3 Technology review and modelling assumptions

This section includes a discussion of the broadband technologies that will be capable of delivering download speeds of at least 1Gbit/s to subscribers by 2025. We review the performance of each technology and the economics of deploying it. We also present the technology-related assumptions that we have made in our cost modelling.

We believe that four access technologies will be capable of delivering speeds of 1Gbit/s or more by 2025:

- **fibre to the premises (FTTP)** based on point-to-point (PTP) or passive optical networking (PON) architectures
- **cable (hybrid fibre-coax)** systems running the latest DOCSIS[13] standard
- future **wireless broadband** technologies
- high-capacity **satellite** systems.

High-capacity satellite systems are expected to continue to play a role connecting sites that are outside the footprint of terrestrial networks, or where there are specialist user requirements that cannot be met by terrestrial networks. However, this study focuses on the technologies likely to be used for mass deployment, and therefore satellite is not discussed further in this report.

For completeness, we have also included a description of **fibre to the node (FTTN)**, which includes fibre to the cabinet (FTTC) and fibre to the distribution point (FTTdp). These architectures allow the use of very-high-bandwidth technologies such as G.FAST over very short copper loop lengths. The technology is still being trialled and an ability to deliver speeds of 1Gbit/s on a large scale has not yet been developed[14]. However, it is expected to be widely deployed by operators, and therefore we consider it to be relevant to this study.

We discuss the key technical and economic features of each technology in a consistent way, highlighting the factors that may affect their attractiveness and usability. For each technology we have produced a summary with the following elements:

Overview	Each technology is introduced, including an overview of its capabilities and deployment characteristics.
Connectivity performance	The connectivity performance is discussed, including the expected improvements due to standards development in the future. The evolution of speeds is also considered, including the actual speeds received by end users (e.g. peak vs. average speeds).

[13] Data Over Cable Service Interface Specification.

[14] Over connections less than 100 metres, G.FAST can currently provide 600Mbit/s of aggregate capacity (downlink plus uplink).

Economics of deployment	We have outlined any relevant issues relating to the economics of deployment, including relative deployment costs and the factors that affect the cost of deployment.

3.1 Fibre to the premises (FTTP)

3.1.1 Overview

An overview of FTTP architecture is shown in Figure 3.1.

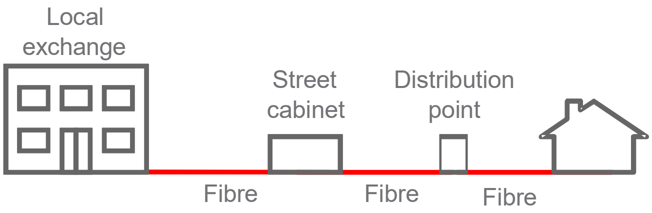


Figure 3.1: Overview of FTTP architecture [Source: Analysys Mason, 2016]

FTTP is a term used to define fibre deployments to individual premises. These ‘full’ fibre network architectures may be broadly divided into:

- PTP active networks (usually Ethernet-based), in which *separate* fibres run from the local exchange to *each* customer.
- PON, which allows a *single fibre* from the exchange to supply a passive splitter to which *multiple end users* are connected by their own individual fibre.

FTTP is regarded as a future-proof solution for high-bandwidth services, including video. Besides its high speed, its strengths include lower maintenance costs than copper networks and connectivity performance which is unaffected by distance from the exchange.

3.1.2 Connectivity performance

PTP

Fibre-based PTP technology is already able to provide 1Gbit/s broadband services and has the potential to provide up to 100Gbit/s (symmetrical) broadband services in the future, making it future-proof. We expect that by 2025, PTP fibre architectures will comfortably be able to deliver 10Gbit/s to each end user, provided each end user has a dedicated fibre connected to the exchange. This architecture provides an uncontended connection in the access network, and we consider it most likely to be required to connect locations at which multiple individual users require connectivity (e.g. schools, medium-sized businesses or wireless base stations), thus providing a natural aggregation of demand.

PON

PON technology is based on the sharing of capacity between multiple end users. The current standard (GPON[15]) allows 2.5Gbit/s to be shared on a frequent basis between 64 users, which gives a download speed in the 10–100Mbit/s range, depending on the activity of other users. Future variants of the technology have the potential to offer much higher capacities, and PON has a strong evolutionary path through the use of new variants of the PON specifications. Although bandwidth is often shared by up to 64 users (or maybe more), these potential improvements make the technology quite future-proof.

The expected evolutionary path of PON has recently been revised. Previously, WDM[16] PON was previously being considered for residential use, and would have allowed each end user to receive a dedicated wavelength. However, this has been discounted by the FSAN standards organisation[17] for large-scale (i.e. residential) use due to the high costs involved.[18] Accordingly, at present the evolutionary path for PON is expected to be:

- GPON: 2.5Gbit/s of total shared download capacity
- Medium-term upgrades, referred to as next-generation PON or NG-PON1: 10Gbit/s total shared download capacity
- Longer-term upgrades, referred to as NG-PON2 (also known as TWDM[19] PON): 4 × 10Gbit/s of total shared download capacity.[20]

With a TWDM PON access architecture, and assuming a 64-way split, each user could receive a minimum of 625Mbit/s, with peak speeds well above 1Gbit/s. This variation between peak and guaranteed speed is due to the shared nature of the connection that PON provides, and therefore we consider PON most likely to be used to connect locations at which a small number of end users require connectivity (e.g. home workers, small businesses and residential users).

