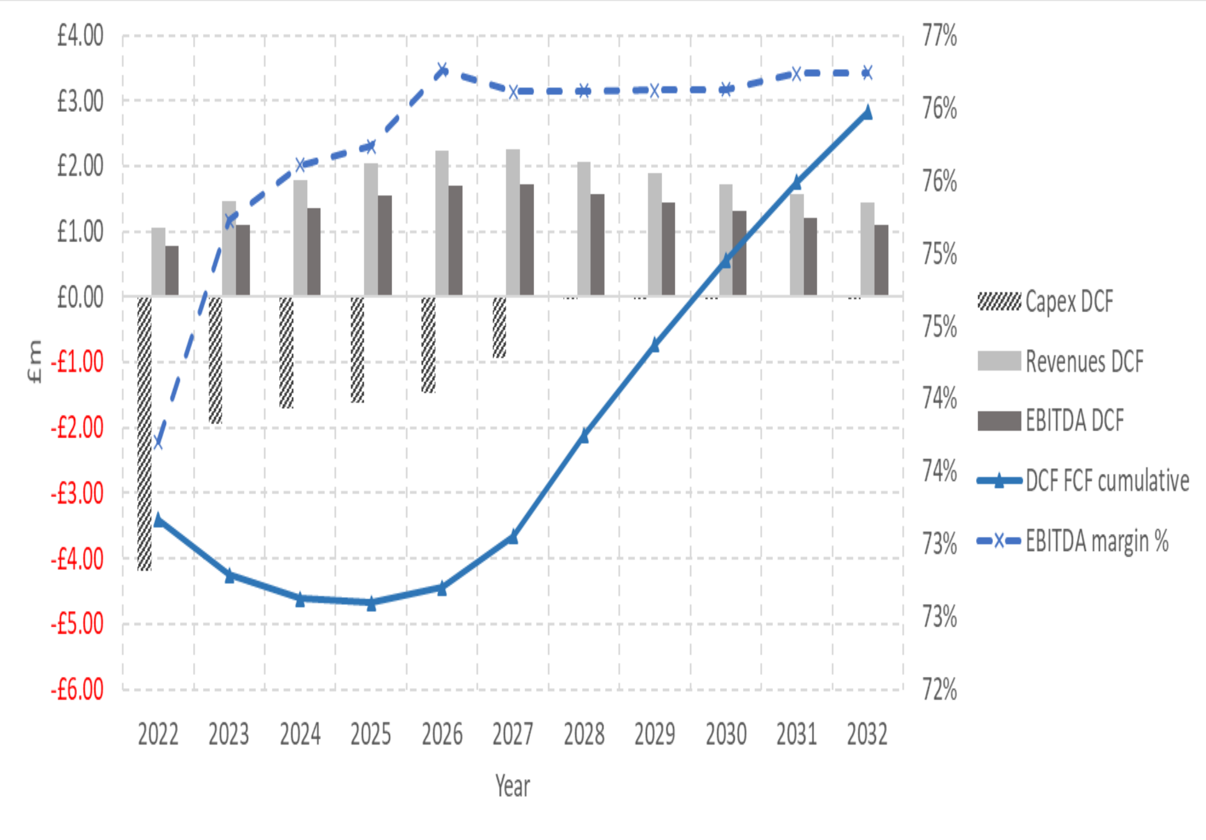
[65] This is somewhat better than system level spectral efficiencies with 5G mobile networks, possible due to the directional gain antennas used with FWA networks, which enable greater use of higher order modulation schemes across the 'cell' area.

[66] See: https://www.openreach.co.uk/cpportal/products/ethernet/ethernet-access-direct

CPCP is modelled at £341 (FWA included, FTTX links excluded).

EBITDA margin is healthy at over 70%, and payback is attainable at around 7 years.

Figure 4.1: Investment case for gigabit capable FWA for a UK rural area (illustrative)



Analysis: Peira Consulting.

