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Reviewing wireless broadband technologies in the peak smartphone era: 6G versus Wi-Fi 7 and 8

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ABSTRACT

With the arrival of the peak smartphone era, users are upgrading their smartphones less frequently, and data growth is decelerating. To ensure effective spectrum management decisions, policy makers require a thorough understanding of prospective wireless broadband technologies, current trends and emerging issues. Here, we review the sixth cellular generation ('6G'), in comparison to two new Wi-Fi standards, including IEEE 802.11be ('Wi-Fi 7') and IEEE 802.11bn ('Wi-Fi 8'). We identify three emerging issues necessary for successful telecommunication policy. Firstly, evidenced-based policy making needs to be able to measure effectively how much demand takes place *where* and *how*. Thus, new datasets are needed reflecting real usage by different wireless broadband technologies, for indoor and outdoor users. Secondly, with data consumption growth slowing, there needs to be an urgent reassessment of spectrum demand versus allocation. Past forecasts do not reflect recent data and regulators urgently need to re-evaluate the implications for spectrum management. Finally, regulators need new and improved Lifecycle Impact Assessment metrics of cellular versus Wi-Fi architectures, to support successful policy decisions which mitigate energy and emissions impacts.

1. Introduction

Wireless broadband connectivity provides one of the most important ways in which citizens, businesses and machines can engage with online content, applications and services. Indeed, society and the economy have a growing dependence on these services, as more and more devices shift to utilizing wireless technologies (such as Wi-Fi, cellular, satellite etc.). Global developments in the wireless industry keep pushing forward new standards, often with a focus on increasing Quality of Service (QoS) (Chowdhury et al., 2020; Lin, 2022), providing greater security (Ahmad et al., 2018; Fadlullah et al., 2022) and integrating Machine Learning (ML) (Szott et al., 2022), all with the aim of providing improved wireless broadband services.

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Currently 5G and Wi-Fi 6 technologies are being deployed across the globe with consumers consequently having access to a range of enhanced wireless broadband services (Zhou et al., 2022). This has led to much debate in industry and government about how to approach these technologies, particularly on spectrum management issues regarding licensed vs unlicensed bands, and with regard to the general economics of the telecom sector (Naik et al., 2020; Oh et al., 2022; Sathya, Mehrnoush, et al., 2020). Cellular technologies generally focus on providing wireless broadband directly to each device, whereas Wi-Fi technologies are usually the final connection for the fixed broadband connection at each premises (e.g., Wi-Fi 6). There has been an incredible amount of hype around 5G, to the extent that some commentators have even incorrectly claimed that Wi-Fi usage would be crowded-out by cellular (Bloomberg, 2017; Light Reading, 2019). In contrast, Wi-Fi continues to serve approximately two thirds of global Internet traffic, with more than twice as many Wi-Fi connected devices than people present on Earth in 2020 (Cisco, 2020), and more than three times as many forecast by 2024 (Ericsson, 2023). These two technologies are ripe for consideration.

Given the current focus on Next Generation (Next-G) wireless networks, there is a strong need for new assessments to support both industry and government decisions. Indeed, research is already underway for the next generation of wireless broadband technologies, ranging from the sixth cellular generation ('6G') to the seventh IEEE 802.11be ('Wi-Fi 7') and eighth IEEE 802.11bn ('Wi-Fi 8) Wi-Fi standards. While neither group represent the only options available, as they also compete against a range of other possibilities (satellite, microwave fixed links, wide-area LPWAN, Bluetooth etc.), they are two of the main wireless broadband technologies. Thus, it is

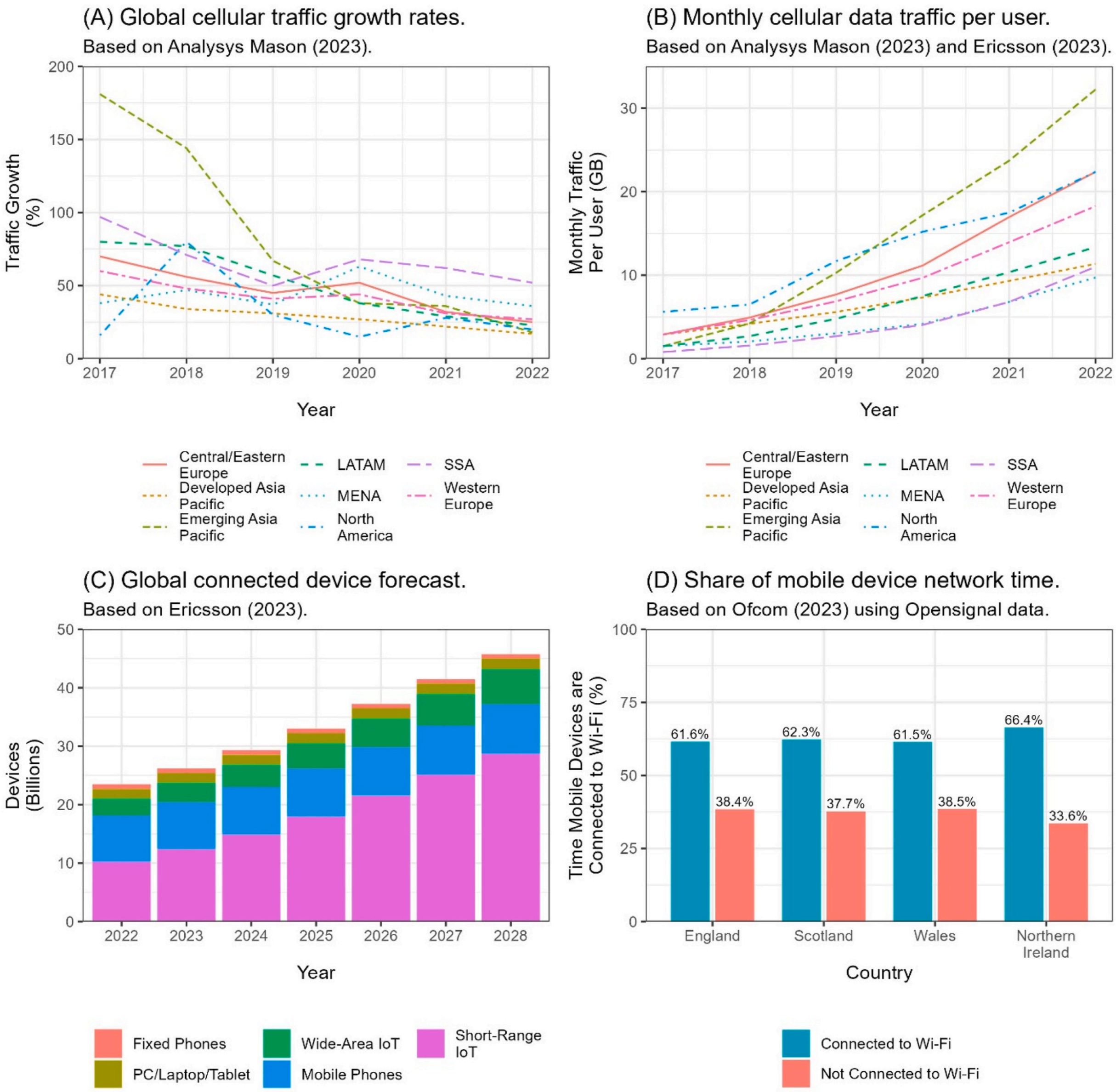

Fig. 1. Key demand trends in wireless broadband.

paramount that we consider the advantages and disadvantages of Next-G options in the peak smartphone era, as having such foresight can help (i) both existing R&D and standardization efforts prior to deployment, and (ii) network operators, telecommunication regulators, and final users understand future demand, potential deployment scenarios, and other ramifications. While comparative assessments of cellular and Wi-Fi technologies have taken place for previous generations, little attention has yet been placed on 6G, Wi-Fi 7 and Wi-Fi 8. Indeed, with standardization at an embryonic stage it is difficult to evaluate and compare performance and features for some technologies. Nonetheless, there exists clear trends in current research and development activities that can provide a basis to answer the following research questions.