3.1.3 Economics of deployment

Cost of passive assets

The cost of deploying FTTP is higher than for FTTC due to the need to lay much more fibre, and the fact that the final connection into the premises is frequently not ducted in the copper networks that are being replaced by fibre. The cost per user is lower for multi-tenanted premises (providing

15 The ITU-T's G.984 Gigabit-capable Passive Optical Networks (GPON) standard.

16 WDM = Wavelength Division Multiplexing.

17 FSAN = Full Service Access Network group; see https://www.fsan.org/

18 WDM PON requires the existing PON splitters to be upgraded to wavelength multiplexors and more expensive lasers in the active electronics, which would affect the cost of customer premises equipment in particular.

19 TWDM = Time Wavelength Division Multiplexing.

20 TWDM PON uses only four wavelengths on the PON (compared to 64 for WDM PON if there were 64 users). These wavelengths are used to increase the total capacity of the PON but are shared by all users, and can be applied as an overlay to existing GPON or NG-PON1 services. Crucially, TWDM PON can be deployed without needing to upgrade the splitter deployed out in the field.

there is an adequate internal distribution network) and can also be reduced through the use of aerial fibre and self-installation techniques.

In its 2013 study for the Commission,[21] Analysys Mason estimated the cost of deploying new duct for FTTP by taking a reference cost of duct deployment for the UK, and then adjusting this for other Member States based on the relative labour rates in each country. For the present study, we have updated the relative labour rates and the base cost for the UK, based on inflation. A comparison of the assumed duct deployment costs between this study and the previous study is shown in Figure 3.2 (for selected countries only).

Figure 3.2: Duct deployment costs per metre for selected countries (EUR per metre) [Source: Analysys Mason, 2016]

Country	Previous study	Current study
Belgium	127	108
France	111	96
Germany	97	87
Italy	87	79
Poland	23	23
Romania	14	13
Slovenia	47	43
Spain	67	59
Sweden	126	104
UK	65	62

Cost of active equipment

Our monitoring of the evolution of the cost of PON equipment shows that every five year, the active components can be upgraded with four times the capacity but at the same cost as the previous generation. This is broadly in line with the current trend in bandwidth capacity, which quadruples every five years (CAGR 30%). The unit cost assumptions for active equipment for the fibre deployments is shown in

Figure 3.3: Unit cost assumptions for fibre active electronics [Source: Analysys Mason, 2016]

Technology	Unit cost (EUR)	Notes
PON	17,765	Cost per OLT at each generation of technology; each supporting 8 fibres with up to 64 users on each (512 users)
PtP at 1Gbit/s	4,788	Cost per Ethernet switch supporting 48 users

[21] See footnote 1.

3.2 Cable

3.2.1 Overview

An overview of cable (hybrid fibre coax, or HFC) architecture is shown in Figure 3.4.

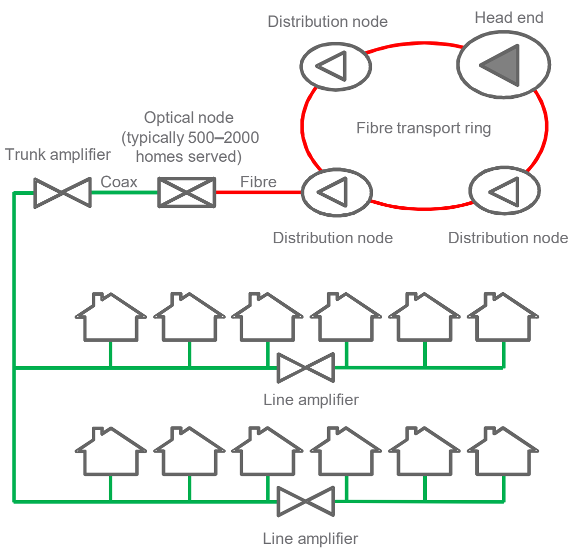


Figure 3.4: Overview of cable (HFC) architecture [Source: Analysys Mason, 2016]

Cable infrastructure provides broadband services using a standard known as DOCSIS, which was developed by CableLabs. The ITU-T has approved various versions of DOCSIS as international standards. Modern cable networks are based on an HFC architecture, with the premises on a coaxial bus which may incorporate line amplifiers to maintain adequate signal levels along its length.

The depth to which fibre penetrates the cable network varies between operators, but for high-speed broadband each coaxial tree will typically pass 500–2000 homes (only a minority of which may subscribe), located within around 500m of the optical node which forms the interface between the fibre and coaxial media. Cable operators can typically increase the depth of fibre penetration at relatively low cost if take-up of high-speed broadband services is leading to congestion on the coaxial portion of the network.

As with FTTC and FTTP, the deployment of cable-based broadband is driven by the desire to offer triple-play services.

