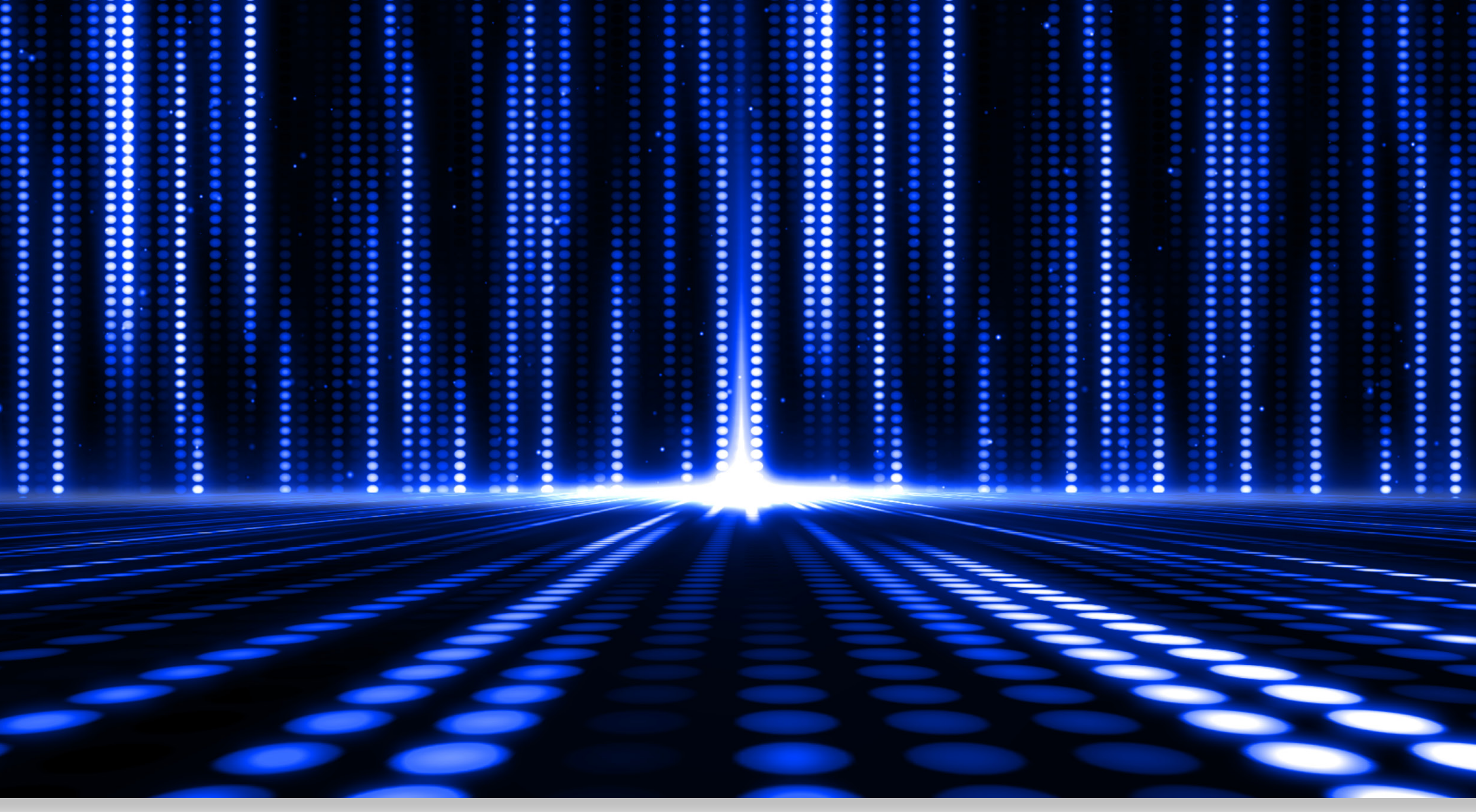
Qualcomm

December 2022

6G

Vision, market drivers, and research directions on the path to 6G

How Qualcomm is setting the stage with 5G Advanced now for 6G in 2030 and beyond



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Executive Summary

Today, the fifth generation (5G) of mobile networks is being commercially deployed worldwide. The momentum continues to grow as expanding coverage and capacity unlock a rich array of new 5G devices and services. In parallel, 5G technologies are evolving into 5G Advanced, a second wave of technology innovations that can deliver on the full promise of 5G. The inaugural release of 3GPP Release 18 will establish the technology roadmap for 5G Advanced, including advanced technologies that will fuel future wireless enhancement and further expansion.