1. What do current and future demand trends indicate about the future of wireless broadband?
2. Where do the similarities between proposed 6G technologies and future Wi-Fi IEEE 802.11 generations, such as Wi-Fi 7 and 8, begin and end, and how do they differ to previous standards?
3. What are some of the key policy issues associated with these two technology groups over the next decade?

To answer these research questions, we subsequently review a range of technical, academic and industry sources, with interpretation complemented by our experiences in (i) developing new cellular and Wi-Fi technologies, and (ii) in advising industry and government policy makers on wireless broadband topics. We follow other similar reviews in considering current and future demand, technical engineering aspects of these technologies, and then synthesizing the emerging policy issues (Bauer & Bohlin, 2022; Lehr & McKnight, 2003; Oughton et al., 2021). Subsequently, the following section reviews future demand scenarios, before an evaluation of prospective 6G technologies is undertaken in Section 3. Next, a review of Wi-Fi technologies is presented in Section 4. Finally, a comparison of these two types of technology standards is then undertaken in Section 5, prior to a discussion in Section 6 which returns to the main research questions, and policy conclusions being provided in Section 7.

2. Scenarios of future demand

It is essential that key demand trends be considered to ensure decision makers have a strategic understanding of the different futures we may face (Iden et al., 2017; Kalem et al., 2020; Kanellos et al., 2023). However, doing so is always a challenge, especially when assessing more than 2–3 years ahead (Hussain et al., 2017; Maeng et al., 2020). Here, we consider a variety of empirical data sources and forecasts to help understand trends in device adoption and data consumption.

Firstly, in terms of future cellular traffic, recent years suggest we are at a turning point in how much data users can consume. Indeed, past traffic forecasts have expected the three global drivers of traffic (video usage, device proliferation and application uptake) to continue growing far into the future, with forecasts reaching 100 billion Machine-to-Machine subscriptions and 16 billion mobile broadband subscriptions by 2030, translating to traffic per user of 257 GB/month and overall traffic of 5000 exabytes (EB) (ITU-R, 2015). Yet, empirical data no longer support this trend, meaning policy makers need to begin to plan for a future without the historical 50–100% annual traffic growth we have all come to expect. This is part of “peak smartphone”, where consumers have begun to maximize the quantity of video they can feasibly share and consume per day, combined with less desire to annually upgrade their cellular devices (The Washington Post, 2023; WIRED, 2023). Currently, global smartphone shipments per quarter have been falling from 342 million in Q3 of 2021, down to 268 million in Q2 of 2023 (Counterpoint Research, 2023). Mobile Network Operators (MNOs) as a consequence have been trying to shift their business models from mainly consumer-focused (via public networks), to expanding into various industrial ‘verticals’, such as automotive, manufacturing, energy and health (via private networks) (Banchs et al., 2019; Banda et al., 2022).

Global growth in data traffic has dropped dramatically from more than 90% in 2018, down to only 34% in 2021, and then to 22% in 2022 (Analysys Mason, 2023a), as illustrated in Fig. 1a. Whereas Emerging Asia Pacific (EMAP) has experienced one of the most rapid growth rates in 2017, this trend has quickly reversed, falling from 181% to approximately 20% by 2022. In contrast, Sub-Saharan Africa (SSA) maintains one of the highest growth rates, falling from roughly 97% in 2027, down to only 60% by 2022. However, most regions are clustered around the 20–25% annual growth rate by 2022, significantly below the trend enjoyed by the telecoms industry over the past decade. This is despite rapid traffic growth from Fixed-Wireless Access adoption which is typified by 10-20x the traffic of average smartphone mobile broadband (and is starting to *skew* combined usage data). The key point is that the cellular industry in general has become used to relying on dramatic increases in user demand to sell data packages which to a large extent helped to plug lost voice and SMS revenue, as users switched to other services (such as WhatsApp, iMessage/FaceTime, Zoom etc.). Now though, lower traffic demand may have strong implications for revenue (and thus, policy too). Unless new services emerge to help drive data growth, mobile spectrum demand will diminish.

Importantly, the relative growth rate is highly affected by the magnitude of the absolute number it relates to, requiring us to examine the raw values presented in Fig. 1b, which focus on monthly cellular traffic per user. Reported monthly cellular data consumption values for 2017 by region (Ericsson, 2023) are compounded forward using the growth rates reported in Fig. 1a. For example, the 181% growth rate in 2017 for EMAP is logical in a context where monthly consumption per user is 1.5 GB, just as the 97% in SSA relates to a monthly consumption per user of 0.8 GB. In general, the countries with the largest growth rates have the lowest monthly cellular consumption and vice versa. In North America (NA) the growth rate in 2017 was as low as 16%, but monthly cellular consumption was already at 5.6 GB. By 2022, most regions have elevated their monthly cellular consumption to between 10 and 30 GB, for example, 32.2 GB in EMAP, 22.4 GB in NA, 18.3 GB in Western Europe (WE), down to 11 GB in SSA, and 9.7 GB in the Middle East and North Africa (MENA). This is important because the expectation was that 5G would accelerate cellular traffic growth, and while this has taken place initially for very high usage consumers upgrading from 4G LTE, there has subsequently been modest cellular growth reported. Therefore, the question of course is where do we end up over the next decade? Policy makers should take note that the current global mean monthly data consumption trend leaves us closer to reaching approximately 30 GB by the mid-2020s, and approximately 40 GB by 2030, which leaves us a long way from previous forecasts of 257 GB/month (ITU-R, 2015).

Hitting peak smartphone has large implications for device composition trends, and thus policy. In Fig. 1c–a device forecast between 2022 and 2028 is presented which illustrates the declining composition of mobile devices (from 33.5% in 2022 down to 18.5% in 2028), despite an otherwise increasing trend in device ownership. However, the largest increases are forecast to be experienced by short-range Internet of Things (IoT) devices which are expected to more than double in number over the next decade (from 43.6% in 2022 to 62.8% in 2028), as users take advantage of the extensive range of low-cost, often Wi-Fi-connected, smart building devices (doorbells, security cameras, TVs, fridges, augmented reality headsets etc.). In contrast, wide-area IoT devices (most likely cellular-connected) see only a marginal increase (from 12.4% in 2022 down to 13.1% in 2028), providing a relatively modest part of the overall device composition. In general, the total number of devices globally is estimated to be roughly 26 billion currently, with this quantity forecast to rise to 46 billion by 2028, with the majority of new devices utilizing Wi-Fi as the key wireless broadband technology (to then connect to a fixed broadband connection). For example, mobile phones and wide-area IoT devices will generally utilize cellular, whereas most other device categories will not. The caveat to this forecast is whether there are new unexpected devices which disrupt expected trends.

Finally, Fig. 1d illustrates the point raised recently by the UK's Office of Communications (Ofcom) in the *Mobile Matters* 2023 report, which analyzes empirical data from the crowdsourced-data provider Opensignal (Ofcom, 2023). Wi-Fi is an essential part of how consumers interact with the Internet using wireless broadband services. For example, on average users spend almost two thirds of their time connected to Wi-Fi (62% across England, Scotland, Wales and Northern Ireland), and only approximately one third of their time not connected to any form of Wi-Fi connection (e.g., 38%). This is unsurprising when humans spend approximately 87% of their time indoors (with 69% at home), versus 13% outdoors (with 5.5% of this time in a vehicle) (Klepeis et al., 2001). These mobility trends are prevalent across many countries (Brasche & Bischof, 2005; Khajehzadeh & Vale, 2017). The relevance for policy is that given 70% of mobile traffic takes place indoors (Ayyash et al., 2016; ITU-R, 2021), this is where Wi-Fi connections are increasingly readily available, and capable of delivering Gigabit user speeds with adequately allocated spectrum (Analysys Mason, 2023b).

To conclude this review, the key traffic growth drivers of the past decade are less likely to continue propelling the wireless broadband system forward over the coming decade, raising a variety of new demand challenges. Unfortunately, much of the consumption data currently available is highly aggregated, and not always broken down clearly by wireless broadband technology for indoor and outdoor users, highlighting a need for new datasets.