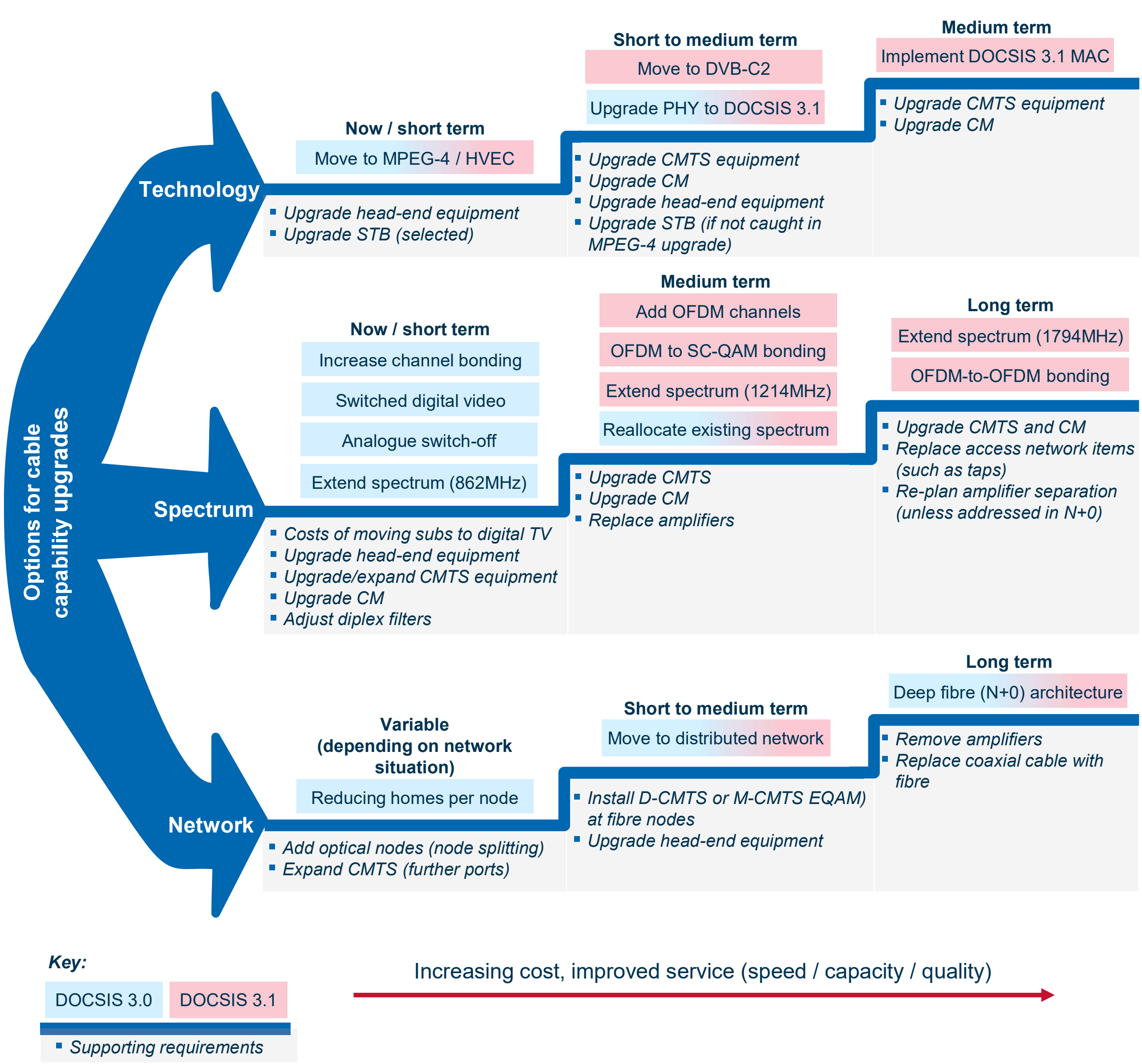
Cable service is not currently available in Greece or Italy.

3.2.2 Connectivity performance

Many cable operators already offer more than 100Mbit/s (downlink) broadband services using DOCSIS3.0, and the bonding of additional channels is able to push this capacity towards 500Mbit/s. The introduction of DOCSIS3.1 will provide downlink speeds of up to 10Gbit/s per segment for all cable services, a significant proportion of which is likely to be available for broadband.

The options for upgrading HFC networks fall into three categories, namely technology, spectrum and the network, as summarised in Figure 3.5.

Figure 3.5: Summary of upgrade options available to HFC operators [Source: Analysys Mason for Ofcom, 2014[22]]



It should be noted that each segment of the network typically serves hundreds of households, so a number of users are likely to be sharing the same bandwidth. The introduction of DOCSIS3.1 technology (which provides more bandwidth) and other measures such as reducing the number of homes per segment by adding additional optical nodes ('node splitting'), moving the cable modem

22 Source: http://stakeholders.ofcom.org.uk/binaries/research/technology-research/2014/cable-sfbb.pdf

termination system to all optical nodes and the further extension of fibre closer to users could all be expected to increase the bandwidth and hence the speed per end user.

