Technology Futures

Spotlight on the technologies shaping communications for the future

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Foreword

The spirit of innovation and decades of pushing technological boundaries have led to the creation of every one of the communication services that we take for granted today.

Whether it's connecting people with fast, reliable broadband so they can work, shop and socialise at home and on the move – or the increasingly diverse range of ways we can now watch high quality broadcast content – technology advances have made what just decades ago would be considered unthinkable, everyday reality.

But these technologies have deep historical roots. The wireless and fibre networks we use today depend on physical principles first established by James Clark Maxwell in 1861, and on mathematical limits developed by Claude Shannon in 1948. And it took another 48 years for Claude Berrou to show how engineers could reach those limits using turbo coding.

We've seen this pattern of early physical and mathematical principles leading to decades of engineering work in computing too. The fundamentals of what can be computed were established by Alan Turing in Cambridge in 1936, and then turned into a practical computer architecture by John von Neumann in 1945. Networked computers communicating through the protocols established by Vint Cerf and Robert Kahn in 1974 led to the creation of the Internet, and the invention of the World Wide Web by British engineer Tim Berners-Lee in 1989.

And with wireless and wired capacity doubling every 18 months from the 1970s into the 21st century, and computing power growing at a similar rate, we have phenomenal growth in data used on mobile, fixed and broadcast systems. Without these advances, the services we rely on today to communicate and get our news and entertainment, simply wouldn't have been possible.

As the UK's independent communications regulator, it's essential Ofcom keeps aware of changing technology. This allows us to consider how these changes can affect the sectors we regulate now, and in the future. And it informs the actions we take to make sure people and businesses in the UK continue to enjoy high quality communications services and are protected from any risks these new technologies pose. We monitor the communications industry closely and many emerging technologies are already well-known to us. But we recognise there will be others that are not, which could still have a major impact on the consumers of tomorrow.

So in spring 2020, we decided to directly ask the world's leading technologists for their views on what the next game-changing technologies could be. We carried out dozens of interviews and also invited anyone with insights and evidence on new technologies to contribute to our research.

Through this process, we discovered a huge range of exciting technologies. Some will lead to new, richer communication experiences, involving immersive technology that enables us to touch, move - and perhaps even smell – at a distance. Others, such as clusters of satellites and new network architectures, could massively expand the coverage, availability, speed and consistency of wireless and wired networks. And some advances might allow optical fibre - in which signals already travel at the speed of light – to carry signals even faster!

New materials, devices and quantum physics, could fire the starting gun for a new wave of engineering advances. And while some of these advances could take decades to come to fruition, others could change the way we communicate in the near future.

This report and the accompanying video content we have produced may be the first output of this work, but it is by no means the end – nor should it be seen as an exhaustive list of every innovative technology being developed. It can be no more than a sample, and the omission or inclusion of any technology shouldn't be taken as a signal of our view of its importance. Nor are these our predictions for the future: this is a summary of the technologies that have been flagged to us by worldwide experts.

But we believe our findings offer a unique insight into how innovation can ensure a bright future for the UK's communications. We will continue to develop our work in this area, leaving no stone unturned as we engage with people and businesses across the communications world to identify the technologies of tomorrow – and what they could mean for you and me as consumers.

So we want to continue this conversation and play our part in helping the communications industry to constantly evolve and innovate.

Finally, I'd like to express our profound thanks to the many experts around the world who have shared their time and inspirational thoughts with us[1].

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[1] See Annexes C and D for a list of contributors.

Contents

Summary

Technology is evolving rapidly across all of the industries Ofcom regulates – bringing new products, services and ways of working for people and businesses. By increasing our understanding of the way technology is changing, we can help make sure these advances benefit people and ensure they are protected from harm.

Scope of our emerging technology work

As the UK's independent communications regulator, our work is wide-ranging – including broadband and mobile; TV; radio; video-on-demand services; post; and the airwaves used by wireless devices. The UK Government introduced new legislation in autumn 2020 giving Ofcom powers to regulate UK-based video-sharing platforms. The UK Government has also confirmed it intends for Ofcom to be appointed as the regulator of the online harms regime. We are also working with the Government to implement telecoms security legislation and working with industry to ensure they adhere to their security obligations.

To provide support for our work across this diverse range of sectors, we have developed our emerging technology programme. The programme looks at how the way we communicate and connect with each other is evolving across fixed and wireless networks for broadcast, broadband, mobile and satellite services.

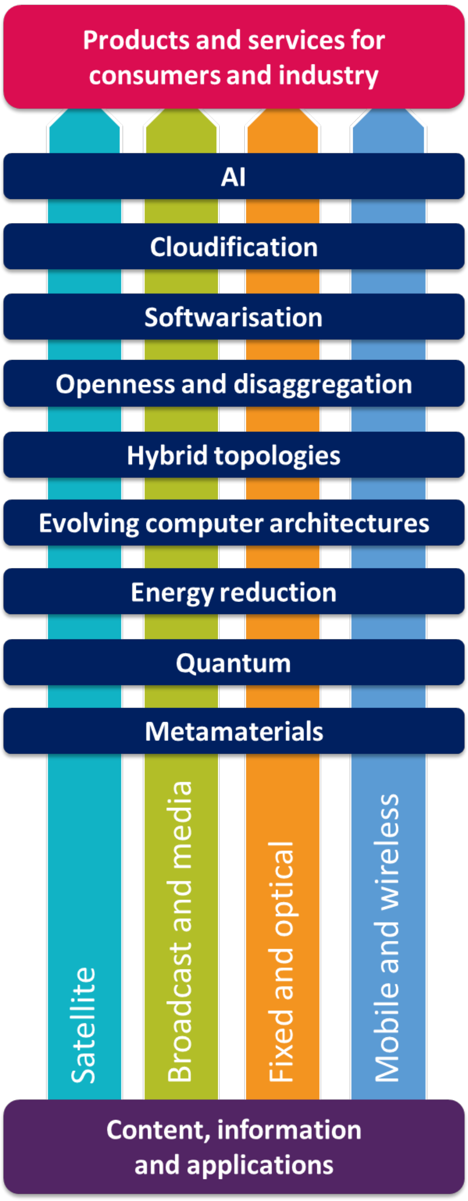
We have also looked at the transport and operational systems that sit behind these services – many of which now use online technologies like virtualised and cloud computing techniques. And we look at the devices that connect to these networks and the services they deliver – to people at home, on the move and at work.

Figure 1: Scope of Ofcom's emerging technology programme. Source: Ofcom.

Identifying and evaluating new technologies

During our work on emerging technology so far, we have looked at how existing technologies are evolving, and which new technologies are starting to emerge now – and in the coming years. In particular, we have focused on identifying technologies with the potential to disrupt communications markets, positively or negatively, in the medium to long term.

Figure 2: Common technology trends across different connectivity sectors. Source: Ofcom.



Emerging technology trends

In this report we focus on technologies in the mobile and wireless, fixed and optical, broadcasting and satellite sectors and on emerging immersive communication services. We found that a number of technology developments will impact more than one of the sectors discussed, as shown in Figure 2. Some of these technologies are discussed in different contexts in different parts of the report. For example, while we discuss AI-driven (artificial intelligence-driven) computer architectures in the mobile and wireless technology chapter, we also touch upon AI's role in interference management in the satellite and space chapter. In the same way, we discuss the emergence of quantum technologies in the fixed and optical chapter. But again, this trend has implications for the other connectivity sectors as well.

Immersive communications and applications

The world is becoming increasingly digitised, with highly innovative digital services that were unimaginable at the turn of the millennium. People and businesses are looking for products and services that are reliable, simple to use and work instantly.

But that's not all.

Technology is playing an increasing role in assisting and even enhancing our sensory capabilities and at distance. As a simple example, we have seen the emergence of the connected doorbell which alerts the resident when there is a visitor at the door; and the addition of a one-way video feed allows them to see who is at the door. Indeed, the smart doorbell takes the concept to a new level where hooking the doorbell to the resident's smartphone enables a live video and voice conversation with the visitor from anywhere.

In effect, this device has extended the reach of the resident's ability to 'see' who is at the door and 'hear' what they say, from a distance, thus enabling them to 'answer' the house door when at work or even if out of town.

Such emerging applications that allow people to project their senses from a distance are underpinned by intelligent and immersive communications between people and technology. This is being helped by a general shift in the design philosophy from people having to adapt to technology (for example through the design and use of the keyboard and mouse) to systems that are adaptive to the natural way human communication takes place in a face-to-face conversation or interaction, such as adjusting to tone of voice, accent, etc.

Similarly, advances in smart communication technology are helping disabled people in their daily lives. Audio-based technology that can respond to human voice commands is able to provide a blind person with access to online music, news, radio, books and many other forms of content without assistance, or control the living environment (turn lights on/off, etc). On the other hand, virtual reality (VR) technology can have a transformative impact on the lives of people who have suffered irreversible sight loss in a similar fashion to audio-based technology.

We are already seeing this quest for immersive experience in the gaming sector, and the notion of immersion is already starting to spill over into the area of personal communications within both the consumer and business spaces as the demand and acceptability of such technology increases.

Immersive digital environments are evolving in two directions. Firstly, effort continues to push the consumer experience of watching video and listening to audio closer than ever to reality. For example, using a VR headset to view 3D/360-degree videos together with advanced audio devices supporting spatial audio. Research is also exploring the possibilities of adding additional senses such as touch and smell to complement video and audio experiences.

As we move further into the new world of immersion, we not only expect to see new products and services, but also significant digital transformation in areas such as retail, sport and entertainment, education and training and health.

Delivering these services will require fixed and mobile networks with higher speeds and consistently low latencies, in some cases even stretching the boundaries of 5G networks, motivating our investigation of connectivity technologies in the rest of the report.

Mobile and wireless technologies

In the last five years, both mobile (3G, 4G and now 5G) and local area (Wi-Fi) networks have seen major changes in how they are designed, deployed, owned and used. For example, new technologies (like the use of a large number of antennas to transmit and receive and the use of higher frequencies) have led to much faster connections and a better experience for people. The mobile industry has been experiencing a move from vertically-integrated (one supplier provides the end-to-end product) to horizontally- integrated (different suppliers provide the different product components) network elements (referred to as "disaggregation").

We have picked out four particular areas where we think progress will have a major impact in the medium to long term:

- *Beyond the traditional wireless communication limits*. This is about going beyond the limits that defined communication technologies since their theoretic foundations were established by Claude Shannon in 1948. For example, systems using smart surfaces made of artificial materials ("metamaterials") , deployed along streets or on buildings' façades, will be able to direct the energy of the wireless signal towards a given point in space and time, thus providing better coverage and decreasing energy consumption.

- *AI native systems*. We found that AI could have an even more disruptive impact in the future for the communications sector. And that to fully exploit the benefits of AI, a major redesign of communication systems might be needed, building on disruptive new computing architectures. For example, researchers are exploring computing and communication architectures that work in a similar way to the human brain, and that could lead to a massive reduction in energy consumption and latencies compared with today's computing and communication architectures.

- *Hybrid topologies*. Since their inception, mobile networks have been based on a "cell-centric" architecture. New trends are calling for the use of a new design that places the person or the device being served at the centre of the architecture. The emergence of drones and Low Earth Orbit satellites as possible mobile base stations in the sky, is leading to the definition of architectures based on hybrid terrestrial/aerial topologies. These new hybrid topologies could provide consumers with a much more consistent quality-of-experience and ubiquitous coverage.

- *Joint communications and sensing*. Historically, wireless communications and radar/sensing systems have developed mostly independently. Recently, however, there is growing interest in the potential for a single system to meet both applications, saving spectrum and extending the range of services. And applications are emerging such as the use of wireless access points normally used to deliver broadband in homes to monitor the health of older people, by detecting their motion patterns.

Fixed and optical technologies

Fixed line systems based largely on optical fibre with some copper near the user in the 'access' region, provide the great majority of the data transport required by all forms of modern communications. Advances over recent years in the underlying technologies have raised the available capacity by literally billions of times.

But the technology continues to improve at a rapid rate and we have picked out three particular areas where we think progress will have a major impact in the medium to long term:

- Two techniques will provide extra capacity in each fibre by either deploying complex multi-core or hollow-core fibres. The former embeds multiple cores in a single glass fibre, and the latter avoids many of the limits of existing fibres by using ultra-thin glass membranes to 'nudge' the light now guided not in glass but in a hollow air core, travelling as much as 50% faster than in existing fibres.

- Denser and more complex integrated optical chips will provide the routing and termination functions needed for newer, more complex 'passive' optical fibre networks. Integrated optical devices could reduce energy requirements significantly.
- Quantum based techniques that use the inherent quantum mechanical properties of light, will have applications in security, computing and communication.

Broadcasting and media technologies

Television and radio are constantly evolving – ultra -high resolutions of 4K and 8K are becoming more common, and people now expect to be able to watch content on a range of different platforms, whenever they want, wherever they are. Increasingly, the devices we use to access these services are seamlessly integrating traditional broadcast, online streaming and podcasts. And voice assistants and the way platforms use algorithms to make tailored content recommendations to us are also changing the way we find and watch new content. The way that programmes are made is changing too – production teams are increasingly using cloud-based tools rather than expensive studio equipment. They are also taking advantage of the capabilities of 5G, with news reporters using it to deliver outside broadcasts. AI is also being explored as a tool for automation (robotic cameras are already prevalent in news studios) and to improve workflows. New distribution and production technologies will allow broadcasters to create programmes that are 'object based', allowing viewers and listeners to choose the balance of sound, the commentator they listen to, the graphics they see and the camera angles that they see.

Satellite technologies

There are three types of services delivered from space:

- Satellite communications are used for broadcasting and internet access, providing broadband to homes and communities in remote locations as well as connectivity for maritime and air passengers;
- Satellite signals are used by Global Navigation Satellite systems (GNSS), such as The US Global Positioning Systems (GPS) to provide accurate position, navigation and timing;
- Satellites are also used to observe the Earth and Space.

Over the last twenty years, small satellites and cheaper launch services have made space much more affordable, even for academics and start-ups. This has attracted many new players, leading to a more diverse sector and is setting the stage for constellations of innovative communications and sensing services in Low Earth Orbit.

In satellite telecommunications, large geostationary satellites remain important. Here, technologies adopted from the mobile sector such as small cell spectrum frequency reuse have enabled higher capacity satellites providing lower cost services. This trend is set to continue with mobile edge computing enhancing both network performance and the user experience for rural residents, and passengers on ships and aircraft.

However, constellations of telecommunications satellites deployed in Medium Earth Orbit and Low Earth Orbit have the potential to increase overall satellite broadband capacity and offer reduced latency services – meaning a more reliable, instant connection. Production-line manufacturing, optical links and flat panel antennas will enable these new services and could benefit the sector as a whole, enabling cheaper satellites, higher capacity data transfer and better connectivity on the move. New downstream services could also be generated from these constellations, for example, their signals could also be used to provide enhanced position, navigation and timing, complementing GNSS services.

Work ongoing at 3GPP (3rd Generation Partnership Project) to develop 5G standards for satellite and non-terrestrial networks will enable greater integration between satellite, High Altitude Platform Stations and mobile networks, creating opportunities for new hybrid architectures to support connectivity for consumers in remote locations.

Earth observation satellites are important for environmental monitoring whether monitoring our weather, forests, urban development or agriculture. Accurate and timely weather forecasting is likely to become more important as climate change increases the risk of extreme weather events; scientists rely on access to specific radio frequencies to measure the presence of moisture and ice. As the weather becomes warmer and wetter, higher frequency links needed to meet future data demands could be affected. Propagation forecasting (predicting how wireless technology might perform depending on weather conditions) could therefore be useful.

The Earth observation community is now attracting commercial actors, many of whom are planning constellations to allow more frequent measurements, providing more timely data for users. To date, commercial satellites have mainly carried electro-optic payloads (cameras) but operators are now adopting different sensors. Some, such as synthetic aperture radar, hyperspectral imagery and video look to generate more significantly more data per satellite. These trends are driving require new methods to move and manage all the data generated in space. Networks of new Earth stations, intersatellite links, optical links, onboard processing and AI and cloud services are just some of the technologies that could be employed.

Finally, space continues to provide a fertile ground for experimentation and innovation. In particular, we are highlighting:

- Small satellites that can fly in formation (swarms), creating virtual antennas;
- Satellites that can connect in space to create larger, more capable systems;
- Re-useable satellites which could help to reduce space debris and further reduce the cost of space services;
- Manufacturing in space, which has the potential to create new materials and medicines; and
- Ongoing studies into solar power from space.

Contribution to this document

Technology experts from across the world have contributed to this report – offering fascinating insights on how the technology we use today is changing for tomorrow. This report shines a light on a sample of technologies that industry and academia are working on. We've selected these technologies based on the responses we received from our call for inputs and the discussions we had with thought leaders in both academia and Industry. We will continue to identify other important technologies as they emerge and in sectors beyond those considered in this report.

Methodology

The content of this report arises from our need to understand the potential role of emerging technologies on the sectors we regulate, and to guide our work programme towards the technologies most likely to have the greatest impact. Our objective was to capture as many technologies as possible which could potentially be impactful on our sectors. We sought to minimise the chances of missing potentially important technologies – i.e. we preferred to have 'false positives' rather than miss significant developments. Naturally, this resulted in a very long list of technologies. We will use this long list of technologies in a more complete assessment to inform our future programme of work.

To achieve this objective, we have engaged with leading research and development organisations in academia and industry internationally (see Annex C for the list of people we spoke to in this context). We spoke to over 70 experts both in academia and industry. We also issued a call for input seeking views from people and organisations and received 30 responses. In Annex D we provide the full list of responders, and a link to where the non-confidential responses can be found.

We are interested in the implications that the longer-term technology has for people and society. We were not seeking to assess the policy implications of technologies at this stage, but we created a list of factors against which each technology was assessed. We made clear in our interviews and the call for inputs that we were primarily interested in technologies which have the potential to significantly impact on at least one, and typically several, of the following criteria:

- Enables the delivery of new services which are valued highly by people and businesses
- Broadens and deepens access to services
- Increases the performance of networks, improving the experience for people
- Lowers barriers to entry for providers, enabling choice for people
- Reduces the cost of delivering services, increasing access and maximising value for customers
- Changes the way we authorise and regulate networks/services
- Reduces the total environmental impact of delivery of communication services and associated activities
- Assures the security and resilience of service delivery

For each technology suggested to us as having potential impact on these criteria, we sought to identify the state of development of the technology, the potential impact on the sectors we regulate, the leading groups working on the technology and the potential path and timescale for the technology to enter the UK market.

In this report we have focused on four technology sectors: mobile and wireless; fixed and optical; broadcasting and media; and satellites and space. We have also presented a discussion on some emerging use cases focusing on immersive experience in human communication.

We continue our engagement with experts in other technology areas that are relevant to us. We aim to share the outcomes of this evaluation with stakeholders through appropriate publications, the exact mode and timing of which will be decided in due course. Meanwhile, we welcome views on the technologies we present here, or on technologies which we have not yet taken account of, via emerging.technology@ofcom.org.uk.

1: Immersive communications and applications

Today and tomorrow

The world is becoming increasingly digitised, with highly compelling and convenient digital services that were unimaginable at the turn of the millennium, in areas such as personal communication, transport and retail. Today, people and businesses look for products and services that work consistently, save time and ultimately increase comfort with more intuitive and natural interfaces. Technology is increasingly in demand and its importance rises as a tool for expanding or even improving our own abilities and senses. These two growing needs require new intelligent and immersive interfaces between people and machines.

Whether within the industry or consumer space, information communication requires the means to bring together people and machines. A shift has been occurring in the Human Machine Interfaces (HMI)[2] design philosophy from humans having to adapt to machines (for example through the design and use of the keyboard and mouse) to systems that are adaptive to the natural way in which humans communicate. This is being furthered by developments in immersive digital technology and internet delivery in both the consumer and industry spaces.

Immersive experience is currently being achieved in a virtual environment (VE) by mixing three-dimensional visualisation and sound with haptic communications – the communication of movement and touch – being added to this mix in the future. From a user experience perspective, if a picture is worth a thousand words, immersive media that combines sound, vision, haptic and olfactory technologies can be worth thousands of hours of video watching. The incorporation of more senses in communications is leading to greater levels of immersion and is closing the gap between reality and virtuality.

Research suggests that high levels of immersion could become an integral part of future communications. Whether it is in personal communication, broadcast or otherwise, a common theme is a move towards the creation of high quality, deeply immersive virtual environment technology (VET) that brings together a mixture of three-dimensional visualisation and sound; and haptics – the transmission of touch and motion – coupled with internet delivery. Research in olfactory communication and brain-to-machine interfacing continues to advance given their challenging nature.

[2] HMI is a technology solution that allows for information to be transferred between people and machines/computers. Keyboard and mouse are basic examples of such technology.

We find that current telecom technology is unable to deliver the full range of. Our finding is based on a comparison between the requirements to deliver any of the sensory communications we looked at in terms of the bit rate, latency and the capability of current telecom network technologies.

Our study indicates that the use of immersive VET is extending beyond its intended uses and within the context of assistive technology. Further progress in this direction could have the impact of increasing accessibility of digital content and increasing societal inclusivity.

VET is creating new opportunities for innovation in new exciting products and services. We find that immersive VET could instigate a significant digital transformation in areas such as retail, sport and entertainment, education and training, and health.

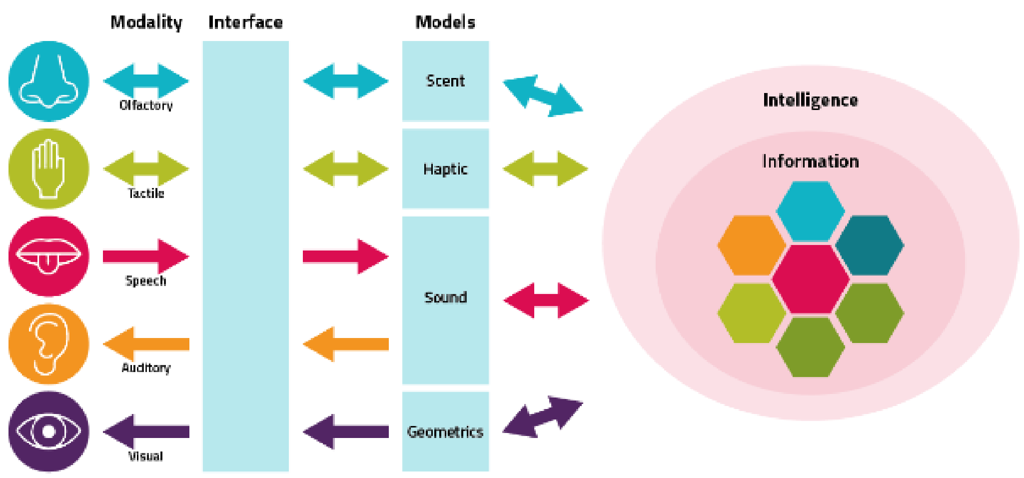
While we acknowledge barriers for the adoption of immersive VET, increased reliance on technology during the Covid-19 may help adoption of new technologies by lowering some people's resistance to technology.

The human connection: a shift towards immersive communications

Multimedia content is commonly accessed via audio visual devices such as screens and speakers. Today, we mainly interact with digital devices such as laptops, smartphones and tablets to gain access to such content. When we think of using our sense of touch in such interactions, images of clicking mouse buttons, and sliding our fingers over a glass display spring to mind. While an immersive experience has been possible from the screens and speakers of today, the user experience is still limited to only two of our five senses: sight and hearing. However, there is a shift to ever more natural forms of communication between humans and machines, with a potential for greater intelligence on the machine side (see Figure 3).

The next evolution in human-machine communications is the design of systems that are even more adaptive to the natural way in which humans communicate and work, with an enhanced quality of experience in terms of immersion and reality.

Figure 3: Framework for immersive multi-sensory communications as a perceptual system of humans. Source: Ofcom.



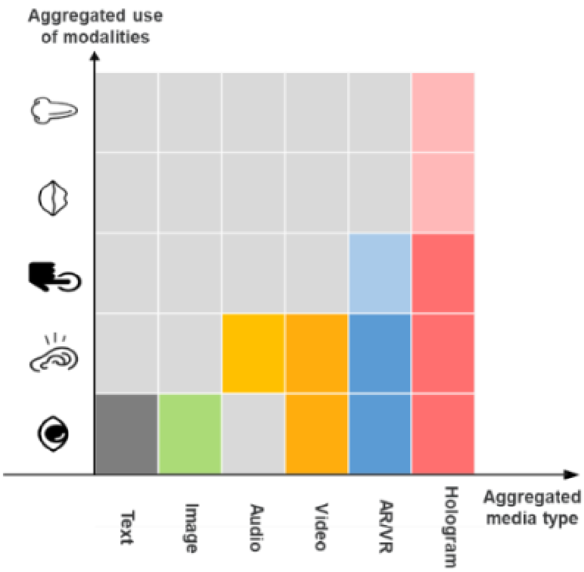
Immersion is the degree to which a particular medium is able to create a sense of presence. It is defined in terms of characteristics such as mono/stereo, and bandwidth for audio; resolution, colour depth, frame rate for video and degrees of freedom for movement. Technology media have been found to have a medium-sized effect on presence, while individual features have been found to vary in their effect sizes [Cummings2015]. Hence, greater immersion achieves greater perception of presence and when such experience is achieved with sufficiently high quality, it becomes very difficult to distinguish between one's existence in a fictitious (digital) or real (physical) world.