3. 6G use cases and emerging technical features

Cellular networks have progressed a long way over the past forty years, from the analog systems of the first generation of cellular networks (1G), to the virtualized, software-defined networks of the fifth generation (5G) (Akyildiz et al., 2020; W. Jiang, Han, et al., 2021). Although significant advances are being made for candidate 6G technologies, at this stage any prospective analysis still contains an element of speculation, given the consideration of futures which are many years away (Giordani et al., 2020; Tariq et al., 2020). However, ITU-R has been working for numerous years on the vision for 6G, with a consensus forming around mid-2023 on future trends for the 6G standard (Wang et al., 2023). Any new standard should ultimately deliver services and applications which enable both communities and countries to properly achieve the United Nations' Sustainable Development Goals (SDGs) (ITU-R, 2023; Matinmikko-Blue et al., 2021). However, the relatively weak economics of the telecom sector are also indicative of the need for 6G to be driven by commercial realities (static or declining revenue) and economic imperatives (reducing costs).

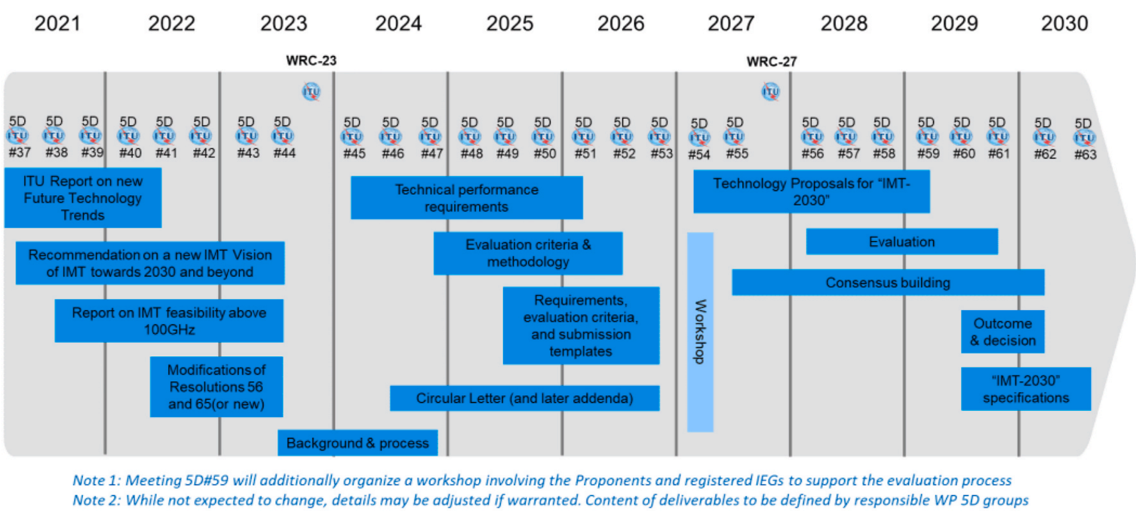

Fig. 2. Timeline of IMT towards 2030 and beyond (6G standardization) (ITU-R, 2023).

While it may take many years for new 6G technologies to come to fruition in real networks, a range of visions have already been identified, with standardization expected around the mid-to late- 2020s (Oughton & Lehr, 2022), as detailed in Fig. 2 based on delivery of IMT 2030 (International Telecommunication Union, 2023a). The usage scenarios outlined for 6G include Immersive Communication, Hyper Reliable and Low-Latency Communication, Massive Communication, Ubiquitous Connectivity, Artificial Intelligence and Communication, and Integrated Sensing and Communication (International Telecommunication Union, 2023b). Although we do not yet know what technologies 6G will consist of, a set of key areas are regularly raised including (i) open, flexible, programmable, and virtualized networks, (ii) carriers in the spectrum above 100 GHz and in the upper midband (7–24 GHz), (iii) integration of ML for network management and data plane adaptation, (iv) incorporation of multi-layered non-terrestrial connectivity, (v) enhanced positioning and sensing, embedded in the cellular network, and (vi) greater security and privacy (Alwis et al., 2021; Bonati et al., 2021; Dang et al., 2020; You et al., 2020). While 6G Key Performance Indicators (KPIs) are still emerging, they are likely to include a peak rate of 1 Tbps, latency of 0.1–1 ms, mobility of 500-1000 km/h and reliability of $1\text{-}10^{-5}$–$1\text{-}10^{-7}$ (International Telecommunication Union, 2023b).

Previous cellular standards have often seen new advances introduced in a certain generation, but finally perfected in subsequent generations. For example, 1G voice services only widely adopted in 2G, or 3G data services only widely adopted via 4G smartphone adoption. Consequently, many of 5G's more embryonic aspects, (e.g., flexible virtualized architectures) may only reach maturity in 6G (Yazar et al., 2021). The set of design challenges we will explore in this section is illustrated graphically in Fig. 3.

3.1. Further progress towards open, flexible and virtualized networks

With the introduction of flexible and virtualized networks in 5G, these characteristics will be both holistic and native to any future 6G standard. Moreover, the concept of an 'open' network will become dominant, where a Radio Access Network (RAN) is fully disaggregated into components connected via easily accessible interfaces, allowing a network operator to utilize multi-vendor interoperable components and closed-loop control for data-driven optimization (Garcia-Saavedra & Costa-Pérez, 2021; Polese, Bonati, et al., 2023; Polese, Cantos-Roman, et al., 2023), as detailed by O-RAN Alliance specifications (O-RAN Alliance, 2023). This is different from how network components have been implemented historically, where key parts of the RAN were deployed as monolithic black-boxes obtained from a limited number of network vendors (Gavrilovska et al., 2020). Essentially, this has held back RAN development hitherto due to limited reconfigurability, restricted coordination among network nodes, and expensive vendor lock-in, preventing optimized management of radio and spectrum resources (Bonati et al., 2020, 2021). Key policy issues associated with virtualized networks include resource sharing between competitors, O-RAN performance, interface standardization and protocol interoperability, and network security (as discussed in further detail later) (Bauer & Bohlin, 2022; Cerroni et al., 2020; Suraci et al., 2021).

3.2. Machine learning (ML) for network management

One emerging area which is gaining considerable traction in 6G is the integration of ML approaches to manage network decisions, to balance out improved QoS with other considerations (cost management, energy reduction, etc.) (Dogra et al., 2021; Mao et al., 2022). For example, the deployment of locally-trained models could enable mobile networks to dynamically and automatically configure network functionalities, including by forecasting changes in network loads and resource utilization, estimated channel conditions, network slicing demand, and security and encryption requirements (Alawe et al., 2018; Ali et al., 2020; Hossain et al., 2022; Mahmood et al., 2022; Perveen et al., 2021). However, despite other fields having readily implemented ML (e.g., in software,

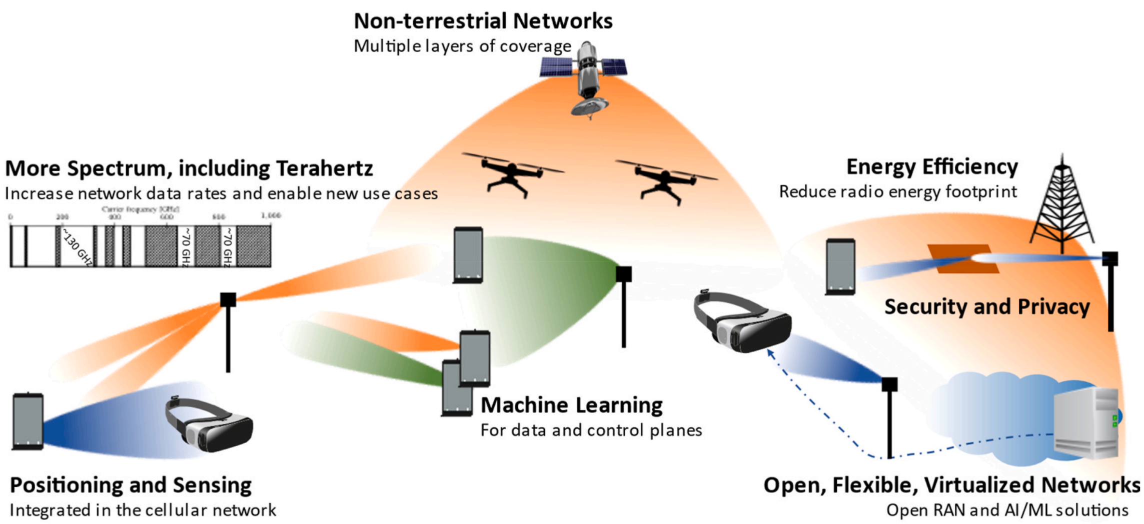

Fig. 3. Key 6G network aspects.

computer gaming etc.), the field of wireless communications is still quite some distance from delivering automatically configured cellular systems. This is due to a range of common challenges including (i) the lack of existing ML explain-ability and trustworthiness, (ii) dataset availability and generation, (iii) scalability and (iv) computation requirements (Alkhateeb et al., 2023; Guo, 2020; Kato et al., 2020). However, over the longer term new computing developments may enable vast improvements in computational efficiency for these techniques (Nawaz et al., 2019). Similarly, the Open RAN paradigm discussed above is seen as a key enabler of advanced RAN ML use cases (Bonati et al., 2023). A key policy issue associated with this technological development involves classic welfare economic concepts such as equity and efficiency (e.g., how are network resources allocated to users?), as algorithmic decision-making needs to be transparent, fair and accountable (Coyle & Weller, 2020; Feijóo et al., 2020; Kuziemski & Misuraca, 2020; Rodolfa et al., 2021). Indeed, there may also be many ethics questions associated with ML deployment.

