Revisiting Wireless Internet Connectivity: 5G vs Wi-Fi 6

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Abstract

In recent years, significant attention has been directed toward the fifth generation of wireless broadband connectivity known as ‘5G’, currently being deployed by Mobile Network Operators. Surprisingly, there has been considerably less attention paid to ‘Wi-Fi 6’, the new IEEE 802.1ax standard in the family of Wireless Local Area Network technologies with features targeting private, edge-networks. This paper revisits the suitability of cellular and Wi-Fi in delivering high-speed wireless Internet connectivity. Both technologies aspire to deliver significantly enhanced performance, enabling each to deliver much faster wireless broadband connectivity, and provide further support for the Internet of Things and Machine-to-Machine communications, positioning the two technologies as technical substitutes in many usage scenarios. We conclude that both are likely to play important roles in the future, and simultaneously serve as competitors and complements. We anticipate that 5G will remain the preferred technology for wide-area coverage, while Wi-Fi 6 will remain the preferred technology for indoor use, thanks to its much lower deployment costs. However, the trend towards providing seamless wireless broadband connectivity, as well as smaller-cell network architectures with increasingly flexible and spectrum-agile technologies, is blurring the traditional boundaries that differentiated earlier generations of cellular and Wi-Fi.

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1. Introduction

Almost in synchrony we are seeing the roll-out of the next generation of wireless technologies for both cellular and Wi-Fi connectivity. While there has been much excitement around the world regarding the fifth generation of cellular technology known as ‘5G’, there is comparable enthusiasm for the next version of the Institute of Electrical and Electronics Engineers’ (IEEE) 802.11 Wireless Local Access Network (WLAN) standard, ‘Wi-Fi 6’. Next generation wireless connectivity technologies are needed to further enable the shift to a Digital Economy given the productivity and social benefits that a successful transition promises (Bauer, 2018; Graham and Dutton, 2019; Hall et al., 2016a, 2016b; Mansell, 1999; Parker et al., 2014; Reisdorf et al., 2020).

Competition between cellular and Wi-Fi is not a new debate. For example, two decades ago the competition between 3G and an earlier version of the Wi-Fi 801.11 standard were each vying to win the wireless Internet crown (Lehr and McKnight, 2003). This was before Apple’s iPhone propelled mass market mobile broadband via smartphone devices toward a must-have platform for ubiquitous Internet connectivity (West and Mace, 2010). In that earlier time, the question was whether 3G and Wi-Fi would be competitors or complements. Upon reflection, the two technologies were evidently complementary, with Wi-Fi predominantly providing high capacity indoor hotspots for broadband, and cellular providing high-speed broadband in scenarios of wide-area user mobility. The question we explore in this paper is whether the future of 5G and Wi-Fi 6 will continue this trend or whether it might herald a new trajectory for wireless connectivity.

The debate between those advocates favouring either cellular or Wi-Fi technology has been heated. Some proponents of cellular have made bold claims stating that 5G will ‘kill-off’ Wi-Fi 6 (Bloomberg, 2017; Light Reading, 2019). There are several different arguments both supporting and refuting this view. Firstly, in a 3G/4G world, data usage has traditionally been limited in mobile phone subscriptions meaning users prefer to access Wi-Fi for data intensive applications to reduce cost. Thus, with the introduction of unlimited data plans for mobile, some expect this cost-optimising behaviour to disappear, meaning users will rely on cellular to a much larger extent for data transfer over the next decade. Secondly, the introduction of a 5G standard (5G NR-U) which can operate in the unlicensed spectrum bands (traditionally the domain of Wi-Fi) have led Qualcomm to hypothesise of the potential demise of Wi-Fi. We feel such predictions necessitate further examination, providing strong motivation for the evaluation presented in this paper.

We begin in Section 2 by reviewing the demand-side changes which will affect wireless Internet connectivity over the next decade. In Sections 3 and 4, we provide a general qualitative overview of 5G and

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1 The earlier analysis by Lehr & McKnight (2003) focused on the roles these technologies played in providing mass-market access to broadband services, rather than for wireless connectivity by business enterprises, which has always involved a more complex array of wireless technologies. Businesses were earlier and heavier users of computing and data communication services than consumers and were the first to deploy WLAN technologies. Cellular has historically focused on the mass-market and has played less of a role in providing wireless connectivity for businesses, except where the two worlds overlap. Examples include consumers who are also employees needing wide-area access or the businesses that by nature require access to ubiquitous wireless (e.g., transport services). This is changing since many anticipate that some of the most interesting and important applications for 5G will be in vertical industrial sectors and other private-network applications (which are often also indoors or deployed in campus environments and hence are less dependent on the licensed spectrum that cellular operators have principally relied on in the past).
Wi-Fi 6 for a policy and economics audience, and then in Section 5, we compare and contrast these technologies. Finally, Section 6 offers concluding thoughts.

2. Future demand-side changes affecting wireless connectivity

Global data flows have been rapidly growing for decades, with the majority consisting of Internet Protocol (IP) traffic carried over the open Internet and/or private IP networks (Claffy et al., 2020; Knieps and Stocker, 2019). For example, over the next decade two thirds of the global population will be online (>5.3 billion), and the number of Internet-connected devices will exceed more than three times the global population (>29 billion). While the traffic growth experienced through the 1990s and 2000s was predominantly due to increased penetration of fixed broadband Internet services, this is now being driven by growth in wireless broadband. Most of the generated traffic will be served by Wi-Fi, with about one fifth being served by cellular (Cisco, 2020). There has generally been a co-evolving relationship between greater availability of wireless Internet connectivity fuelled by the proliferation of Wi-Fi hotspots, and the expanding coverage and improved performance of 4G. When combined with much more capable devices there has been growing demand for near-ubiquitous connectivity to broadband content, applications and services (Stocker et al., 2017).

In this review we identify a variety of demand-side factors which will affect the future of wireless Internet connectivity, which will be driven by the increasing number, and changing composition, of devices, the ongoing rise in the quantity of data generated per device, and the growing number of total users (which increasingly may include ‘things’).