The sense of vision plays a significant role in the link between perception and physical reality, while the sense of hearing provides us with some evidence of reality. When one needs further evidence of reality, other than via the vision or hearing senses, one intuitively tries to touch the object to investigate. Touch seems to be the ultimate perceptual experience to achieve the sense of reality. Clearly, increasing immersion can be achieved by higher quality media and sense technology.

Figure 4 shows that the more senses that are incorporated in the communications process, the greater the number of media that are required in the process.

Social touch technology (STT) has been studied to understand its effectiveness in communicating effects and emotions. It involves communication that also includes social touch mediated through technology. It also includes situations where people interact with artificial social agents that have the capability of responding to, and/or applying social touches [Huisman2017]. It could be useful in situations where physical interactions may not be possible, both socially and professionally, whereby STT offers an opportunity to enhance the sense of togetherness and collaboration from a distance.

Figure 4: Higher levels of immersion are achieved with more sensory communication. Colour shadings depict the degree to which each sense contribute to the impressiveness of the media type. Source: [Li2019].



To date, digital interaction has been based primarily on sight and hearing; and touch is likely to be further incorporated. Very little interaction has been based on smell, a sense considered very difficult to manage and to use for creating more pleasant and effective experiences. However, olfactory stimuli can make the interaction between users and objects more engaging and effective on sub-conscious levels and on long-term memory [Carulli2019, Braun2019].

R&D has continued in visual, haptic and olfactory technologies. While audio technology appears to have matured, it has also been benefiting from R&D. With virtual and augmented reality technologies advancing further, the demand for consumer-grade haptic technology could also intensify, and perhaps olfactory technology will too.

Seeing pictures from reality and towards virtuality

Conventional screen specifications such as resolution, length, width, and bezel are factors that are visible while viewing the screens and have been known to negatively affect the telepresence experience [Kong2020]. Key visualisation technologies that can achieve highly immersive experiences are head mounted stereoscopic displays (headsets) and light field/holographic displays, with the former being more mature. Headsets overcome the physical constraints of length, width, and bezel, and leverage the 360° space/sphere to significantly improve the telepresence experience, shifting the viewer's experience from being an onlooker to the sensation of being in the picture.

Virtual reality (VR) is considered an HMI technology which attempts to immerse a person in a digital 3D environment by using a headset, instead of watching on a computer display. Computer-generated imagery and content, alternatively known as computer-simulated environments, aim to simulate a real presence through senses. As a result, VR is a fully enclosed environment that replaces the user's real-world environment with an entirely computer-generated one which the user perceives as real and can interact with in real time.

The first VR headset was patented in the 1960s by inventor Morton Heilig [Brockwell2016]. Recent years have seen a developmental leap in VR technology. This is because of the significant advances made in the production of high-resolution screens, precision lenses and significant increase in computational power. All of which, when put together, allow the formation of highly detailed imagery at very high frame rates with smooth and almost entirely realistic motion.

Augmented reality (AR) is another form of visual HMI using a headset in which the physical and digital world converge. To achieve this, AR applies sophisticated algorithms and sensors to detect the position of the user's view and then superimposes 3D graphics/objects onto the view: effectively data and images are superimposed onto the physical world leading to a potential increase in the value of the experience of reality. While VR enables high immersive experiences, AR lets the user interact with the physical world with enhanced access to information and ability to interact with virtual objects within the field of view.

Generally, display technology requires high refresh rates, frames rates and resolution, all of which places demand on throughput to achieve an immersive experience. However, latency also plays a key role in achieving an immersive experience because human perception requires accurate and smooth movements in vision. Large amounts of latency can lead to a detached immersive experience and is reported to contribute towards the sensation of motion sickness [Mania2004].

Latency considerations impact network design from a component, architecture and traffic management perspective and the total processing time along the delivery chain (wireless components, codecs, queues, etc).

Table 1: Impact of throughput on type of service to maintain quality of immersive experience. Source: Ofcom.

	Interactive (Bidirectional)	Streaming (Unidirectional)
Low throughput allows sending video in field of view only	**Low end-to-end latency** need for interactivity of signalling back to source in both cases of bidirectional and unidirectional exchange; and for conversational experience in the case of directional exchange.	
High throughput allows sending 360 video	**Low end-to-end latency** needed for interactivity. Unicast delivery needed for video.	**High end-to-end latency** tolerated. Multicast/broadcast can be used.

Table 1 summarises the trade-off between the end-to-end (E2E) throughput, E2E latency and the type of service to maintain the quality of immersive experience.

Low E2E throughput means that only the portion of video in the field of view of the user can be transmitted. Low E2E latency is needed for low throughput in the bidirectional interactive and unidirectional steaming services because of the conversational type of exchange that takes place in the former and the signalling back to source needed for both cases. High E2E latencies can only be tolerated in the case of streaming multicast/broadcast delivery (considered in Chapter 4).

The ultimate immersive video experience is of a high-quality picture with extensive details and spatial sensation - including depth and with accurate and smooth picture motion. Latency is key in the delivery of VR/AR. Large latencies can deteriorate the VR/AR experience and contribute to a motion sickness sensation. The bit rate can be determined by the image sampling rate in time (smoothness), space (details) chromaticity (colour) and sensation of depth.

A raw bit rate of 2.45 Tbps has been calculated to encode a 360^{o} spherical video that achieves the ultimate immersive experience [Holman2000][3] – essentially, this is the 'bit rate of reality' and sets an upper bound on the potential bit rate needed.

In a production environment, 4K video dominates, and it requires a bit rate of 12 Gbps[4] for uncompressed video.

Today, video content is being delivered through innovation in compression that reduces the bit rate to more manageable levels, consistent with the capacities of broadcast and broadband (mobile and fixed) networks. For example, headset-based visualisation technology reduces the bit rate by selecting the video from the direction towards which the headset points.

[3] The raw bit rate is based on the number of pixels per minute arc angle, chroma sampling, the number of bits representing each pixel and frame rate. The calculated raw bit rate is based on 2 pixels per minute arc (Nyquist), 4:4:4 chroma sampling, 10-bit colour space (Y'CbCr), 120 frames per second and two images for right and left eyes.

[4] 3840×2160 pixels 100/120 fps with high dynamic range is the latest most common target for 4K and comes in around 12Gbps with 4:4:2 chroma sampling. 8K is expected to dominate in the future in professional environments.

Table 2: Estimate of throughput and latency requirements for VR/AR technologies. Source: [Mangiante2017].

	VR Resolution	Equivalent Resolution	Minimum Throughput	Maximum Streaming (S) Latency	Maximum Interactive (I) Latency
Early VR	1Kx1K 2D (30fps) 8bit 2K	240p	25 Mbps	40 ms	10 ms
Entry VR	2Kx2K 2D (30fps) 8bit 4K	SD	100 Mbps	30 ms	10 ms
Advanced VR	4Kx4K 2D (60fps) 10bit 8K	HD	400 Mbps	20 ms	10 ms
Extreme VR	8Kx8K 3D (120fps) 12bit 16K	4K	1 Gbps (smooth play) 2.35 Gbps (interactive)	10 ms	10 ms

Today, video content is being delivered through innovation in compression that reduces the bit rate to more manageable levels, consistent with the capacities of broadcast and broadband (mobile and fixed) networks. For example, headset-based visualisation technology reduces the bit rate by selecting the video from the direction towards which the headset points.

Table 2 gives more practical estimates of the required maximum bit rate with different resolutions and frame rates for network-based/cloud-based delivery. The table gives the required throughput and latency for different VR resolutions and their equivalent on a TV screen [Mangiante2017].

The table shows an important aspect of delivering good quality VR: the need for both high throughput and low latency. The latency requirement for almost all VR options is difficult to meet with existing networks. For example, for the most basic streaming VR, delivering a consistent minimum 25 Mbps throughput concurrently to end users is challenging. It is even more challenging to deliver with maximum latency of 10 ms for all users concurrently.

While headsets do achieve total immersive experience by eliminating the above-mentioned constraints of conventional screens, they can themselves become a burden thus lowering their rate of adoption. The following recent developments could potentially help:

- Smart glasses display a digital overlay of text and images onto the lenses within the field of view without obscuring the real-world view. These partially transparent digital displays have the power to create AR experience. Two projection methods are being used, namely curved mirror combiners or waveguide holographic optics. Smart glasses were originally started by Google in 2014 [Stevens2018].
- While development is continuing in this space, recent breakthroughs in smart glasses could potentially bring smart glasses into the mainstream [Goode2019, Wong2017].

- Smart contact lenses attempt to achieve similar functionality to smart glasses by embedding a very small display in the lens, but such technology is some way from commercial reality [Chokkattu2020].

Hearing sound

Instead of using channels (rear-left speaker, for example), spatial sound technology assigns sound to a place (for example rear-left corner, three meters height). Adding a height dimension creates a smoother, more realistic surround sound experience as sounds are passed from place to place around the listener. Freed from channels, individual sounds can now be precisely placed in the room and can move around you, including overhead and down low, thus immersing the listener in each story and song. These individual sounds can be encoded independently of the speaker placement. This spatial audio is so similar to what we hear in real life, it has the potential to immerse the listener more fully than standard audio [Pike, Parson2020, Roberts2020]. There has also been indication that full spatial audio could be achieved from a pair of earphones [Cvetkovic2020], potentially connected to a phone. The combination of this technology with VR/AR is likely to increase the immersive experience by a fair amount.

For sound, the ultimate experience is spatial sensation combined with high sound quality. Technically, it is determined by the audio sampling rate in both time and spatial domains. With 100 sound channels achieving such ultimate experience with perceptual transparency, a raw upper bound bit rate of 120 Mbps has been calculated [Holman2000] For high definition audio, a bit rate of 4.6Mbps is required per channel[5].

Today, delivering audio content is being achieved through innovation in compression that reduces the bit rate, achieving high degrees of delivery efficiency over broadcast and broadband (mobile and fixed) networks.

Table 3 gives the throughput and latency requirements for different sound transfer requirements, ranging from the case of musicians playing together to downloading audio files, and including voice communications and streaming.

[5] High definition audio requires a top sampling rate of 192 kHz and 24 bits per sample per channel leading to 4.6 Mbps uncompressed [WhatHiFi2020].

Table 3: Estimate of minimum throughput and maximum latency for different sound requirements. Source: Various external sources.

Scenario of sound exchange	Minimum throughput	Comments		
		Type	Amount	Comment
Geographically distributed musicians (orchestra)	4.6 Mbps [6]	Real time / Live	≤ 25 ms[7]	Driven by the human psycho-perception limits of sound content.
Conversational	8 kbps-3 Mbps[8]	Real time	≤ 200 ms	
Push-to-talk	8 kbps-3 Mbps[Error! Bookmark not defined.]	Real time	≤ 300 ms[9]	
Streaming	48 kbps-3 Mbps[10]	Real time / Live	≤ few seconds	Driven by technical limits of delivery (buffering) and tolerance of service reception.
Download	48 kbps-4.6 Mbps[11]	Non real time	≤ several seconds[12]	

Haptics for touch and motion

Touch is a key element of the human sensory system. We can determine hardness, geometry, temperature, texture and weight only by handling something. The human skin senses (somatosensory system) make it possible to perceive touch, pressure, pain, temperature, position, movement and vibration.

Generally, the term haptic relates to the sense of touch, the sense of relative positioning of one's body and the strength of effort used in a given movement. It addresses human touch-based perception and object manipulation.

Figure 5 gives a breakdown of the haptics elements namely the skin (tactile) and posture (kinaesthetic) senses [Runde2019].

The skin senses make it possible for humans to perceive temperature, pain and tactile stimuli of the skin (pressure, touch, hair follicle and vibrations receptors). The signal bandwidth required to cover the most sensitive tactile sense (Vater-Pacini) is 200 Hz [Steinbach2019].

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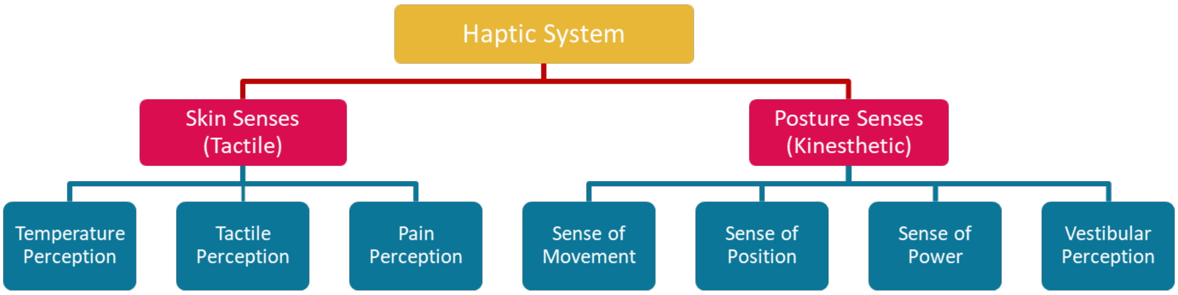
[6] This is uncompressed and based on the bit rate range offered by different voice codecs used in the fixed and mobile networks [Cisco2016, Radnosrati2014].
[7] [Lakiotakis2018].
[8] This is compressed and based on the bit rate range offered by different voice codecs used in the fixed and mobile networks [Cisco2016, Radnosrati2014]. Compressed high-definition audio requires 3 Mbps [TIDAL Specs].
[9] This is compressed and based on [ETSI2018].
[10] This is compressed and based on the extremity of bit rates from broadcast radio and online streaming [AstraSpecs, BBCSound, SpotifySpecs, TIDAL Specs].
[11] The 48 kbps is compressed, while the 4.6Mbps is uncompressed, based on these assumptions (1) the throughput is dependent on how the audio has been stored on the server side, which could range from the lowest music bit rate up to orchestra quality and (2) no transcoding takes place prior to delivery.
[12] [Nah2003].

Figure 5: Elements of haptics. Source: [Runde2019].



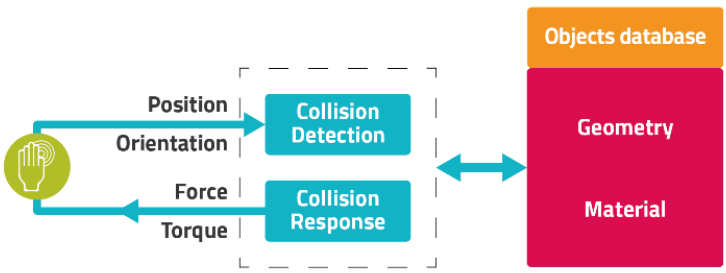
The posture senses can be subdivided as well into the sense of position (generates information about the position of the body in space and the position of the joints and the head – Ruffini corpuscles), the sense of motion (allows the sensation of movement and the recognition of the direction of movement), the sense of power (provides information about the state of tension of muscles and tendons) and the equilibrium organ in the inner ear that allows the vestibular perception.

Kinaesthetic technology aims to capture and simulate the movement, position, power and vestibular sensation. Tactile senses could be used as a feedback system to communicate information to and from the user from an object they touch remotely or in a virtual world. For this, both tactile and kinaesthetic information needs to be digitised. Once digitised, tactile and kinaesthetic information could be communicated from one place to another within both physical and virtual worlds.

The anatomy of a kinaesthetic system is given in Figure 6 [Basdogan96]. A user manipulates a probe acting as a kinaesthetic device, such that the new position and orientation of the probe are acquired, collisions with the virtual objects are detected and hence the need for collision detection.

To this end, a typical rendering algorithm is required for collision detection and collision response management. If a collision is detected, the interaction forces are computed using pre-programmed rules and conveyed to the user through the kinaesthetic device to provide the user with the tactual representation of 3D objects and their surface details, and hence the need for collision response.

Figure 6: Anatomy of a kinaesthetic system. Source: [Basdogan96].



It has been estimated that the kinaesthetic loop needs updating at around every 1 ms (equivalent to an update rate of 1 kHz) in order to maintain stability – which would be beyond the capabilities of even 5G networks [Simsek2016]. Similarly, for robots to interoperate in a harmonious fashion and for some forms of dynamic control, latency in the order of 100ms have been reported [Simsek2016, ITU-T2014].

There is a fair amount of work currently being undertaken to further advance this area. This is reflected in the current standardisation work seeking to define haptic codecs within the context of the tactile internet [IEEE-P1918.1]. The codecs address application scenarios where the human is in the loop (such as remote touch applications) as well as scenarios that rely on machine remote control. The standard defines perceptual data reduction algorithms and schemes for both closed-loop (kinaesthetic information exchange) and open-loop (tactile information exchange) communication. The codecs are designed so they can be combined with stabilising control and local communication architectures for time-delayed remote operation. The reported frequency range for tactile sensory communication is 200-1000 Hz [Steinbach2019].

Table 4 gives the requirements for delivering haptic information. Delivering haptic traffic over existing networks is very challenging from a latency perspective.

Table 4: Estimate of range of throughput and latency requirements for haptic systems. Source: Various.

	Throughput	Latency
Tactile	6.4[13]–128 kbps[14]	50–100 ms[15]
Kinaesthetic	1–10 Mbps[16]	0.2 – 10 ms**Error! Bookmark not defined.**

The use of haptic technology for touch-based social interactions is referred to as social touch technology (STT). It includes situations where human communication partners engage in social touch mediated through technology [Huisman2017], as well as situations where humans interact with artificial social agents (virtual) that have the capability of responding to, and/or applying social touches.

Table 5 shows the types of actuation and modalities that need be communicated to reflect different types of social touch and meanings.

The addition of haptics to multi-sensory communications generally requires mixing haptics sensing and actuation with other modalities such as vision and sound in a VR/AR context.

STT could be relevant in situations where physical interactions may not be possible, both socially and professionally, whereby social touch technology offers an opportunity to enhance the sense of togetherness and collaboration from a distance.

[13] 200 Hz sampled at Nyquist with 16 bits per sample [Steinbach2019].
[14] [Berg2017].
[15] From discussion with E Steinbach.
[16] [Fettweis2018, Çizmeci2017].

Table 5: Mixing actuation and modalities within a multi-sensory communication framework. Source: [Huisman2017].

Meaning	Type of touch	Body Location	Modalities	Actuation
Affection	Abstract, Contact, Hug, Squeeze, Stroke, Kiss, Press, Tickle	Hand, Abdomen, Leg, Arm, Chest, Torso, Back, Side, Lips	Touch, Vision, Audition	Vibrotactile, Temperature, Force
Greeting	Handshake	Hand	Touch, Vision, Audition	Temperature, Force
Inclusion	Holding Hands	Hand	Touch	Temperature, Force
Playful Aggression	Arm Wrestling	Hand	Touch	Force
Symbolic	Abstract, Poke	Hand, Cheek, Finger, Arm	Touch, Vision, Audition	Vibrotactile, Force

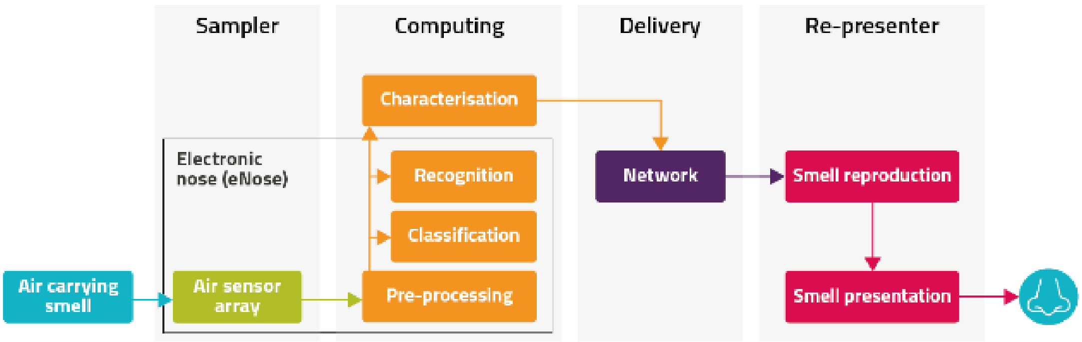
Olfactory: the sense of smell

We sense a smell by detecting and identifying airborne molecules in the environment, which bind to olfactory receptors in the human nose sending electrical signals to the brain to create a sense of smell. This allows humans to detect 10,000 to 100,000 different scents. While humans' sense of smell may not be as acute as that of other mammals, it is still sufficiently sensitive to distinguish between different scents, as well as being able to detect the presence of small amounts of certain scents and thus provide a bridge to feelings, emotions and memories. The sense of smell arising from these molecules is influenced by several factors, from what other molecules are present in the air to how our brain processes that information. People have about 350 different types of olfactory receptors [Gosain2014].

Figure 7 depicts a general olfaction communication system [Wen2018]. A sensory array captures and digitises the incoming air-carrying smell. After processing, the digitised smell information is transmitted over a telecoms network where it is reconstructed and presented to the end user.

One main area of research is in characterising and digitising scents. There have been a number of developments in this area, especially in the development of 'digital noses' - which are commonly referred to as 'eNoses'. These devices use a combination of technologies to characterise scents and transform them into electronic information [Aryballe].

Figure 7: Architecture for transmission of scents over a communication network. Source: [Wen2018].



Recently, researchers at Intel and Cornell University have successfully used neuromorphic chips to develop an electronic nose that can learn the scent of a chemical after just one exposure to it and then identify that scent even when it is masked by others [Moore2020].

Another approach to understanding human olfaction is the application of non-invasive neuroimaging methods to understand neural activity in the brain and more recently even in the olfactory bulb (the neural structure involved in the sense of smell) [Iravani2020]. Researchers are also looking at different approaches to realistically recreate scent. Combined with VR systems, one approach that uses a subset of primary scents is able to synthesise smells in near real-time [Feelreal, Olorama]. Another approach to recreating smell is using electrodes to stimulate olfactory receptors inside the nasal passages [Hariri2016]. This is an invasive method in its early stages of research and requires further development before it could be considered for practical applications.

Brain-machine interface and realising the power of thought

A brain machine interface (BMI) is a direct communication interface between an external device and the brain, bypassing the need for any of the above described technologies. The signal directly goes from the brain to the computer, rather than going from the brain through any of the human sensory or neuromuscular systems (vision, hearing, etc). A brief history of BMI is given in [BrainVisionUK2014]. The research suggests communication at thought level could be possible one day. But more importantly and in the medium term, it lays the groundwork for developing what could be very effective assistive technologies. For example, such technology could help people who have lost the ability to speak, or people recovering from a stroke, to regain their ability to make use of ordinary digital communication services. In general, BMIs are said to have the potential to help people with a wide range of clinical disorders.

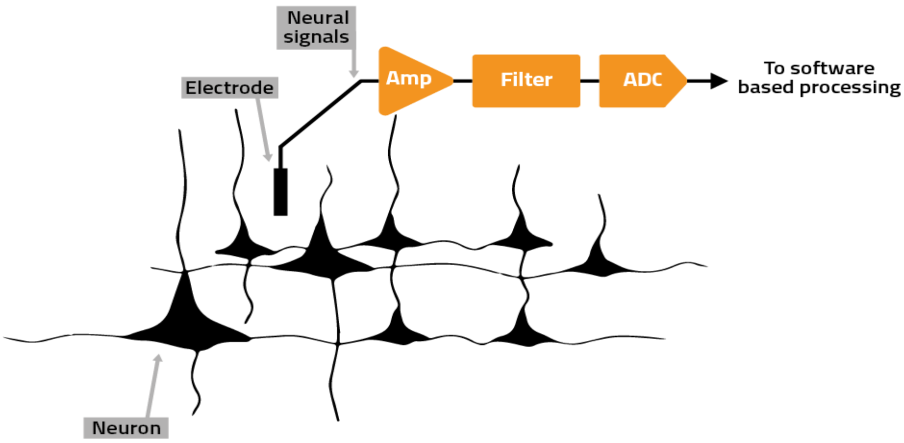
For example, a recent research breakthrough has shown the way to harness the power of speech synthesisers and artificial intelligence; and is paving new ways for machines and computers to communicate directly with the human brain. This research created a system that translates thought into intelligible, recognisable speech. This is done by monitoring a person's brain activity during speech, synthesising and reconstructing the words a person hears with clarity [Techxplore2019]. Other researchers have demonstrated human neuroprosthetic control of computer cursors and robotic limbs using no more than 256 electrodes [Musk2019, Anumanchipalli2019, Aflalo2015, Wang2013, Collinger2013, Hochberg2012, Hochberg2006]. Research also continues into development of less intrusive methods of interfacing [Oxley2020].