There is a clear evolutionary path for HFC to provide increased speeds, and therefore it is future-proofed. We expect that by 2025, cable networks will be able to deliver peak speeds of 10Gbit/s. Similar to a PON network, the shared nature of the connection in the access network will create a variation between this peak speed and guaranteed speed provided to each end user.

3.2.3 Economics of deployment

The cost of upgrading an existing digital cable network footprint to higher DOCSIS standards is relatively low since the amount of fibre involved is typically similar to, or less than the amount of, fibre required for FTTC, while the cabinet electronics are less expensive on a per-subscriber basis because the cost is shared between all of the users on the bus. Nevertheless, the cable operator will have to overcome challenges across each of the three upgrade areas: technology, spectrum and the network.

The cost of expanding the coverage of cable networks is, however, high since it typically requires new ducts to be installed. In countries that already have high cable coverage we would expect cable to be laid to new housing developments. In countries with low or medium cable coverage, there may be limited expansion to peripheral areas, but expansion to near-universal coverage seems unlikely. In the countries that have no cable networks at present, we think it highly unlikely that cable networks will be installed.

3.3 Fibre to the node (FTTN)

3.3.1 Overview

An overview of FTTN architectures is shown in Figure 3.6.

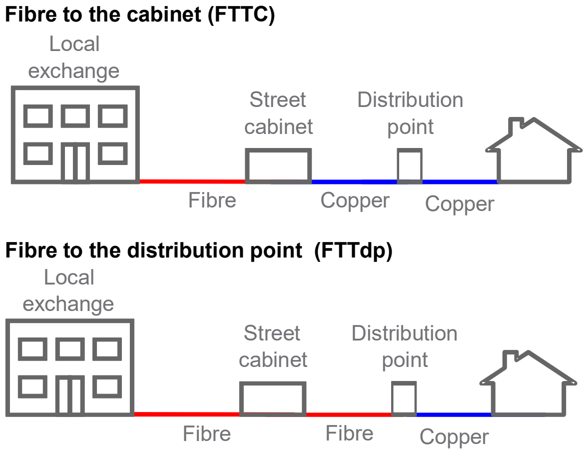


Figure 3.6: Overview of FTTN architectures [Source: Analysys Mason, 2016]

FTTN refers to fibre deployments to a street cabinet or distribution point with short copper sub-loops for the final drop to the subscribers' premises; these final connections usually run a variant of DSL technology such as VDSL.[23] FTTC combined with VDSL2 is being deployed widely, and offers significantly higher maximum speeds than ADSL2+ over short distances (up to around 1000m), and equivalent performance over distances in excess of around 1500m. In practice, most commercial FTTC/VDSL deployments are aiming for maximum length of around 500m for the copper sub-loops, which means that the vast majority of end users can benefit from next-generation broadband speeds.

A further development of FTTC is fibre to the distribution point, or FTTdp. This pushes fibre even closer to the end user and allows the use of G.FAST, a DSL technology offering even higher bandwidths over short sub-loops. G.FAST can also be deployed in cabinets that are close to customers' premises.

3.3.2 Connectivity performance

The speed of broadband connectivity provided over copper networks is limited by the length of the copper line. This means that in an area covered by FTTN, there will be a (potentially wide) variation in the speeds received by users. In recent years, operators have reduced the length of the copper line by installing FTTC and operating VDSL over the shorter copper line. Operators are further upgrading the capabilities of FTTC/VDSL networks by using a noise cancellation technique known as *vectoring*.

Beyond vectoring, there are further options for increasing the speed available over copper access lines. One is to deploy G.FAST technology (discussed above), while another is the use of additional bonded pairs (either in straightforward combination of the separate pairs or using 'phantom mode').[24] The use of additional pairs is difficult in many countries due to a lack of existing spare pairs in the copper network and the additional operational complexity that such an approach introduces. The deployment of G.FAST is therefore attracting interest among incumbent operators, with combined upstream and downstream speeds of 600Mbit/s being quoted. However, these speeds are likely only achievable if fibre can be brought to within 100m of the end user.

While copper-based technologies are not *currently* suitable for providing 1Gbit/s connectivity, we consider FTTN relevant to the present study because (a) research and development activity is continuously pushing the capability of copper-based technology; and (b) the fibre deployed by commercial operators to support FTTN could be re-used for providing 'full' fibre connections, and should be considered when calculating the total cost for each connectivity option.

3.3.3 Economics of deployment

FTTN can be much less expensive to deploy than FTTP if equipment is installed at the cabinet, but costs increases when equipment is deployed closer to the customer, e.g. at the distribution point.

[23] VDSL = Very-high-bit-rate DSL.

[24] When two pairs are bonded there are two signal wires and two ground wires, whereas in phantom mode there is one ground wire and three signal wires, which provides additional capacity.