3.3. Non-terrestrial connectivity

Early 5G developments focused exclusively on terrestrial cellular networks, although later releases have come to embrace this important communications domain (Lin et al., 2021). Indeed, 6G is likely to further this trend, with a focus on integrating non-terrestrial connectivity options into a hybrid architecture, with the goal of extending coverage. For example, there is ambition to bridge terrestrial and space-air–sea environments, often utilizing new developments in Uncrewed Aerial Vehicles (UAVs), High Altitude Platforms (HAPs) and satellites (Geraci et al., 2022; Shen et al., 2023). Non-terrestrial networks can provide cost-efficient wireless broadband services, particularly to those rural and remote users who live in hard-to-reach places (Ozger et al., 2023). Ideally, provision of broadband connectivity is desired to both end-users (especially those requiring high-speed global mobility), and to remote cell sites needing backhaul and trunk services. Although we still lack information on how non-terrestrial architectures will fully integrate to form integrated multi-layer networks (Geraci et al., 2023; Giordani & Zorzi, 2021). The key policy issues to consider range from spectrum allocation and coordination (especially as 6G shifts to more of a 3D network structure) (Polese, Cantos-Roman, et al., 2023), through to collision and space debris risks for drones and mega-constellations. Environmental impact assessment will also be important to avoid negative environmental externalities, including light pollution and emissions (Boley & Byers, 2021; Guyot et al., 2023; Osoro et al., 2023; Wilson, 2022).

3.4. Positioning and sensing

Improved radio-based positioning and sensing in 6G will provide enhanced situational information regarding the location of transmitters and receivers, including information on the status of the channel between transmitters and receivers (H. Chen, Chen, et al., 2022; Hong et al., 2022). Both larger spectrum bandwidths and massive arrays, combined with network densification, have made it possible to cost-effectively utilize radio-base positioning and sensing using the same cellular infrastructure, making this an integral part of recent and ongoing 3GPP standards, focusing on positioning active devices transmitting radio signals (Behravan et al., 2023). Policy issues may well arise around privacy and data collection, particularly the degree to which positioning and sensing may be used to estimate/capture personal identifiable information, and then the degree to which this data might be stored (Isaak & Hanna, 2018; Li et al., 2022; Ribeiro-Navarrete et al., 2021). As discussed later, the collection and use of sensitive data requires policy consideration, including (at a minimum) industry standards, and in some cases regulation.

3.5. More spectrum, potentially including the upper mid-band and Terahertz

The upper mid-band—FR3 in 3GPP terminology, roughly between 7 and 24 GHz— provides a good balance of coverage and spectrum, overcoming the spectral shortage of the sub-6 GHz bands while having favorable propagation and penetration relative to the mmWave bands (Kang et al., 2023). Realizing the full potential of these bands, however, will require coexistence with incumbent services including communications satellites (Testolina et al., 2024). Currently, there is also considerable research exploring the possibility of integrating Terahertz frequencies into 6G, given existing spectrum scarcity and the aim to deliver Terabit-per-second (Tbps) throughput (Akyildiz & Jornet, 2016; Polese et al., 2020; Shafie et al., 2022). Indeed, by doing so 6G is expected to take advantage of an order-of-magnitude more spectrum, including frequencies between 100 GHz and 10 THz (Chen et al., 2021; Tataria et al., 2021). By increasing the carrier frequency range relative to 5G, it is anticipated that 6G will be able to take advantage of much larger bandwidth for data transfer (Shafie et al., 2022). For example, in 5G the maximum carrier bandwidth for sub-6 GHz bands is 100 MHz, and 400 MHz for mmWave bands. In contrast, 6G is expected to have a theoretical maximum bandwidth which exceeds 400 MHz in the sub-6GHz band (even if this is very challenging in reality), and potentially 10–100 GHz bandwidth in the Terahertz bands (Tataria et al., 2022). As with any new generation of cellular technology, a key policy issue will be the (re)allocation spectrum to avoid interference, specifically considering passive incumbents of these frequency bands which tolerate no or very little interference. Additionally, given the hysteria associated with 5G millimeter wave spectrum, there should be careful attention paid to environmental health considerations, particularly how risks (if any) should be communicated to the general public (Chiaraviglio et al., 2021, 2023; Di Ciaula, 2018; Kostoff et al., 2020; Simkó & Mattsson, 2019).

3.6. Energy efficiency

Energy efficiency is another key research and development direction in 6G (J. Hu, Wang, & Yang, 2021; N. Hu, Wang, & Yang, 2021; Malik et al., 2022; Sodhro et al., 2021), with multiple pre-standardization activities that mention reducing the carbon footprint of future cellular networks and other sustainability metrics (Ahokangas et al., 2023; Matinmikko-Blue et al., 2023). An example is the NextG Alliance in the U.S., whose Green G working group has released multiple white papers that define key performance indicators toward improving network energy efficiency and achieving net-zero (Next G Alliance, 2023a; 2023b). Research on green networking has already received significant interest in the transition from 3G to 4G, without however making significant headways into commercial deployments. In 6G, there is more attention being placed towards these themes, which may help bridging the gap between proposed technological options and their commercial adoption, particularly if the architecture is designed around enhanced network sharing to reduce overall infrastructure duplication (Huang et al., 2019; Kumar & Oughton, 2023; Mukherjee et al., 2021). The policy issues of consideration here are how MNOs are potentially going to reduce energy consumption, meet the net-zero commitments many have signed up to, and do this within the 6G era where RAN capacity is expected to be expanded up to 1 Tbps (Han et al., 2021; X. Jiang, Han, et al., 2021; Mao et al., 2022, 2022; Verma et al., 2021). Governments may need to encourage additional environmental standards which address emissions reduction, as well implementing market-based incentives to decarbonize, with regulatory action saved as a last resort (Hoβfeld et al., 2023; Oughton et al., 2023; Zhang et al., 2023).

3.7. Security and privacy

Whereas security and privacy have always been imperative, these aspects of cellular systems have been rising up the list of important requirements for 6G. Early generations of cellular systems had multiple security and privacy issues, such as cloning, illegal physical attacks, eavesdropping encryption issues, and authentication and authorization problems (Wang et al., 2020). Later generations (e.g., 4G onwards) were then susceptible to Media Access Control (MAC) layer security threats (e.g., denial of service attacks, eavesdropping, replay attacks) and malware applications (e.g., viruses, tampering into hardware) (Porambage et al., 2021). Looking to the future, innovative parts of the 6G ecosystem open up new vulnerabilities (Abdel Hakeem et al., 2022; Mao et al., 2023). For example, the shift to O-RAN may increase attack surface size (Abdalla et al., 2022; Dik & Berger, 2023; Liyanage et al., 2023; Mimran et al., 2022). A key policy area therefore is the need for increased network security standards in the 6G era, both for MNOs, but also for actors involved in the supply chain of software, hardware and associated services. Special consideration should be given to vendors who may raise national security concerns around intelligence gathering (or intellectual property theft) (Mascitelli & Chung, 2019). From a privacy perspective, another key policy issue is the continual collection of personal data (particularly geospatial data), as all aspects of our lives are continually interfaced with the Internet (Mao et al., 2023; Nguyen et al., 2021; Sun et al., 2020). Governments needs to evaluate data collection, storage and use policies to ensure citizens and their basic rights are protected.