Since the original debate regarding wireless broadband began between 3G and Wi-Fi almost twenty years ago, consumer device ownership patterns have shifted considerably. For example, Figure 1 (A) illustrates how device adoption has evolved in the United States, a pattern that has been echoed in Europe.²

² See UK (Ofcom, 2020) or European Union (Eurostat, 2020).
The exhibit highlights multiple important trends: (1) a shift from fixed landlines to cellular phones, leading first to the loss in second lines and then for a growing number of households, becoming cellular-only telephony households; (2) basic cell phones being replaced with data-capable/Internet-connectable smartphones, connected first via Wi-Fi for broadband but increasingly with 4G after it began to roll-out after 2010; (3) expanded adoption of other wirelessly-connected devices like tablets, e-readers, etc., supplementing personal computer connectivity options; and (4) increasing numbers of Internet-connected devices per user (as more users have multiple devices). In the future, we expect these trends to continue with an even wider array of post-PC devices such as smart TVs, connected cars, and IoT devices. In the
US and Europe, evidence suggests that PC and laptop ownership may even be falling as users shift to mobile wireless devices for their principal mode of connectivity and usage (GlobalWebIndex, 2018; Pew Research Center, 2018). The next decade will likely see a continued shift away from fixed computing devices, towards those which rely exclusively on wireless connectivity. And, the trend toward multiple devices per user will be driven by the rise of IoT/M2M, as all kinds of ‘things’ are connected to the Internet, although the magnitude is highly debated (Webb and Hatton, 2020).

Figure 1(B) illustrates how the largest number of connections are in the home or office, and thus more likely to use Wi-Fi as a form of wireless Internet connectivity. There are a number of key trends which include: (1) M2M and IoT devices will be the primary driver for the increasing number of connections, moving from approximately 8 billion globally in 2020 to over 14 billion by 2023; (2) the two major use cases involve the connected home and connected workplace; and (3) the other M2M and IoT use cases will be relatively minor in comparison, including connected health, cities and cars.

Finally, the ongoing improvements in video quality will continue to increase the quantity of traffic generated per device. For example, huge advances in network capacity have enabled the growth of higher-data-rate applications such as High Definition (HD) video conferencing, streaming entertainment media, and highly interactive gaming replacing lower-data rate text and voice-only communication services. Currently video accounts for over three quarters of total consumer and household traffic, and has a multiplier effect whereby an Internet-connected HD TV generates as much daily traffic as an average household (Cisco, 2020). With the ongoing shift to higher quality video there is an even greater requirement for increased connection capacity, which has an impact on wireless broadband requirements. For example, Netflix is one of the most popular video streaming platforms and can provide a service on relatively low connection capacity, ranging from 0.5-1.5 Mbps (Netflix, 2020). However, Standard Definition (SD) video requires at least 3 Mbps, HD requires at least 5 Mbps and Ultra High Definition (UHD) requires at least 25 Mbps. Thus, as consumer preferences increasingly move towards a minimum of HD, but preferably UHD video quality, the quantity of data demand generated per device will increase, which affects demand for wireless connectivity. Video is expected to continue driving global consumer data demand over the next decade, resulting from more devices serving users with better quality streamed content.

3. An overview of 5G technical features

The first specification released by the 3rd Generation Partnership Project for Phase 1 of the 5G system (Release 15) states there are three key technical use cases for the technology (3GPP, 2019), including

1. Enhanced Mobile Broadband (eMBB)
2. Ultra Reliable and Low Latency Communications (URLLC)
3. Massive Machine Type Communications (mMTC)

Within 5G eMBB, one of the first use cases is using this approach to provide broadband via Fixed Wireless connectivity. Additionally, URLLC is technically made up of multiple use cases, either Ultra Reliable or Low Latency communications, or a combination thereof. The launch of Release 16 takes place in 2020, followed by Release 17 in 2022, following an approximate 15-month standardisation, as illustrated in Figure 2.
The aim of eMBB is to move beyond what is capable in 4G to provide improved data-rates, traffic/connection density and user mobility (Cave, 2018; Oughton et al., 2019; Oughton and Frias, 2016). The use case is expected to be delivered for a range of coverage scenarios and applications such as streaming, video conferencing, Augmented Reality (AR) and Virtual Reality (VR). This includes different service areas ranging from indoor to outdoor, urban to rural, home to office, and local to wide area connectivity, as well as special deployment circumstances for mass gatherings, broadcasting, residential access and vehicles travelling at very high speeds. Ultrafast mobile broadband of 100 Mbps is expected outdoor (for the mean user experienced throughput), with peak throughput up to 10 Gbps on an indoor 5G network (3GPP, 2016a), should sufficient spectrum be available and network conditions allow.

In contrast, the aim of delivering low latency and highly reliable communication services is driven by new industrial automation applications in vertical sectors (manufacturing, automotive etc.) (Vuojala et al., 2019). Current 4G systems can experience significant latency issues resulting from delay on the radio interface, transmission within the system, transmission to a server which may be outside the system, and data processing. Hence, 5G aims to reduce this latency through the RAN and core, along with taking advantage of local service hosting called ‘edge computing’. Note though, that edge computing is not limited to 5G networks, as it can support multi-access networks, including both cellular and Wi-Fi. However, the architecture of 5G, with the increased use of virtualisation of network infrastructure, compared to previous cellular generations and Wi-Fi, makes better use of edge computing capabilities. The aim is to provide reliability of 99.9999% for process automatic, with a data rate <100 Mbps and an end-to-end latency of <1-2ms for the user plane and less than 10ms for the control plane (3GPP, 2016b).

Additionally, mMTC is extending LTE IoT capabilities—for example, through 4G-based narrowband IoT (NB-IoT) to support huge numbers of devices with lower costs, enhanced coverage, and long battery life, reaching thousands of end-devices (3GPP, 2016c). Later 3GPP releases (e.g. 17 or 18) are expected to provide a narrowband IoT capability using the 5G New Radio interface. Figure 3 shows the 5G overall architecture.
Taking advantage of the proposed architectural structure, one of the fundamental features that is being supported is infrastructure ‘slicing’. Network slicing requires a continuous adjustment of customer-centric Service Level Agreements (SLAs) with infrastructure-level network performance capabilities. As customers such as vertical industries request new types of connectivity services from providers, both the creation and operation of these services will have to demonstrate a very high level of automation to ensure very efficient lifecycle management of network slice instances, via the use of an end-to-end framework.