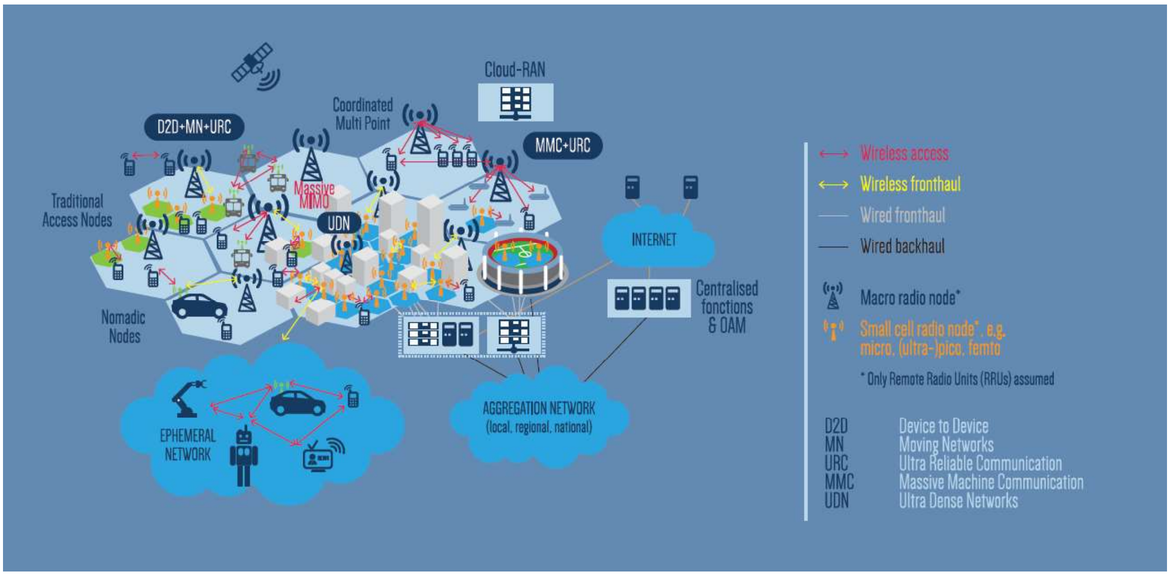
It should also be noted that the economics of sub-loop unbundling at the *cabinet* are considerably less attractive than for local loop unbundling (LLU) at the *exchange*: the distribution of lines per cabinet can be much flatter than the distribution of lines per exchange, and therefore an unbundling operator is no longer able to address a large proportion of the population with a relatively small number of unbundling locations.

3.4 Future wireless broadband technologies

3.4.1 Overview

An overview of a future wireless architecture is shown in Figure 3.7.

Figure 3.7: Overview of future wireless architecture [Source: 5GPP (Vision document)[25] and European Commission, 2016]

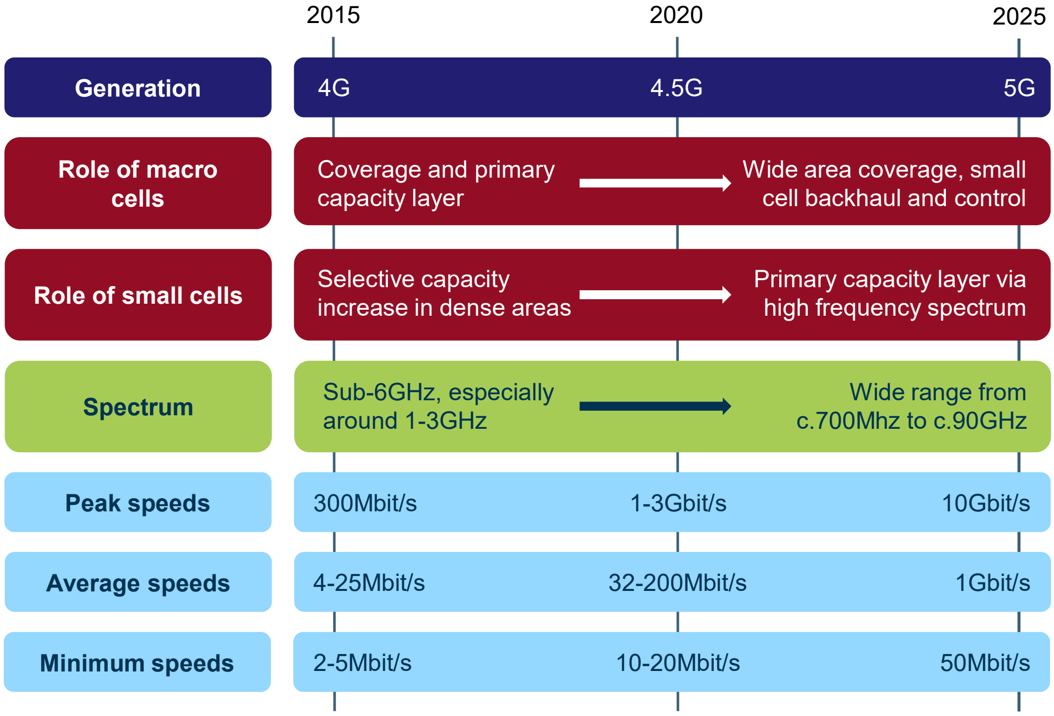


In this study we are considering the evolution of 4G and introduction of 5G networks together as being representative of how mobile networks will evolve to provide faster speeds, greater availability and connectivity. In practice, until the detailed standards for 5G are defined, it is not possible to define more precisely what the capabilities of 5G networks will be.