4. 4. Emerging Wi-Fi 7 and Wi-Fi 8 technical features

Wi-Fi is a key enabler of low-cost Internet connectivity. For example, home users can enjoy wireless services using their fixed broadband connection, which is increasingly a Fiber-To-The-Premises (FTTP) link. Whereas laptops and desktops were the key data producers a decade ago, Wi-Fi now underpins a wide array of smart home devices which can easily connect to the Internet and exchange data, from smart TVs, to doorbells, thermostats and surveillance cameras. Similarly at a workplace or café, Wi-Fi is an essential way for users to quickly and readily connect to a wireless Internet service. For example, there are projected to be three times as many Wi-Fi-enabled devices as people in the world, indicating the success of this technology (Cisco, 2020). Moreover, 3.8 billion Wi-Fi products shipped in 2022 (International Data Corporation, 2023), with 628 million public Wi-Fi hotspots forecast by 2023 (up from 169 million in 2018) (Cisco, 2020), highlighting the popularity of this set of standards.

One recent study estimating Wi-Fi's contribution to global economic value puts this at $3.3 trillion in 2021, potentially growing to $4.9 trillion in 2025, when considering a wide range of factors including business and consumer connectivity needs, technology research and development, spectrum access, and wider macroeconomic impacts (Wi-Fi Alliance and Telecom Advisory Services, 2021). This is not surprising given the data rates users can enjoy. For example, from the first generation of Wi-Fi throughput has increased from 1 Mbps to a theoretical peak of nearly 30 Gbps in the latest products, increasing by almost four orders-of-magnitude over the past two and a half decades, providing cheap, high-speed wireless services in unlicensed spectrum bands (Galati Giordano et al., 2023).

Two main organizations take a role in the development of Wi-Fi technologies. Firstly, the Institute of Electrical and Electronics Engineers' (IEEE) 802 Committee sets relevant standards for key Wi-Fi technologies, focusing on MAC and Physical Layer (PHY) protocols for Wireless Local Area Networks (WLAN) (IEEE 802 LMSC, 2023; IEEE 802.11, 2023). Secondly, the Wi-Fi Alliance is responsible for both ensuring Wi-Fi interoperability, security, and reliability by certifying Wi-Fi products, and also driving Wi-Fi adoption and evolution through thought leadership, spectrum advocacy and industry collaboration (Wi-Fi Alliance, 2023).

Wi-Fi 7 is currently being standardized, with finalization due by 2024, and deployment via unlicensed spectrum bands expected shortly after (Garcia-Rodriguez et al., 2021). Indeed, the commercially known product labelled Wi-Fi 7 is a new amendment with a range of key technical enhancements focusing on providing Extremely High Throughput (EHT), and thus higher data rates with lower latency. These enhancements include (i) use of 320 MHz of channel bandwidth and of higher modulation and coding schemes, (ii) a more efficient utilization of noncontiguous spectrum through multiple resource unit allocation, (iii) multi-band/multi-channel aggregation and operation, and (iii) more stringent QoS management, e.g., via restricted target wake time (Chen, Chen, et al., 2022). With a theoretical peak data rate of more than 40 Gbps, the Wi-Fi 7 standard is more than four times higher than its predecessor Wi-Fi 6, which has a peak speed just under 10 Gbps. As an overview of Wi-Fi's evolution, Table 1 details the most recent Wi-Fi standards, focusing on how current and future radio technical specifications compare.

When compared to Wi-Fi 6, which first introduced spectrum utilization of the 6 GHz band, Wi-Fi 7 improves performance by introducing a range of advanced features. These specifically include much larger channel bandwidths (up to 320 MHz) and 4K

Quadrature Amplitude Modulation (Au, 2023), together providing greatly enhanced throughput. Continuing from Wi-Fi 6, both Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Frequency-Division Multiple Access (OFDMA) will be available in Wi-Fi 7 (IEEE P802.11be, 2023), via similar OFDM symbol times, guard intervals and total symbol time, as well as continued utilization of Multi-User Multiple-In, Multiple-Out (MU-MIMO) techniques in both Up-Link (UL) and Down-Link (DL). Additionally, a key new feature of Wi-Fi 7 is the introduction of a Multi-Link Operation (MLO) framework where Wi-Fi devices are able to concurrently operate on multiple channels via a single connection (C. Chen, Chen, et al., 2022; Korolev et al., 2022). Analysis suggests that in ultra-dense and crowded scenarios when both available links are often busy, MLO attains the highest throughput gains because this approach can take advantage of multiple intermittent transmission opportunities, compared to traditional Single-Link Operation (SLO), with benefits also for lowering latency (Bellalta et al., 2023; Carrascosa-Zamacois et al., 2023).

As illustrated in Fig. 4, the current timeline for Wi-Fi 7 is to produce the final amendment by 2024. By the time 6G is released, the wireless industry will have moved onto the eighth generation of Wi-Fi technology (Wi-Fi 8), labelled Ultra High Reliability (UHR). At the stage of this review, the new Wi-Fi features being considered for the final standard include higher order MIMO, Hybrid Automatic Repeat Request (HARQ), Access Point (AP) coordination and potentially higher spectrum bands (45 GHz and/or 60 GHz , whose usage is being investigated by a dedicated IEEE 802.11 Integrated mmWave Study Group).

Wi-Fi 8 is set to prioritize UHR as its key characteristic (Galati Giordano et al., 2023), as opposed to previous standards which focused on increasing peak throughput. Indeed, delivering ultra-low deterministic latency is a key challenge for next generation Wi-Fi technologies (Cavalcanti et al., 2022). As detailed in Fig. 4, Wi-Fi 8 has a target standardization cycle ending in 2028, with the UHR Study Group already established in July 2022 focusing on defining the protocol functionalities for future products (IEEE Standards Association, 2023). The four key areas of focus include (i) improved throughput at lower Signal-to-Interference-plus-Noise (SINR) ratios, (ii) reducing tail latency and jitter, (iii) enhanced spectral reuse, (iv) greater power savings and peer-to-peer operations (Galati Giordano et al., 2023; Reshef & Cordeiro, 2022).

Given the interest in ML, a new IEEE 802.11 topic interest group has been established focusing currently on three key use cases, including (i) feedback compression of Channel State Information (CSI) using ML, (ii) improved sharing of supervised, unsupervised and reinforcement learning ML models, and (iii) ML distributed channel access (Au, 2023; IEEE 802.11 AIML Topic Interest Group, 2023). An ML approach may also be key to implement some of the multi-AP coordination mechanisms envisioned for Wi-Fi 8.

Business model innovation is also taking place, for example, via the Wireless Broadband Alliance OpenRoaming initiative, which is a roaming federation to enable automatic and secure Wi-Fi connectivity for all providers who join (akin to the Eduroam approach for university campuses). The aim is to allow users of one network to openly roam on to any network managed by a federation member (providing an agreement is in place), reducing nomadic Wi-Fi activity, and eliminating the need to acquire separate login details at each new premises (Wireless Broadband Alliance, 2023). Should such a system be implemented there would be seamless handoff from an outdoor cellular connection to an indoor WBA-certified Wi-Fi connection, providing uninterrupted connectivity. Given the complexity (and thus cost) of trying to serve indoor locations from infrastructure asset located outdoor, resolving this hand-off process could have a significant impact on user experience, and is an area policy makers should take note of.

Finally, an emerging major policy issue for Wi-Fi is around spectrum allocation, and the necessary availability of a substantial quantity of unlicensed spectrum, particularly at 6 GHz. For example, severe congestion in the 2.4 and 5 GHz bands means users desire improved QoS for key use cases (video streaming, gaming etc.) (Dogan-Tusha, Rochman, et al., 2023; Dogan-Tusha, Rochman, et al., 2023). It is therefore imperative that Wi-Fi 7 and future generations have plentiful access to contiguous spectrum at 6 GHz, so that users can benefit from channel bandwidths of up to 320 MHz (Akhmetov et al., 2022). There are concerns that only partial allocation at 6 GHz equates to only a single 320 MHz channel, or three 160 MHz channels, failing to deliver on desired consumer experiences, especially augmented/virtual reality (Mehrnoush et al., 2022).