4.4 FWA for gigabit solutions in non-rural areas

For the non-rural case, the methodology as above applies, but radio design parameters are different, as below.

4.4.1 Gigabit capable FWA link range

We assume a generic typical FWA point to multi-point radio link, with the following parameters:

- Carrier frequency: 802.11ay Terragraph (TDD), covering the 60GHz (V) band.
- Channel bandwidth: 2160MHz.
- Tx EIRP: 55dBm, in line with Ofcom regulations.

- Receiver sensitivity: -59dBm[67].
- Receiver net front end gain (incl. 30dBi antenna, 2dB cable losses): 28dB.
- Atmospheric losses at 60GHz (oxygen, rain attenuation): est. 25dB.
- Maximum allowable path loss (MAPL): 117dB.

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 300m at the acceptable MAPL of 117dB. Without line of sight, range could be lower.

4.4.2 Link capacity performance (peak)

We use vendor data which indicates a link (uplink or downlink) throughput capability of 1Gbps using 16QAM modulation per 1000MHz channel bandwidth.

This requires a receive signal level (RSL) of -59dBm or better.

4.4.3 Link capacity performance (mean under load at busy hour)

With a meshed radio design, using 30dBi antennas, individual user premises will be supported over the meshed radio network, i.e. with peak gigabit capability throughput.

Degradation could occur at busy times due to congestion on the network mesh, with similar terms as above, although channel bonding can be used to improve capacity for users. Meshing also enables higher user capacities where link distances are short, and additional nodes can be added at will, rendering meshing a highly flexible design approach – useful where market conditions are changing. Further, mesh networks need not be designed homogeneously, enabling further flexibility to market needs.

With a meshed FWA network, the number of connected premises will affect the available mean capacity per connected user at the busy hour. We estimate that 20-25 connected users will be supported with a 1Gbps mesh, in line with the technical specifications as above.

A higher volume of connected users could be possible if backhaul capacity greater than 1Gbps were deployed (e.g. 2 x 1Gbps local backhaul links at separate points across the radio mesh).

4.4.4 Capital cost per FWA site

Based on dialogue with 60GHz mesh FWA operators, we assume costs as: £150 per CPE unit, and £1k per mesh radio unit (at volume) (4 x 90 degree sectors, typically up to 15 CPE per sector).

[67] i.e. Received Signal Level (RSL) of -59dBm or better required.

Mesh networks will typically be designed with a mix of mesh radio units and CPEs, and thus capital costs for the access network will be driven by area coverage requirements and the density of mesh nodes deployed (depending on mesh node range).

With meshing, we estimate that capital cost per connected premises (CPCP) can be around £100 (radios only, at volume, excluding site hardware) (CPEs not capitalised, subject to sufficient backhaul capacity to meet market needs).

Meshed radio networks are also attractive from a resilience perspective, and can provide higher throughput capacity at the user level (subject to network loading conditions).

Another benefit is with network capacity, which can be developed flexibly with implementation of active and latent backhaul nodes which can be switched on as capacity demand increases.