The proposed 5G architecture is accomplished in a recursive structure, which can be specified as a procedure that is applied repeatedly. This philosophy increases scalability since the same service category can be deployed repeatedly, and simultaneously, at different locations. From the perspective of virtualised infrastructure, this recursive approach permits the operation of a slice instance on top of the resources provisioned by another slice instance. As an example, each tenant can own and deploy its own MANagement and Orchestration (MANO) system using these principles.

Figure 4 illustrates the technical features of 5G for providing higher capacity and improved user experience.
The millimetre-wave band (technically 30–300 GHz, although commonly all bands above 20GHz are called ‘mmWave’) contains over 90% of allocated radio spectrum with much of this resource being underutilised (Niu et al., 2015; Roh et al., 2014). Previous generations of cellular technology made little use of these frequencies due to poor propagation characteristics. However, the amount of bandwidth that can be obtained at these frequencies is significant and therefore attractive. Early results indicated that significant Non Line Of Sight (NLOS) outdoor street-level coverage is achievable, however only up to approximately 200 meters from the serving cell (Akdeniz et al., 2014; Rangan et al., 2014). Building parts of 5G networks based on millimetre wave spectrum will lead to key changes including (i) a large increase in the number of antennas, (ii) propagated signal being far more sensitive to blockages, (iii) variable propagation laws (with NLOS being far worse than LOS) and (iv) fewer multipath components in the radio channel being used (Bai et al., 2014).

Given the need to massively densify the cellular network to provide the capacity to support significant growth in traffic in hot-spot areas, MNOs are shifting to small cells architectures. These facilitate spatial reuse, support lower-power devices, and enable use of higher frequency millimetre wave spectrum which has limited range (<200m). Moreover, in scenarios where small cells are deployed within macro cell areas there has been shown to be a beneficial effect in spectral efficiency (Jungnickel et al., 2014). While poor network planning always leads to significant cost ramifications (Haddaji et al., 2018; Taufique et al., 2017; Wisely et al., 2018; Yaghoubi et al., 2018), the mass deployment of small cells presents a set
of unique challenges related to spectrum management, energy efficiency and the logistics of deploying backhaul (Ge et al., 2016, 2014; Wang et al., 2015). One way to address some of these issues is the disaggregation of small cell architectures, based on the virtualization principles discussed later in relation to Figure 5.

The deployment of Massive Multiple Input Multiple Output (mMIMO) technologies are a key capacity enhancing technique (Bogale and Le, 2016; Jungnickel et al., 2014; Mumtaz et al., 2016). Compared to 4G MIMO, 5G mMIMO provides large spectral efficiency gains by taking advantage of multiple antennas at each Base Station (BS) and item of user equipment thanks to beamforming gains achieved by spatial filtering at the transmitter (precoding) and/or the receiver (Papadopoulos et al., 2016). By adding more antenna elements these gains from beamforming can be increased, leading to improvements in the received Signal to Interference Plus Noise Ratio (SINR). Multiplexing gains can also be achieved, with multiple streams of information being transmitted simultaneously. By adding additional antennas at each site additional overheads in Channel State Information (CSI) are avoided, focusing the radiated energy toward the intended directions while minimising intra-and intercell interference (Boccardi et al., 2014). For successful integration into 5G networks a key challenge for mMIMO will be cost-efficient integration, balancing capacity delivery with trade-offs in equipment costs and energy consumption (Panzner et al., 2014), particularly when operating at higher frequencies where propagation characteristics may be challenging (Huang et al., 2017).

The use of beamforming in 5G is a key feature and enables a single stream of information to be focused towards a user, rather than being transmitted radially, significantly reducing the level of interference experienced at other cells. In combination with mMIMO, a BS can then estimate the most efficient route to send information packages based on reduced interference, by triangulating the location of the user device.

Basic radio antennas can only perform a single task at one time, such as transmitting or receiving information. In 5G the introduction of full duplex model allows both UL and DL directions on a single stream. So rather than using Frequency Division Duplexing (FDD) where streams are split into UL and DL channels, or Time Division Duplexing (TDD) where information travels in just one direction at one point in time.

To deliver the technical specifications of the 5G standard in a cost-efficient way MNOs are examining the migration of a traditionally Distributed RAN (D-RAN) characterised by the co-location of Base Band Units (BBUs) and Remote Radio Heads (RRHs), to a Centralised/Cloud-RAN, as illustrated at the top of Figure 5. A C-RAN architecture would consist of a central location providing shared BBU resources to reduce capital expenditure, operational expenditure and ultimately the Total Cost of Ownership, with RRHs connected directly to the pool of BBUs via high bandwidth, low latency transport links known as fronthaul, as illustrated at the bottom of Figure 5. As a part of the 3GPP framework, multiple functional splitting options, one of which covers C-RAN (Option 8), have been proposed to meet the diverse requirements of 5G (3GPP, 2016d). OpenRAN has introduced a set of open APIs specifications between the components comprising this disaggregated RAN, namely the Central Unit (CU), Distributed Unit (DU) and Radio Unit (RU). This disaggregation extends also between the hardware and software, with introduction of virtualisation of RAN, allowing for general purpose platforms to be used. This allows for flexibility and adaptability in the implementation, but depending on where the RAN is split, new issues however arise, particularly the requirement for high bandwidth, very low latency links to meet the demands for the backhaul, midhaul and fronthaul. Innovative solutions such as Integrated Access and Backhaul (IAB), Hybrid Fibre Coax (HFC), and Nexgen Fibre have been introduced to handle them. Recent
analysis found a positive 5G business case for eMBB over the period 2020-2030 (Rendon Schneir et al., 2019).

*Figure 5 The evolution of cellular RAN configurations (Alsharif and Nordin, 2017)*

4. An overview of Wi-Fi 6 (802.11ax) technical features

In this section, we turn to highlighting the main features of the Wi-Fi 6 technology.