5. 5. Comparing key features of 6G and Wi-Fi 7/8

In this section, the different cellular and Wi-Fi technologies are compared based on the key engineering and economics aspects, as summarized in Table 2. Important policy issues are also considered.

Unsurprisingly, the peak data rates of these new technologies are targeted to increase, with 6G aiming to theoretically deliver 1

Table 1
Technical capabilities across legacy and current wireless standards.

Features	Wi-Fi 4 (802.11n)	Wi-Fi 5 (802.11ac)	Wi-Fi 6/6E (802.11ax)	Wi-Fi 7 (802.11be)	Wi-Fi 8 (speculative)
Peak data rate	600 Mbps	7 Gbps	9.6 Gbps	≤46.4 Gbps	>46.4 Gbps
Carrier Frequency (GHz)	2.4, 5	5	2.4, 5, 6	2.4, 5, 6	2.4, 5, 6 at a minimum
Channel Bandwidth (MHz)	20, 40	20, 40, 80, 160	20, 40, 80, 160	Up to 320	>320
Frequency multiplexing	OFDM	OFDM	OFDM and OFDMA	OFDM and OFDMA	OFDM and OFDMA
OFDM symbol time (μs)	3.2	3.2	12.8	12.8	12.8 at a minimum
Guard interval (μs)	0.4, 0.08	0.4, 0.8	0.8, 1.6, or 3.2	0.8, 1.6, or 3.2	0.8, 1.6, or 3.2
Total symbol time (μs)	3.6, 4.0	3.6, 4.0	13.6, 14.4, 16.0	13.6, 14.4, 16.0	13.6, 14.4, 16.0
Modulation	≤64-QAM	≤256-QAM	≤1024-QAM	≤4096-QAM	>4096-QAM
MU-MIMO	N/A	DL	DL and UL	DL and UL	DL and UL
OFDMA	N/A	N/A	DL and UL	DL and UL	DL and UL
MIMO	4x4	8x8	8x8	8x8	16x16

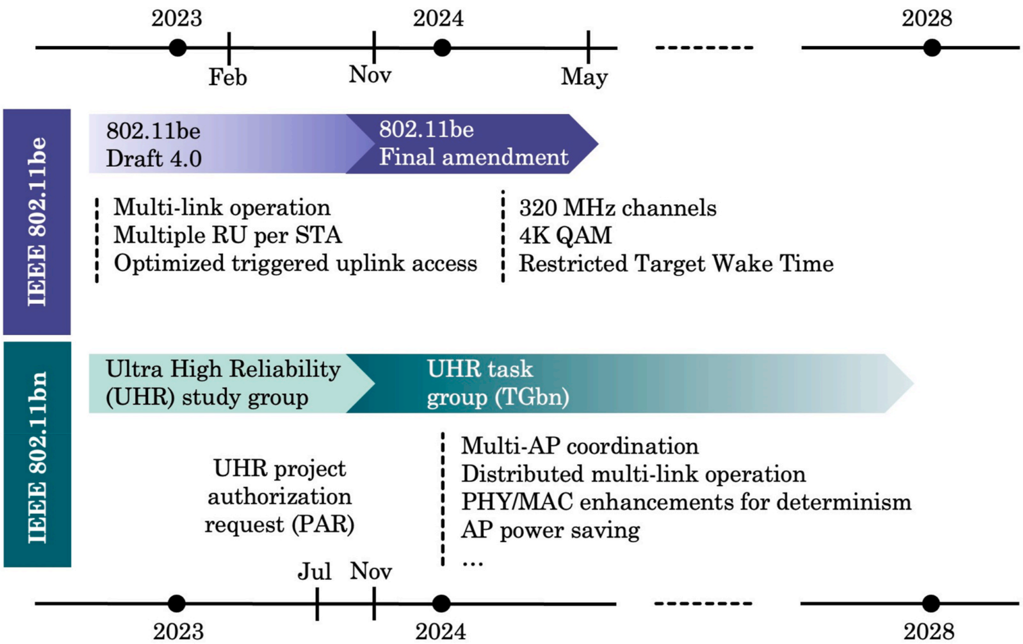

Fig. 4. Timeline for Wi-Fi 7 and 8 (Galati Giordano et al., 2023).

Tbps, Wi-Fi 7 theoretically aiming for 46 Gbps, and Wi-Fi 8 theoretically aiming to exceed 46 Gbps. One key caveat to these peak speed targets is the cell size, as a Wi-Fi hotspot may only aim to serve up to 50 m indoor (thus, a single household), and 300 m outdoors, compared to cellular which has a range of anywhere from 300 m for a small cell, up to tens of kilometers for larger cells (and therefore targets serving at least one order-of-magnitude more users per cell). Within 6G, and the target of providing global coverage via non-terrestrial and satellite networks, cell sizes could rise to 100s of kilometers. Another caveat to these targets is that they are highly dependent on spectrum allocation and the frequencies in use. For example, a recognized long-term issue with cellular is attempting to take an Outdoor-to-Indoor (O2I) approach, due to significant building penetration loss (Rappaport & Sandhu, 1994; Shakya et al., 2022). This makes it challenging to solely serve indoor locations, especially with limitations on low frequency spectrum, and a greater emphasis in 6G on ever higher frequencies (e.g., Terahertz). Indeed, a key policy issue here is therefore how spectrum will be allocated moving forward. The cellular industry is advocating for more 6 GHz spectrum, despite the large frequency allocations that have already taken place elsewhere (e.g., 3.5 GHz). However, additional unlicensed spectrum is essential for meeting growing indoor traffic demand and QoS, which can be met via newer Wi-Fi standards (thanks to channel widths of 320 MHz). New datasets can help us reassess current demand against future allocation of spectrum resources.

Although considerable research emphasis is being placed on integrating much higher frequency spectrum into 6G (Alsaedi et al., 2023; J. Hu, Wang, & Yang, 2021; Saha, 2020), there is no clear indication that Wi-Fi intends to follow this path. While the benefit of taking this approach for cellular systems may be to access much larger spectrum bandwidths, there are also significant downsides, in terms of poor propagation properties and the associate cost added to devices (along with increasing energy consumption). Telecommunication regulators also need to be cognizant of public concerns around health impacts (whether warranted or not), as well as considering that MNOs are still struggling to utilize their millimeter wave spectrum holdings.

Business models are also worth consideration, which represent the way wireless companies offer value to target customers via heterogenous engineering-economic cost configurations. Traditionally, mobile companies offer either a monthly subscription-based or a pay-per-use service which is likely to continue (Banda et al., 2022). However, there is a growing range of services based on free or temporary non-subscription models, particularly enabled by Embedded-SIMs (eSIMs), which begin to complement the traditional pre- or post-pay cellular subscription models. Whereas Wi-Fi will continue to utilize a low-cost "plug-and-play" approach which "piggy-backs" on a paid fixed broadband subscription (as geographic coverage will remain patchy) (Yang et al., 2022).

An area of growth is private cellular networks where commercial (or other) entities purchase both the relevant spectrum and the necessary equipment to provide connectivity services. Currently this is an expensive endeavor which may become simpler (and cheaper) in the future. Yet for now, this approach keeps this type of connectivity the preserve of larger companies with the investment capital (and associated profit margins) to support bespoke network needs. For example, private networks represent less than 1% of the current 5G market (FitzGerald, 2023). Certainly, regulators who are yet to allocate private local spectrum licenses should consider exploring this option, providing proper interference mitigation protocols are in place.

In terms of access equipment, cellular smartphones continue to be expensive consumer devices at the very top end of the device price distribution (premium smartphones >US$550), and new 6G handsets are likely to begin well over US$1200. In comparison, Wi-Fi-enabled devices can be purchased from US$100 upwards, making this a more affordable way to connect wirelessly (should a fixed broadband connection already be available). The cost difference arises from state-of-the-art cellular chipsets providing more

Table 2
Prospective comparison of 6G and Wi-Fi 7/8 potential features.