As the basic working unit of the brain, neurons are cells within the nervous system that exchange information to other neurons, muscle, or gland cells. The neurons of the human brain interconnect to form a large network: of the order of 100 billion neurons with an average of around 1000 connections each [Glover2020]. Neurons exchange information using chemical signals called neurotransmitters. These are released in response to an electrical spike called action potential, which produces an electric field that spreads from the neurons and can be detected by placing electrodes nearby - allowing recording of the information represented by a neuron.

At the neuron level, the electronic design of neuron interface follows a typical analogue-to-digital-conversion (ADC) architecture [Lewicki1998]. That is, it is made up of an electrode that captures the analogue variation of electric field generated by the neuron, followed by analogue signal amplification and ADC to complete the digitisation process, thus enabling storage, analysis and transmission of the captured data, see Figure 8.

Recently, an ADC of 20 kHz sampling at 10 bit resolution per electrode has been used, leading to 200 Mbps being generated from 1024 channels [Musk2019]. Given the large number of neurons in the human brain, it follows that the raw bit rate required to capture the activity of the whole brain is approximately 20 Pbps[17] assuming access to all neurons was possible.

Figure 8: Connecting neurons to machines. Source: [Lewicki1998].



More innovation needed to deliver richer multi-media services

Figure 9 brings together the throughput and latency requirements for the different senses that were covered in previous sections. These requirements are expressed in terms of the estimated minimum throughput and the maximum latency in order to maintain good quality of immersive experience for each type of media and its corresponding sense. The figure also sets out the relative variation in requirements for different types of media and their corresponding senses.

[17] Petabits per second – or 1,000 terabits per second.

It shows that maxima and minima throughput and latency are as follows:

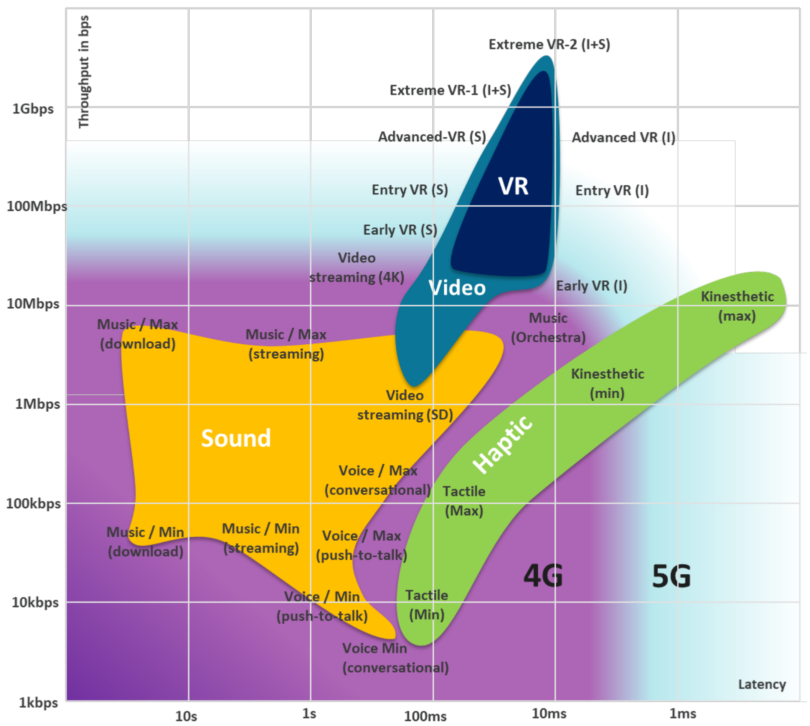
- A haptic/kinaesthetic system requires a maximum end-to-end latency of around 1 ms and extends up to 100 ms.
- Extreme-VR requires the maximum throughput because of the amount of video data needed to be delivered to a headset, while delivering conversational voice in real time requires the lowest amount of throughput.

Today, mobile and fixed broadband networks are being used to deliver rich multimedia including video, audio, images, voice, web and text as well as gaming. These networks are successfully connecting consumers to platforms such as BBC iPlayer, Netflix, Amazon Prime and YouTube and facilitating file transfer with a number of cloud storage services.

Figure 9 also gives an illustrative performance range for 5G and 4G technologies [5GAmericaReport2019]. Clearly, 4G is capable of meeting the current demand for some aspects of multi-sensory communications.

The diagram also shows that the services that fall in the right, upper and upper-right regions are expected to be challenging to deliver even over 5G. Generally, to successfully deliver these services, network technology, architecture, topology and protocols need to further advance beyond what is currently available in the mobile, fixed, broadcast, and satellite spaces. Such developments are discussed in depth in later chapters in the context of mobile, fixed, broadcast and satellite technologies.

Figure 9: Estimate of minimum throughput and reciprocal latency requirements for delivery of each form of sensory communications[18]. Source: Ofcom.



[18] Note that the 1 ms and 10 ms represent over-the-air interface latency for or 4G and 5G, respectively. Real-world latency might be larger, depending on where relevant core network functions are implemented. e.g. a deployment with core functions at the edge will be able to achieve latencies closer to the numbers indicated in the figure.

Beyond HMI intended use allowing greater inclusion

Assistive technologies are dedicated products or systems that support and assist individuals with disabilities, restricted mobility or other impairments to perform functions that might otherwise be difficult or impossible; and thus, improve the lives of people with disabilities. There have been reports in recent years of VR helping people with dementia [Williams2020, BBC2019].

Reports have described the transformative impact VR has had on the lives of hundreds of people who had suffered [5GAmericaReport2019] irreversible sight loss by allowing them to live more independently. For example, AR/VR solutions are said to 'radically improve patients' remaining sight by simulating their human vision. It does this by using a camera to process any incoming images and then projecting the augmented feed onto the working part of a patient's retina' [Forbes2020]. This technology is helping some registered blind people to regain their ability to watch ordinary TV for example. Similarly, VR/AR based gaming provides access to games for people with varying physical abilities. This has been aided by game technology designers specifically addressing disability with text-to-speech, button remapping and a larger font. Also, eye-tracking lets people control on-screen action through eye movements [Pollack2019].

Clearly, these advances in HMI and internet delivery could further help the ability of people with multi-sensory impairment to gain access to digital content and make use of ordinary digital communications. While a hearing-assistive device can help a deaf person to gain access to music, broadcast radio and audio books, a hearing-vision assistive device can help a deaf and blind person gain access to newspapers, books, online video and broadcast TV as well as music, broadcast radio and audio books. The addition of haptics further enables people with restricted mobility to enjoy gaming as well as communicate via the internet or help blind people to experience sculptures at a distance. Similarly, advances in HMI and internet delivery could further help people with multi-sensory impairments to gain a wider range of work across different sectors.

Applications impacted by immersive communications

Below is a non-exhaustive list of areas that are likely to see further developments - either as a result of advances in immersive virtual environment technology (VET) or where such technology is expected to play an increasing role.

Education: Educators predict a bright future for immersive VET in education because of the increasing need for tools that will help ease the process of learning and bring it closer to the student's interests [Vlasova2020].

Figure 10: Immersive virtual technology in education.
Source: Photo by CC BY.

There is consensus that VET is an effective way of providing differentiated and personalised learning experiences for students that increases the effectiveness of the teaching process. While on average, a regular student can remember 30% of what they hear and 20% of what they see, statistics indicate that students remember 90% of the material if taught using VET.

Training: Immersive VET is gaining acceptance as a methodology for training delivery, given that the medium leads to higher knowledge retention than conventional classroom or video training; and with large scalability and lower cost [Cook2020,Dohler2019,Swan2018]. The benefits extend beyond this to include learning in a safe, realistic, controlled environment; simplification of complex problems and situations; and adaptation to different learning styles.

Figure 11: Immersive virtual technology in medical training. Source: Photo by CC BY.

Areas that are likely to see increased use of immersive VET for training include medical training [Daley2020a, Daley2020b], learning manual skills and crafts (such as joinery, carpentry, building constructions, knitting, sewing); learning and practising music [Rottondi2016]; laboratory-based training; and training to work in hazardous environments that involve aspects such as mining, deep sea diving or working with dangerous chemicals.

Culture: Immersive VET presents an opportunity for museums, zoos and safari parks to provide an immersive and interactive experience to visitors. To some extent, it can offer an even more enriching experience than traditional on-site visits as, for example, it has the potential to project visitors into an historic museum artefact's original context [Recupero2019, Kidd2019]. Concerns over animal rights and the environment could help intensify adoption in the area of zoo and safari park tours [Davidge2018].

Sport and entertainment: Advances in immersive VET could pave the way for new ways of enjoying sports, concerts and theatre. Many sports channels are already experimenting with this technology, by incorporating AR as part of their broadcasting and play-by-play analysis about the game in real-time. Fans' in-stadium experience is also expected to become more personalised, bringing visualisations that enrich the game play and half-time [Roettgers2019]. The future of in-home reality might generate certain features like player profiles, rewind ability, and the option to voice-text with other fans in real-time. eSport is also likely to be significantly enhanced with immersive VET [Alton2019, Sachs2018].

Figure 12: Immersive virtual technology for entertainment. Source: Photo by CC BY.

Retail: The way consumers shop could also dramatically change. Applications of immersive VET are expected to enhance consumer interactions with products and retailers before, during and after purchase.

In addition to allowing shoppers to replicate their physical experience of exploring and testing products, these applications can function as a virtual and personalised sales associate. Ongoing post-sale and product support also improves and allows retailers to build a more direct relationship with consumers [IBM2020].

Figure 13: Immersive virtual technology in retail. Source: Photo by CC BY.

Industry 4.0 and 5.0: All industries are increasingly engaged on a journey towards "Digital Transformation". Exactly what this journey entails, and its desired impact may vary from sector to sector, as will the speed of this transformation. Amongst wireless connectivity, VET is likely to play an increasingly pivotal role in this up and coming era of Industry 4.0 and 5.0 [Jardine2020, Deloitte2014], which is reported to potentially unlock £445bn for the UK by 2030 [Monaghan2017]. Ofcom has previously published on connectivity in UK industry [Ofcom2019].

Figure 14: Immersive virtual technology in manufacturing industry. Source: Photo by CC BY.

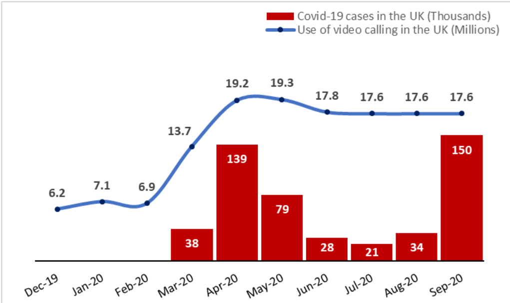
Barriers and opportunities for adoption

The introduction of new technology often raises critical questions about how technology fits into our everyday life and changes our lives. These questions could have the effect of slowing down adoption [Child2011, Sklar2020, Laumer2010]. This is also the case in business, where it is has been said that 'deficiencies in HMI present both a psychosocial risk and an accident risk' [Flaspöler]. In general, perceptions of safety, security and privacy can present themselves as barriers to adoption.

Aside from the technical challenges that still need to be overcome, there will be a continued need to for aspects of user perceptions to be addressed to lower the barriers for adoption.

In contrast, the importance of communications has been rising - particularly as the Covid-19 pandemic has unfolded and people have relied on online services more than ever. Online retail, for example, was reported to have seen significant acceleration in adoption rates [McKinsey&Company2020], while growth in video calling services has more than doubled, see Figure 14[19]. While still speculative, reports indicate that Covid-19 could be instigating a cultural change in which people become more accepting of technology in their daily lives [Gartner2020, O'Halloran2020]. This may help adoption of new technologies by lowering some people's resistance to technology.

Figure 15: Adult visitors to at least one video calling sites and/or apps during the Covid-19 pandemic. Source: [UKGovernment2020, Comscore].



[19] Video calling is a critical way of people staying in touch in lockdown, with many using it for the first time – growth was greatest in older people: online adults aged 65 and over increased their use of video calling at least weekly from 22% in February 2020 to 61% in April/May 2020 [Ofcom2020].

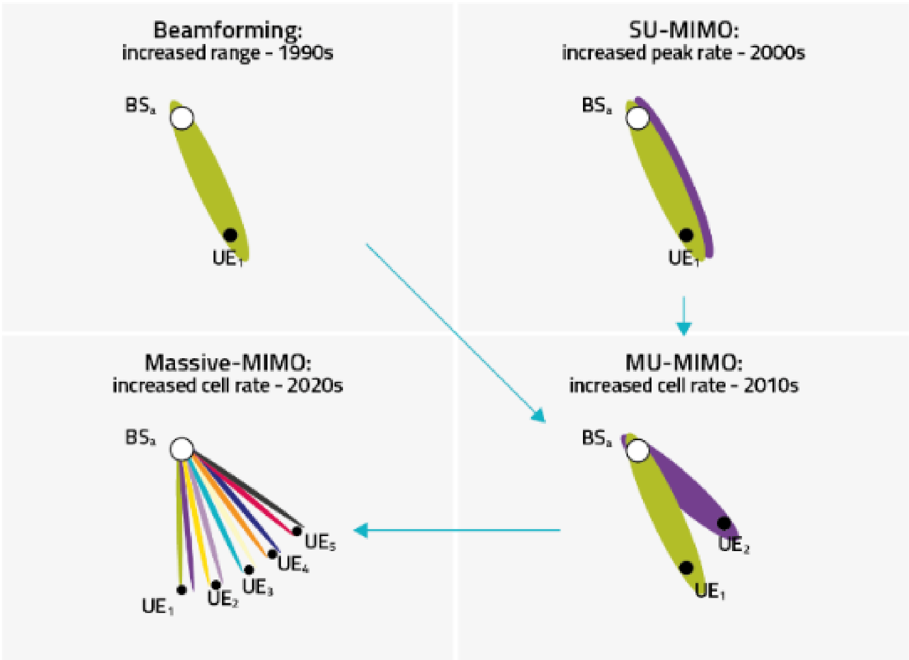
2: Mobile and wireless technologies

Where we are today

In the last five years, both mobile (4G-5G) and local area (Wi-Fi) networks have seen major changes in how they are designed, deployed and owned; and in how they are used.

Both mobile and Wi-Fi systems have been using an increased number of antenna elements. More than 25 years since the seminal work on multiple input, multiple output (MIMO), and ten years since the first proposal of massive MIMO [Mar2010], multiple antenna systems have continued to evolve and are finally well-understood – see Figure 16 for a simplified view of the evolution of MIMO techniques. They have led to substantial increases in spectrum efficiency, coverage and service consistency, with massive MIMO offering up to five times the practical capacity of more traditional MIMO techniques (see e.g. [Björnson2018, NokiaMM]), although there is still a significant gap between theoretical and real-world gains. A flexible baseband and radio frequency design has allowed the aggregation of different frequency bands and supported different types of deployments, from large macro cells to outdoor and indoor small cells. Both mobile and local area networks have been supporting increasingly high frequencies and wider bandwidths, up to 70 GHz.

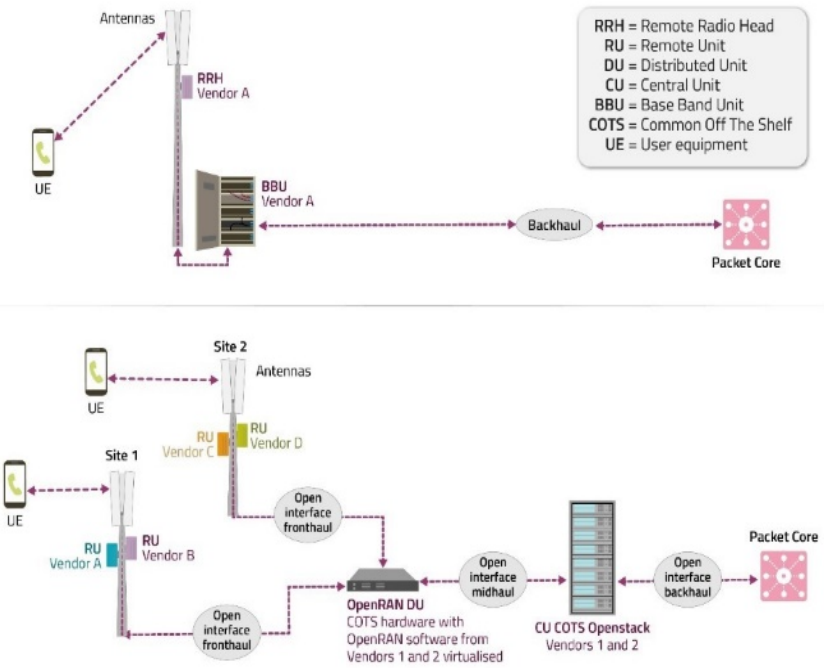
Figure 16: Evolution of MIMO techniques, and years of initial commercial deployments. Beamforming increases the signal level, single-user MIMO (SU-MIMO) increases the peak rate, multi-user MIMO (MU-MIMO) increases the cell rate. Massive-MIMO is an evolution of Multiuser-MIMO using a large number of antenna arrays to increase cell rate. Source: Ofcom.



At both radio and network level, there is a move from vertically- to horizontally-integrated network elements (referred to as disaggregation). For example, Open Radio or Open RAN (see Figure 17 for a comparison between a traditional deployment and an Open RAN deployment) aims to disaggregate mobile base stations by standardising open interoperable interfaces between the radio and signal processing elements, with the aim of increasing supply chain diversity, lowering costs and increasing innovation [ORAN2020]. Similar disaggregated architectures have been proposed for Wi-Fi (see e.g. [TIP2020]). This trend is reminiscent of the shift from vertical to horizontal integration of products for personal computers during the early 1980s [Pop2020]. Disaggregated radio or network solutions also facilitate building network elements as software functions running on virtual machines or containers which themselves run on top of general-purpose hardware. While for core networks software-based solutions are already becoming mainstream (see e.g. [Nokia2019]), for radios there is still some work to do for software-based products to provide solutions that are able to fully replace vertically integrated base stations. But things are moving, and commercial ‘virtual’ radio solutions have recently become a reality [TTV2020].

Related to the trends above, the boundaries between radio, network and IT infrastructure are dissolving, with some of the radio functions being pushed more towards the centre and some network and cloud platform functions being pushed towards the edge - underpinned by distributed processing, storage and software infrastructure. This trend is referred to as mobile edge computing. For example, recently Rakuten (a Japanese marketplace and IT giant) deployed its own mobile network in Japan[RKT2020] . And Amazon, Google and Microsoft have all leveraged their cloud infrastructure and skills and expanded their offerings (either via organic growth or acquisitions) to provide cloud-based network solutions.

Figure 17: Simplified comparison between a traditional deployment and an Open RAN deployment. Source: Ofcom, based on the O-RAN Alliance architecture



On the spectrum side, the emergence of new regulatory regimes allowing shared and local access licences [AM2020], has broken the traditional dichotomy between nationwide licence models (as usually used for deployment of cellular systems) and unlicensed/licence-exempt spectrum (usually used for deployment of local area network technologies like Wi-Fi). For example, in the UK shared access licences are currently available in four spectrum bands, including the 3.8 – 4.2 GHz band and the 24.25 – 25.5 GHz band [OfcomSL2019]. In the US, a dynamic spectrum sharing mechanism is available for the 3.550 – 3.7 GHz Citizens Broadband Radio Service (CBRS) band. Other shared access licence mechanisms are available in other countries.

While traditionally mobile and local area networks provided solutions for connecting people to each other or to the Internet, recently new use cases have emerged including the trend to connect things (such as sensors and actuators) and to use wireless networks for control rather than communication. The former trend drove the emergence of new low-power wide-area (LPWA) network technologies, either using unlicensed bands (like long range (LoRA) or Sigfox) or mobile bands (like LTE-M or NB-IoT) (see e.g. [OfcomCN2019]).

The latter trend led to 5G being designed to natively support much lower latencies and more reliable connections, leading to the so called 5G ultra-reliable low-latency communication (URLLC) standard features. So, in the last few years mobile and Wi-Fi standards (together with non-standardised proprietary solutions) have started to be used to provide connectivity solutions for so called ‘vertical sectors’, including logistics, manufacturing, transportation, automotive and utilities [Ofcom2019].

Artificial intelligence (AI) is being used to solve a different set of problems in networks [EricssonAI2020, NokiaAI2020] and devices [SamsungAI2020]. These applications include network optimisation (such as 5G-aware traffic management, dynamic spectrum management, predictive resource allocation and cell-sleep optimisation), service operation (predictive maintenance, security management and automated issue resolution), customer engagement (via identification and prediction of customer satisfaction) and customer care (chatbots, real-time analytics to monitor quality of experience), among others. Gains can be quite substantial. For example, Ericsson claims a 14% saving in site energy consumption by using machine learning for sleep mode management and the ability to increase 5G coverage up to 25%, by directing 5G devices to the best 5G capable cells [EricssonAI2020]. In devices, it has been used in cameras, to provide extended reality services and to enable virtual assistants. To make in-device AI faster, mobile processors integrate neural processing units and use optimised deep learning software.

Where we are going next

The design of future mobile systems, such as 6G and Wi-Fi 7 and beyond, will be the result of evolutionary changes of technologies already used in previous generations, and of the emergence of new technologies. This section analyses the impact of emerging, potentially disruptive, technologies. We focus on four potentially disruptive technology trends: beyond Shannon’s limits; AI native systems; changing topologies; and joint communication and sensing.

Beyond Shannon’s limits

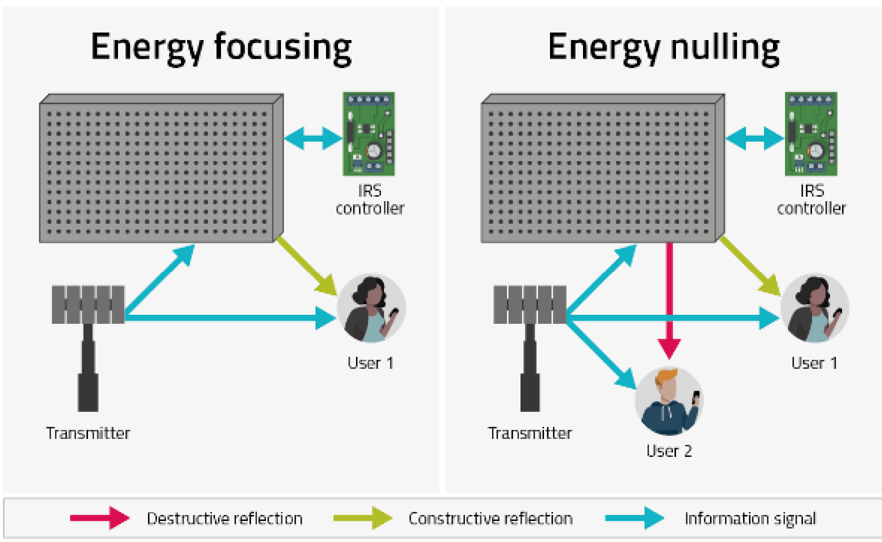
Emerging trends are leading to rethinking some of the fundamental assumptions that underpin the way we design wireless systems today, opening the potential for a dramatic increase in system performance.

Probably the most influential fundamental work in the design of communication systems is Claude Shannon's seminal 1948 paper *A Mathematical Theory of Communication* [Shannon1948]. Shannon established the fundamental capacity limits of a communication channel i.e. the maximum number of bits per second that can be transmitted over the propagation medium between a transmitter and receiver in a given bandwidth, also referred to as channel capacity. Engineering developments in the intervening years (notably turbo codes and MIMO antenna systems) have enabled 4G and 5G systems to deliver performance close to the Shannon limit, raising the question of whether any major improvements are still possible.

Remoulding channels. One of the main assumptions in Shannon's work is that the channel is the part of the communication system that is 'unwilling or unable to change' [Popovski2020]. That is, wireless communication technology has focused on designing transmitters and receivers on the assumption that the channel, for example the outside world of terrain, buildings, trees, etc., is a given over which the designer can have no control. But recently researchers have been investigating the use of intelligent reflecting surfaces (IRS) to also change the propagation medium [Björnson2020, Huang2019]. An IRS uses collections of low-cost passive elements (typically resonating structures, potentially based on the use of metamaterials, see box below) designed to couple and interact with the free-space propagating electromagnetic waves, rather than be excited directly by a waveguide or transmission line, so as to reflect the signals at a desired direction, phase and frequency. In practice, it is like introducing a whole new node in a wireless network that is fully programmable. If carefully designed and placed, IRSs could improve coverage and create a much more consistent experience for users.