5 Investor perspectives

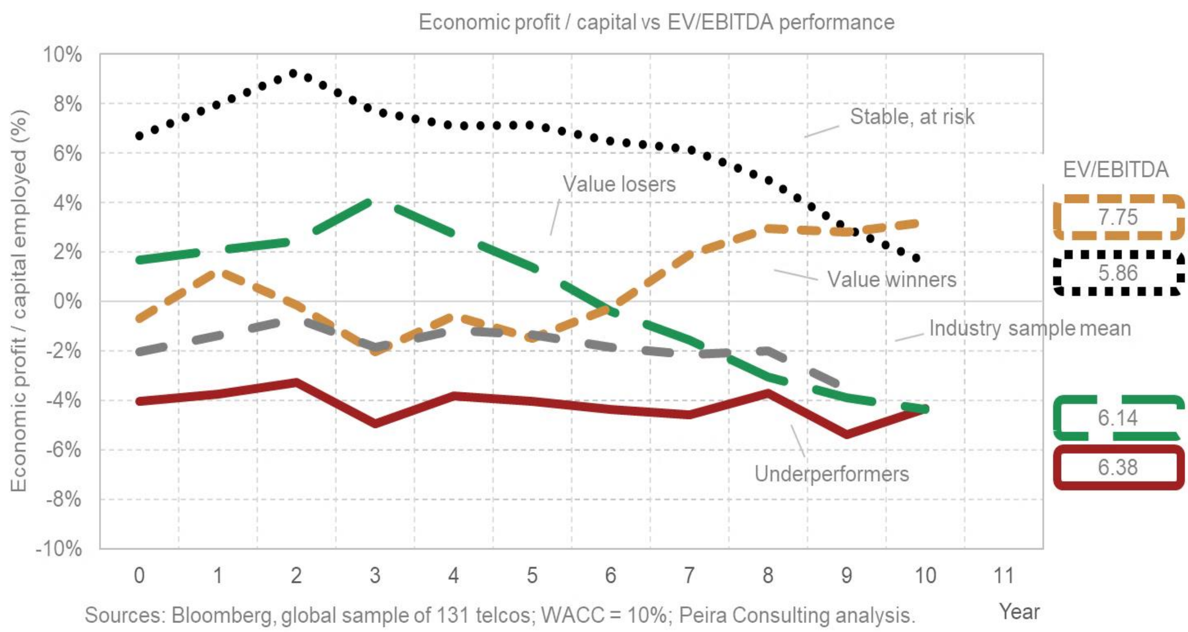
Below, we provide comments on key investor interests, namely: development of economic value, and risk management, applicable to FWA systems.

5.1 Development of economic value

Investors of course seek value from their investments, and value is typically defined with EV/EBITDA multiples, where EV is essentially the market value of a firm (as opposed to book value; also EV is adjusted for debt and cash levels). For some time, multiples on telco firms have been significantly lower than those with digital services players such as Microsoft, Google, Apple, and others. This is reflective of the markets' views on growth. Valuation multiples tend to rise when investors see evidence of past growth (in EBITDA margins) and there are firm expectations of future growth.

Put another way, market value tends to run higher for those telcos able to produce a level of consistent economic profit (calculated in the standard way as net operating profit after tax, less a charge on capital employed) (see Figure 5.1 – sample analysis of over 100 telcos: by segmenting market performance according to economic value trends, it becomes evident that market value tends to run higher for those telcos able to produce a level of consistent economic profit (EVA[68])).

Figure 5.1: Market value accrues for telcos with sustained EBITDA growth and strong ROIC



[68] EVA (Economic Value Added) is an indicator of profitability and a measure of financial performance, based on residual wealth. It is the excess profit above the cost of capital, generated by the business, adjusted for taxes, and presented on a cash basis. EVA = NOPAT – (WACC * Invested Capital). NOPAT = Net Operating Profit After Tax.

Analysis aside, our own practical work with investors supports this; investors tend to seek economic value from investments – borne out with proven and sustainable EBITDA growth, and good returns on capital invested (ROIC).

FWA systems can support a route to economic value, with time and cost to market improvements over those for full fibre networks in particular cases, as illustrated above.

It is worth noting that such returns depend as much on solid operational performance as they do on effective commercial models and good strategic plans.

5.2 Managing risk effectively

Whilst the level of engagement with management will vary across investors, from our direct experience of working with investors in the UK and other markets, there tends to be a strong requirement for focused delivery to agreed targets, to ensure management of risk. This means strong focus on key metrics, heavy use of reliable data to support business strategy and operations, and adherence to core business activities (i.e. per agreed targets with investors, without too much divergence).