Two different industry organisations have led in the development of Wi-Fi. First, the IEEE's Project 802 is the development body responsible for many networking standards, including the suite of Wi-Fi technologies. Second, the Wi-Fi Alliance is a non-profit organisation comprised of a global network of companies tasked with ensuring interoperability and certifying and promoting different Wi-Fi products (including adding more accessible marketing terms such as the Wi-Fi 4, 5 or 6 labels). This includes being
responsible for both technical aspects, such as creating additional specifications for products such as Wi-Fi mesh-networks, and governance issues, such as engaging with policy makers regarding suitable spectrum allocations.

IEEE 802.11ax, known now as ‘Wi-Fi 6’, is the first amendment in the Wi-Fi family to go beyond small indoor environments, and aim to optimise its performance in large outdoor deployments. Although, it enhances the nominal data rate by 37% compared to Wi-Fi 5, it aims at providing 4x improvement in terms of throughput and spectrum efficiency in dense deployments, through new features such as OFDMA, MU-MIMO, and spatial reuse. At the same time, Wi-Fi 6 is reducing the power consumption per device. Whereas 2.4 and 5 GHz frequencies are used by legacy Wi-Fi technologies, the deployment of Wi-Fi 6E specifically relates to the use of the new 6 GHz spectrum band which has already been assigned in frontier markets (e.g. USA, Korea, UK etc.) and is expected to receive similar allocation elsewhere (e.g. Europe).

Table 1 provides comparative technical information on recent Wi-Fi generations.

Table 1 Technical capabilities across legacy and current wireless standards

| Features                  | Wi-Fi 4 (802.11n) | Wi-Fi 5 (802.11ac) | Wi-Fi 6/ Wi-Fi 6E (802.11ax) |
|---------------------------|-------------------|--------------------|------------------------------|
| Data rate                 | Up to 600 Mbps    | Up to 7 Gbps       | Up to 9.6 Gbps               |
| Carrier Frequency         | 2.4, 5            | 5                  | 2.4, 5, 6                    |
| Channel Bandwidth         | 20, 40            | 20, 40, 80, 80+80, 160 | 20, 40, 80, 80+80, 160       |
| Frequency multiplexing    | OFDM              | OFDM               | OFDM and OFDMA               |
| OFDM symbol time (μs)     | 3.2               | 3.2                | 12.8                         |
| Guard interval (μs)       | .04, .08          | .04, .08           | .08, 1.6, or 3.2             |
| Total symbol time (μs)    | 3.6, 4.0          | 3.6, 4.0           | 13.6, 14.4, 16.0             |
| Modulation                | BPSK, QPSK, 16-QAM, 64-QAM | BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM | BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM, 1024-QAM |
| MU-MIMO                   | N/A               | DL                 | DL and UL                    |
| OFDMA                     | N/A               | N/A                | DL and UL                    |
| Radios                    | MIMO (4x4)        | MU-MIMO (DL) (8x8) | MU-MIMO (DL & UL) (8x8)      |

Four example scenarios for Wi-Fi 6 deployments include (Merlin, 2015):

1. Residential, where the deployment of Access Points (APs) is uncontrolled and unmanaged, resulting in high interference between the APs.
2. Enterprise, with low interference between the APs as the deployment is now managed and controlled.
3. Indoor small hexagon-based, representing the indoor dense scenarios (i.e. stadiums, auditorium etc.) where there is strong interference between the APs.

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4. Outdoor large hexagon-based to assess the performance in outdoor hotspot deployments.

The deployment of Wi-Fi APs in these scenarios has traditionally been based on a relatively simple ‘plug and play’ setup for a single piece of equipment. Increasingly the use of Wi-Fi mesh systems has become popular, whereby rather than a single AP, the system consists of a main hub with multiple linked nodes spatially distributed throughout a building or home which are capable of capturing and rebroadcasting information (Navío-Marco et al., 2019). Such an approach helps to eliminate areas with poor signal coverage, improving both speed and reliability for users. The ability to easily deploy Wi-Fi strongly contrasts with the technical requirements of 5G deployment (Forge and Vu, 2020).

A variety of technical features have been introduced into the design of Wi-Fi 6 to help cope with the challenges of delivering consistent wireless connectivity. Figure 6 illustrates these new features which generally help to improve spectral efficiency and overall throughput, while still ensuring backward compatibility with previous generations.

Figure 6 Overview of Wi-Fi 6 technical features

One of the most important changes is the adoption by Wi-Fi 6 of mandatory support of Orthogonal Frequency Division Multiple Access (OFDMA) in both the downlink (DL) and uplink (UL). In contrast to cellular communications, where OFDMA is already in use, this is the first time this technical feature has
been introduced to the Wi-Fi family. Indeed, OFDMA is one of the two techniques that allow Multi-User (MU) transmissions, where an AP can simultaneously transmit and receive information, to and from multiple users, in the same DL/UL. Like the legacy approach of Orthogonal Frequency Division Multiplexing (OFDM), where the entire bandwidth is divided into multiple subcarriers, OFDMA allocates groups of these subcarriers, known as Resource Units (RUs), to different users, each one of them using different Modulation and Coding Scheme (MCS) and/or Transmit Power. Hence, OFDMA can improve spectral efficiency and provide up to 4x throughput gain when compared to OFDM (Khorov et al., 2019) by allocating either single or multiple RUs to users based on their needs (e.g. data to transmit) and the available channel conditions (e.g. SINR).

The second key MU technique is the support of Multi-User MIMO, otherwise known as MU-MIMO in both the DL and UL. Essentially, MIMO enables data transfer to take place across multiple antennas to take advantage of ‘multipath propagation’, which is a technique for increasing the rate of data transmission using different spatial streams of data. Although previous versions of Wi-Fi contain MIMO, Wi-Fi 6 enables multiple simultaneous beams (up to 8) to be supported by an AP, connecting to several devices concurrently (for both DL and UL). Additionally, with higher 1024-QAM (standing for Quadrature Amplitude Modulation) available, where very high signal quality is anticipated (e.g. high SINR) this much more efficient method of data transfer can be utilised (compared with a 256-QAM being the maximum in 5G).