We provide two different examples of ways of using IRSs in Figure 18, for energy focusing towards a user or to nullify or reduce the interference towards another user. We note that the assessments of IRS gains are still largely theoretical, and more work is needed to establish real-world gains.

Figure 18: Examples of ways of using intelligent reflecting surfaces (IRS) for energy focusing towards a user or to nullify or reduce the interference towards another user. Source: Ofcom and Emil Björnson.



Metamaterials

Natural materials are very versatile but have a limited range of physical characteristics; for example, the refractive index (the factor by which they slow down electromagnetic waves passing through them) is normally greater than one, that is the wave does slow down. But as a result of work by Sir John Pendry at Imperial College London and co-workers [Ball2017] it was realised that artificial materials can be made that avoid these limitations. These are highly structured composites usually of metal and dielectric with microstructures much smaller than the wavelength. In many cases the structures are arrays of fine three-dimensional metal patterns embedded in dielectric, often with relatively little metal by volume. They appear to waves that encounter them to be just like natural materials but with extraordinary characteristics like a refractive index of less than one (meaning that waves speed up in them) or even a negative refractive index (meaning that the wave reverses direction). The engineering possibilities this enables are remarkable, for example regions of space can be 'cloaked' in the sense that waves pass around them and any object in them without any disturbance that can be observed externally, albeit only in limited bands. This is not quite like the science fiction version of 'cloaking devices', but it is close! Metamaterials have now been made covering RF, infrared and optical bands, though the last is challenging because of the very fine structures needed and material limitations, although the use of them for super-resolution (that is seeing structures smaller than the usual wavelength-determined limits) makes this a very interesting area. For wireless, in addition to being used for IRSs, metamaterials could also help significantly in the design of compact and multi-element RF antenna arrays with low sidelobes and in applications like wireless power charging. They are also relevant to the design of RF absorbing materials to reduce unwanted reflections, which was in fact the application that inspired the original work.

Extremely large antenna arrays. Another example of how changing fundamental assumptions could lead to disruptive innovations in wireless systems is related to the development of MIMO systems. Massive-MIMO arrays that have been deployed in initial 5G networks typically contain tens of antennas [BjoSang2019], in a form factor that is not very different from more traditional antennas. While in theory the spectral efficiency of massive-MIMO grows monotonically with the number of antennas, there are some practical limits to the number of antennas that can fit in a single array. Thus, researchers have started to look at new deployment solutions, referred to as extremely large aperture arrays (ELAAs), where antennas can be distributed over, for example, a building façade [BjoSang2019] or over large geographical areas. The possibilities of ELAAs are very promising, although it is too early to assess their gains compared to existing technologies. However, coming up with practical ELAA systems requires a very different design approach and rethinking classical assumptions in wireless communication and antenna theory: with ELAA the antenna separation is much larger than a wavelength and users are located in the near field of the array. It will also require coming up with practical standardisation enablers and cost and energy-effective hardware solutions.

Quantum communications. In the long-term, quantum communications could lead us to beyond Shannon's limits. Shannon's theory of information was built on the assumption that the information carriers were classical systems. Its quantum counterpart, quantum Shannon theory, explores the new possibilities arising when the information carriers are quantum systems [Chiribella2019]. We cover quantum communications in Chapter 3.

AI-native communication systems

Computing is based on inventions that are almost 100 years old. Alan Turing formulated the concept of algorithms and computing machines in 1936. In 1945, John von Neumann proposed a practical computing architecture based on the separation between computing unit and memory. Gordon Moore first introduced a law to predict the rate of engineering progress in computing in 1965, and then modified it ten years later forecasting a doubling in the number of transistors per integrated circuit every two years [MITGL2020]. For example, a central processing unit (CPU) model introduced two years after an earlier CPU model has twice the number of transistors.

In recent years there have been some indications that Moore's Law is close to fundamental physical limits [MITGL2020], and that graphics processing units (GPUs) have seen higher improvements in performance than CPUs [Saracco2019]. The emergence of processing units for Machine Learning (e.g. tensor processing units or TPU [GoogleTPU2020]) can be viewed as a natural post GPU step in the evolution of computer processing units.

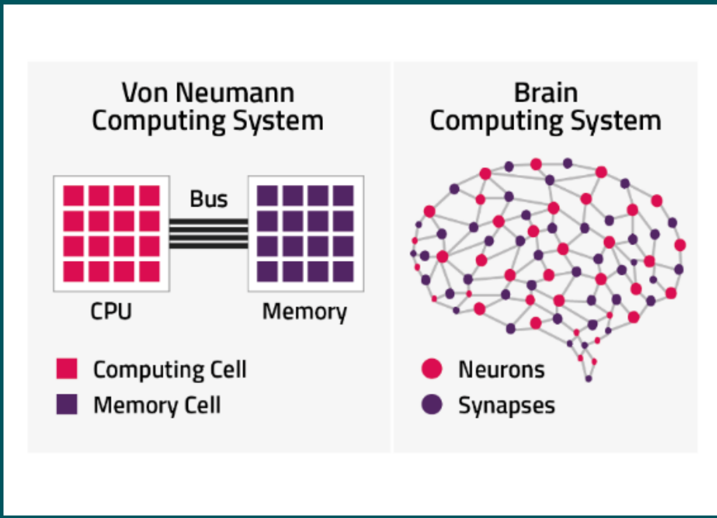
In the longer term, AI could lead to major changes in computing architectures with implications in networks and devices. For example, researchers are working on a new architecture for computing referred to as neuromorphic computing, based on spiky, asynchronous and event-driven neural networks, that achieves an increased energy efficiency and lower latencies compared with traditional Von Neumann architectures [Mehonic2020] (see the 'neuromorphic computing' box below).

Neuromorphic computing

While the performance of traditional computing architectures is still increasing rapidly, researchers are also looking at alternative designs. One of the challenges with the von Neumann architecture is the need to move large amounts of data between the computing unit and memory, leading to increased latency and energy consumption [Mehonic2020]. Approaches based on using processors in parallel or using application-specific processors are not likely to fundamentally solve this problem. New developments in memristors (resistors with memory) [Mem2012], devices that can store and process information via linking their resistance to their history of electrical stimuli, is leading to work looking at non-von Neumann architectures, where computational tasks are performed in the memory itself. These architectures work in a similar way to the human brain, which is why this area of research is usually referred as neuromorphic computing. We provide a comparison between Von Neumann and neuromorphic architecture in Figure 19.

At the same time as developing neuromorphic hardware, researchers are also working on developing new types of algorithms to run on neuromorphic hardware. One example is spiking neural networks, a type of artificial neural network that represents quantities with a series of irregularly spaced spikes similar to the action of human neurons rather than the synchronous processing of binary numbers (as in today's deep neural networks). Benefits of spiking neural networks compared to deep neural networks include much higher energy efficiency and an increase in computational efficiency.

Figure 19: Von Neumann architecture vs neuromorphic architecture. Source: Ofcom, derived from [An2017].

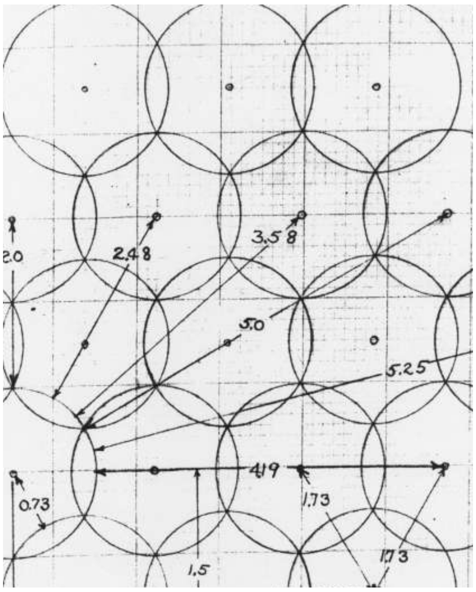


But there are other medium and long-term applications of AI to existing wireless and more general communication systems. For example, in [Oshea2017] the authors demonstrate that it is possible to replace the traditional transmitter and receiver design, based on the guiding principle of splitting the processing chain into multiple independent blocks, with a deep neural network. Potential benefits include a design that adapts to the specific propagation and environment conditions, the possibility of an end-to-end optimisation (rather than based on the optimisation of the single blocks, as in a traditional design) and the possibility of running on off-the-shelf GPUs rather than on specialised DSPs (Digital Signal Processors). Another important area is federated learning, that involves training statistical models over remote devices while keeping data localised [Li2020]. Federated learning has implications for large-scale machine learning, distributed optimisation and privacy.

Changing topologies

The concept of cellular radio networks was first proposed in 1947, the same year the transistor was invented, by Bell Labs' engineers William R. Young and Douglas H. Ring. Young and Ring proposed placing radio towers using a cellular layout (see Figure 20) and using frequency reuse, in a way to 'provide service to any equipped vehicle at any point in the whole country' [Ring1947]. As the cell spacing is reduced, the density of frequency reuse increases, allowing in principle an unlimited network capacity at the expense of needing to build and run a large number of cells. Today's systems still rely on the concept of the cell as the fundamental unit of radio access networks.

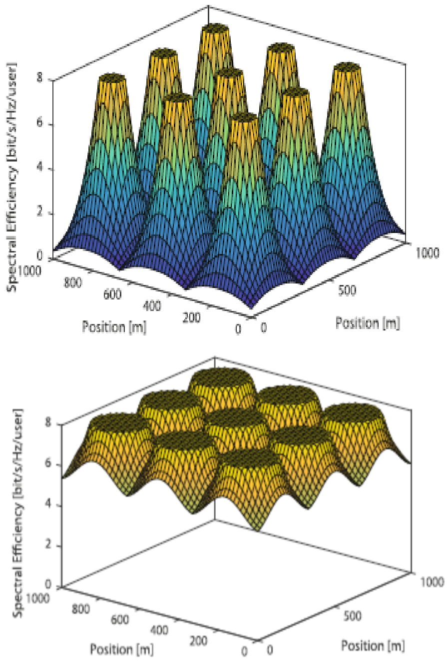
Figure 20: Example of traditional cellular layout. Source: [Ring1947]



Beyond the cellular layout. There are now suggestions that going beyond cell-centric architectures could yield benefits [Boccardi14] and some elements of this have already made it into standardisation and commercial deployments. At a basic level, dual connectivity [Dah18] allows connecting a single device simultaneously to multiple cells, so that control, data, downlink and uplink channels could use different base stations.

A more advanced concept, referred to as cell-free networks, is related to extremely large aperture arrays, presented in the previous section. It has roots in the cooperative distributed systems from the early to late 2000s [BjoSang2019]. With cell-free networks, jointly controlled antennas are distributed over large geographical areas and cooperate to deliver service to each user. The major benefit compared to a traditional architecture, is signal-to-noise ratio increase (e.g. [Int2019] indicates gains in the range of 5-20 dB) and a more consistent quality-of-experience (see Figure 21) across users in different locations. Implementation would require very tight and accurate synchronisation between antenna locations and the transport of large amounts of data between sites, placing greater reliance on a dense fibre-based backhaul/fronthaul transport network.

Figure 21: Comparison between the variations in efficiency of a traditional cellular network and a cell-free network, showing the potential for much more consistent user experience. Source: [Int2019].



Into the skies – and beyond. While Young and Ring's work targeted geographic coverage at any point in the whole country, they did not consider coverage *of* the skies – or indeed coverage *from* the skies. The increasing popularity of unpiloted autonomous vehicles (drones) and potentially high altitude balloons, coupled with increasing demand for coverage on planes, and in rural areas, spurred the emergence of work looking at the sky as the next frontier for mobile communications [Moz2019]. Drones could be used as mobile base stations, to improve coverage on the Earth, particularly in remote areas or for emergency operations. Drones and planes need to communicate with ground systems, for applications like broadband-on-planes, video streaming or control-at-distance. And swarms of drones need to communicate between themselves, to achieve a common goal. Effectively this has led to rethinking cellular architecture in a way to incorporate base stations located in the air and on the earth to provide coverage both on the ground and in the sky. There is a great deal of academic effort looking at these challenges, and in June 2020 plans to build a nationwide 4G LTE Air-to-Ground network for the emergency services across Great Britain were announced [EAN]. Looking further up in the sky, other disruptive opportunities come with the integration of mobile networks with satellite networks, in particular low Earth orbit satellites. We cover this topic in Chapter 5.

Joint communication and sensing

Historically, wireless communications and radar systems have developed mostly independently [Rah2020]. Recently, however, there is growing interest in the potential for a single system to meet both applications. First, the use of higher frequency bands for communication [Huang2019] at so-called mmWave or terahertz frequencies, which have a much smaller wavelength, enables a much finer spatial resolution to characterise even subtle movements, such as recognising user hand and finger gestures. Second, the use of MIMO enables radio devices to achieve a higher resolution and hence separate more numerous objects. Third, the use of machine learning, allows reuse of signals designed for communications rather than sensing, for sensing applications. Emerging new use cases including vehicular networks, indoor positioning, drones and smart homes could benefit from joint communication and sensing.

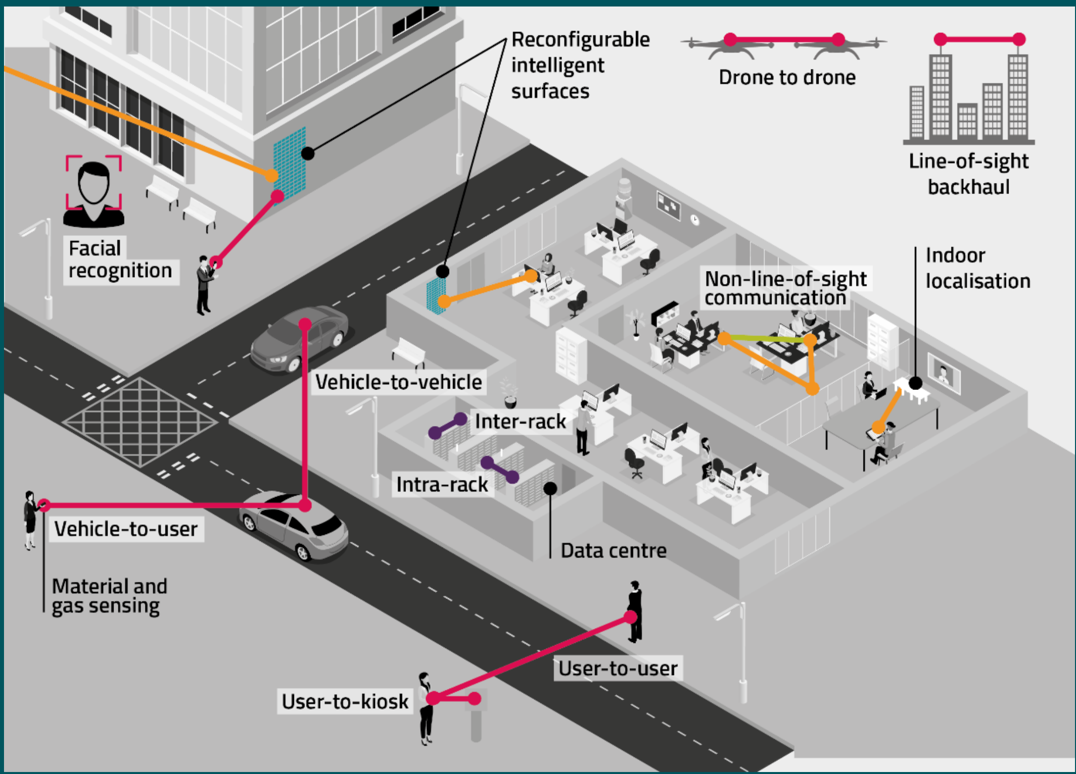
Sensing capabilities can be provided as an add-on to existing communication technologies (see [He2015] and [Abib2013]): in this case the challenge is how to design sensing functions as an add-on to an existing system without affecting its performance. For example, in [Abib2013] Wi-Fi is used to track the 3D motion of a user from the radio signals reflected off her body. There are larger opportunities, however, when it is possible to natively design a system to support both communication and sensing, requiring optimisation of waveforms, frame, system and network architecture [Rah2020]. The development of terahertz systems (for example in the context of 6G systems) is being driven by the vision of providing a joint native design for communication and sensing (see ‘Terahertz communication and sensing’ box).

Terahertz communication and sensing

Terahertz (THz) refers to frequencies in the 300 GHz to 3 THz range. As pointed out in [Sarieddeen2020] proponents of THz communication systems claim that THz provides advantages compared to mmWave systems (amount of bandwidth available, smaller footprint and higher directionality, and optical systems (THz signals require less precise pointing, acquisition and tracking, among others). But they also come with some major challenges due to the nature of propagation at these frequencies (including very short communication distances, blockage, frequency-dependent molecular absorption), hardware and system design. We note that the need to find cost-effective solutions for various hardware challenges show that softwarisation alone will not be the enabler for future communication systems.

While THz communications systems have the potential to allow short-term communications with a very high throughput and a very low latency, a major opportunity with THz frequencies is to jointly design systems for communication, sensing and positioning. For sensing applications, the different transparency of materials to THz signals allows their use for product inspection, spectroscopy, material characterisation, security and various medical applications. For positioning applications, THz can provide centimetre and sub-centimetre level accuracy using high-resolution maps of the environment [Sarieddeen2020]. Thus, THz communication, sensing and positioning is regarded by some as one of the most promising technologies for future 6G systems.

Figure 22: Examples of applications for THz communication and sensing. Source: Ofcom, based on [Sarieddeen2020].



Other emerging technologies

We have found other emerging technologies that could have a potentially disruptive impact in the medium to long term.

Optical wireless communications. Optical wireless communication is already widely used in some areas and has the potential to become even more prevalent [Haas2020]. For example, barcode scanners and remote controls all use optics for short range data communications. There has also been considerable interest in “light fidelity” (LiFi) systems that use modulated light-emitting diodes (LEDs) (visible or not) to provide a short-range alternative to RF. The range for exterior use is limited by difficult atmospherics, particularly fog, but there may be some cases where this is less significant at shorter ranges or where atmospherics are less important such as space-based communications. In these cases, there is considerable work ongoing and the range can be long, partly enabled by the high antenna ‘gain’ from the short wavelength.

Orbital angular momentum. Generally, the propagation of electromagnetic waves has an associated property called angular momentum which comprises of two components, namely spin angular momentum (SAM) and orbital angular momentum (OAM). SAM is an additive component linked to polarisation and the OAM is related to the angular change in signal phase around the plane that is transverse to the direction of propagation. It is being suggested that exploitation of OAM for communication could provide high spectrum efficiencies, in particular for fixed line-of-sight applications, such as in the form of a linear array for communication to trains [Brown2020].

However, some commentators suggest that OAM is not new but a subset of the solutions offered by traditional MIMO communication [Edfors2012].

Dynamic spectrum allocation. In the first part of this chapter we discussed the emergence of new regulatory regimes allowing shared and local access licences and the commercial adoption of dynamic spectrum sharing mechanisms. Going forward, trends like radio self-optimising networks, distributed ledgers and ML/AI could bring a new paradigm in spectrum sharing, although [as discussed in our spectrum strategy consultation,] considerable uncertainties remain.

An example of a major project on dynamic spectrum sharing is the defence advanced research projects agency (DARPA) spectrum collaboration challenge [Hao2019]. This was a three-year competition between different research groups, that lasted between 2016 and 2019. The research groups were asked to leverage ML to design radios capable of optimising the use of shared spectrum bands in a real-time manner, with both non-collaborative algorithms and collaborative algorithms. The winning team applied an AI technique based on reinforcement learning to make the best use of the available spectrum. Ofcom has recently published proposals for its spectrum management strategy for the 2020s [OfcomSS2020]. This highlights several opportunities for automated spectrum management techniques to be relevant to future spectrum management.

3: Fixed and optical technologies

Where we are today

The copper- and fibre-based networks that deliver high-capacity broadband connections to homes and businesses are known as fixed line networks. Growth in the capacity and speed they deliver has been impressive over the last few decades and continues to accelerate. From the late nineteenth century telegraph to the advent of optical fibre around 1970 (following Nobel Prize-winning, UK-based work by Sir Charles Kao [Kao1966]), data rates increased by around 100,000 times [Agrawal2016] and since then the additional gains are at least another million times [Winzer2018]. If your car's fuel consumption had improved by the same proportions a thimble-full of fuel would last you a lifetime.

The total fibre optical spectrum available, depending upon the technology used, is more than 1000 THz, enough on each single fibre to provide simultaneous video communications for every person in Britain (that is >10MHz each). Theoretically at least, because current systems use less than 100 THz. And that is on each single fibre; around 200 million kilometres of new fibre is being installed worldwide each year and around five million UK homes already have access to full fibre [Ofcom2020]. The latest research results indicate a single fibre could provide enough capacity to download the entire Netflix library in less than a second [Galdino2020], using a 16.8 THz bandwidth.

Developments in fixed technologies tend to address the needs of two distinct regimes, with distinct challenges:

Access

- Short distances (generally less than a kilometre)
- Originally delivered via copper phone lines, now with a mix of technologies

Core

- Longer distances and high capacity
- Almost entirely delivered via fibre.

Access. Access is usually delivered by one of the following technologies.

- Copper is used all the way between the exchange and the customer's premises, via digital subscriber line (DSL) technology.
- Fibre is used from the exchange to the cabinet (usually known as fibre to the cabinet (FTTC)), and copper to connect the customer, via very high-speed digital subscriber line (VDSL).
- Fibre is used to the cabinet and a coaxial cable to connect the customer (originally for cable TV systems), via the data over cable service interface specification (DOCSIS) standard.
- Fibre-optic connectivity is used all the way to the customer's premises (usually referred as fibre to the premises (FTTP) or fibre to the home (FTTH)), via a passive optical network (PON) where multiple

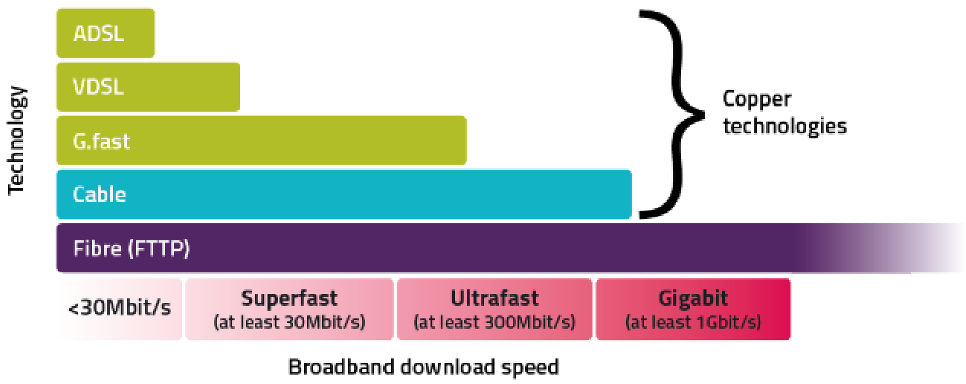
terminals are connected to one shared fibre network and distinguished by frequency or timing, similar to how radio frequencies are shared.
- We note that fixed wireless access can also be used, via either mobile (4G or 5G), point-to-point or point-to-multipoint technologies.

While we are approaching the limits of copper capacity (see box 'the limits of copper') and few new copper lines are being laid, DSL is still evolving. For example, 'G.fast' enables higher speeds, but it requires a shorter distance from the cabinet. At 100m distance from the cabinet it enables 900 Mbps (downlink + uplink). In the long term there are efforts to upgrade copper-based technologies to support multi-Gbit speeds, but over very short distances from the cabinet [Mariotte2017].

Coaxial cable systems using DOCSIS are also evolving. DOCSIS 3.1, which is being commercially rolled out, supports a maximum download speed of 5 Gbps and upload speed of 1 Gbps, shared between all customers connected to the same node[20] [DOCSIS3.1]. Specifications for DOCSIS 4.0 were released in March 2020. DOCSIS 4.0 supports a maximum download speed of 10 Gbps and upload speed of 6 Gbps, again shared between the customers connected to the same node [DOCSIS4.0].

FTTH technologies are also evolving. One example is NG-PON2/TWDM-PON (ITU-T G.989), which can achieve up to 40 Gbps downlink and uplink, via multiplexing four wavelengths [BF2018]. It requires updates at the cabinet at the end-user device. We note that, while achievable speeds are very high, multi-wavelength laser transmitters are currently expensive to deploy into households. Figure 23 provides a comparison between the speed achievable by some of the main commercial fixed access technologies available today.

Figure 23: The various technologies used for access with an indication of the speeds they can normally achieve. Source: Ofcom.



[20] With DOCSIS the access network capacity is shared with neighbours, and therefore the experienced speed is a function of the number of premises that are connected to the same node.