- With capital funding on infrastructure projects, investors are typically strongly focused on realisation of value, and risk management.
- Practically, in our experience, this means firm management on:
    - Volume of passed premises delivered against capital released;
    - Capital cost per premises passed and connected (against industry norms); and
    - Quality of target market (ensuring take-up levels, aversion to overbuild, focus on markets of sufficient scale).
- Typical metrics of interest to investors, based on our experience with investors in due diligence work, are shown below:
    - Addressable market: number of homes and businesses unserved by full fibre or cable.
    - Competition by other operators to addressable market, and impact on addressable market over time.
    - Achievable penetration (retail and wholesale), including assessment of overbuild risk by another Full Fibre operator (if, where and when) and the impact on likely penetration over time.
    - Achievable ARPU (retail and wholesale) including an assessment of multiple services offering.
    - Expected churn.
    - Capital cost per property passed (CPPP).
    - Capital cost per property connected (CPPC) including costs both for retail and wholesale.

- Gross margin.
- EBITDA margin, including past and projected growth levels.
- Market or economic value (EV).
- EV/EBITDA multiple.
- Debt and equity ratios.
- Clarity and management on funding sources (e.g. commercial, with gap / PPP funding).
- Capex/sales ratio.

6 Looking ahead: what's next for wireless and FWA?

6.1 Market developments

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. And the need for mobility varies; users now consume wireless services across a variety of spaces: from indoors, to high speed vehicles. With each new generation, operators are faced with increased challenges of managing return on capital invested to viable levels. The accepted approach is not sustainable. A new approach is needed which meets developing demands effectively.

The 3GPP technical standards group is continuing its work on 5G[69]; 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, 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. The next wave of 3GPP Releases 17 and 18, currently in planning, can be expected to drive 5G product releases over the 2020-25 timeframe.

Development on 5G and 6G wireless technology is continuing with clear recognition that the economics of radio networks are reaching a point of inflexion where new approaches are required. The engineering challenge in designing any one system such as 5G to serve all market segments is increasing. Therefore, as 5G and 6G continue to develop, wireless capacity levels will be related to environments served, radio bands used, and market demands. Practically, this can be expected to evolve with network 'layers' with focus on indoor areas, urban markets, and wide area coverage, with 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 very high gigabit wireless capacity cannot be expected for the whole of the UK landmass, but must be targeted at key regions and vertical segments, according to focused demand and where economic 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. Increased market access and competition, with regional shared spectrum access, will provide important consumer benefits and remove the innovation log-jam that has long existed with the cellular industry. FWA and FTTX *together* will support the development of pervasive gigabit connectivity for the whole of the UK.

[69] See: https://www.3gpp.org/release-17

6G will provide advanced services through combinations of ultra-high definition sensors and devices, edge processing 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 links, and cloud-native networking – supported by edge and core datacentres.

Hence, the opportunity for investors and operators with FWA is increasing. Winners are likely to be those able to effectively scale up, and develop new commercial models with neutral hosts, and carrier-neutral segment-focused datacentres, leveraging regional shared spectrum access.

6.2 Policies and regulation for new wireless systems

The wireless industry value system continues to evolve, with significant developments from the large global technology firms such as Google, AWS, Dell, and Microsoft now further entering the telecoms sector with cloud native solutions on core networks, IT stacks, and at the digital services, content, and application platform levels. Further, large technology players are investing heavily in backbone infrastructure such as international subsea cables to reduce their conveyance costs. All of this stacks up to further undermine the established incumbent telecoms industry, which many would argue has been slow to innovate against the internet giants. Other very significant changes are in radio spectrum management, spectrum being a key resource for any wireless system.

Spectrum sharing, now present in the industry in limited form can be expected to develop further with new technologies such as AI, with dynamic spectrum access (DSA) now being codified into regulations in some leading jurisdictions. Regional and shared access to spectrum must be developed further to ensure a path to vibrant competition in the wireless industry. Other changes will arise due to novel technologies including software defined networks, cluster and edge computing, data centre developments, and new 6G technologies.