This technology evolution is considered along with the evolving nature of key infrastructure elements: macro cells and small cells. A summary of the expected evolution is shown in Figure 3.8.

[25] Full document available at: https://5g-ppp.eu/wp-content/uploads/2015/02/5G-Vision-Brochure-v1.pdf.

Figure 3.8: Summary of future wireless evolution [Source: Analysys Mason, 2016]



Overall, we expect a gradual evolution of deployment from 4G to 5G, with an accompanying evolution of the role of different network elements (macro cells vs. small cells), spectrum needs and the associated speeds delivered to users. In the following sections we provide more commentary on the characteristics of 4G and 5G technologies.

4G wireless networks

Long term evolution (LTE) represents the current version of the GSM family of mobile technology standards from the UMTS standards body, 3GPP. LTE represents a shift from the wideband code division multiple access (WCDMA) technology used in UMTS and HSPA networks to a downlink based on orthogonal frequency division multiple access (OFDMA) and an uplink based on single carrier frequency division multiple access (SC-FDMA). It is an all-Internet protocol (all-IP) technology in both the core and access sub-networks and offers significant performance improvements compared with legacy networks.

The designation LTE refers to Release 8 and Release 9 of the 3GPP standards, which are already implemented in commercial networks, while LTE-Advanced (LTE-A) refers to Release 10 and beyond, which is currently being rolled out by many operators worldwide. The reason for the change in designation is that Release 10 meets the requirements set by ITU-R for IMT-Advanced, while Release 8 and Release 9 do not.

A large number of spectrum bands have been specified for LTE use, but in the short to medium term in Europe the technology is predominantly being deployed in the 800MHz, 1800MHz and 2.6GHz bands. The 800MHz band is ideal for both rural LTE deployments and providing indoor coverage in dense urban areas because of its superior propagation characteristics, compared to the higher bands. The higher bands, by contrast, offer better capacity by virtue of the increased bandwidth that is available, and so provide the bandwidth necessary for operators to increase the peak download speeds from their networks towards the upper end of the speeds shown in Figure 3.8 above.

Because of the change in access technology, considerable investment has been made by mobile operators to upgrade UMTS or HSPA networks to LTE. Some further investment in hardware and software is required to achieve the full benefits of LTE-A, over initial LTE services.

The continued growth in use of mobile data services and strong competition in the 4G market has resulted in a rapid acceleration from LTE to LTE-A, such that most operators in Europe are already deploying carrier-aggregated LTE-A services (and initial Release 8/9 LTE networks are already becoming obsolete). Hence, despite the associated costs, it is apparent that operators value the benefits of LTE-A in terms of being able to offer higher peak speeds. LTE-A typically involves upgrading networks to enable carrier aggregation (CA) to occur between either contiguous or non-contiguous carriers, which is feasible for most network operators, providing they have sufficient spectrum available. Operators are marketing these high-speed LTE-A services by using terms like 4G+, 4G++, 4.5G, or double speed, evoking notions of speed and advanced technology.

5G wireless networks

The standard for 5G mobile technologies has not been defined yet, but there is strong debate and discussion in the industry on what the specifications should be. Technology trials are focusing on using advanced antenna techniques to increase downlink capacity and speeds, and using extremely high frequency 'mm-wave' spectrum bands,[26] much higher than those currently used by mobile services, in order to ensure that wide contiguous channels are available. However, it is clear that the spectrum needs for 5G will extend beyond mm-wave, and a range of other frequency bands (both existing mobile bands, and possibly new ones) will be needed to provide the necessary coverage and reach for 5G networks, as is the case for 3G/4G today.

There are a number of goals for 5G that go far beyond improved download speed[27]. These include:

- more capacity
- lower latency
- more mobility (i.e. connectivity on transport routes and at high speed)
- more accuracy of terminal location
- increased reliability and availability.

5G networks are being proposed to provide very high peak downlink speeds in ultra-dense environments, but also to provide mobile broadband services to a range of vertical network industries including automotive, energy, food and agriculture, city management, government,

[26] These bands fall in the range of so-called millimetre-wave frequencies – see page 51 below.

[27] 5G PPP (Heidelberg, Germany, 2015). The 5G Infrastructure Public Private Partnership: the next generation of communication networks and services. Available at http://5g-ppp.eu/wp-content/uploads/2015/02/5G-Vision-Brochure-v1.pdf.

healthcare, manufacturing and public transport. These vertical industries do not necessarily require the highest peak downlink speeds to meet their requirements, but will require networks to provide sufficiency capacity, reliability and availability to meet robust performance requirements.

We expect that any 5G network deployment will happen after 2020[28] with commercial availability between 2020 and 2025.