The limits of copper cables

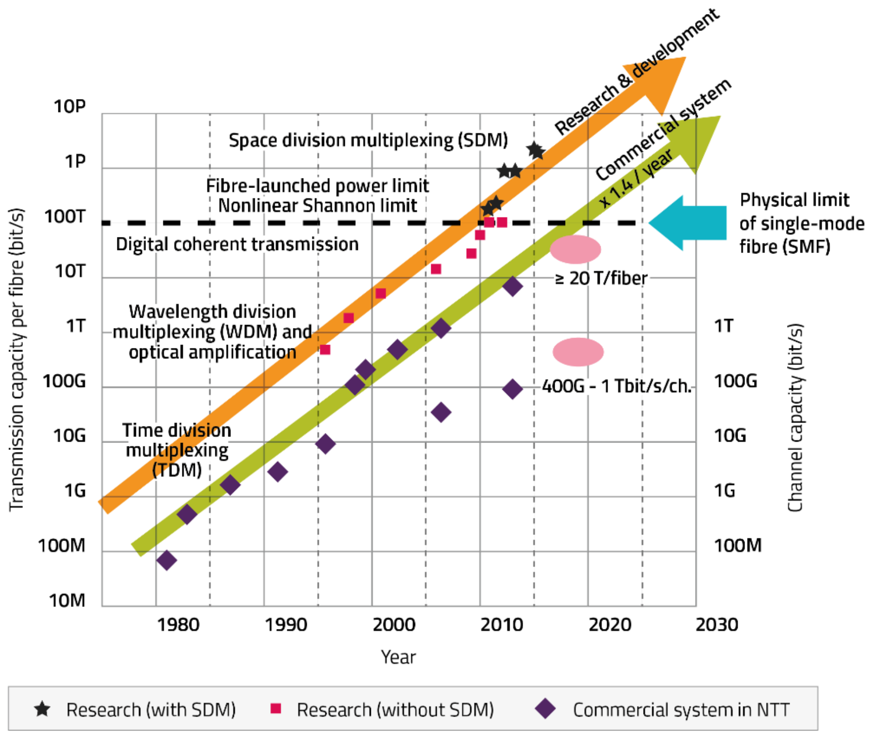
Both traditional telephone and higher-performance coaxial cables are made of copper. Copper is limited due to a combination of losses from the alternating field in the dielectric (plastic) insulator and resistive losses in the metal. Both of these loss effects increase fairly rapidly with frequency thus limiting data capacity at any given range, especially in ADSL and VDSL cables, that are not designed for high speed. Coaxial cable, which is near-air-insulated, has a superior performance. The dielectric losses rise with frequency due to intrinsic effects in the material and the metal losses rise because high radio frequencies (RF) are confined to a thin layer of metal near the surface by the 'skin effect' (basically the RF cannot penetrate the electron gas that gives the metal its shine), thus reducing the effective conductor area.

Core. Core networks rely almost entirely on fibres. We will discuss the evolution of fibres in the next section.

Evolution of fibre links

Core networks rely almost entirely on fibres. Figure 24 shows some of the main technologies that have impacted the evolution of high-capacity optical transport networks in the last twenty years [Miyamoto2017]. This is a commonly-used description of the 'limits' of optical fibre technology, somewhat analogous to Moore's Law which shows the exponential growth in the number of devices in semiconductor circuits and of similar log gradient growing by a factor of 1.4 per annum [Miyamoto2017]. Commercial systems lag a few years behind research systems, as would be expected, but physical limits that appeared insurmountable at various times have eventually been successively overcome by new technology.

Figure 24: The evolution of high-capacity fibre networks over time, showing the consistently exponential growth over many decades and with successive technical improvements. Yellow line experiments, green line commercial systems. Source: Adapted from [Miyamoto2017].



The single mode fibre (SMF) (a fibre where light takes a single path through the fibre core) has been the mainstay of optical fibre communications for the last three decades. Today an SMF fibre is capable of reaching speeds of the order of hundreds of Tbps over a single fibre, using a large number of separate wavelengths, via a technology called wavelength/frequency division multiplexing (WDM). Optical amplification via erbium-doped amplifiers has enabled longer ranges, reaching thousands of kilometres. Digital coherent transmission, via modulating amplitude and phase of the light, has allowed even better performance. In recent years, however, we have been approaching the limits of SMF (see call out box 'the limits of single mode fibre'). The use of multi-core fibres, via space division multiplexing (SDM), and hollow core fibre has been proposed to further increase the achievable speeds.

Installation. Constraints on progress besides conventional technical limits on the fibre itself are also important. For fixed lines of any kind the cost of installation remains stubbornly resistant to productivity improvements on anything like the digital scale, possibly reflecting slow productivity growth in civil engineering and construction more generally. But there is hope here - robotic installation for overhead and underground cables is being experimented with and could drive change; developments for autonomous road vehicles and for mining are advancing quickly. See, for example, techniques for adding fibre to power lines [aerial2020], or the well-established BT-developed technology for blowing fibre into tubular cables [BT2020].

The limits of single mode fibre

The limits of single mode glass fibre come from the glass. They come not from the choice of glass (the currently dominant silica glass is excellent by glass standards) but from the density of optical power within the glass dictated by the need to transmit ever more information. This results in:

- non-linear effects in the glass that guides the light, leading to both degradations arising from non-linear interactions between signals (referred to as the 'non-linear Shannon limit' [Essiambre2010]) and damage-driven limits on the ability to keep raising transmission powers;
- limits on the optical bands that can be used, both from limits on intrinsic materials loss and from the limited band coverage of available optical amplifiers; and
- losses and latency due to the glass in glass fibre. The current limit on low loss in conventional fibre (that has not improved in many years) comes from intrinsic losses in the glass.

Where we are going next

Fibre-optical communications remains a very hot topic, and progress is still rapid, both in the way the technology is used and in the technology itself.

Here we focus on two key areas where substantial technical advances in fibre-optical communications changes are expected in the medium- to long-term: complex optical fibres, such as multi-core fibres and hollow core, and dense integrated optics. Both of these are targeted at allowing more complex and adaptive networks as well as increasing capacity.

In addition to these two areas, we will also look at quantum technologies: light is a quantum phenomenon and it is natural for optical communications to use quantum phenomena to extend performance.

Complex optical fibres – multi-core (SDM) and hollow core

For the fibre itself we noted above that the bandwidth available on each fibre is a thousand times wider than the whole range of traditional radio frequency bands and that even considering the limitations of existing fibre and electronics we are only using perhaps 10% of what we could. But with improved optical fibre amplifiers emerging, which cover an ever-growing part of the optical spectrum, this is changing [Galdino2020]. While one way to further increase capacity is to use multiple parallel channels via WDM, there are other approaches based on using multiple spatial channels. We note that some bands are less well used and this gives scope for comparing the very different approaches to achieving a higher capacity.

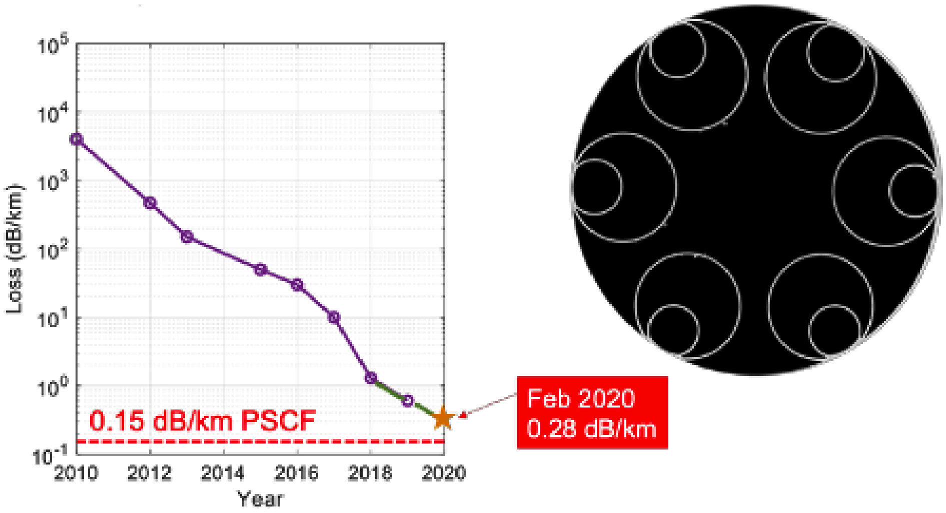
Spatial division multiplexing. A single optical fibre can carry multiple potentially independent signals in a number of ways. It can carry signals on multiple electromagnetic frequencies via WDM, and this is almost universally used in current fibre communications systems, especially within the erbium optical amplifier bands [Mears1987]. Although most current communications fibres are single mode, fibres can also carry multiple modes at each frequency, if the fibre is large enough to allow this and each mode can exist in two independent polarisations. And beyond this one fibre can contain multiple parallel light-carrying cores, because the diameter of current fibres is set largely by the need for mechanical stiffness to resist fine-scale bending that causes loss rather than by any direct need for optical isolation. Orbital angular momentum is another potential route, though this overlaps in a complex way with the modal and polarisation properties (see Chapter 2 for a discussion on orbital angular momentum).

The use of multiple modes, and in particular multiple cores, is normally called space division multiplexing (SDM) [Miyamoto2017]. This has considerable potential for increasing single fibre capacity and is widely researched. There is some issue in these cases with crosstalk, but in general the reduction in optical power density by spreading power over a larger area will reduce nonlinear effects and raise nonlinear capacity limits.

Hollow core fibres. A more radical approach is to remove most of the glass in the fibre core altogether, as in the hollow core fibres described below [Southampton2020] [Yerolatsitis2019]. This could also deliver lower loss than existing fibres, possibly within only a few years. This and other characteristics could have a big impact on undersea fibre cables, which carry most intercontinental traffic. And the lower and more stable latency could impact different types of applications. These fibres are challenging to fabricate but there are now multiple suppliers [Photonicsguide2020].

As already mentioned, the key idea is to get rid of the glass in glass fibres, at least insofar as its light-carrying functions are concerned.

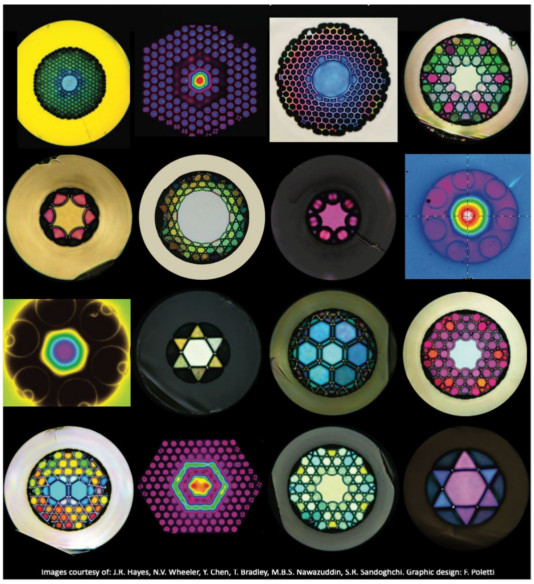
Figure 25: The best-case loss achieved in hollow core fibres over time (left) with the loss of standard solid core silica fibre shown as a horizontal red dashed line. (right) a photograph of the end of a hollow core fibre (see text). Source: Prof D. Richardson, Southampton University [Southampton2020].



The diagram in Figure 25 shows the progress in the loss achieved in hollow core fibres in research. It suggests they might be surpassing conventional fibre (shown as a red dashed line) quite soon. On the right is a micro-photograph of the core region of such a fibre (a few 10s of microns across). The dark areas are open space (air) and the light regions, including the surround, are glass. The light carrying the signal is confined in the centre, 'nudged' there by the effect of the thin glass membranes shown as circles around the centre. These glass membranes are tenths of microns in thickness, though because of their low mass they are not particularly fragile in use.

It is not easy to see why these techniques work – at least not compared to conventional fibres that work by the core glass pulling the light inwards. For hollow fibres the grazing incidence just gently pushes the light inwards, and this is extremely effective provided the membranes are carefully shaped, and considerable lengths of the fibre have been fabricated.

Figure 26: Hollow core fibres can be very beautiful, even if this is incidental to their function. The colours are genuine in that this is what you see if you insert white light, although the fibres are actually designed for infrared use. Source: J. R. Hayes et al.



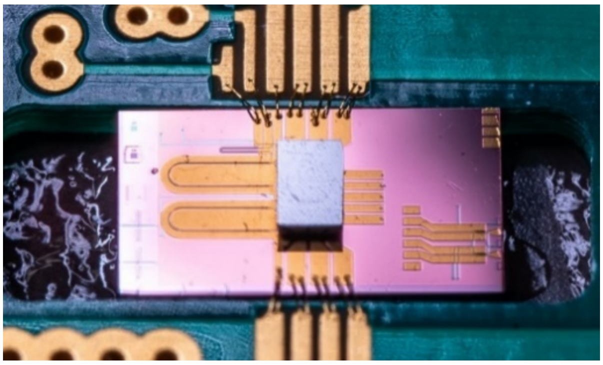
The resulting guided mode has only a tiny fraction of a percentage of its power in the glass (in the membranes). It is this last aspect that is important in most applications. Advantages are:

- nonlinear effects are reduced just as the power in glass is reduced and this leads to higher capacity;
- power handling capability is similarly improved, also implying potential capacity gains;
- the latency, that is optical delay in transmission, is reduced by 30% because the effective refractive index is about 1 rather than around 1.5 in the glass;
- the optical bandwidth available is potentially significantly broadened, again because this is normally limited by the glass; and
- the ultimate loss should be less than that of conventional fibre - as evidenced above this is still to be experimentally demonstrated but the modelling suggests it should be possible and progress so far is promising.

While research results are promising, challenges remain - in particular in scaling up the process needed to produce and deploy fibre.

Dense integrated optics

Figure 27: Fast silicon integrated optic chip. Source: G. Reed.



Developments in terminal and intermediate opto-electronic devices are also very significant. A simple yet profound impact could arise from reductions in device cost that would enable technologies currently used in the core parts of the network to be deployed in access. A good example would be tunable semiconductor lasers [Ueda2019] and the corresponding passive and active wavelength routing devices. Another would be coherent technology, that uses a laser local oscillator mixed with the received signal to increase sensitivity and channel selectivity, rather like a traditional radio. These devices have already been used in research to direct signals in PONs to particular terminals but have the potential to create a 'big PON' space with many parallel connected terminals that would operate rather like an extended aether, with many terminals able to talk to one another across a shared fibre network.

Next-generation optical integrated circuits can be made in a number of technologies, including glass devices already widely used for WDM components. This includes:

- Passive devices that can be made in various technologies, for example the arrayed waveguide gratings [Lee2019] that are widely used for WDM today.
- III-V and related semiconductors (such as indium phosphide). These are used especially for active components, particularly laser sources and detectors, because the direct bandgap nature of the semiconductor enables them to readily turn electrical signals into light and vice versa, and they can be tailored to operate across the low loss fibre bands.
- Silicon and silicon-germanium [Silicon2020]. Silicon is the workhorse for the vast majority of electronic applications and integration with electronics can be important. It has the capability to produce relatively low cost and compact devices and circuits. A key objective would be the application of this to access networks to enable the deployment of wavelength tuning and coherent techniques currently used in the core network.

- For ultra-dense optical chips, meaning micron-scale devices more comparable with the scales used for electronic devices, silicon can be used but the densest devices use plasmonic metal layers to confine the light. The possibilities are vast, for example the ultra-small modulator described in [Mardoyan2019].

Integrated optical devices that have been reduced to electronic scale, often on silicon, can enable more complex networks [Luis2020], and could reduce energy requirements significantly, just as is the case in electronics. This generally requires close optical confinement that can be achieved using plasmonic or air-surrounded devices [Koch2019].

The small scale can also enable electro-photo-mechanical active devices that, because of their size, can operate at GHz speeds [Haffner2019]. This technology could also help to make access coherent cost-effective.

There are a number of motivations here; but the key is making devices small, and thus higher speed and lower energy. This is routine in electronics but is now appearing in integrated optics. It is enabled by combinations of high refractive index difference guidance, for example silicon-air, and plasmonic metal-dielectric guidance.

The reducing scale also enables mechanical effects to be used for modulation and switching [Haffner2019].

Quantum

Light is, in many respects, the most accessible of the quantum phenomena and it is natural for optical communications to use quantum phenomena to extend performance. Example of applications of quantum phenomena for communication networks include quantum-secure transmission and random number generation. They also include the potential use of quantum computation for network control - and the adaptation of conventional crypto technology to counter the potential impact of quantum computation (called 'post quantum encryption'). Considerable effort is being applied to this worldwide [quantum2020] and its potential significance is widespread. The following provides an overview of the areas of application.

Secure communications*.* Normally called quantum key distribution (QKD), which implies use of the quantum link to distribute digital keys for subsequent use in conventional encrypted transmission. There are several approaches to this, but all rely on the inherent unknowability of information below the quantum limit - so that any kind of interception of the signal destroys the link, thus advertising the attempt. Rates of transmission on QKD links can approach Mbps but the links are very sensitive to degradations such as loss, and there is no way to amplify the signals to increase range without destroying the security (though data can be relayed through multiple sequential links). It is even possible to overlay conventional signals on a QKD link though great care must be taken to avoid interference. Many demonstrated QKD links [Tessinari2019] have shown that the technology works, and a good deal of progress has also been made on single-photon devices for use in them. Trials are extensive around the world and it is likely that commercial networks will exist soon. Researchers have different views on whether QKD links are the most practical way to offer extra security [GCHQ2020].

Another area related to security is to design encryption transmissions to be much harder than current encryption for a potential quantum computer to break. It is somewhat more demanding of the electronics than current techniques, but it works and could be deployed on a precautionary basis long before the necessary quantum computer is available [UKquantum2016].

Random number generation. Truly random numbers needed e.g. for secure encryption are remarkably hard to generate. This process appears trivial but tossing a coin, which looks random, actually is not. True randomness is challenging, as Einstein[21] understood - quantum processes can be inherently and fundamentally unpredictable rather than just hard to predict [quantum2020].

Quantum computation. This is still at a small scale but is attracting considerable research worldwide, both in industry (for example at Google and IBM) and Academia (e.g. at the University of Oxford [Oxford2020]), with recent claims of 'quantum supremacy' (that is quantum systems that are better than conventional computing architectures, albeit in very limited ways). If it can be done on a large scale it poses some problems for the current public key encryption that is vital to the internet. But it also provides a powerful method for real time complex system optimisation, which is a very challenging and energy-consuming problem for conventional computers. This could have many applications, but a particularly interesting candidate is the control of large complex dynamic communications networks. This is some way off at present but could one day be very important as networks continue to become more complex and rapidly adaptive to meet growing needs.

Quantum communications. Some kinds of quantum-based communications that make use of entanglement can be used to connect two or more quantum computers [Vienna2020], [Cacciapuoti2020], [Chiribella2019]. Quantum communication, in other words, involves moving away from classical forms of communication to instead take advantage of the laws of quantum physics to communicate via the transmission of quantum states. Traditionally, data would be sent as classical bits representing 1s and 0s. Quantum communication proposes using photons (which are the underlying elements of all electromagnetics including light and radio waves), for transmitting data to take on a state of superposition, which means they can represent multiple combinations of 1 and 0 simultaneously. Researchers [Chiribella2019][Cacciapuoti2019] also propose further advances where both information carriers and the channels can be in quantum superposition. Therefore, as discussed in Chapter 2, in theory recent advances in quantum technology could take us beyond Shannon by establishing new fundamental limits and the potential of extending Shannon's theory to situations where different transmission lines can be combined in a quantum way. But there is a lot of engineering work required before this potential can be reached.

Other trends

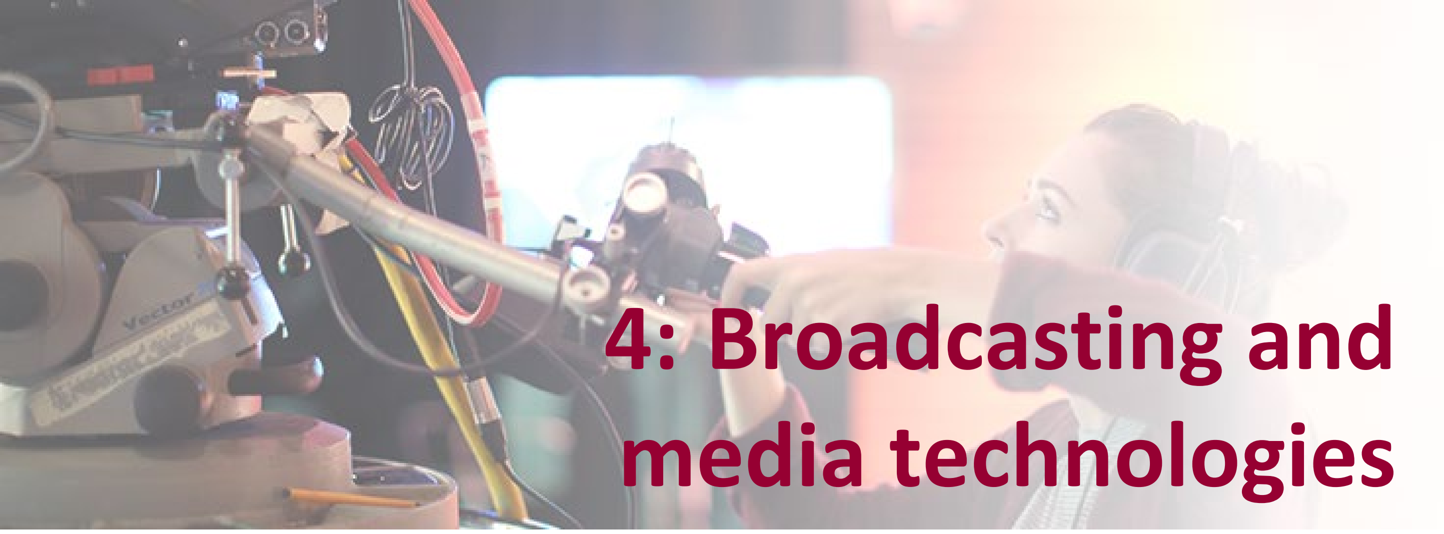
Various technical trends, including those above, will mean that future networks, already composed of hybrid blends of fibre and wireless links, will become both more complex and more integrated (as, for example, BT indicated in its response to our CFI). Some of these trends are:

- The boundaries between fibre and wireless will become more diffuse, for example fibre systems can carry phase-coherent radio frequency signals [Ishimura2019], which could thus be used

[21] "[God] does not play dice with the universe".

to link multiple antennas together, as already widely researched. Hollow-core fibres with more predictable, less environmentally sensitive latency could also be important here.

- Managing more complex and increasingly virtualised and disaggregated networks will be more challenging, with applications potentially for AI [Mata2018], open source software and even quantum computation. Software defined networks (SDN) is already common in optical systems but it will play an even more relevant role, and offer larger gains, in bigger integrated networks. SDN systems also require security designed in.
- The steadily improving performance of conventional electronics will have an impact on what is possible in communications - for example through more complex coding and real-time digital correction of the deleterious effects of nonlinear interactions in transmission. Nonlinear interactions are ‘scrambling’ rather than classical additive noise so just as Shannon realised that smarter coding could overcome the effects of noise, much smarter systems can also help to overcome nonlinear degradation.



4: Broadcasting and media technologies

Significant developments are expected in the next ten years in the field of television and radio broadcasting, live-streaming and on-demand media technology. These include the tools for content creation and production; content distribution routes; the experiences that audiences will enjoy; and the way we navigate content and use our devices. There are close interrelationships between these elements: for example, new consumer devices (such as ultra-high definition screens) create an appetite for higher quality content, while new content navigation technologies abstract the consumer experience from the actual means of delivery.

Creation and production

The world of media production is being transformed by the advent of internet protocol (IP) distribution and cloud computing. The traditional picture of a TV studio – manually-operated cameras connected by thick and heavy cables to a studio gallery – is already less common, as cameras are connected by optical fibre to standard IT equipment, and switching, mixing and post-production [IBC2020] are all carried out in the cloud. For outside broadcast events, today's specialised and proprietary radio camera systems can be augmented with 5G communications to connect remote cameras to the cloud - enabling a rapid set-up and tear-down with a minimal level of equipment and staff on-site [SVG2020].

The use of 5G for content production is of considerable interest to major broadcasters throughout Europe. The European Broadcasting Union (EBU) and 5G Media Action Group (5G MAG) are actively working to build consensus and facilitate trials [5GMAG2020] (See callout box "5G for content production").