We see innovation, enabled by new entrants and start-ups, as an engine for growth in the UK's developing digital economy and a means for access to capital to drive build-out, whether this be in full fibre for 5G backhaul and dense coverage, or in novel wireless networks. Without it and effective competition, the result, as evidenced by the MNOs is a race to the bottom on data pricing, and value added services and content provided by offshore internet giants.

National coverage is best left to national players where lower radio bands are most economically efficient. Higher radio bands, especially those above 6GHz, should be made available to the market for regional use, at reasonable cost. However, in cases where national spectrum lies fallow, it should be made available to those who see application under reasonable terms and conditions.

As the wireless industry continues to develop, with innovations in spectrum sharing, regional licensing, release of new millimetre radio bands, increased competition, and new commercial models, wireless industry stakeholders have direct interests in providing and supporting these and other novel solutions, which will provide economic, consumer, and social benefits across the whole of the UK.

We see good opportunities for those able to capitalise on release of new gigabit capable radio spectrum bands, build strategic relationships with equipment suppliers, leverage key technologies such as DSA and MIMO, and forge new commercial models addressing specific market segments.

7 Conclusions

One of our main objectives has been to assess the value and risk with FWA and new wireless systems, as the market continues to develop.

- Does FWA present a window of opportunity, that is steadily closing as full fibre gets progressively built out, or does the technology offer value in the long term?
- Where does FWA offer most value for investors and operators?

Our focus has been towards the UK market, but FWA technology offers potential in markets across the world; key differences across jurisdictions include: availability of radio spectrum via regulatory processes and licensing, and market variations (including demand levels, infrastructure availability, and terrain types).

To the first question. With the availability of gigabit capable FWA solutions, we do not see a market closure issue. Rather, we see a positive shift in the market, with growth in new applications and market solutions that are uniquely facilitated by wireless systems – including vehicular data connectivity, gigabit connections for outdoor areas and event spaces, and support for smart cities. These new opportunities will augment the more established and continued application of FWA networks, where cost structure and time to market can be superior to fixed line and full fibre solutions in ‘hard to reach’ areas (e.g. with sparsely located premises in more rural areas, and where cabling may not be possible for a variety of logistical, administrative, and financial reasons). Whilst it is not correct to state that FWA can replace FTTP networks, like for like, and without qualification, FWA can provide gigabit capable solutions that can match the performance of FTTP networks in some key dimensions – such as data capacity. In all cases, technology solutions should be considered carefully against well-defined business objectives, and sweeping comparative and high-level statements on relative performance are of little use.

To the second question, we have addressed this in part above; FWA solutions are of great practical commercial value where the cost structure of full fibre networks prevents attractive investment cases at the regional level. Capital cost per connected premises with new build FTTP programmes escalates as sparsity across premises and network hubs increases. Practically, this means that FWA solutions can be very valuable in sub-urban and rural areas. However, new gigabit capable FWA systems operating in the EHF bands provide new valuable solutions for urban areas also. Noting that FTTP build will continue to progress in many areas, and that the relative scale of demand in rural areas in mature markets can be limited, we see good value for investors with FWA systems in:

- non-urban markets which do have attractive scale (e.g. developing or mainly rural regions); and
- mature and developed markets where is there is proactive engagement, and good demand and support towards new commercial models which require wireless solutions (e.g. gigabit connectivity for vehicles, smart city solutions, gigabit services for event spaces).

Appendix: 95% busy hour requirements

Increasingly, policy makers and regulators require some level of quality of service to be met. This could be associated with access to gap funding, or to meet regulatory requirements.

In the UK's Project Gigabit programme, technical specifications are set requiring that minimum data speeds shall be met for at least 95% of the busy hour period.

There is thus a need to take this quality of service (QoS) requirement into account with network design.