To further reduce power consumption, Wi-Fi 6 adopts the power-saving technique introduced in IEEE 802.11ah, namely Target Wake Time (TWT). In contrast to the power-saving mechanisms introduced in the previous Wi-Fi generations, TWT allows devices to increase their sleep time, instead waking up at a specified time slot previously agreed to exchange data with the AP or other users.

To cope with the challenges in dense deployments where multiple Basic Service Sets (BSSs) might be operating on the same channel, the Spatial Reuse (SR) mechanism is introduced in Wi-Fi 6. The core functionality of this new feature is the ‘BSS Colour’, a 6-bit value carried on the physical header that aims to assist the devices to early identify whether a frame is an inter-BSS or an intra-BSS. Hence devices can abandon the reception of an inter-BSS frame, based on the interference level, to initiate a transmission to their BSS. This can increase the number of concurrent transmissions in a network, providing a throughput gain of 30% in outdoor dense deployments (Selinis et al., 2016).

With the emergence of new use cases (e.g. 8k video, holographics etc.) posing even stricter requirements in terms of latency and throughput, the next generation of Wi-Fi is looking to fulfil these needs. IEEE 802.11be (Lopez-Perez et al., 2019), will be the successor of Wi-Fi 6E, enhancing throughput by at least 3-4 times, whilst maintaining backward compatibility. The support of larger channels (from 160 MHz to 320 MHz) and the increase of the number of spatial streams to 16 will boost the peak data rates to 30 Gbps. Multi-band aggregation, where channels in different frequency bands could be aggregated and used for data transmissions, is also under consideration for Wi-Fi 7.

Currently Wi-Fi is a half-duplex system due to the challenges that full-duplex communications pose and to keep manufacturing costs low. However, Wi-Fi 7 aims at addressing these challenges by considering full-duplex systems. The coordination among the APs has also been proposed for Wi-Fi 7, to further utilise available resources and improve spatial reuse in dense deployments. Following cellular systems, the separation of data and control frames has been proposed, whilst the use of HARQ is also under consideration to provide reliable and low latency transmissions. Finally, Time-Sensitive Networking (TSN) technology could also be incorporated in Wi-Fi 7 to assure time synchronisation and low jitter (Adame et al., 2019), which has a significant impact on live-streaming applications.
Having now described the technical characteristics of both 5G and Wi-Fi, we will review the extent to which these technologies are similar or different with reference to wireless broadband connectivity.

5. Comparing and contrasting 5G and Wi-Fi 6

In this discussion, we compare 5G and Wi-Fi 6. As we have already discussed, both 5G and Wi-Fi 6 offer significant enhancements in performance with much faster speed connections, higher device densities, and lower latency, relative to prior technical generations. Although many of the use cases may be addressed with legacy 4G or Wi-Fi 5, the improved capabilities of the newer technologies enhance the potential to support more consistent Quality of Service. Improved throughput, reliability, and other features will be needed to support more demanding peak usage of proposed immersive applications such as AR/VR (e.g., for gaming, remote control, telemedicine, etc.). Enhancements are also required for large-scale enterprise connectivity such as industrial IoT applications.

Table 2 makes a comparison of the key 5G and Wi-Fi 6 variables based on different technical dimensions, spectrum usage, the business model, costs, ease of installation and the required skill.
Table 2 Comparing key 3GPP 5G and Wi-Fi 6 (IEEE 802.11ax) features

| Category                    | Variable                  | 5G                                      | Wi-Fi 6 / Wi-Fi 6E                      |
|-----------------------------|---------------------------|-----------------------------------------|----------------------------------------|
| Technical                   | Peak data rate            | 2 Gbps (DL), 1 Gbps (UL)                | 10 Gbps 8x8 (DL), 5 Gbps (UL)          |
| Technical                   | MU-MIMO                   | 128x128                                 | 8x8                                    |
| Technical                   | Coverage range            | 100-300 meters for small cells, up to   | <50 meters indoor, up to 300 meters    |
|                             |                           | tens of km for macro cells              | outdoor                                 |
| Technical                   | Carrier aggregation       | Yes                                     | Yes, 40, 80, 160 (or 80+80)            |
| Technical                   | Inter-cell interference   | Controlled                              | Mainly uncontrolled                    |
| Technical                   | Channel Access Scheme     | OFDMA                                   | OFDMA                                   |
| Spectrum                    | License type              | Mostly licensed                         | Unlicensed                              |
| Spectrum                    | General bands             | Low, mid and high                       | Low and mid                            |
| Spectrum                    | Specific frequencies      | 700 MHz, 3.5 GHz, 26 GHz, 60 GHz        | 2.4 GHz, 5 GHz, 6 GHz                   |
| Spectrum                    | Channel Bandwidth         | 20, 40, 80, 100 MHz                     | 20, 40, 80, 160 MHz                    |
| Business model and cost     | Revenue model             | Pre- or post-pay billing for data       | None ('piggybacks' on fixed broadband   |
|                             |                           | services                                | connections)                           |
| Business model and cost     | User equipment price      | High (>= $300)                          | Low (>= $100)                          |
| Business model and cost     | Public versus private     | Traditionally publicly provided by an   | Traditionally privately provided       |
|                             |                           | MNO                                     |                                        |
| Business model and cost     | Chip/modem cost           | High ($10-50)                           | Low ($1-5)                             |
| Business model and cost     | Data cost                 | Monthly subscription ($5-20)            | Free ('piggybacks' on fixed broadband) |
| Installation and skills     | Deployment approach       | Controlled and managed                  | Uncontrolled and unmanaged             |
| Installation and skills     | Installation skill level   | High                                    | Low                                    |
| Installation and skills     | Development skill level   | High                                    | Low                                    |