5G for content production

Broadcasters currently rely on a wide range of technologies to get pictures and sound from cameras and microphones into their outside broadcast vans and broadcasting centres. Cables, fixed link fibre connections, satellites and, more recently so-called 'bonded cellular' which takes a number of 3G or 4G connections and groups them together to provide sufficient bandwidth and reliability. Bonded cellular systems have revolutionised the work of newsgathering in particular, allowing journalists to contribute live from almost anywhere with just a simple backpack or camera mounted device. However, these proprietary devices (meaning that receivers will only work with transmitters from the same manufacturer) need to be equipped with SIM cards from multiple operators and, in order to be practical, use compression to reduce the bit rate required. Often, the bandwidth available is only sufficient for one camera, fine for a newslink but not good for a sports match, and the cameras are simply sharing capacity with the general public –

meaning that network congestion can affect the performance.

5G, through the work of 3GPP in its latest mobile broadband standards will offer a range of benefits, amongst others:

Higher capacity: allowing multiple cameras to be supported and without the need for bonding technology;

Improved support to private networks: allowing the possibility to introduce additional high capacity for events and for studios;

Network slicing: giving broadcasters a guaranteed capacity irrespective of other network congestion; and

Edge computing (computation and data storage closer to the user): allowing the processing of signals closer to the point of acquisition and the streamlining of production workflow.

The resolution of new TV cameras is increasingly converging towards ultra-high definition (UHD) at 4K and 8K, significantly higher than today's high definition (HD) and standard definition (SD). Table 6 lists these resolutions and their bit rates (both uncompressed and typical compressed). Ultra-high definition cameras can also capture pictures with high dynamic range (HDR), which captures extreme light and dark elements of the same scene without 'crushing' (losing detail in the whites or the blacks), a wide colour gamut giving the ability to reproduce the vivid colours that it has not been possible to see on television before [ITU2019], and higher frame rates, enabling motion to be more faithfully captured [Salmon2014].

Looking further forwards, so-called light-field or plenoptic technology might even permit the camera's focus and depth of field to be adjusted in post-production [IHR2016]. See the callout box "Light-field (plenoptic) cameras" for additional information.

Table 6: Resolution, and typical raw and compressed bit rates for video content. Source: Ofcom.

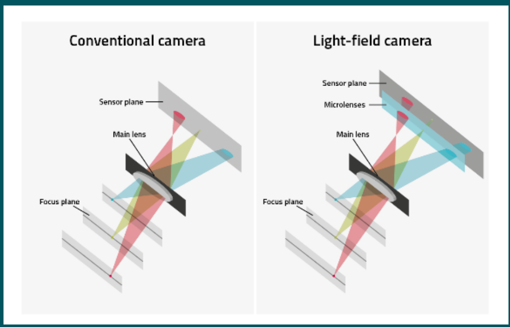
Resolution	Pixels (Horizontal x Vertical)	Typical raw bit rate	Typical average compressed bit rate
SD	720 x 576	622 Mbps	2.9 Mbps (MPEG2)
HD	1920 x 1080	3.1 Gbps	4.9 Mbps (MPEG4)
UHD - 4K	3840 x 2160	12.4 Gbps	22.5 Mbps (HEVC)
UHD - 8K	7680 x 4320	49.8 Gbps	40.0 Mbps (HEVC)

Light field (plenoptic) cameras

The light field camera was originally proposed by Gabriel Lippmann in 1908. It captures information about both the intensity of a scene and the direction in which light rays are travelling, in contrast with a conventional camera which records only the intensity. Such cameras employ a large array of so-called 'microlenses' placed behind the normal image plane, producing an array of micro-images on the sensor behind (Figure 28). The resulting images are then processed to recreate the final image. Each element of the scene will be manifested in a multitude of micro-images with a difference between these which is dependent on the depth away from the camera. In processing the focal point and depth of field of the image can be altered. Thus, it is possible to record a scene, and to alter the focus in post-production.

Furthermore, because each of the microlenses sees the scene from a slightly different viewpoint, it is also possible to create a 3D image from what appears (to outside observation) as a camera with a single lens.

Figure 28: The components of a Light-field camera. Source: Copyright CineD.com.



Research shows that metadata extracted by AI systems from the video and audio content itself, when processed – producing data identifying people and objects and their positions – can be used to automatically control robotic cameras (or select a portion of the image from within the frame of a UHD picture) for some types of events such as small scale stand-up comedy and panel shows – see Figure 29 [BBC2018]. Such metadata, which might also include the script and other production data, can also be used by AI driven systems to automatically trim the content to produce different lengths (run times) to suit a network or even individual viewers' requirements.

Figure 29: Robotic cameras as used in a news studio. Source: Copyright Ross Robotics.

Football matches and other sporting events are increasingly monitored by dedicated wide-angle fixed cameras whose output is processed to provide a metadata stream describing the positions of the ball and of each of the players. Such data flows can be used, in conjunction with AI based tools to control robotic cameras and for both vision and sound mixing - providing automatic coverage and multiple outputs - suitable for audiences who might have different equipment (large/small screens for example) or different viewpoints on the game as fans of one side or the other. Graphics and other objects can be separately delivered to viewers allowing the creation of rich experiences, so that a viewer with a very large UHD screen might be able to choose a wide angle of view with relatively smaller graphics than a viewer who is watching on a small mobile device.

Similarly, audio production and coding technologies such as next generation audio (NGA) enable the creation of sound objects, which can be used as the viewer wishes. Coverage of a football match, for example, might include crowd noise, or more than one commentary (perhaps one from each team's perspective). A viewer with the right equipment will be able to select and mix the elements that they want with surrounding crowd noise and their chosen team's commentator speaking from the rear loudspeakers [EBU2019].

Computer generated imaging (CGI) [Wiki2020] is a well-known technique - responsible for the production of cartoons and synthetic characters that are ever more realistic - but the accompanying sound has so far been human. Generative language models provide the opportunity to create high-quality synthetic voices that can read text, and accompany character-driven synthetic video, at a quality that is nearly indistinguishable from a natural human speaker

[DeepMind2016]. The models mimic human responses and are built from the generalised combination of thousands of real human communications.

Object-based media - with a variety of separate optional and combinable audio, video and graphical elements that a viewer can use according to the viewing equipment available and the experience desired - is a central theme to many broadcasting developments today. See callout box "Object Based Media" for additional information.

Object Based Media

In the 1980s, so called closed-caption subtitling was added to television, an additional data stream which could be rendered (made visible) at the receiver, enabling viewers to choose whether they want to see the subtitles or not. At first intended for the hard of hearing, this feature is today also used by a wide variety of other users – gyms, offices etc. Other optional elements are perhaps less widely known, such as audio description, providing a commentary on the picture for those who can't see it.

These features are examples of 'objects', separable and optional parts of the content that can be selected or deselected as viewers wish.

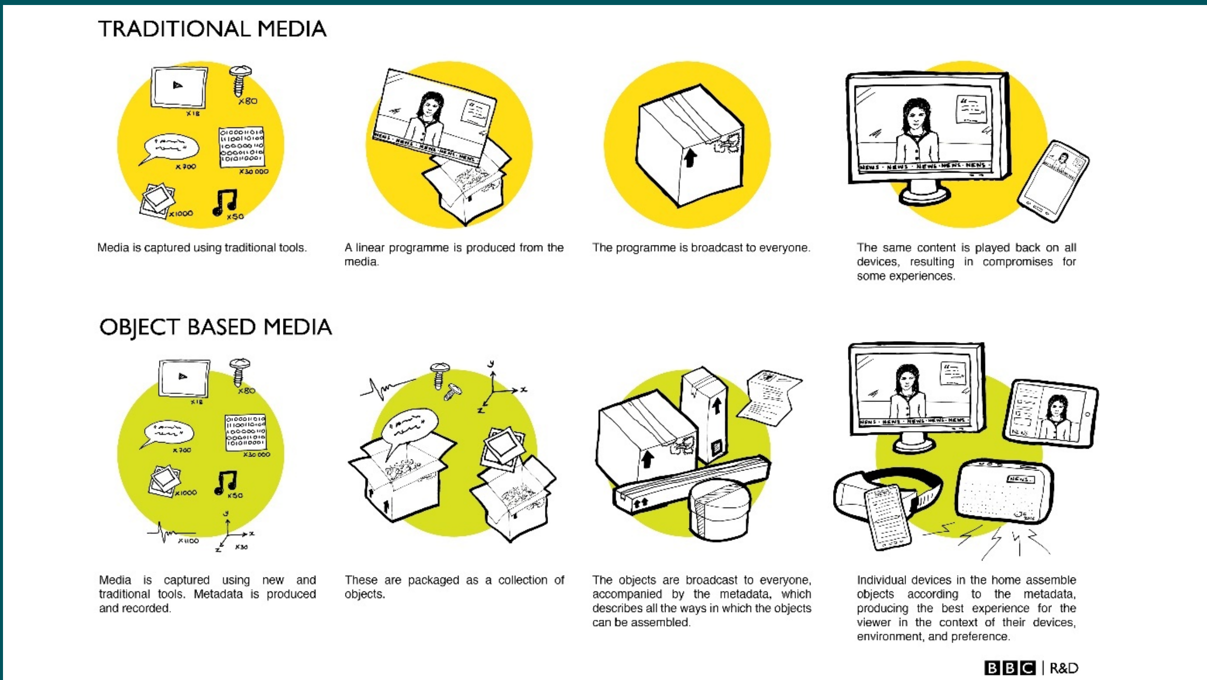
The concept of object based media takes this principle further, allowing the content of programmes to change according to the requirements and circumstances of each individual audience member. The viewer might choose to select audio signing rather than subtitles, choose not to have graphics and other information displayed over the picture of a football match, to have the commentary over the crowd noise or even to choose from a variety of commentaries to listen to. And for those members of the audience with very large, high resolution screens, maybe a single viewpoint along the centreline of the football pitch would be preferred to the closeups that viewers need on a mobile device.

These scenarios are made possible because the content is created as a number of components which are assembled together in the receiver as the user wants, components that are referred to as 'objects' (see Figure 30). And, just as it is possible to consider the parallel objects within a live programme (picture, captions, commentary etc), so it is possible to consider additional objects which might be made available after the programme has been created – for example language translations, additional commentaries, audio signing etc.

A programme can be created as a series of temporal objects, maybe the individual stories in the 10 o'clock news, or a set of different parts of an episode of a soap opera, which can be assembled according to the needs of each viewer.

Agent technologies, operating on behalf of the user, can be used to assemble the objects simply and in accordance with the user's needs and wishes.

Figure 30: The differences between traditional and object-based media. Source: Copyright BBC R&D.



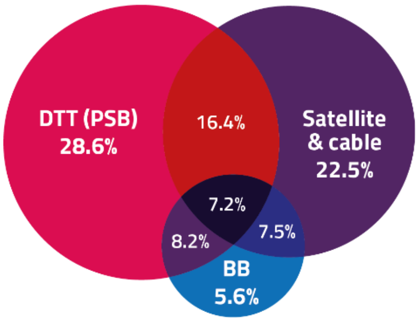
Augmented reality (AR), which is being commoditized in mobile device capabilities, provides the opportunity to provide contextually aware content - tailored to a person's location and augmenting the image of the real world seen by them. This can, for example, be used to provide text and graphical information hovering over the scene of a live sports match (similar to the depiction of thoughts in the BBC's Sherlock Holmes TV series), so that the attending crowd might benefit from some of the rich enhancements available to the television audience.

Finally, broadcasters have concerns about disinformation and the manipulation of content, and several companies are exploring the use of cryptographic techniques and distributed ledger technologies to provide embedded signatures and watermarks within content so that audiences can validate its integrity and authenticity [BBC2020].

Distribution

Distribution is the process by which audiovisual content is moved from the broadcaster to the consumer. Historically this was done using only terrestrial transmitters, and all content was transmitted and consumed live. Distribution today involves both live and catch-up services, and their distribution over the wide range of delivery technologies in use - from terrestrial broadcast, satellite, cable and broadband IP delivery to technologies that will also be available in the future, including 5G. For interest, the split of live public service TV distribution today is shown in Figure 31, which shows the use of DTT (Digital Terrestrial), Satellite & Cable, and Broadband sources. Many consumers use just one source, but some use multiple sources – often in different rooms.

Figure 31: Split of live TV reception in the UK by population as of July 2019. Source: Ofcom [OfcomLE2019].



The range of devices that such technologies reaches today includes traditional television receivers, set-top boxes and hybrid devices (which can access both broadcast and online services). Computers, tablets, mobile phones and other devices access online services, through IP broadband, normally via Wi-Fi when in the home and via mobile networks (or having previously downloaded the content) when on-the-move.

Each of these pathways is subject to constraints - the requirements and limitations (technical and contractual) of the respective delivery pipe and the capabilities of the receiving device; and, in the case of live broadcast, different coders are used to compress the high-quality source material to suit the capabilities of each of the delivery media (see Table 6 above).

UK terrestrial television today carries both low bit rate SD and higher bit rate HD services, the latter carried in the more capacious multiplexes (collections of services) which use the DVB (Digital Video Broadcasting) -T2 specification (providing 40Mbps per multiplex). Some older receivers can only receive and decode the original DVB-T services (24Mbps per multiplex) and are unable to access the equivalent HD services. Hence, there remains a need to carry both SD and HD versions of some channels. This is described as 'simulcasting'.

The DVB-T2 [WikiDT22020] and UK D-Book [DTGDBook2020] specifications provide for the inclusion of 4K services but, to date, such broadcasts have only been made on a demonstration basis in the UK. The French CSA (Conseil supérieur de l'audiovisuel) authorised an experimental, market-proving 4K service in Paris from the Eiffel Tower in 2014, which has now been expanded to two other regions [BBTVNews2018], and Spanish public broadcaster RTVE has successfully demonstrated an 8K transmission over its DVB-T2 platform [BBTVNews2020]. The addition of terrestrial UHD services (4K or 8K) in the UK would require a very significant capacity (see Table 6). However, the total bandwidth available for DTT transmissions is limited. The only degrees of freedom today are the use of DVB-T2 rather than DVB-T (increasing capacity from 24 to 40 Mbps) and the use of more efficient compression technology, such as High Efficiency Video Coding (HEVC) - rendering older receivers obsolete, a reduction in simulcasting and the transfer of some services to IP delivery.

A proposal was made in a 2016 paper [IET2017] to transform the ultra-high frequency (UHF) broadcast spectrum, adopting so-called wideband broadcasting WiB) technology which can treat the entire UHF broadcast allocation as a single multiplex and operate as a single frequency network, allowing a reduction in transmission power (of up to 90%) and a significant (37-60%) increase in capacity. However, despite the advantages, such development would require new and more complex receiver technology.

The evolution of mobile networks to 5G heralds the opportunity to include distribution of some broadcast services as the specifications support broadcast through additions such as free-to-air, downlink-only carriers and greater inter-cell distances. Standardisation developments are in progress for a 5G broadcast mode (which could require a dedicated network) and a mixed-mode (which could be integrated with more general connectivity) [Garro2020].

Satellite and cable TV services, transmitted using Digital Video Broadcasting standards DVB-S and S2 (for HD) and DVB-C and C2 respectively, provide around 160 free-to-air and additional pay channels in the UK, including all the regional variants of the public service broadcasting (PSB) services. Some 4K demonstration services are also available.

IP services are normally delivered using adaptive bit rate (ABR) coding, meaning that the resolution and degree of compression used will change (normally automatically), depending on the capabilities of the channel and the receiving device – and 4K streaming is readily available from many providers. Both live and catchup streams originate from content delivery networks (CDNs) – a set of servers throughout the country, often physically close to end consumers, from which streamed content is delivered – usually as unicast, meaning that there is a separate stream from the CDN carried over the network to each receiver. Some internet service providers (ISPs) can and do use multi-casting technology for live content, which effectively allows a single IP stream to be replicated and feed a multitude of devices simultaneously, reducing the number of streams that are carried in the core network. Work is being conducted to develop opportunistic multicast [BBCDAS2020], whereby a receiver might be able to seamlessly switch between a unicast stream from a CDN, and an equivalent multicast stream where this is available from the consumer's ISP, thereby reducing load on the CDN and core network whenever possible.

IP brings the advantages of flexibility in services, offering an effectively limitless number of channels, and can give the opportunity for audiences to access the different forms of content and new experiences described above. Furthermore, the emergence of new lower-latency codecs, essential to the functionality of videoconferencing, enables the evolution of interactive broadcast content [Vonage2020].

Hybrid platforms bring together conventional broadcast and IP services, often with disc-based or solid-state storage capability in the home. The disc provides a means for consumers to store content, allowing long term retention and/or the ability to overcome rights limitations (for example for sports programming). The disc also provides the means for the platform operator to strategically store content in advance - delivered either via the broadcast or the IP channel. Such content might include film libraries, pre-loaded recommended material or targeted substitutional advertising. The disc becomes - in effect - an edge cache device; storage under the control of the operator. These platforms manage the delivery pipes (broadcast, IP and storage), and the viewer is presented with a holistic experience, abstracted from the need to know how any element has actually been delivered. A contemporary but proprietary example of this hybrid functionality is SkyQ [SKY2020], while DVB-I [DVB2019] provides an emerging suite of specifications for open solutions.

Hybrid platforms are often capable of content substitution - and a typical use of such functionality is in targeted advertising where, in a particular 'slot', a viewer might be shown a different advertisement, sourced from the disc or from an IP stream, according to their locality or demographic. Such technology might also be used for targeted promotion of a channel's content, or even for local news and information.

The inherent advantages in the abstraction provided by hybrid platforms will be extended further by the widespread implementation of technologies such as DVB-I (approved and published in 2019), which can facilitate a consistent user interface on devices of all types (TV receivers, mobile devices, computers etc) and allow each device to use the best or the most appropriate source available at any given moment, whether that be terrestrial, satellite, cable, broadband or 5G. Technologies such as DVB-I will be able to exploit dynamic capabilities in the way that multiplexes and online services are constructed, allowing the creation of pop-up services, switching to and from broadcast and IP versions of content, and the merging of catch-up and live services; capabilities that will also allow broadcasters to make strategic and business-based decisions about how services should be carried and permit relatively simple migration between delivery technologies.

Consumption

The equipment used by audiences to receive television will continue to widen - from the small screens of mobile devices to very large wall-sized screens and projection systems (Figure 32). Such screens are, of course, not only used for television reception but for other home video sources too, including games consoles which now readily produce a 4K or 8K output and at higher frame rates.

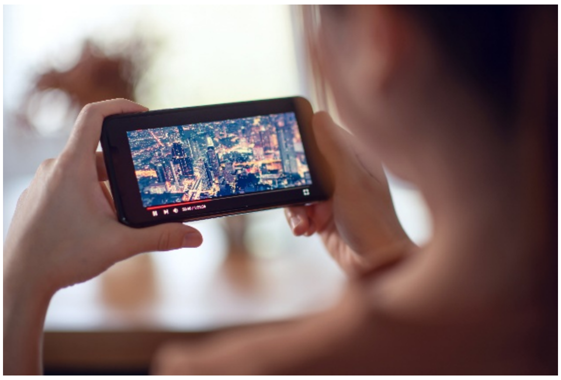
Also, companion screens such as tablets and mobile devices will be used in conjunction with such large-screen systems to deliver supporting, perhaps personalised, content and provide interaction opportunities.

Figure 32: Ultra-High Definition screens permit the audience to sit close and to be immersed in the picture. Source: iStockPhoto.

Screen technologies normally provide 4K and, increasingly, native 8K resolution; and often HDR. 16K screens are also available. While an HDR image is distinguishable at almost any distance because of its vivid brightness and extended colour, the ability to distinguish the underlying resolution of a screen depends on the viewing distance or, more particularly, the angle subtended at the eye by a pixel, see Figure 33. The advantages of a higher resolution screen are that the eye becomes unable to see the underlying structure of the screen. Images shot at 8K, down-converted to 4K for distribution, and then up-converted in the receiver for display on an 8K screen will appear almost indistinguishable from native 8K images.

The scope and range of the overall angle of view of the television screen presents a significant challenge. As screen resolutions increase, so the viewer can sit closer to the screen without being aware of the underlying pixel structure (an equivalent to raising the volume of a hi-fi until becoming aware that the sound becomes distorted). The angle subtended by the whole screen then becomes larger - and when this reaches around 90 degrees or more horizontally the viewer becomes 'immersed' in the picture as it dominates her field of view. Wide angle shots are appropriate, cuts become distractive and close-up images become unnecessary (even invasive), as detail can be already seen in the wide-angle picture. A football match could thus be very satisfactorily viewed from the perspective of a single camera mounted in an ideal location on the halfway line. However, for the viewer using a small-screen mobile device, with a limited angle of view, such composition would be totally unacceptable and closeup shots are required. A similar argument applies to the use of on-screen graphics - which can be diminutive with respect to the large image in the case of the very large screen but need to be comparatively larger for the small screen. These, together with the sonic options afforded by next generation audio (NGA) are some of the reasons that broadcasters are exploring the use of video and audio objects, separable elements which can be assembled to give the viewer an experience which is appropriate to the viewing situation.

Figure 33: Some viewing experiences will be on small screens and at low levels of immersion. Source: iStockPhoto.



The user experience will evolve too. Remote controls will embrace motion and haptic features (enabling gestures, user identification and emotion detection as detailed in Chapter 1), and voice control will improve beyond simple search as the power and capability of AI and conversational agents are realised. These likely developments will bring into question the value of traditional prominence and raise the importance of the provision of ever richer metadata.

The capability and capacity of computing power in the cloud is increasing so rapidly that much of the computing power required for home viewing and navigation will be able to move from the end device into the cloud, increasing simplicity, reliability, energy efficiency and security.

Radio and audio streaming services

Radio has long been regarded as a very different medium to television - in production, distribution and consumption. Terrestrial television reception has been gauged in terms of the percentage of households served, but radio has been measured in terms of land mass covered; and whereas a typical household might have two or more television sets [BARB2020], the number of radio receivers (including those in cars) will often be higher.

Radio broadcasts are made using Digital Audio Broadcasting (DAB), FM, medium wave and long wave. Services are streamed online and PSB (and some other) services are also available on satellite, cable and via digital terrestrial television (DTT). International radio services use high-power short wave transmissions upon which some broadcasters are also carrying Digital Radio Mondiale (DRM) – the standard for digital radio broadcasting in short wave and other bands – to provide better quality and clarity.

Radio licensing in the UK has provided, since the 1980s, the ability for local groups to operate community and limited period 'special-event' radio stations, originally using FM or medium wave. In 2020, Ofcom extended this capability to DAB [OfcomDABL2020], building on the technical capability to use open-source software to simplify the transmission infrastructure by using a single transmission site with all the encoding, multiplexing and modulation taking place on a PC.

FM (through the Radio Data System (RDS)) and DAB have long since provided the means to carry limited textual information about radio programmes, and new services such as RadioDNS [RDNS2020] help to transform radio into a hybrid experience with rich media including video from some production studios.

Probably the greatest forces on radio distribution will be from new devices for consumption - of which the most significant are surely voice assistants such as Amazon Alexa and Google Home; stand-alone network streaming devices - and consumption on mobile phones and tablets through apps. These apps not only stream live radio but give access to catch-up services and podcasts. However, today's voice assistants are limited in their ability to support 'discovery' and, being unable to provide a list of options through a graphical interface, tend to return a single result. The evolution of conversational functionality in these devices will help to resolve this problem.

New car technologies, for which connectivity is becoming the new norm for navigation, safety and maintenance, will also incorporate live and catch-up streaming services and podcasts to the dashboard, delivered through mobile networks and selected through the vehicle's voice assistant.

These new consumption devices - increasingly capable of reproducing NGA sound and with the capability to show text, graphics and images - are providing demand and impetus for further development of production capabilities.

5: Satellite technologies

Satellites provide global services, reaching parts of the world that terrestrial services cannot. While satellite broadcasting has achieved a price point that global audiences are willing to pay, satellite-delivered communication services have to date been too costly to benefit many unconnected consumers and businesses. However, that is changing. The incorporation of technologies from terrestrial mobile communications, miniaturisation of satellites, access to cheaper commercial launch platforms and tech sector financing have made space services increasingly affordable.

In this chapter, we will describe some of the exciting developments that have shaped the space sector over the last 20 years and what might (literally) be coming over the horizon in the next 15 years.

Where we are today

Affordable, commercial launch

Affordable and reliable access to space has in itself become a driver for innovation. US company SpaceX has helped to drive down the cost of launch from well over $100 million per rocket to around $47 million through the development of reusable rocket stages (Figure 34). This means costs to satellite operators are now as low as $1,400/kg compared with > $10,000/kg prior to 2000 [Jones2018].

However, with just over 100 space launches globally in 2019 and less than 15% of those wholly available for commercial launch, additional capacity is required to meet the needs of future NGSO (non-geostationary) satellites [Bryce2019].

Figure 34: Falcon 9 launching 60 Starlink satellites in March 2020. Source: Image Courtesy of SpaceX.