Capacity dimensioning on networks can be approached in various ways. A simple approach often adopted in high level designs or with high level strategic planning is based on traffic averages: in any given cell with N users, each consuming c Mbps, the total required capacity of the cell C can be estimated simply as C=c*N.

At a high level, the approach is not unreasonable, as commercial packet radio networks adopt scheduling algorithms at the layer 2 MAC level (such as the proportional fair – PF scheduling algorithm) which aim to apportion the total radio resources available to all users on a fair (i.e., averaged traffic) basis.

However, in reality, user traffic levels are not constant; they can vary due to user demand and channel conditions and location of users within a cell. With quality of service requirements, it is also important to ensure that network dimensioning is sufficient – taking into account these factors.

There will invariably be bursts within the measurement interval that are above the average rate. If traffic bursts are sufficiently large, temporary congestion may occur, causing delay, jitter, and loss, which may result in the violation of SLA commitments even though the link is, on average, not 100 percent utilised. To ensure that bursts above the average do not affect the SLAs, the actual bandwidth may need to be overprovisioned relative to the measured average rates.

A key capacity planning consideration is therefore to determine the amount by which bandwidth needs to be overprovisioned relative to the measured average rate, in order to meet a defined SLA target for delay, jitter, and loss. The overprovisioning factor required to achieve a particular SLA target depends on the arrival distribution of the traffic on the link, and the link speed.

Opinions remain divided on what arrival distribution describes traffic in IP networks. One view is that traffic is self-similar, which means that it is bursty on many or all timescales (that is, regardless of the time-period the traffic is measured over, the variation in the average rate of the traffic stream is the same). An alternative view is that IP traffic arrivals follow a Poisson (or more generally Markovian) arrival process.

For Poisson-distributed traffic, the longer the time period over which the traffic stream is measured, the less variation there is in the average rate of the traffic stream. Conversely, the shorter the time interval over which the stream is measured, the greater the visibility of burst or the burstiness of the traffic stream. For Poisson traffic, queuing theory shows that as link speeds increase and traffic is more highly aggregated, queuing delays reduce for a given level of utilisation. For self-similar traffic, however, if the traffic is truly bursty at all timescales, the queuing delay would not decrease with increased traffic aggregation.

However, while views on whether IP network traffic tends toward self-similar or Poisson are still split, this does not fundamentally affect the capacity planning methodology we are describing. Rather, the impact of these observations is that, for high-speed links, the overprovisioning factor required to achieve a specified SLA target would need to be significantly greater for self-similar traffic than for Poisson traffic. A number of studies[70], both theoretical and empirical, have sought to quantify the bandwidth provisioning required to achieve a particular target for delay, jitter, and loss, although none of these studies has yet been accepted as definitive.

To address these issues, the established approach in packet network capacity dimensioning is with inclusion of a 'safety margin' (i.e. capacity over-dimensioning) in the network design, intended to prevent packet blocking, and to accommodate variance (i.e. positive or negative bursts) in traffic rates away from the mean. A de facto (or 'rule of thumb') approach for this has emerged in the network engineering community, with such a margin typically set at +30%; i.e., the network would be dimensioned at 1.3 times that of the expected average aggregated use[71].

Higher variance in traffic rates (i.e., more bursty traffic) is characterised by greater variations of data rate (in any short sample period) from the long-term average data rate. If the network is not sufficiently dimensioned on capacity to cope with a number of bursts that could occur, then data packets will be lost, and data packet blocking occurs. Greater variance indicates that higher safety margins will be required. The problem with such an empirical approach is that in general it is not obvious how to choose the right safety margin. In general, the burstier the traffic, the larger the safety margin needed to ensure a design to meet the stated QoS levels.

In addition, network usage at the busy hour or busy time must be taken into account, as well as any expected growth in traffic usage over time (given a defined planning time period).