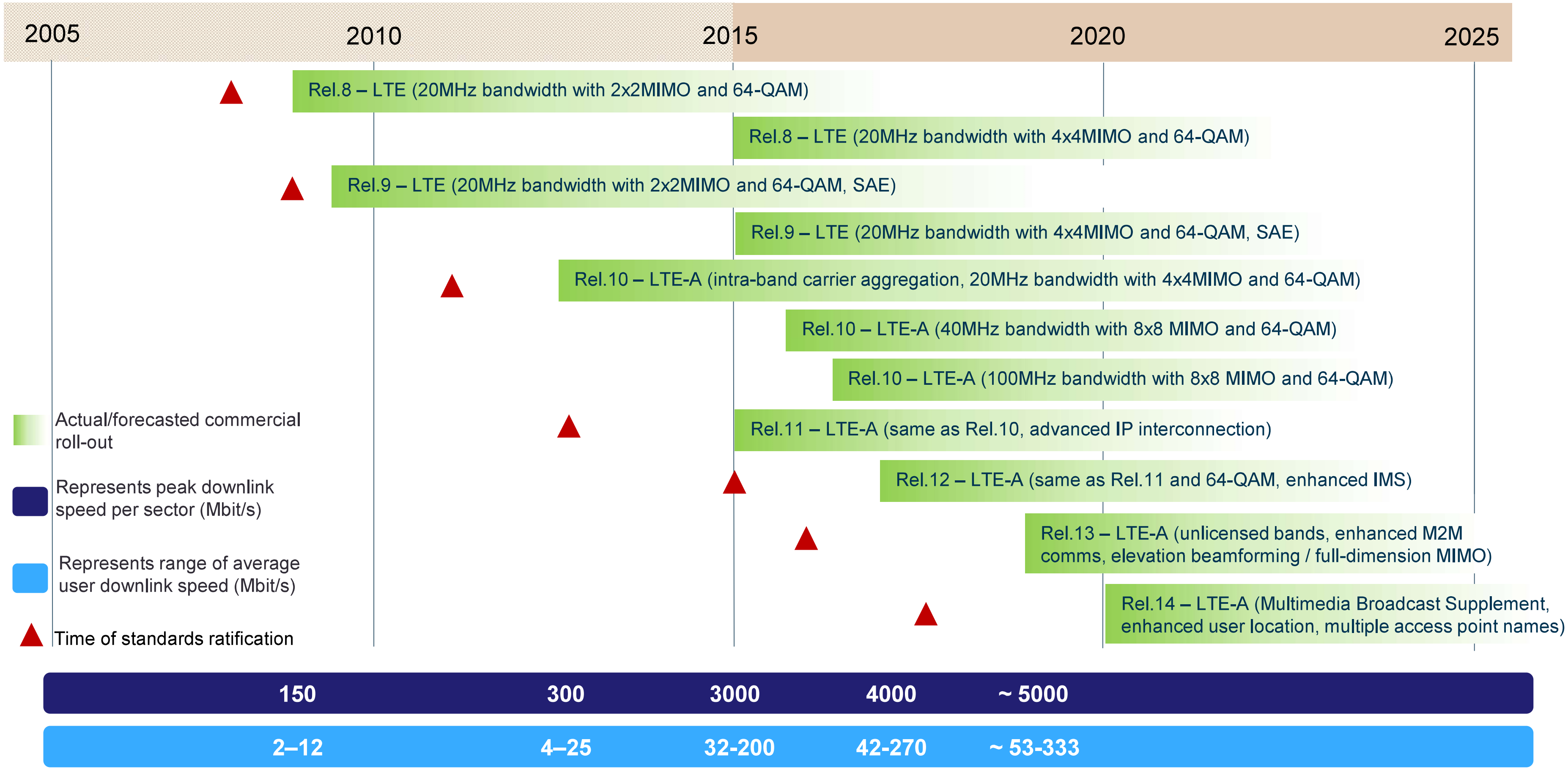
3.4.2 Connectivity performance

4G wireless networks

LTE-A can provide 300Mbit/s (downlink) broadband services, depending on the category of user equipment and the amount of spectrum used. LTE has a strong evolution path supported by all industry players, as it has been or is being adopted by the largest wireless network operators. The technology roadmap for LTE is shown in Figure 3.9; this is focused on increasing the carrier bandwidth and the use of multiple antenna arrays (MIMO) to increase speeds.

28 http://www.analysysmason.com/About-Us/News/Newsletter/5G-spectrum-Oct2014/#13%20October%202014

Figure 3.9: Roadmap for LTE technology [Source: Analysys Mason, 2016]



5G wireless networks

There are a large number of use cases being considered for 5G, but there are three main aspects of service that we may note here:[29]

- *Continuous user experience*: users will be able to access the network anywhere (urban/rural, indoors/outdoors, stationary in-motion), and the 5G system will select the best access method from a range of different technologies (e.g. 4G, Wi-Fi, new technologies).
- *Internet of Things*: 5G will provide a platform to connect a massive number of objects to the Internet.
- *Mission-critical services*: public safety services (which were previously operated on separate networks) can be carried on 5G due to the high performance available. Vehicle-to-vehicle and vehicle-to-road services will also be possible.

5G technology is being developed to meet a stringent set of quantitative technical capabilities, as shown in Figure 3.10.