A number of countries have eyed this gap in the market and are encouraging indigenous launch operators. The UK, for example, is hoping to begin offering commercial launch services to small satellite operators in 2021 [UKSA2020].

From the very big – geo-stationary orbiting (GSO) satellites

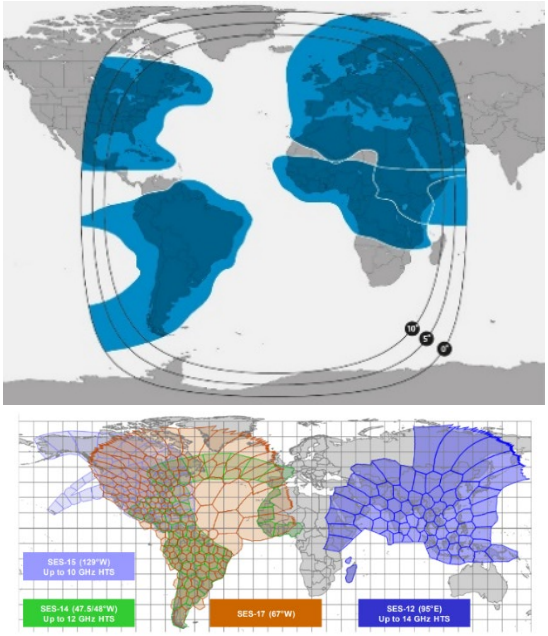
Since the 1970s, GSO satellites have become an integral part of the global telecommunications and broadcasting infrastructure, providing long-distance phone calls and connecting the world during high-profile events. Broadcasting has been the most lucrative service in the commercial space sector, contributing up to three quarters of income from Space Services [SIA2020]. Today, GSO operators serve a more varied mix of sectors providing government services, backhaul, direct to home broadband and the aviation and maritime sectors, providing connectivity in parts of the world where terrestrial services are unavailable. Satellite operators are also exploring hybrid networks, which allow users to roam between terrestrial and satellite services (see box Connecting From Above).

Over the past 20 years, high throughput GSO satellites (HTS) have adopted technologies from the mobile sector, combining higher frequencies with cell frequency reuse to increase the capacity of fixed satellite services. Satellites built with digital elements, combined with beamforming techniques have enabled satellite operators to deliver greater capacity in routes and markets where it is most needed. Figure 35 illustrates how the footprint of satellites has changed as a consequence of these technologies.

The next generation of very high throughput satellites launching from 2021 has the potential to deliver up to 500x capacity (1 Tbps globally) at 1/400th relative to the cost of satellite services in the early 2000s (as Viasat indicated in its response to our CFI).

GSO satellites orbit the Earth at 36,000 km altitude so latency is around ~280 ms one way. For some applications, such as broadcasting, this is not a significant delay but for broadband applications this is less desirable. Satellite operators are using multiservice edge computing (MEC) and other techniques to help minimise the effects of this latency (as SES indicated in its response to our CFI).

Figure 35: Spot beams from SES Astra-1 wideband satellite vs SES-17 High Throughput Satellite. Source: images courtesy of SES.



Another approach to achieve this and keep pace with terrestrial services is to move the satellites closer to the Earth. This is the concept behind constellations such as O3B in medium Earth orbit (MEO) and the OneWeb and SpaceX constellations being deployed in low Earth orbit (LEO). These will be discussed in the next section on future technologies.

To the very small

Small satellites built using commercial off-the-shelf (COTS) electronics were pioneered in the 1970s and 80s by the University of Surrey (and then Surrey Satellite Technology Limited) in a bid to make space-based communications more affordable. Its first satellite, UoSat-1, weighed 73 kg but was still substantially smaller and one-tenth the weight of the government-built communications satellites of the time [SSTL2020]. In 2000, California Polytechnic State University developed the Cubesat standard, which was designed to help the academic community build affordable nano-satellites around units of 10 cm^3 (or 1U) [Cubesat2020]. The most common size for a cubesat today is the 3U (a satellite built using 3 × 10 cm^3 cubes) or 6U (a satellite built of 6 × 10 cm^3 cubes). Picosatellites adopt a similar principle but are built around blocks of 5 cm^3; sprites and swarm satellites are smaller still but opt for flatter 'beer mat' configurations. A classification of satellite sizes can be found in Table 7.

Table 7: Satellite Mass Classification.
Source: https://www.nanosats.eu/cubesat

	Satellite Mass Classification
Large Satellites	> 1000 kg
Medium Satellites	500-1000 kg
Small Satellites	< 500 kg
Minisatellites	10-100 kg
Nanosatellites	1-10 kg
Picosatellites	100g-1 kg
Femtosatellites	10g-100g
Attosatellites	1g-10g
Zeptosatellites	0.1g-1g

A number of dedicated cubesat companies have emerged to serve this new market. The simplicity of some of these platforms means it is possible to design, build and launch a cubesat within 12 months. The total cost can be as low as $20k for academic institutions, although a more typical figure to design and launch a cubesat is between $200k and $1m, with launch costs being the biggest expenditure. This is still remarkable compared with geostationary communications satellites, which can cost up to $500m and take 2-3 years to design, build and launch.

The low cost of nanosatellites means large constellations are much more affordable. Earth observation (EO) companies Planet and Spire have built large constellations enabling more consistent and persistent sensing (although at lower resolution than some of the larger EO satellites). Planet [Planet2020] alone has built and launched over 360 satellites and until 2020 was the largest constellation in orbit. Its global network of sensors that will overpass any point of the Earth at least twice a day.

This trend is not just being seen in the commercial sector. In 2018, both the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA) recommended a combination of government satellites along with imagery bought from low-cost/commercial sensing [NSOSA2018] [DECADEL2020] to help optimise value for money. The European Space Agency (ESA) has set up a programme office dedicated to exploring how nanosatellites could be used for its missions [ESACS2019].

Radio navigation satellite services

In the 1970s, the US built the global positioning system (GPS) to provide accurate position, navigation and timing to the US military from Medium Earth Orbit (22,200 km in altitude). The US GPS constellation has since been opened up to civilian users around the world and has been joined by three more global navigation satellite systems (GNSS): Russian "GLONASS", Chinese "BEIDOU" and European "Galileo" constellations. Each uses similar but slightly different frequencies and slightly different network architectures but provides essentially the same service.

Collectively they are known as radio navigation satellite services (RNSS) and they have become indispensable to many facets of modern life. Our reliance on RNSS has become a source of concern [RAEng2011]. Indeed, the UK Government Office of Science published a report in 2018 outlining some of the man-made and environmental threats to satellite derived position and timing [GSO2018].

Ground network architecture

Commercial satellite teleports are building out across the globe to support the growing numbers of satellites in low Earth orbit. They provide a gateway to the internet and/or private networks so require good fibre connectivity. Increasingly, teleports are often co-located with cloud entry-points allowing more rapid downlinking of imagery and other sensing data and better network management for communications providers.

Communications satellites need to be able to simultaneously see both the gateway Earth station and the user terminal in order to connect the user to the internet or a private network in real time. For geostationary satellites with a large coverage area (as depicted in Figure 34), this is not a constraint; the satellite can operate with very few gateways. Constellations, on the other hand, require a large ground network as the satellites move relative to the Earth and have much smaller spot beams (50-100 km).

Earth observation satellites can also downlink their imagery more rapidly if they have access to several ground stations.

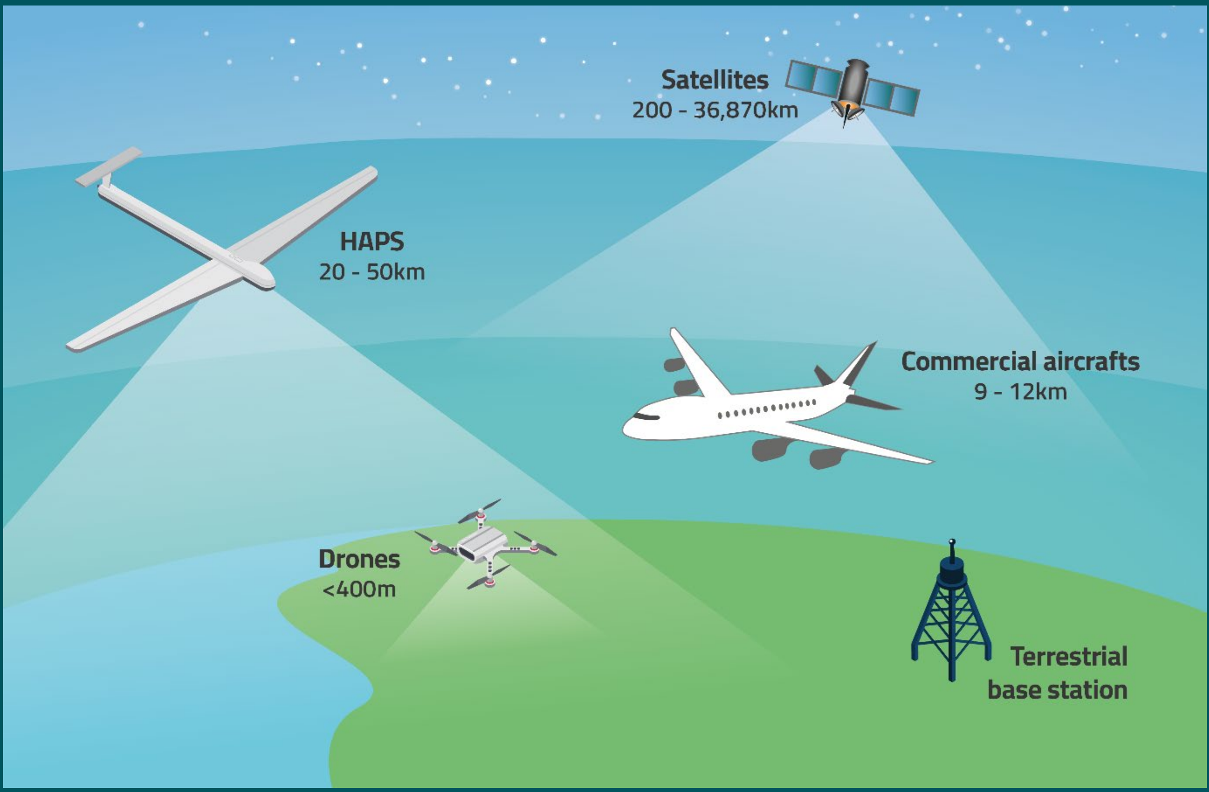
As with terrestrial networks, satellite operators are adopting cloud technology for a variety of applications.

- In the science and Earth observation communities, cloud technology and artificial intelligence will help process some of the large databases of imagery and other sensing data.
- Satellite Communications operators are moving to cloud services paired with artificial intelligence to better manage networks, reduce ground infrastructure and optimise the use of existing assets.
- For start-ups, access to ground station networks and cloud services on a pay-per-use basis can reduce upfront costs. There are even proposals to virtualise satellite operations centres so that satellites can be controlled from a laptop anywhere in the world.

The relationship between cloud service providers and satellite operators is a symbiotic one as public cloud providers like Microsoft Azure and Amazon Web Services are turning to satellite operators to help them provide connectivity for their cloud services – even in very remote regions of the world.

Connecting from above

Figure 36: Connectivity can be achieved via a range of platforms on the ground in the air or in space. These could lead to new mesh architectures. Source: Ofcom.



As mentioned in the mobile and wireless chapter, network architectures are changing and will increasingly need to take into account vertical as well as horizontal deployments. This is both to increase the reach of networks but also to safely track, monitor and communicate with the growing number of (connected) air and space users across a range of altitudes. In connectivity terms, altitude allows for a wider footprint but this comes at the expense of increased latency and a higher contention ratio.

Space debris is one of the biggest challenges for the space sector. As the number of satellites increases, tracking space objects will become more important. At present the US Air Force provides a global tracking service and conjunction warnings on behalf of the UN to satellite operators if their satellite comes within range of another space object. But as the sector becomes more commercial, a civilian “space traffic management” system with both radar and electro-optic sensors will be needed. Beacons on-board satellites may also help identify active satellites.

Satellites can also help track aircraft and ships from space. LEO satellites can detect “Automatic Dependent Surveillance- Broadcast” (ADS-B) signals transmitted from aircraft which are designed to tell other aircraft their position, altitude, velocity and heading. This normally helps aircraft avoid collisions but now allows satellites to track aircraft anywhere in the world – even when travelling over oceans far out of range of air traffic control radars. Similarly, satellites can now track Automatic Identification System (AIS) signals on ships which can help maritime authorities monitor (illegal) activity on our rivers, seas and oceans.

High altitude platform stations (HAPS) have been proposed as a halfway house between aircraft and satellite. The ITU defines a HAPS as a platform operating at between 20-50 km altitude and able to persist for several weeks or months. HAPS can be used as an Earth observation platform or can provide local mobile and broadband connectivity. HAPS can use terrestrial links or satellite links to provide backhaul.

Ongoing work at 3rd Generation Partnership Project (3GPP) to develop standards for satellite and non-terrestrial networks in 5G should help satellite and airborne services such as HAPS integrate more easily with terrestrial networks. It is expected that this work will start to bear fruit in the Release 17 of the standard, which is expected to be published in September 2021.

Aircraft can be connected from the ground or via satellite. These connections can be for operational reasons (to aid the pilot and communicate with air traffic control); for engineering reasons (to monitor the aircraft and engine) or to provide connectivity to passengers. All three are kept separate for safety reasons.

For short-haul aircraft travelling over land, connectivity is provided via terrestrial base stations, pointed at the sky. Passenger connectivity is provided via an 'air-to-ground' (ATG) network. In Europe, the European Aviation Network provides a 4G-like service with speeds of up to 100 Mbps per aircraft. Satellite connectivity is used for aircraft travelling across oceans, typically on long haul flights. Satellite-delivered services can provide 50-200 Mbps per aircraft, depending on the operator. This will rise to 400 Mbps as newer satellites come online. The airline market would like to move from a pay-per-use model to providing free connectivity to their passengers but this will require much higher throughput rates to keep pace with passenger expectations. Aviation is therefore seen to be a growth market for the satellite industry.

Looking ahead, both terrestrial and space services are likely to be required to support future unmanned air vehicles (UAVs) in airspace. Once again, terrestrial networks are likely to be appropriate for smaller, land-based UAVs while satellite connectivity could be used to support larger UAVs supporting longer range activities such as border operations or fisheries monitoring. UAVs of all sizes are likely to rely on accurate positioning and navigation through the use of GNSS services.

Where we are going next

Demand for space data and connectivity requirements

In space as in the mobile and wireless sector, consumer demand for high bandwidth, low latency, ubiquitous connectivity is driving many of the innovations we are seeing. Space-based services have a global footprint and are therefore better placed to provide connectivity in rural and remote locations. This translates into applications such as direct to home broadband, community wifi, IOT and connectivity for the transport sector (air, maritime, rail and road vehicles). However, the communications satellite sector is also evolving to meet new requirements generated by Earth Observation satellites.

Earth Observation

As we have already heard, commercial Earth observation (EO) operators are moving to constellations to increase the number of measurements and generate more timely data for their customers. In addition, satellites are increasingly capable of very high-resolution imagery i.e. <25 cm/pixel resolution for electro-optical cameras and synthetic aperture radar, with infrared sensors moving towards a similar sensitivity. Hyperspectral sensors (combining several hundred measurements in the visual, infrared and ultraviolet range) are now maturing; other satellite operators are considering video from space. These could dramatically increase the data generated on board each satellite, creating new demand for bandwidth. A range of solutions have been proposed including onboard processing and AI, new compression techniques, greater numbers of ground stations or using GSO satellites for back haul. While this may seem a longer route down, GSO satellites are in view of LEO satellites for longer than a ground station and operate on higher frequencies than links to most ground stations, which allow for more rapid data transfer. We will see later that optical links are also maturing and offer even higher bandwidth.

As outlined in the callout box “Connecting from above”, connectivity is often used on vehicles to provide additional support to the operator of the vehicle (e.g. navigation), to pass engineering data to the manufacturer and to provide connectivity for passenger entertainment or work. For now, connectivity to passengers generates the largest data demand. However, all modes of transport are likely to become more autonomous. This will increase the need for ubiquitous connectivity to ensure safety and performance. Most urban areas are likely to be well-connected by terrestrial networks but for vehicles travelling through more remote areas, satellite or HAPS could be used to extend that connectivity service. This blended service is already used on trains in Spain and Italy [OFCOM2018]. In Table 8 we provide some examples of data requirements for future satellite services.

Table 8: Indicative data requirements for different 5G satellite services. Source: Reproduced with permission from slide presented by Stefano Ciomi, ESA, 10th ASMS Conference October 2020 based on [Release163GPP].

Use case	Experience Data-Rate (Downlink/Uplink)	Max user equipment speed	Environment	Example of user equipment categories
Pedestrian	2 Mbps/ 60 kbps	3 km/h	Extreme coverage	Handheld
Vehicular	50 Mbps/ 25 Mbps	250km/h	Along roads in low population density	Vehicular mounted
Stationary	50 Mbps/ 25 Mbps	0 km/h	Extreme coverage	Building mounted
Airplane	360 Mbps/ 180 Mbps	1000 km/h	Open Area	Airplane mounted
IoT	2 kbps/ 10 kbps	0 Km/h	Extreme Coverage	IoT devices

Smaller, flexible communications satellites

The trend to date has been for ever-larger GSO satellites in order to generate power and deliver greater capacity, but advances in electronics are now allowing that trend to reverse. Even as satellite manufacturers are working to deliver satellites capable of more than 1 Tbps, the incorporation of technology advances from terrestrial telecommunications will allow them to meet the demands for increased performance with new, smaller GSO satellites. This should help to reduce the development time and cost of launch. The next generation of satellites will be all-electric, software-defined satellites, providing operators with greater flexibility over either the frequencies the satellite operates and/or the capacity delivered in different locations over the lifetime of the spacecraft. Active antennas paired with hybrid analogue/digital beam forming networks will help create denser networks of spot beams that reuse at least partially the available spectrum. Beam-hopping will allow the operator to move beams in real time to track aircraft and ships or meet changing terrestrial demand [Gaudenzi2018].

Satellite feeder links and user links have increased in frequency since 2000, moving from Ku band (10-12 GHz downlink, 12.5-14.5 GHz uplink) to wider spectrum bands in Ka (18-20 GHz downlink, 28-30GHz uplink) in order to increase the throughput of the satellites and improve user experience. This trend is set to continue with satellites launching in the 2020s expected to carry feeder links in V band, thus freeing up more Ka band spectrum for user links. Q/V band feeder links are likely to require a greater diversity of gateways in order to mitigate the effects of weather [Ventouras2020]. Satellite manufacturers are also examining optical wavelengths for future feeder links, which have the potential to provide even higher bandwidth and deliver data in a more secure fashion [Gaudenzi2018] [Saathof2017].

Artificial intelligence and deep learning techniques are now being applied to satellite networks to help interference management to make better use of network capacity.

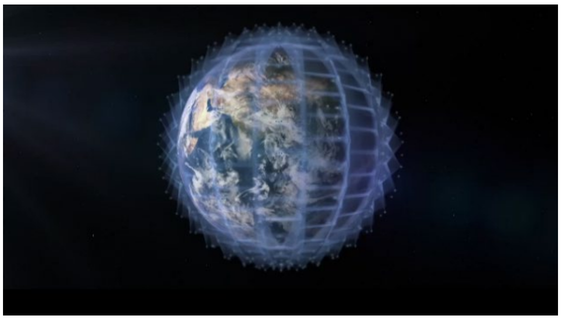
Finally, studies have been carried out to investigate whether Multi-Input, Multi-Output (MIMO) techniques, currently being deployed in terrestrial 5G mobile networks, could be used in space – combining signals to or from multiple users using several antenna elements [Arapoglou2010] [Vazquez2016] [Schwarz2016] to further improve spectrum reuse [You2020]. As explained in the mobile chapter, this approach could increase either the capacity within a spot beam or the number of users that might be served within the beam. No satellite network yet exploits these techniques.

Table 9: Comparison of five low Earth Orbit Mega-constellations. Source: information presented to ITU Webinar: Non-Geostationary Satellite Systems: entering the era of actual service delivery. 7 October 2020.

Satellite network	Number of satellites planned	Altitude (Km) (orbit: inclined (i) /polar(p))	Latency (ms)
O3B	20	8063 (i)	~135
O3B MPower	11	8063 (i)	~135
Telesat	300	1015(p) 1325 (i)	~50
OneWeb	640	1200 (p)	~50
SpaceX	4408	550 (i)	<40

NGSO Constellations

Figure 37: The first generation of the OneWeb constellation will comprise 680 satellites in polar orbits. Source: Image courtesy of OneWeb.



Perhaps the greatest interest for the next 15 years is focused on NGSO constellations. These comprise several hundred satellites in low Earth orbit to provide connectivity services (see Figure 37above).

The first commercial NGSO constellations were designed and launched in the early 1990s [Butash2020]; most were voice-only narrowband services. They were innovative in their own right, with Iridium introducing the first satellite production line and intersatellite links. Of the seven constellations proposed at the time, only Orbcom, Iridium and Globalstar still exist today. The first broadband constellation, Teledesic, was proposed in 2000. It proposed a constellation of 860 satellites using optical intersatellite links and terminals based on phased array antennas. The company failed because many of the enabling technologies were not sufficiently mature and therefore cost effective. In many ways, Teledesic was the precursor to the constellations being designed and deployed today [Butash2020].

There are several trade-offs to consider when designing an NGSO constellation. While latency improves when lowering the satellite, this also means individual satellites have a smaller geographical coverage, therefore more satellites are needed to provide a continuous service. Larger satellites provide more capacity but are more expensive to build and launch, especially in large numbers. Constellations based on polar orbits provide global coverage, with concentrations of satellites over the poles. This complements the footprint of GSO satellites and supports better broadband along popular air and maritime routes. Constellations with inclined orbits provide better capacity over more populated regions but don't provide global coverage. Table 9 provides a comparison of five proposed NGSO constellations, demonstrating some of the different approaches that might be taken.

The current generation of mega-constellations are driving more fundamental changes to the sector: manufacturing production lines are producing satellites at a rate of one to two per day for around $1 million per satellite. Demand for gateway Earth Stations, terminals, satellite components and space launch services to support the deployment of these constellations are all driving innovation, encouraged new market entrants, attracting investment and helped to reduce costs in all these sectors.

And if building an NGSO constellation was not innovative enough, a recent paper by the UK Satellite Applications Catapult suggested that resilient position, navigation and timing augmentation system might be possible using signals emitted by satellites in mega-constellations in Ku-band. The wideband signals from these satellites would allow the system to acquire sub-30 cm positioning within less than 1 second, effectively a higher accuracy at a faster rate than existing GNSS receivers [SAC2020]. In addition, this GNSS augmentation service has the potential to be more secure and less vulnerable to deliberate interference (jamming) than traditional L-band GNSS systems. This is due to the higher power signals radiated from the LEO satellites, highly directional antennas in the receivers and the fact that the higher frequency Ku-band signals have a reduced propagation range (do not travel as far) in a terrestrial environment. The system would be more resilient to space weather. Work is on-going to develop this concept.

Small Sat innovations

Cubesats are still where much of the innovation in the space sector is happening. Here are just some of the developments in satellite communications.

Connecting mobile phones from space.

According to the Annual GSMA Mobile Connectivity Report [MCI2019], mobile coverage continues to improve but in low- and medium-income countries, mobile connectivity can be as low as 30%.

Satellites have global coverage so can be used to overcome the economic challenges of rolling out terrestrial networks in remote areas. To date, satellites have provided backhaul for 3G and 4G services, helping mobile network operators to serve some of these communities. The additional commonality between satellite and terrestrial networks offered by 5G standards should make that easier still.

Satellite terminals and phones have also been adapted to be able to operate across both satellite and terrestrial networks. However, the reverse is not true. Consumer handsets are currently designed to only operate to base stations within a maximum range of 120 km and are unable to close the uplink link budget required to communicate with satellites in LEO or GSO.

However, as we have seen with AIS and ADS-B signals in the maritime and aviation sectors, satellites in LEO are now able to pick up faint signals that were not originally designed to communicate with satellites. A couple of companies claim to have found a way to close the link budget with unmodified mobile handsets [Lynk2020] [AST2020]. This potentially extends at least a messaging service anywhere on the planet. However, the technology is in development and will need international regulatory approval.

Internet of Things from space

There are many locations in the world where environmental monitoring or agritech are out of range of terrestrial networks. Satellite-delivered IOT services could help provide connectivity for these growing markets. The ESA has estimated that there are at least 20 satellite companies looking to deliver space-based IoT.