Accurate dimensioning of networks is thus important, and with obvious commercial and economic implications, it is important to ensure that any approach on network dimensioning is reasonably accurate, taking into account defined QoS parameters (such as delay, delay-jitter, packet loss, service availability, and throughput). Over-dimensioning on links will lead to economic inefficiencies; under-dimensioning will result in congestion and QoS target failures – and economic inefficiencies.

Given the variations in internet and mobile traffic, statistical methods can be useful in developing more accurate approaches for network dimensioning. Research in this area has led to quantitative

[70] See Schmidt, van den Berg, and Pras, (2015). Measurement-based network link dimensioning. Proc. of IFIP/IEEE, 2015.

[71] See: Alasmar and Zakhleniuk (2017). Network Link Dimensioning based on Statistical Analysis and Modelling of Real Internet Traffic. Available at: https://arxiv.org/pdf/1710.00420.pdf

expressions for internet link capacity, as in the work from Pras et al[72], assuming Gaussian traffic[73] (the Pras/Meent formula):

$$C(T,\varepsilon)=\mu+\frac{1}{T}\sqrt{(-2\log\varepsilon)\cdot v(T)}.$$

Where:

- ε represents the fraction of time T where the offered traffic exceeds the link capacity C.
- ε thus represents the packet loss ratio; at a 5% packet loss level, ε=0.05.
- μ represents the mean data rate of the data stream, over a long time average period >> T.
- T represents the time period over which the statistics of the data stream are measured.

$v(T)$ represents the variance (square of the standard deviation) in the traffic data rate, measured over the time period T. The variance is a function of the period T. For applications such as web browsing and IP video, T periods of around 1 second or so have been used to gain insight on granular burstiness of data traffic streams.

Though more accurate than the de facto approach, the challenge with the Pras/Meent method is in obtaining accurate measurements on the data rate standard deviation or variance. Using real-world measurements, Pras et al indicate a safety net value of around 35% of the long term mean, although higher safety net levels could be possible depending on the data statistics[74].

A 2020 analysis also using real-world measurements, carried out by Cisco/Telkamp, suggests provisioned link bandwidth should be 1.42 times the average link utilisation (in other words, a safety net figure of up to 42%) .

We conclude that, in the absence of very detailed statistical information to describe data flows over the selected network, a reasonable overprovisioning factor is 1.4 (i.e. a +40% safety net).

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[72] See: Pras et al (2009). Dimensioning Network Links: A New Look at Equivalent Bandwidth. IEEE Network March/April 2009.

[73] See: The assumption of Gaussian traffic is discussed in Schmidt, Sadre, and Pras (2013). Gaussian traffic revisited. Proc. of IFIP Networking, 2013. Available at: http://dl.ifip.org/db/conf/networking/networking2013/SchmidtSP13.pdf

[74] See: Pras et al (2009).

Glossary of terms

A non-exhaustive glossary of terms is provided below:

CPCP	Capital cost per connected premises
CPE	Customer premises equipment (i.e. user terminals)
DSA	Dynamic spectrum access
EHF	Extra high frequency (radio bands)
EIRP	Effective isotropic radiated power (with radio systems) (dBm)
FTTC	Fibre to the (street) cabinet
FTTX / P	Fibre to the node / premises (full fibre)
FWA	Fixed wireless access (networks)
IOT	Internet of things (also, machine to machine communications – M2M)
LEO	Low Earth Orbit (satellites)
LOS	Line of sight (in radio systems deployment and planning)
Mesh (network)	Network architecture with many end users connected together
mmW	Millimetre wave (radio bands)
MP2MP	Multi-point to multi-point (radio links)
MU-MIMO	Multi-user multi-input multi-output (array antenna systems)
P2MP	Point to multi-point (radio links)
P2P	Point to point (radio links)
PoP	(Network) point of presence
R&D	Research and development
RSL	Received signal level (dBm)
TRP	Total radiated power (dBm)

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