Figure 3.10: Summary of 5G target technical capabilities [Source: 5GPP and European Commission, 2016]

Capability	Target value
Peak data rate	10Gbit/s
Guaranteed data rate	50Mbit/s
Mobility	500km/h
Number of devices	1million/km^2
Energy efficiency	10% of current consumption
Service deployment time	90 minutes
Reliability	99.999%
E2E latency	5ms
Mobile data volume	10Tbit/s/km^2
Accuracy of outdoor terminal location	1m

A number of the capabilities shown are not necessary for us to consider further in the present study. However, the data rate targets for 5G *are* directly relevant; these are subject to certain cell spectrum and size requirements, as discussed below.

[29] 5G PPP (Heidelberg, Germany, 2015). The 5G Infrastructure Public Private Partnership: the next generation of communication networks and services. Available at http://5g-ppp.eu/wp-content/uploads/2015/02/5G-Vision-Brochure-v1.pdf

3.4.3 Economics of deployment

Macro-cell equipment costs

Macro cells will continue to be an important element of future wireless networks, to provide wide area coverage and to provide a supporting layer for small cells, for control and backhaul. A summary of the parameters affecting the economics of macro-cell deployment is shown below.

Figure 3.11: Summary of parameters affecting the economics of macro-cell deployment through to 2025 [Source: Analysys Mason, 2016]

Parameter	Value	Comment
Cell radius	4.0km	Average value across a country; only affects coverage-limited cells in the model Taken from previous study, and assumes sub-1Ghz spectrum is used for coverage
Cell capacity	425Mbit/s per sector average throughput (3 sectors)	Based on the 1Gbit/s peak speeds being discussed for LTE-A Pro[30] We estimate that average throughput will be around 35-50% of peak speeds based on analysis of current technologies. Note: we assume that 5G-type peak speeds beyond 1Gbit/s (e.g. 10Gbit/s) will require small cells and large amounts of higher frequency spectrum
Base station electronics upgrade costs	EUR20 000 per site for interim upgrade EUR40 000 per site for full upgrade	Note: excludes passive infrastructure Includes fully installed/commissioned cost for base station electronics and antenna upgrade to existing sites We assume that two upgrades will be required: one between now and c.2020, and one between c.2020 and c.2025: • The first (interim) upgrade will include increased processing power and support for additional spectrum bands • The second (full) upgrade will include a full hardware refresh Cost is in 2016 terms We assume that each upgrade costs a similar amount, We assume that the upgrades increase capacity/functionality towards the 2025 5G requirements (mobile broadband, machine to machine (e.g. LPWA) and mission-critical applications)

Small-cell equipment costs

A development that is critical to estimating the access network cost of future connectivity is the *increased prevalence of small cells*, leading to ultra-dense networks (UDNs). The very high data and bandwidth requirements of 5G will require large amounts of contiguous spectrum. This requirement will push 5G to use increasing amounts of spectrum at higher frequencies to that used by mobile networks today, including in the 24–86GHz range. This lies in the range often referred

30 Peak speeds of 1Gbit/s have been demonstrated using aggregation of multiple carriers, see: http://www.lightreading.com/mobile/4g-lte/lte-advanced-pro-gigabit-4g-anyone/a/d-id/721036

to as millimetre wave (mm-wave) spectrum,[31] and will be used in addition to spectrum at lower frequencies (including both licensed and unlicensed spectrum bands).

High-frequency spectrum is characterised by a high capacity for data transfer but a low ability to penetrate the atmosphere and physical objects (such as the walls of buildings). This leads to a lower range than lower-frequency spectrum, which has the drawback that cell size is reduced, but the benefit that frequency re-use can be increased.

Small cells are already being deployed for 4G services to increase the capacity of networks. The higher data demands being designed for on 5G and the use of much higher frequency spectrum will see small cells become much more prevalent for 5G services. The key parameters for future wireless small cells are presented in Figure 3.12.

Figure 3.12: Summary of parameters affecting small-cell deployment economics through to 2025 [Source: Analysys Mason, 2016]

Parameter	Value	Comment
Cell radius	200m	Estimated value appropriate for mm-wave spectrum associated with 5G services
Cell capacity	Very high (coverage limited only)	For modelling purposes, we assume that the small-cell deployment will be limited by coverage (as use of mm-wave spectrum gives very high capacity)
Base station costs	EUR1000 per site	Note: excludes passive infrastructure Includes fully installed/commissioned cost for base station electronics upgrade to existing sites Cost is in 2016 terms; we assume that each upgrade costs a similar amount, but increases capacity/functionality towards the 2025 5G requirements (mobile broadband, machine to machine (e.g. LPWA) and mission-critical applications). Cost also includes option for wireless ‘front haul’ on some base stations

Backhaul costs

Backhaul will be a key consideration. Ideally, a fibre connection will be provided to each small cell, but where this is not possible, a wireless fronthaul solution may be used. We test the impact of different proportions of cells using wireless fronthaul in a sensitivity analysis in Section 5.2.3.

Spectrum costs

Spectrum costs are not considered within the scope of this study.

31 Technically, mm-Wave frequencies extend from 30GHz to 300GHz, though 5G will not utilise the full range.