Legacy cellular networks were designed to provide wide-area connectivity for large numbers of users roaming across vast coverage areas. This was most efficiently supported with higher-power, macro cell architectures that could provide single-cell coverage. This approach could reduce the need for high-speed cell hand-offs and reduce wide-area costs. However, the drawback of a macro cell design is the limited per-user capacity when compared to the peak capacity available via Wi-Fi 6 or smaller cell 5G deployments. A new approach to deal with this issue in wide-area networks (e.g. dense urban or rural scenarios) is to use much higher order MU-MIMO (128x128) when compared to Wi-Fi 6 (8x8). Another is to for MNOs to shift towards ever-smaller cell architectures to gain the capacity benefits of network densification. This flexibility assists MNOs in integrating 5G with MNO carriers' macro cell networks, and helps them rapidly provide wider-area coverage with scalable capacity as small cells are built out (first in high-demand locations, and potentially later as supporting infrastructure such as backhaul connectivity is built out). As higher power is allowed in licensed bands, current 5G small cells target larger coverage areas (100-300 meters) than Wi-Fi cells (e.g. <50 meters indoors). Both technologies take advantage of carrier aggregation and OFDMA as the main channel access scheme to provide greater capacity to users via increased spectrum agility (Chavarria-Reyes et al., 2016).
Traditionally, Wi-Fi technologies have operated at reduced power, offering limited range coverage for each Wi-Fi AP. This small cell architecture is consistent with the design goals of Wi-Fi as a WLAN technology operating using unlicensed spectrum, benefiting from frequent spectral reuse to provide very high capacity local Internet connectivity (Up to 10 Gbps in Wi-Fi 6). By definition, a Local Area Network (LAN) is intended to provide coverage for a relatively small contiguous geographic area, but via gateways and repeaters, the range of WLANs can be extended to ever-larger coverage areas such as a corporate or academic campus locations. Additionally, consistent with the unmanaged and uncontrolled end-user-based deployment model for WLANs, the goal in Wi-Fi 6 is to continue to provide local wireless connectivity to a relatively small community of users and devices over a contiguous area, most typically indoors but connectivity is readily expanded outdoors in campus environments. Small cells, by their nature, support a smaller number of users and when deployed indoors (or on a campus), make it easier to manage shared connectivity to avoid destructive interference among users and to avoid interference from WLANs deployed by other network operators. Taken together, these WLAN usage requirements avoid the need for including extensive capabilities to manage large numbers of APs and enabling high-speed hand-offs as users move across coverage areas of adjacent APs. This contrasts with the approach in 5G where inter-AP interference mitigation and coordinated operation is intrinsic to the design of the technology and the service architecture.

After the first AP (whether Wi-Fi or cellular), the interconnection to wide-area networks or other APs may be via wired (often fibre) backhaul connections, or if small cells are deployed densely enough, via wireless backhaul. This means that both the network backhaul connection and last-hop AP performance of Wi-Fi 6 and 5G networks may be quite similar so long as the usage-case does not call for supporting fast-movement (e.g. at highway or airplane speeds), necessitating rapid hand-offs to adjacent APs. Supporting such applications was a focal requirement for the design of cellular technologies, including 5G. In contrast, the mobility support for Wi-Fi was based on supporting nomadic use, where users move between high-capacity hotspots, but generally do not expect to remain seamlessly connected in transit between hotspots (although this can happen at slow speeds on campus networks). The question is how much of future usage will fit with the nomadic mobility model, with many users being quasi-fixed, as opposed to requiring fast-mobile connectivity. As highlighted earlier in this paper, most existing data traffic demand is produced in-homes, within range of in-home Wi-Fi hotspots using unlicensed spectrum. Moreover, although Wi-Fi deployments often consist of one or only a few APs, in private networking contexts where the deployment of unaffiliated WLANs may be controlled, contiguous Wi-Fi coverage and support for low-speed roaming among APs is readily implemented for entire building complexes and campus environments.

While fast mobility will remain important, we anticipate that much of the growth in traffic and usage models for both 5G and Wi-Fi 6 will be associated with quasi-fixed, nomadic usage cases. The 5G standards are anticipating this and future standards will enable standalone 5G APs and unlicensed spectrum connectivity to compete directly with Wi-Fi WLANs. Alternatively, while Wi-Fi WLANs were originally targeted principally at single AP WLANs or WLANs consisting of a relatively small number of APs in a local, geographically contiguous area to support hotspot coverage, the 802.11 protocols have been expanded to support management of greater numbers of APs over a larger area and to support higher-speed AP hand-offs. For example, Dedicated Short-Range Communications using IEEE 802.11p was developed for use in automotive applications (Katsaros and Dianati, 2017; Mir and Filali, 2014). Hence, vehicular networking is another battleground for the two technologies, with the 802.11p competing with an LTE 4G/5G cellular vehicular networking standard called Cellular V2X (Mir and Filali, 2014).
The type of spectrum used in legacy architectures has had an important impact on the design of wireless technologies and has helped shape the evolution of cellular and Wi-Fi technologies.

For example, we have already highlighted that cellular has a history of providing wide-area support for fast-moving mobile users, with longer-range macro cells mounted on high towers, using licensed spectrum (mostly acquired via auction). Large up-front and continuing capital investments are needed to deploy wide-area coverage networks and acquire the requisite spectrum licenses before service revenues are obtained, and those investments need to be amortised over many years. Licensed frequencies have enabled MNOs to have predictable spectrum quality since they can manage how users (i.e., MNO subscribers) share available spectrum resources. Hence, initially 4G, but 5G over the long term, is likely to be the preferred choice for supporting applications which fit this niche, such as providing connectivity to autonomous vehicles, drones, and enabling those smart cities or IoT applications which require ubiquitous connectivity over wide areas (Oughton and Russell, 2020). In contrast, Wi-Fi has traditionally used unlicensed spectrum which is free to use but is shared non-cooperatively with other local users competing for spectrum.

Additionally, legacy MNO networks focused on supporting mobile telephony relied on paired bands using FDD to allow symmetric uplink/downlink channels, whereas WLANs relied on a single shared spectrum band that was better suited to the asynchronous, variable rate traffic typical of data networks. However, in cellular this is now starting to change. For example, as cellular traffic becomes more variable rate and heterogeneous, the trend is toward increasing usage of unpaired spectrum bands which can utilise TDD. This is possible in the 3.5 GHz band which is central to delivering high capacity 5G but will also be widely used at millimetre wave frequencies (e.g. the 26-28 GHz band) (Oughton et al., 2017).