Blended terrestrial-space solutions are also being explored: British start-up Lacuna Space has partnered with French company SEMTEC to create a low power Long Range Wide Area Network [LORA2020] IOT terminal that will either operate on a terrestrial network (if it is available) or over satellite. Eutelsat's ELO constellation aims to do the same thing with the SIGFOX IOT standard [SIGFOX2020]. For critical national infrastructure IOT applications, traditional satellite operators (both LEO and GEO) who can meet the strict service-level guarantees are likely to continue to be the preferred suppliers until newer entrants are more established.

Creating large structures

Antennas - In both Earth observation and communications, large antennas are advantageous. They are more sensitive to the signals they are designed to receive and can provide more focused spot beams, which potentially allows for greater spectrum reuse.

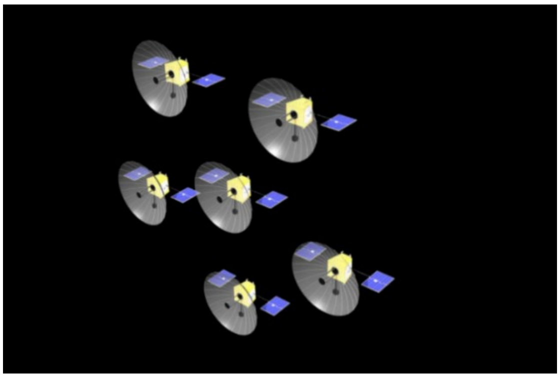
The largest antennas in space today are around 40m in width. There are innovative proposals for in-orbit fabrication of very large structures, which could increase this to 100m [Stuttard2018].

A number of organisations are now experimenting with satellite flocks to mimic much larger structures. This allows operators to take advantage of smaller, cheaper satellites to generate imagery of a resolution that would normally require a much larger antenna on a single satellite.

In addition, given the hostile nature of the space environment, multi-satellite systems provide a level of resilience and redundancy; only a portion of the overall system capabilities will be degraded in the event of one satellite failing, rather than the loss of the entire service.

This concept has application for both communications and earth observation. Figure 38, for example, demonstrates a concept for a constellation of satellites carrying synthetic aperture radar.

Figure 38: UK Ministry of Defence has contracted Airbus to develop a constellation of Synthetic Aperture Radar satellites which will fly in formation. Source: Image courtesy of Airbus (Image: Project Oberon).



Current satellite flocks involve small numbers of satellites, but these will likely grow in size. The NASA Ames Starling-1 project, for example envisages an approach that could scale a flock to 100 picosatellites [Sanchez2018].

'Lego' satellites - NASA and Cornell University are exploring docking cubesats [CUBESAT2013]. It is hoped that this mission, which will launch in 2021, could lead the way to satellites and future scientific instruments built from cubesat 'modules', which could be launched and then assembled in space.

Reusable satellites

In 2017, SpaceX became the first company to reuse a rocket stage to launch a satellite into orbit. This more than halved the cost of access to space. To date, they are the only launch company to have successfully retrieved and reused launchers, although a couple of Chinese launch companies (iSpace and LinkSpace) are seeking to emulate them. Now, UK company Spaceforge has proposed a design for a reusable satellite [SF2020]. This innovative platform is designed to manufacture new materials in microgravity but the concept could have much wider ramifications for the sector helping to further reduce the cost of space services and to mitigate some of the risks of space debris.

Enabling Technologies

Optical links

Radio frequency (RF) links will continue to be important to the space sector but optical links are increasingly attractive to the space sector for a variety of applications. Optical links are capable of carrying 40 times more data than RF links allowing data to downlink faster. They do not need to share spectrum with other users and are harder to intercept, which makes them attractive for applications requiring secure communications. In addition, optical flight terminals are 50% smaller than RF equivalent systems, allowing more room on the satellite for other payloads [NASAOpticalBenefits2018]. However, optical links can be adversely affected by water vapour and dust in the atmosphere. Adaptive optics using moveable mirrors to focus the beam can compensate for some atmospheric effects while gateway diversity can help to mitigate the impact of local weather systems.

The bullets below give a flavour of the wide range of applications for which optical links are now being considered:

- LEO to GEO: The European Space Agency's European Data Relay System was launched in 2017. It uses laser links to transmit imagery data in real time from their Sentinel satellites in LEO to GEO at a data rate of 1.8 Gbps. The data is then transmitted back to Earth via RF from a GEO platform [EDRS2020].
- LEO-LEO: Intersatellite links can help satellite networks overcome the requirement for a large number of ground stations by passing data through the satellite network to the nearest gateway; Over large distances, intersatellite links are thought to pass data faster than fixed line networks as the signals are travelling in free space;
- Space-Earth: One of the key applications envisaged is the provision of very high capacity feeder links for future high throughput satellites [Saathof2017]. Additionally, new Space to Earth links systems have been designed to meet the requirements of Earth Observation operators, with some weighing just 350g [Laser2018].
- Quantum key distribution - small satellites are also being considered for quantum key distribution. Satellite networks have a predictable and easily verifiable latency from space to Earth, which helps with key verification. They can also provide faster intercontinental links than fixed line networks as the signals travel in free space. China first demonstrated quantum key distribution via satellite in 2016

[LIAO2017] and the first intercontinental QKD transmission between China and Austria in 2017. European missions are also expected to launch over the next 2-3 years.

- Near-space and deep space – NASA has published a timeline for development of laser links for a range of missions. It anticipates launching a relay link for near-Earth missions capable of transmitting 1.244 Gbps by 2021 and a deep space link capable of 400 Mbps for deep space missions in 2022 [NASAOPT2018].

In summary, laser links are being considered for a wide range of applications. While costs remain high, they have the potential to bring significant change to space-based communications over the next decade.

Flat panel antennas (FPAs) – connectivity on the move

The requirements of satellite terminals are changing. As satellites connect more aircraft, ships, rail and road vehicles with high-speed connectivity, the size, weight and drag caused by the terminal all become much more important. For moving platforms connecting to fixed GEO satellites, it is also important that the terminal is able to maintain connection with the satellite as the platform travels. This tracking is currently achieved using gimballed or mechanically steered antennas but these can be heavy and bulky, which are not ideal for aircraft, trains or cars. Similarly, premises wishing to connect to NGSO constellations for broadband will require new terminals which can rapidly track one or more satellites as they move through the skies overhead, thus providing a continuous link between the terminal on the rooftop and the satellite network. Even more complex geometries will be required when ships and aircraft connect to NGSO networks as both the vehicle and the satellites will be moving.

For all these reasons, flat panel antennas using beamforming technologies are seen to be essential for the next generation of satellite networks. Here are some of the approaches under consideration:

- *Mechanically steered antennas*. These are still in use in the aviation and rail sectors. They are lower-profile rather than truly flat panel.
- *Phased array antennas* have been used by the military and in terrestrial communications for decades. They are able to electronically form a moving beam (rather than mechanically steer the transmitter) allowing them to track multiple satellites at multiple altitudes. Phased arrays are either passive electronically scanned phased arrays (PESA) or active electronically scanned phased arrays (AESAs). PESAs (sometimes known as analogue) use one transmitter and a number of phase converters so are simpler and less expensive; AESAs (digital) use a large number of transmitters and are therefore more power hungry and costly, but more flexible and potentially higher performance.
- *Hybrid mechanical/electrical solutions* comprising sliding mechanical structures to create 2D tracking. These are more cost effective than the phased array antennas (and have been in operation since 2015) but are thought to be more likely to develop faults as they have moving parts.
- *Metamaterials* to create a holographic beam with no moving parts. These are cheaper than AESAs but only track one satellite at a time.

Most of these technologies are maturing but are still at a price point that is more suitable for enterprises rather than individual consumers.

Space Benefiting Life on Earth

Understanding our planet

As the price of space-based services continues to fall, we will see more government agencies launch and use their own Earth observation satellites or buy data to support their activities. Applications might include urban development, monitoring of (illegal) mining and logging activity, pollution monitoring, fisheries management, border security, monitoring transport infrastructure, and supporting better agricultural and forestry management. Earth observation will also continue to be important for defence and security applications.

Scientists will continue to rely on high resolution data generated by space agency satellites to gain greater insights into global warming, weather patterns, changes in oceanic patterns, the winds or the presence of particular elements in our atmosphere. Open source data from US Landsat and European Sentinel satellites in particular offer imagery taken over decades, allowing for long term trends to be observed. This will, over time, be complimented by commercial Earth Observation data, particularly for niche data products.

We mentioned earlier some of the sensing technologies being adopted by the commercial Earth Observation sector (Electro-optic, synthetic aperture radar, infrared imagery, ultraviolet, hyperspectral imagery). Here we highlight two emerging techniques for the Science community: Terahertz sensing and Quantum Gravity Sensing. Terahertz technology [Dhillon2017], which we also discussed in the mobile & wireless chapter, will allow climate scientists to better measure the upper echelons of our atmosphere and increase their understanding of ice clouds [STFC2020]. Space-based Quantum Gravity Sensing, which detects tiny perturbations in the Earth's gravity could help identify changes in glaciers and ice sheets, changes to ocean currents and water storage. It could also help detect underground holes, caverns and tunnels. This technology has flown in previous missions but will mature over the next 10 years [MADDOX2019].

For all of us, accurate and timely weather forecasting is likely to become more important as climate change increases the risk of extreme weather events. Scientists rely on access to specific frequencies to measure the presence of oxygen, moisture and ice. As the MET Office points out in its response to the CFI, access to these frequencies must be protected (even as new wireless services seek access to spectrum) if scientists are to continue to take accurate measurements.

Propagation data

For terrestrial wireless operators, higher frequency millimetre wave links that are needed to support increasing data demands are more prone to atmospheric effects. Backhaul networks may need to use different frequencies in order to ensure continuation of service during periods of unfavourable weather conditions. Predictive modelling for wave propagation (how far waves might travel through the air) based on satellite-derived atmospheric data is now being developed to help mobile network operators manage their networks and select frequency channels in anticipation of weather conditions. [SØNDERBY2020].

Manufacturing in space

In April 2019, NASA announced it would be offering launch capacity and astronaut time on the International Space Station (ISS) to explore commercial opportunities, examples of trials include manufacturing and regenerative medicines in micro-gravity environments [NASALEO2019]. It is thought some of these technologies could help support future human missions to the Moon and Mars. However, some of these technologies could also benefit life on Earth. For example, microgravity experiments are looking to test and develop new or purer materials. Space is a natural vacuum which makes it attractive for any manufacturing process which requires a clean environment (for example semiconductor fabrication). In the production of metal alloys, gravity can cause stratification, a process by which denser elements sink and lighter elements rise, potentially causing impurities. Microgravity environments could allow for more even mixing throughout the fluid, creating purer substances. NASA has also found that crystals tend to grow larger and more uniformly in microgravity environments, which could improve medical treatments [NASAMG2014].

One of the more promising telecommunications technologies offered by microgravity manufacturing include fluoride glass ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF). ZBLAN is a fibre-optic cable made from a fluoride glass rather than silica. It is thought to have at least ten times lower signal losses compared to existing optical fibres but like metal alloys, it is hard to produce on Earth without impurities forming. Several companies are now looking to produce ZBLAN on the International Space Station; for now the costs of launch might make this material too expensive for commercial use and (as discussed in Chapter 3) hollow fibre is already producing very low propagation losses [Glass2018].

Power from Space

There has been renewed interest in the concept of solar power from space. Sunlight is 11 times brighter in space than on Earth and could, in principal, be harvested and beamed back to Earth via RF or optical links. While the concept was first conceived in 1920s, the first patent emerged in 1970s and there have been successive attempts to revive the idea, it has traditionally been seen to be too expensive to produce. The most comprehensive feasibility study to date was presented at the International Astronautical Conference in 2000 [OLDS2000].

More recently, the UK government has commissioned a study to examine the feasibility of the concept [UKSASOLAR2020]. ESA too, has launched a call for input [ESASOLAR2020]. Perhaps with low cost, lightweight solar panels and in-orbit assembly, this might become a reality.

Annex A: List of accompanying videos

Below is the list of experts who have contributed accompanying videos for the report. These video contributions are available to watch on the Ofcom website.

Chapter	Name of the expert
Mobile	Prof. Emil Björnson, Professor, KTH Royal Institute of Technology, Sweden
	Harish Viswanathan, Head of Radio Systems Research group, Nokia Bell Labs.
Fixed	Vint Cerf – Chairman, Marconi Society
	Prof. David Richardson FREng, FRS, Optoelectronics Research Centre, University of Southampton
	Prof. Polina Bayvel CBE FRS FREng, UCL
Broadcasting	Richard Lindsay-Davies, CEO, DTG
	Jon Piesing, Chairman of the DVB Technical Committee
Satellite	Prof. Barry G. Evans, Institute for Communications Systems-5G/6G Innovation Centre, University of Surrey
	Paul Febvre, Chief Technology Officer, Satellite Applications Catapult
Use cases	Petar Popovski, Professor, Head of the Section on Connectivity Department of Electronic Systems, Aalborg University, Denmark
	Prof. Mischa Dohler, Fellow IEEE/RAEng/RSA, King's College London
	Linda Doyle, Professor of Engineering & the Arts, Computer Science, Trinity College Dublin

Annex B: Acronyms

16K TV with 15360 pixels on 8640 lines

3D Three dimensional

3G Third generation of mobile systems

3GPP Generation Partnership Project (the international standards body for mobile networks)

4G Fourth generation of mobile systems

4K TV with 3840 pixels on 2160 lines

5G Fifth generation of mobile systems

5G MAG 5G Media Action Group

8K TV with 7680 pixels on 4320 lines

ABR Adaptive bit rate coding

ADC Analogue to digital conversion

ADS-B Automatic dependent surveillance - broadcast

ADSL Asymmetric digital subscriber line

AI Artificial intelligence

AIS Automatic identification system

AR Augmented reality

ATG Air to ground (broadband service for aircraft)

BBC British broadcasting corporation

BMI Brain machine interface

CBRS Citizens broadband radio service

CDN Content Delivery Network

CGI Computer Generated Imaging

CPU Central processing unit

CSA Conseil supérieur de l'audiovisuel

DAB Digital Audio Broadcasting

DARPA Defense advanced research projects agency

DOCSIS Data Over Cable Service Interface Specifications

DRM Digital Radio Mondiale

DSL Digital Subscriber Line

DTG Digital Television Group

DTT Digital Terrestrial Television

DVB Digital Video Broadcasting

DVB-C Digital Video Broadcasting – First Generation Cable

DVB-C2 Digital Video Broadcasting – Second Generation Cable

DVB-I Digital Video Broadcasting – specifications for IP centric TV

DVB-S Digital Video Broadcasting – First Generation Satellite

DVB-S2 Digital Video Broadcasting – Second Generation Satellite

DVB-T Digital Video Broadcasting – First Generation Terrestrial

DVB-T2 Digital Video Broadcasting – Second Generation Terrestrial

EBU European Broadcasting Union

ELAAs Extremely large aperture arrays

ESA European Space Agency

FM Frequency Modulation, as used on Band II radio transmissions

FPA Flat Panel Antennas

FPS Frames per second

FTTC Fibre to the Cabinet

FTTH Fibre to the Home

GBAS Ground Based Augmentation System (for positioning navigation and timing)

Gbps Giga bit per second

GNSS Global Navigation Satellite Service

GPU Graphics processing unit

GSO Geostationary Orbit

HAPS High Altitude Platform Station

HCI Human computer interface

HD High definition

HDR High dynamic range

HEVC High efficiency video coding

Hifi High Fidelity Sound

HMI Human machine interface

HTS High throughput satellite

I Interactive

ICT Information communication technology

IP Internet Protocol

IRS Intelligent reflecting surfaces

ISP Internet service provider

IT Information technology

kHz Kilo Hertz

LEDs Light-emitting diodes

LEO Low Earth Orbit

LiFi Light fidelity

LoRa Long range

LPWA Low-power wide-area

Mbps Mega bit per second

MEC Multiservice edge computing

MEO Medium earth orbit

MIMO Multi-input multi-output

NASA National aeronautics and space administration (US)

NGA Next generation audio

NGSO Non-geostationary orbit

OAM Optical angular momentum

OTT Over-the-top

Pbps Peta bit per second

PON Passive optical network

PSB Public service broadcasting

QKD Quantum key distribution

R&D Research and development

RadioDNS An organisation that promotes the use of open technology standards to enable hybrid radio

RDS Radio data system

RF Radio frequency

RNSS Radio navigation satellite service

S Streaming

SAM Spin angular momentum

SATCOM Satellite communications

SBAS Satellite based augmentation system (for positioning navigation and timing)

SD Standard definition

SDM Space division multiplexing

SIM Subscriber identity module

SMF Single mode fibre

STT Social touch technology

THz Terahertz

TV Television

UAV Unmanned aerial vehicle

UHD Ultra-high definition

UHF Ultra-high frequency

UK United Kingdom

UK-D-Book The D-Book is the technical specification produced by the DTG for all DTT based platforms

UKSA United Kingdom Space Agency

URLLC Ultra-reliable low-latency communication

VDSL Very high speed digital subscriber line

VET Virtual environment technology

VR Virtual reality

WDM wavelength [/frequency] division multiplexing [optical]

WiB Wideband broadcasting

Wi-Fi A family of wireless network protocols, based on the IEEE 802.11 family of standards

Y'CbCr colour space used as a part of the colour image pipeline in video and digital photography systems

Annex C: Acknowledgements

1. **Alan Carlton**, VP, InterDigital Europe, InterDigital Europe Ltd.
2. **Alastair Macpherson**, Partner, PwC
3. **David Hassman**, Head of Corporate Development & Strategy, Syniverse
4. **David Meyer**, Ofcom Spectrum Advisory Board (OSAB) member
5. **Dean Bubley**, Director, Disruptive Analysis.
6. **Dr Ben Allen**, Royal Society Industry Fellow, University of Oxford
7. **Dr Bipin Rajendran**, Reader in Engineering, King's College London
8. **Dr Ebrahim Bushehri**, CEO, Lime Microsystems
9. **Dr Gustav Wikström**, Research Leader in the area of radio networks, Ericsson Research, Stockholm, Sweden
10. **Dr Hamed Ahmadi**, Department of Electronic Engineering, University of York, UK
11. **Dr Howard Benn**, VP Communications Research, Samsung R&D Institute, UK
12. **Dr Marco Mezzavilla**, Research Scientist, Tandon School of Engineering at New York University, Co-Founder at Pi-Radio
13. **Dr Maria Kalama**, Business Development Director, Lacuna Space
14. **Dr Peter Marshall**, Vision Lab Strategic Director, Ericsson, Group Marketing, Reading, UK
15. **Dr Sundeep Rangan**, Professor, Tandon School of Engineering at New York University, USA
16. **Dr Tim Brown,** Institute for Communication Systems, University of Surrey
17. **Elfed Howells**, CEO, Macroblock Ltd
18. **Gavin Young**, Head of Fixed Access Centre of Excellence, Vodafone Group Technology
19. **Geoff Varrall**, Director, RTT Programmes
20. **George Tsirtsis**, Sr Director of Technology, Qualcomm Technologies Intl. Ltd.
21. **Gerhard P. Fettweis**, Vodafone Chair Professor, 5G Lab Germany, Coordinator TU Dresden, Germany
22. **Graham T Reed** FREng, Professor of Silicon Photonics and Deputy Director of the Optoelectronics Research Centre, University of Southampton
23. **Harish Viswanathan**, Head of Radio Systems Research group, Nokia Bell Labs.
24. **Hugues Favin-Lévêque**, VP Connectivity Roadmap Owner, Airbus Technology
25. **John Baker**, SVP Business Development, Mavenir
26. **John M. Cioffi**
27. **Kieran Arnold**, Director of Ubiquitous Connectivity, Satellite Applications Catapult
28. **Lajos Hanzo**, Chair of Telecommunications, University of Southampton
29. **Leonard Lee**, next Curve, founder and managing director.

30. **Linda Doyle**, Professor of Engineering & the Arts, Computer Science, Trinity College Dublin
31. **Mansoor Hanif**, Executive Director Emerging Technologies, Neom
32. **Maryvonne Tubb**, SVP Marketing, Mavenir
33. **Matthew Baker**, Head of Radio Physical Layer and Coexistence Standardisation, Nokia
34. **Niall Murphy**, CEO & Founder, EVRYTHNG
35. **Nick Crew**, Chief Operating Officer, Endeavr (Wales), Airbus
36. **Nick Thexton**, Group Chief Technology Officer, Synamedia.
37. **Orpheus Warr**, Chief Technology Officer, Channel 4
38. **Pardeep Kohli**, CEO, Mavenir
39. **Paul Febvre**, Chief Technology Officer, Satellite Applications Catapult
40. **Per Björkman**, Head of Distribution, Sveriges Television AB (Swedish Public Service TV)
41. **Petar Popovski**, Professor, Head of the Section on Connectivity Department of Electronic Systems, Aalborg University, Denmark
42. **Peter Hadinger**, Chief Technology Officer, Inmarsat
43. **Peter MacAvock**, Head of Distribution, Platforms and Services, EBU Technology & Innovation
44. **Peter Pitsch**, private communications policy consultant and former Chief of Staff to FCC Chairman
45. **Pradeep Bhardwaj**, Head of Industry Standards, Syniverse
46. **Prof. Maziar Nekovee**, Head of Centre for Advanced Communications, Mobile Technology and IoT, University of Sussex, UK
47. **Prof. Alan Marshall**, Head of Department, Dept of Electrical Engineering & Electronics, School of Electrical Engineering, Electronics and Computer Science, University of Liverpool
48. **Prof. Barry G. Evans**, Institute for Communications Systems-5G/6G Innovation Centre, University of Surrey
49. **Prof. Brian Ellison** FREng, CEng, FIET, Head of Millimetre-wave Technology and Chilbolton Radio Group, UKRI-STFC RAL Space Department, Rutherford Appleton Laboratory
50. **Prof. Dimitra Simeonidou**, Director Smart Internet Lab, Co-Director Bristol Digital Futures Institute, University of Bristol
51. **Prof. Dr.-Ing. Eckehard Steinbach**, Chair of Media Technology, Technical University of Munich, Germany
52. **Prof. Emil Björnson**, Professor, KTH Royal Institute of Technology, Sweden
53. **Prof. Merouane DEBBAH**, Director, IEEE Fellow, Huawei, Lagrange Mathematical and Computing Research Center
54. **Prof. Mischa Dohler**, Fellow IEEE/RAEng/RSA, King's College London
55. **Prof. Osvaldo Simeone**, Professor of Information Engineering, King's College London
56. **Prof. Polina Bayvel** CBE FRS FREng, UCL
57. **Prof. Tim Whitley**, PhD, BSc, FIET, FITP
58. **Prof. Timothy P. Spiller**, University of York, UK
59. **Richard Lindsay-Davies**, CEO, DTG
60. **Richard Waghorn**, Director of Operations, Technology and Transformation, RTÉ
61. **Rob Spurrett**, CEO and co-founder, Lacuna Space
62. **Ros Singleton**, Chair UK5G Advisory Board, CEO Spring Fibre
63. **Sergio Bovelli**, Head of Spectrum Management for Aero Connectivity, Airbus
64. **Simon Fell**, Chairman, DTG

65. **Skip Pizzi**, Media Technology Consultant
66. **Space Exploration Technologies Corp.**
67. **Stefano Cantarelli**, CMO, Mavenir
68. **Stephen Speirs**, Cisco Systems, and Member of Ofcom Advisory Committee for Scotland
69. **Steve Papa**, CEO, Parallel Wireless
70. **Tony Azzarelli**, CEO and Founder, Azzurra Telecom Ltd
71. **Upkar Dhaliwal**, CEng MIET SMIEEE, President, Future Wireless Technologies. San Diego, USA
72. **Vint Cerf**, Chairman, Marconi Society
73. **Vladimir Komendantskiy**, Rustiq Technology Ltd
74. **Volker Ziegler**, Head of Department Communication Technologies, Airbus
75. **Wassim Chourbaji**, Senior Vice President Government Affairs and Public Policy, Qualcomm EMEA
76. **Yvonne Thomas**, Strategic Technologist, DTG
77. **Zoran Cvetkovic**, Professor of Signal Processing, Department of Engineering, King’s College London

Annex D: Responses to our call for inputs

Below is the list of respondents who submitted non-confidential or partially confidential responses to our call for inputs. Their responses are available on the Ofcom website: https://www.ofcom.org.uk/consultations-and-statements/category-2/emerging-technologies.

Avelalto Ltd

BBC

BT

Enablersinc

Facebook

Federated Wireless Inc

GuRu Wireless

Internet Telephony Services Providers' Association (ITSPA)

JCDrawn

Lacuna Space

Lime Microsystems

Mastdata

Met Office

mmWave Coalition

N&M Consultancy Limited

Nextivity

SES

Starlink Internet Services UK

The Besen Group

The Telecom Infra Project

Viasat Inc

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