Category	Variable	6G	Wi-Fi 7	Wi-Fi 8 (speculative)
Technical	**Peak data rate**	Target of 1 Tbps	Up to 46.4 Gbps	>46.4 Gbps
Technical	**MU-MIMO**	Ultra-massive MIMO	8x8	16x16
Technical	**Coverage range**	<50 m Terahertz, 100–300 m mmWave small cells, >10 km macro cells, global satellite coverage	<50 m indoor, up to 300 m outdoor	<50 m indoor, up to 300 m outdoor
Technical	**Carrier aggregation**	Yes	Yes, via multilink operation	Yes, via distributed multilink operation
Technical	**Inter-cell interference**	Controlled	Controlled within isolated networks	Controlled in dense environments via AP coordination
Technical	**Channel access scheme**	OFDMA	OFDMA	OFDMA
Spectrum	**License type**	Mostly licensed	Unlicensed	Unlicensed
Spectrum	**General bands**	Low, mid, high, very high	Low and mid	Low and mid. High band operation targeted by the 802.11 Integrated mmWave Study Group (IMG).
Spectrum	**Specific frequencies**	<6 GHz, 24–30 GHz, 100 GHz to 10 THz	2.4 GHz, 5 GHz, 6 GHz	2.4 GHz, 5 GHz, 6 GHz. 45 and 60 GHz targeted by the IMG.
Spectrum	**Maximum channel bandwidth**	400 MHz < 6 GHz and 10–100 GHz > 100 GHz	Up to 320 MHz	≥320 MHz
Business model and cost	**Revenue model**	Free/temporary (via eSIM) versus pre/post-pay billing for data services	Either a service, 'free', amenity, or pure WLAN without external connection	Either a service, 'free', amenity, or pure WLAN without external connection
Business model and cost	**User equipment price**	Higher (e.g. premium smartphones retail for >$550)	Lower (e.g. Wi-Fi only devices can retail from >$100)	Lower (e.g. Wi-Fi only devices can retail from >$100)
Business model and cost	**Public versus private**	Traditionally publicly provided by an MNO/MVNO	Traditionally provided via a private fixed broadband subscription. Enterprises have privately managed services	Traditionally provided via a private fixed broadband subscription. Enterprises have privately managed services
Business model and cost	**Chip/modem cost**	Higher (e.g., >$100 for a 5G system-on-a-chip at launch)	Lower (e.g., ~$10–20 for a Wi-Fi 6 chipset at launch)	Lower (e.g., ~$10–20 for a Wi-Fi 6 chipset at launch)
Business model and cost	**Data cost**	eSIM enables free/temporary through to pre/post pay	Free ('piggybacks' on fixed broadband)	Free ('piggybacks' on fixed broadband)
Business model and cost	**Energy consumption**	Higher (with newer cellular generations using >2-3x energy)	Lower (≥50% more energy efficient than cellular)	Lower (≥50% more energy efficient than cellular)
Installation and skills	**Deployment approach**	Controlled and managed	Uncontrolled and mostly unmanaged	Uncontrolled and mostly unmanaged

functionality, leading to the necessary implementation of Reduced Capability (RedCap) devices to improve affordability (Moloudi et al., 2021; Veedu et al., 2022). This is also reflected in the style of provision, with cellular networks usually provided publicly by a private MNO, whereas Wi-Fi is often provided privately by the owner of each premises. Thus, this deployment approach is expected to continue to be largely centrally controlled in 6G, with the exception that the technology may make use of unlicensed spectrum should it be available, whereas newer Wi-Fi generations will continue to take a decentralized, uncoordinated approach to deployment, with private users placing their devices wherever they choose on their private premises. Policy makers do need to put proper thought to the accessibility and digital divide aspects of 6G and Wi-Fi 7/8, so that these technologies can be used to reduce disparities, not enhance them.

Unfortunately, we still lack comprehensive data to draw key conclusions on the energy intensity, emissions, and broader environmental impacts of different broadband technologies (Pihkola et al., 2018), such as cellular versus Wi-Fi services. In general, the available evidence suggests that Wi-Fi is >50% more energy efficient than cellular 4G LTE (Zou et al., 2017). When we consider newer technologies, such as 5G, empirical measurement exercises suggest this escalates power consumption by 2−3x when compared to legacy 4G (Xu et al., 2020). Video streaming is a particularly intensive activity which dramatically increases cellular chipset power consumption, thus the savings made by switching from streaming video over a macrocellular network, to a local indoor cell, can reach a 30–73% reduction (Cao et al., 2013; Yan et al., 2019). This is not surprising when FTTP is one of the most energy efficient broadband technologies and can be readily combined with a Wi-Fi router, using only 31% of the energy consumed by other wireless approaches (Europacable, 2022). Future research needs to undertake full Lifecycle Impact Assessment of 6G, Wi-Fi 7 and Wi-Fi 8 to help provide policy decisions with metrics on energy and emissions impacts (e.g., for spectrum allocation).

Despite significant cellular hype (e.g., 5G or 6G), empirical evidence suggests that Wi-Fi outperforms this group within local indoor environments (for an Outdoor-to-Indoor approach), with respect to both metrics on throughput and latency, and the provision of superior uplink performance (Hoppari et al., 2021). At this time, it does not seem as if this trend will change based on the technologies proposed, given that cellular systems often face challenges when taking an Outdoor-to-Indoor approach to providing wireless services, as radio waves propagated from the cell site can suffer from blockages by trees, steel framed buildings, and increased insulation standards to boost building energy efficiency. Inevitably, this means continued coexistence and collaboration in unlicensed bands, much like with previous generations (Oughton et al., 2021), and also potentially healthy competition in the technologies used to provide wireless broadband connectivity (Sathya, Kala, et al., 2020; Sathya, Mehrnoush, et al., 2020).

6. Discussion

In this discussion we return to the research questions previously articulated in the introduction of this article, with the first research question articulated as follows:

What do current and future demand trends indicate about the future of wireless broadband?

Whereas the last decade was characterized by growing smartphone adoption, intensive growth in video consumption and uptake in new applications, the fact that many countries are now effectively reaching "peak smartphone" is shaping the future needs of wireless broadband. For example, declining mobile traffic growth rates have decreased from a high of 50–100% annually through the 2010s, down to a more modest 20–25% annually (Analysys Mason, 2023a). The ITU's global mobile traffic forecast of >257 GB monthly per user is based on an annual growth rate of approximately 35% up to 2030 (ITU-R, 2015). However, if the growth rate falls to only 20% annually, starting from a base of 20 GB per user in 2023 (Ericsson, 2023), this equates to only 76 GB monthly by the end of the decade. Whereas, for 10% annual growth this would be only 32 GB monthly per user.

Device composition forecasts are also highly interesting. For example, smartphones are expected to only modestly grow from 7.8 billion devices in 2022, up to 8.4 billion by 2028. Therefore, while devices overall will increase from roughly 23 billion in 2022, to 46 billion in 2028, the device share of smartphones will decrease from 34% to 19%. In contrast, the proliferation of short-range IoT devices, frequently utilizing Wi-Fi, is forecast to increase from 10.2 billion in 2022, up to 28.7 billion in 2028 (equating to an increase in the overall device composition of 44% in 2022 to 63% in 2028). Additionally, empirical data currently indicates that users spend as much as 87% of their time indoors (70% at home), and connected to Wi-Fi two thirds of the time, highlighting the importance of unlicensed spectrum use.

Where do the similarities between proposed 6G technologies and future Wi-Fi IEEE 802.11 generations, such as Wi-Fi 7 and 8, begin and end, and how do they differ to previous standards?

With both cellular and Wi-Fi technologies continuing to vie for dominance as the main way to access broadband services, it is unsurprising that there are commonalities in the properties of these two groups. For example, both have focused on increasing the provided throughput for each generation to ensure future traffic demands can be met, often relying on increasingly higher-order MIMO combined with wider spectrum bandwidth (which has been a fairly common approach for many generational upgrades). However, there have also been continual efforts by cellular technologies in recent years to reduce latency and provide greater reliability, beginning in 5G with URLLC and progressing to 6G. Consequently, Wi-Fi technologies are also focusing on new standards which develop innovative ways of providing increasingly reliable broadband services (e.g., Wi-Fi 8), with guaranteed lower latency rates (which is a serious challenge for either technology). One similarity is that cellular generations in recent years have also been attempting to take advantage of unlicensed spectrum, which has traditionally been the preserve of Wi-Fi technologies, again emphasizing a hybridization between the two groups. In the opposite direction, newer Wi-Fi generations with Automated Frequency Coordination are starting to be granted access to use licensed bands on an unlicensed basis, in specific locations. Similarly, Wi-Fi systems are now including scheduled spectrum access schemes, which are typical of cellular systems, as they allow for higher service level guarantees (e.g., for low latency).