Significant new licensed and unlicensed spectrum is now being made available for both 5G and Wi-Fi 6 deployments. For licensed spectrum, new allocations of high-band frequencies above 28 GHz will be auctioned along with prime, mid-band spectrum in the 3-5 GHz range (often used by satellite broadcasters). For unlicensed spectrum, in the U.S., the Federal Communications Commission has allocated 1200 MHz for unlicensed use in the 6 GHz band, and other countries are following but with debate around the size of the allocated bandwidth. It is anticipated that both the next generation of 5G that will enable standalone 5G deployments (i.e., use of unlicensed spectrum without requiring control via a licensed band) and Wi-Fi 6 will compete head-to-head to co-exist and share the 6 GHz unlicensed spectrum.

Traditionally over the past two decades there have been quite clear demarcations between public and private networks. However, changing norms and regulations for spectrum usage are beginning to blur these boundaries (Disruptive Analysis, 2020). For example, spectrum policymakers are looking to expand management options to enable greater sharing among heterogeneous spectrum users, including government and commercial users (Massaro, 2017; Massaro and Beltrán, 2020; Saint and Brown, 2019; Sohul et al., 2015). A noteworthy example is the model for sharing 3.5 GHz spectrum in the newly enabled Citizens Band Radio Service (CBRS), that began operations in the U.S. in the fall of 2019. The CBRS allows multiple tiers of priorities of users (i.e., legacy government users, new priority commercial and unlicensed commercial users) to share the spectrum according to dynamic control of tiered interference protection rights (Grissa et al., 2019; Souryal and Nguyen, 2019; Yrjölä and Jette, 2019). Equally, other countries have displayed leadership in providing localised spectrum licensing including the UK, Japan, Germany and France. Additionally, to adjust to the higher capital costs associated with smaller cells (which are also needed to make use of high frequency millimetre wave spectrum), regulators and MNOs are looking towards new shared spectrum usage models (Gomez et al., 2019, 2020; Weiss et al., 2019; Weiss and Jondral, 2004). Such changes provide greater efficiency, by allowing users to access a greater quantity of the spectrum resources available. Figure 7 illustrates how the types of wireless
services which can be deployed are changing, partially driven by the availability of local and/or shared spectrum resources.

*Figure 7* Shifting public-private boundaries towards hybrid networks

Such spectrum policy changes have led to a variety of new hybrid network deployment models. For example, ‘semi-public’ or ‘semi-private’ networks are starting to emerge, such as 4G/5G networks run by enterprises or specialised Business-to-Business or wholesale MNOs. Whereas in previous decades there were well defined boundaries between public and private networks, using either unlicensed or licensed spectrum, this strict delineation is fading. Whereas cellular was traditionally based on licensed bands, and Wi-Fi based on using unlicensed bands, there is now a hybridisation in the provision of private cellular networks which can take advantage of either unlicensed or local and shared spectrum, provided by specialist communications providers (so not by MNOs or the enterprise which takes advantage of the provided services). Despite this supply-side shift, many technologies are likely to co-exist with users having multiple devices and each device having multiple radios. Thus, depending on the availability of wireless services, devices may simultaneously or dynamically make use of both private or public cellular (4G/5G), and Wi-Fi networks (Wi-Fi 5/6) both in and outside of homes or businesses.

In terms of business model and cost, Wi-Fi 6 may have an advantage for indoor and private local network deployments. This arises because of its legacy as the technology choice for WLANs due to the low cost and scalable deployment of IEEE 802.11. Historically, end-users could deploy WLANs with a few APs using off-the-shelf, inexpensive Wi-Fi equipment that operates in unlicensed spectrum. These WLANs provided local wireless connectivity to shared fixed access broadband in the home, office, or coffee shop. Wi-Fi 6 offers an enhanced WLAN and so may be the preferred technology of choice for connecting all
IoT devices around the home, from laptops to security cameras and home appliances. Indeed, price is a highly important factor for adoption, because whereas a cellular 5G chip/modem ranges from $10-50, the Wi-Fi equivalent is a fraction of the price at around $1-5. Many consumer IoT devices will aim for a price range of $50-200, therefore adding a 5G chip/modem is not an insignificant cost and could affect product viability. Path dependence is also important. For example, most existing smart home devices such as TVs and voice assistants use Wi-Fi, with practically none using cellular, making a full shift to cellular look extremely unlikely.

Importantly, the economic outlook for the mobile telecommunication sector is poor with ARPU either static or declining in many countries, which may make it hard to deliver on the high societal expectations of new technologies such as 5G. When ARPU decline is then combined with falling data prices and exponentially increasing traffic growth, MNOs are anxious to create new sources of revenue. Thus, important new markets for these technologies are perceived as being industrial IoT and other vertical sectors such as energy, health and automotive. This is part of the specialist communication services mentioned previously. While most businesses already use Wi-Fi, some may now have the option to choose which wireless connectivity technology best suits their needs. For example, Wi-Fi 6 would be the natural successor to most existing networks providing a low cost, scalable option for uses with low Quality of Service requirements. However, for automation at a factory or campus with very high Quality of Service requirements, either working with an MNO or gaining locally licensed spectrum for private 4G LTE or 5G bands might offer a better option by ensuring dedicated access to spectrum resources (Matinmikko et al., 2018). However, ultimately these decisions will be very application and sector specific and will also depend on the (i) level of mobility, (ii) the area needing wireless coverage and (iii) cost. For static uses (e.g. machinery) a fixed fibre connection could be the best option, but a factory using moving robots may be more suited to a private network. For example, the UK food distributor Ocado currently uses unlicensed cellular networks in their factory automated robotics but switching to privately licensed spectrum could be a future development. Given these circumstances, it is hard to see how either cellular or Wi-Fi will dominate over the other given the range of different requirements each use case has. Indeed, both wireless connectivity technologies may also face competition from fixed connectivity if no mobility is required.

6. Discussion and conclusions

Herein we revisited the debate associated with wireless Internet connectivity by providing a new evaluation of the two main technologies involved in the provision of next generation wireless broadband: 5G and Wi-Fi 6. The previous competition between 3G and Wi-Fi was shaped by the networking challenges of an earlier era, but now this landscape has shifted considerably. In Section 2, we highlighted some of the long-term trends expected to shape demand for wireless Internet connectivity over the next decade. Sections 3 and 4 took described the key features of each of the technologies, which were then compared in Section 5. This analysis demonstrates that while each of the technologies has relative advantages stemming in large measure from their different legacy trajectories and focal usage scenarios, the two technologies will find themselves appropriately viewed both as alternative and substitute options for many contexts, as well as complements in many others.