However, in contrast there are multiple developments where the two technology groups have gone in separate directions. A prime example is the aim in 6G to provide global coverage utilizing non-terrestrial and satellite approaches, which is one domain newer Wi-Fi standards are understandably avoiding. In many ways this proposal in 6G is complementary to cellular technology's existing competitive advantage of providing wide-area connectivity utilizing the many advantages of licensed spectrum. Therefore, this move is logical, given the user desire to access seamless, reliable, mobile connectivity (and the current challenges faced by MNOs in providing coverage).

There are also a set of unchanged factors from previous generations. For example, the business model of delivery for each technology looks generally set to continue on the current path. Cellular 6G services will largely be provided by private companies to public users, yet with increased business innovation in subscription offerings enabled by eSIM developments (including free or temporary subscriptions, complementing traditional pre/post-pay options). In contrast, the Wi-Fi 7 and 8 standards seek to build on their past success of being a very low-cost way to provide local wireless broadband services within homes, businesses, and offices, deployed in tandem with existing fixed (increasingly full fiber) broadband connections (and which may increasingly make use of federated OpenRoaming).

What are some of the key policy issues associated with these two technology groups over the next decade?

This paper outlines a range of emerging policy issues pertaining to both new cellular and Wi-Fi technologies. These include changes in global device composition, privacy and data collection, equity and efficiency implications of machine learning, negative environmental externalities from new satellite constellations, environmental health considerations around the use of higher frequency spectrum, network security, and energy efficiency and net-zero commitments. However, the three key issues that have emerged which we emphasize are as follows.

Firstly, much has changed over the past decade in how we utilize wireless broadband, and this has important repercussions for measuring usage. Policy makers need to collect new datasets which truly represent real usage for different wireless broadband technologies (e.g., for cellular and Wi-Fi), especially for both indoor and outdoor users. We know that at least 70% of mobile data traffic takes place indoor, maybe more. Before considering how best to serve this traffic, we need to be able to measure effectively how much data consumption takes place *where* and *how*. For example, the introduction of mass market Fixed Wireless Access has complicated this picture, as this static indoor traffic is often consolidated into mobile data consumption (skewing what we consider to be wide-area traffic generated by users on the go). Should indoor data demand be growing at a greater rate than outdoor, it would suggest spectrum allocation to unlicensed usage is more pertinent, due to the benefits of Wi-Fi outlined in this paper. Gaining *ex-post* evidence on usage is absolutely essential for successful spectrum management decisions over the next decade, as it helps regulators understand how consumers are really utilizing different wireless broadband technologies, leading to our next major issue.

Secondly, plateauing cellular data demand has strong implications for revenue generation, and thus for spectrum allocation. Past ITU forecasts expecting mobile traffic per subscription of 257 GB by 2030 appear increasing less likely, with recent empirical data indicating decelerating mobile traffic growth. We have already pointed to the issue of including Fixed Wireless Access into existing mobile traffic data and the problems this can cause. Indeed, if cellular traffic by mobile users is indeed slowing (as there is only so much video one can consume on the go), it would be prudent to make more spectrum available to static indoor technologies (e.g., Wi-Fi 7, private cellular connectivity, and beyond), especially in urban areas. We know cellular technologies struggle to provide service here due to an outside-to-in approach, and commitments to net-zero by many countries will only see this worsen as building insulation levels increase. Therefore, once telecommunication regulators have the new datasets capable of identifying realistic usage by technology, there needs to be an urgent reassessment of current demand and spectrum allocation.

Finally, a major emerging issue is how the telecommunication sector decarbonizes, with many regulators now increasingly adding this as a key interest area. Ofcom's recent Connected Nations report addresses climate change and telecoms networks, emphasizing its interest in the long-term sustainability of the telecom sector (Ofcom, 2024). Telecommunication regulators know they need to be addressing sustainability, but are still trying to seek this path. Currently, we have a very weak literature on the energy and emissions impacts of cellular versus Wi-Fi technologies, with no readily available comparative studies in the peer-reviewed literature. We believe spectrum management decisions need to be accompanied by Lifecycle Impact Assessment metrics on energy demand and emissions for different wireless broadband technologies, to help this angle be factored into policy decisions. Indeed, policy should actively encourage technologies which reduce energy consumption and environmental emissions. By doing so, we can ensure government is sending the market signals that it favors sustainable network architectures, particularly given the commitments they have signed up to via the Paris Climate Accords.

To end this discussion, it is worth pointing out that in any analysis there are limitations of the approach and thus areas of necessary future research. Over the coming years the technologies prospectively considered here will become standardized, providing greater certainty over realistic KPIs, use cases and technological approaches. Moving forward, it will become easier to undertake more formal quantitative comparative analysis of the various technology architectures which is a key limitation of this more qualitative appraisal. Indeed, as relevant spectrum bands are identified, along with likely bandwidths, spectral efficiencies etc. there will be improved opportunities to quantitatively assess the implications for capacity, coverage, cost, energy consumption and emissions, and other relevant metrics of interest.

7. Conclusions

This paper has undertaken a prospective assessment of the key technologies emerging in the peak smartphone era for providing wireless broadband connectivity, including a comparative evaluation of 6G, and the Wi-Fi 7 and 8 standards. Importantly, we raised a range of emerging policy issues and discussed these with reference to telecommunication regulators and the management of scarce spectrum resources over the next decade. We emphasize three important conclusions which successful policy will need to address over the next decade, and implore relevant institutions to begin tackling immediately.

Firstly, this paper highlights the changing demand context the telecommunication sector faces. The driving forces of data growth have changed from the 2010s, with quarterly smartphone sales declining, and annual data growth rates diminishing to ~20–30%. However, we need more data to understand this context, as current datasets are not up to standard to inform effective policy decisions on spectrum allocation for 6G, Wi-Fi 7 and Wi-Fi 8. As analyzed in Section 2, we often can only undertake a highly aggregated review of demand. Decision makers need a true understanding of real usage for indoor and outdoor devices utilizing different wireless broadband technologies. This includes separating out static Fixed Wireless Access from users that are truly *mobile*.

Secondly, while there is increasing awareness that cellular data growth appears to be slowing, it is not yet clear that all telecommunication regulators have understood the ramifications of this for the next decade of policy making, especially with regard to 6G, Wi-Fi 7 and Wi-Fi 8. Past ITU forecasts of each subscriber consuming more than 257 GB of data per month seem less likely to come to fruition based on recent empirical data. Therefore, there needs to be an urgent policy re-evaluation of current demand for, and allocation of, spectrum resources. Such an activity can be supported by the collection of new datasets raised in our first conclusion.

Finally, our third conclusion pertains to the need for telecommunication regulators to support government commitments in the Paris Climate Accords. New research is needed which utilizes Lifecycle Impact Assessment for different wireless broadband network architectures (e.g., 6G versus Wi-Fi 7 and Wi-Fi 8), to provide spectrum managers with metrics on energy and emissions impacts. We are not yet aware of such comparative metrics within the peer-reviewed literature, but recognize the importance of this endeavor. Researchers examining this issue have the opportunity to establish new methods for undertaking this activity, setting future standards for this practice in telecommunication regulators globally over the next decade, especially with reference to 6G, Wi-Fi 7 and Wi-Fi 8.

CRediT authorship contribution statement

Edward Oughton: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Giovanni Geraci:** Writing – review & editing, Methodology, Conceptualization. **Michele Polese:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Vijay Shah:** Writing – review & editing, Conceptualization. **Dean Bubley:** Writing – review & editing, Validation, Conceptualization. **Scott Blue:** Writing – review & editing, Validation, Project administration, Methodology, Funding acquisition, Conceptualization.

Data availability

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