In terms of the demand-side trends identified, data traffic is expected to continue to grow significantly with an increasing proportion of devices utilising wireless connectivity as the first connection point. The COVID-19 pandemic of 2019-2020 has highlighted the importance of enhanced digital connectivity to support remote work, education, and social engagement during the global crisis. But there may also be potentially new trends which could arise out of the shifting work and social patterns produced by the pandemic. Such changes could have repercussions for the spatial and temporal usage of wireless
broadband connectivity and the associated economics of each technology. Additionally, the ongoing consumption of higher and higher quality video content will also be an important factor driving consumer data demand, while enterprise use will reflect growing adoption of cloud-based applications and compute platforms.

In terms of the supply-side technologies, as expected both new generations of cellular and Wi-Fi aim to provide more spectrally efficient radio interfaces to support a better user experience. But we find that generally 5G is still focusing on delivering high mobility to users, as with previous cellular generations. While Wi-Fi remains aimed at providing nomadic high-capacity hotspots which can be easily deployed by anyone. Meanwhile, 5G is allowing the next generation of cellular technology to target new private and standalone networking opportunities, especially in industrial vertical sectors, that were previously the niche of a wide variety of legacy Wi-Fi or other proprietary radio systems. For example, while the main difference is generally the use of licensed rather than unlicensed spectrum, there is now even a standard which enables 5G to operate in unlicensed bands (5G NR-U). At the same time, the growth of quasi-nomadic usage and the expansion of small cell deployments is allowing wider-area network providers (like wired broadband providers) to expand into mass-market mobile services. 5G’s new ‘network slicing’ mechanisms, together with extra specifications for verticals, also should enable customised virtual networks to have specific capabilities for enterprise, especially from 3GPP Release 17 onwards.

Changes in spectrum policy have had a substantial impact. For example, the introduction of private spectrum licensing regimes for local areas has opened new opportunities for specialist communications providers to deploy cellular networks in private enterprises. Therefore, while much of the rest of the consumer telecommunications landscape is moving towards increased infrastructure convergence, with fixed operators selling mobile and vice versa, the opposite is true for business wireless connectivity. Rather than a shift towards more centralised monolithic communications providers, there is divergence driven by the need for many specialist providers to deliver bespoke private, semi-private and neutrally hosted 4G and 5G networks for different industrial sectors.

These changes mean that the use of industrial IoT across a range of manufacturing and warehouse facilities leaves firms with new options. They can choose to outsource their networking needs to an MNO or newer specialised provider, and those may offer a variety of options. Moreover, if they elect self-provision (because of the control or perceived cost benefits of such a choice), industrial users will have additional options. Self-provision could take place by either continuing to use existing Wi-Fi connectivity, deploy a private enterprise 4G or 5G network with locally licensed spectrum, or take advantage of both technologies. Indeed, the range of options has expanded and become more scalable. If industrial users select a private cellular network, that will provide a high degree of control over the provision of wireless connectivity with strict Quality of Service requirements, thanks to exclusive access to locally licensed spectrum resources. Such an opportunity could be highly useful for automating processes which require reliable wireless connectivity (e.g. for mobile robots). The benefit of remaining with Wi-Fi is the ability to cheaply and quickly provide wireless Internet connectivity to traffic which does not require high Quality of Service. In the past, over-provisioning for capacity often proved adequate to ensure the requisite level of service quality, and in closed spectrum environments (indoors, campus environments etc.) the risk of interference from unaffiliated radio networks may be minimal. We expect businesses that decide to deploy their own private cellular network are highly likely to continue using Wi-Fi simultaneously, suggesting that these technologies will remain complements to each other for the foreseeable future.

For non-industrial sectors such as enterprise offices and retail sites, or for visitor-heavy venues such as hotels and airport terminals, there will be parallel needs for Wi-Fi and public cellular access, although private cellular may have less impetus for deployment.
**Will 5G ‘kill-off’ Wi-Fi?**

This is one of the main questions which motivated this analysis, given the ongoing debate in industry on this topic. Ultimately, the competition between 5G and Wi-Fi 6 technologies offers important benefits by enabling greater flexibility for users to mix-and-match the technologies, business models, and spectrum usage models to best fit their needs. Proponents of one or the other technology, however, may argue for the benefits of their chosen technology displacing the other, and may argue for regulatory policies that would serve to tilt the marketplace in their favour. We believe such efforts need to be resisted, and that both technologies have important roles to play in the marketplace, based on the needs of different use cases. This is particularly important given that apart from smartphones, some devices will remain Wi-Fi-only, while some cellular-only, with just a fraction actively using both technologies to steer traffic based on user preference. Additionally, we expect cost economics to play a major role.

Given the path dependence exhibited by sunk costs in legacy infrastructure, it is unlikely that either technology will be able to usurp the other due to the additional costs of transitioning, except in a few specific circumstances. For example, cellular will remain the dominant wide-area technology thanks to the sunk investments made in existing brownfield infrastructure (towers, backhaul fibre etc.) which can be reused to provide generational upgrades at a lower cost than new greenfield deployments. Equally, it is hard to see how Wi-Fi would be threatened by 5G cellular for indoor locations, particularly for homes, given the ongoing challenges cellular technologies have with trying to serve inbuilding users with a high degree of reliability. If wireless devices do not require mobility or high Quality of Service, it is hard to find a justification for using 5G given it is generally more expensive, particularly for consumer electronics. Certainly, cost economics will be a major factor which affects the design of wireless devices, as well as consumer behaviour, and Wi-Fi has the advantage in this area, even if cellular is moving towards unlimited data subscriptions.

With the ongoing blurring of boundaries between 5G cellular and Wi-Fi 6 we will have to continue our evaluation over the next decade to understand which of these technologies will be more dominant in each consumer and industrial use case.
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