While the advancement of wireless technologies is continuous, there is a natural cadence of a new mobile generation emerging approximately every ten years. The goal of the next-generation platform is to bring major leaps in performance and efficiency that are not currently achievable. As 5G Advanced evolves, an early vision for 6G is emerging. Besides garnering the latest technology advancements and continuing the quest to address economic growth and societal sustainability goals, 6G will also bring new possibilities for enhanced experiences and use cases.

6G will be more than just a new radio technology. It is envisioned as a smart, wireless communication fabric that connects people and things, and also as a platform that can sustain the continued expansion of the connected intelligent edge. Beyond enhanced communication capabilities, 6G will also fully unleash the synergistic potential of artificial intelligence (AI), integrated sensing, and novel green technologies. 6G will build on the evolutionary, technical foundation established by 5G Advanced and usher in revolutionary technologies to become the unified innovation platform for 2030 and beyond.

This paper describes the role that Qualcomm is playing in preparing the evolution of 5G Advanced into 6G. Readers will learn about our work on six research vectors in mobile innovation:

1. Enabling technologies for the merging of physical, digital, and virtual worlds

2. AI-native, end-to-end communications

3. Scalable network architecture

4. Air interface innovations

5. Expanding into new spectrum bands

6. Communication resiliency

Today, we are actively researching and collaborating with technology leaders across the mobile and broader vertical ecosystem. Our goals are to fully deliver on the vision of 5G Advanced and make 6G a reality in 2030 and beyond.

Our vision: A smarter society enabled by the connected intelligent edge

At 8 billion and counting, the world's mobile connections now outnumber its people[1]. That statistic underscores the importance of mobile communication in everyday life and in continued progress through expansion into new geographic regions, use cases, and vertical industries.

[1] "The Mobile Economy 2022" by GSMA, https://www.gsma.com/mobileeconomy/. (Does not including cellular IoT.)

More mobile connections bring an increased level of intelligence, but they also mean a greater need to scale. For mobile to address society's existing and future requirements, intelligence must be efficiently distributed end to end across the system, from the central clouds to edge clouds, and to smart devices such as mobile phones, computers, vehicles, robots, wearables, and machines. This will fuel the growth of the connected intelligent edge, consisting of both distributed processing in the networks and intelligence on devices (see Figure 1). The connected intelligent edge portends user benefits such as enhanced privacy, greater reliability, and lower latency. It also promises network benefits such as more efficient use of bandwidth.

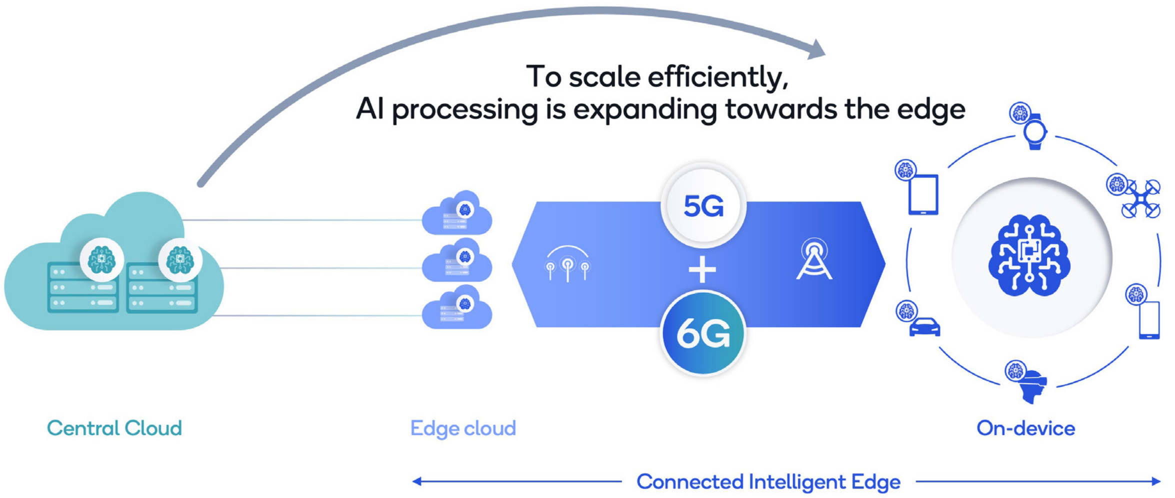


Figure 1: The connected intelligent edge

To address society's requirements for mobile communication, the connected intelligent edge will furnish the technology platform to scale intelligence across the cloud and the network to a wide range of devices. The mobile platform of the future comprises foundational technologies such as advanced wireless connectivity, efficiently distributed computing, ubiquitous AI, and high-resolution sensing. In accordance with our vision, we are actively researching, building, and commercializing those technologies to help establish a solid foundation for future innovation.

From 5G to 5G Advanced, and the transition to 6G

With the first three releases (3GPP Releases 15, 16, and 17) of the 5G standards completed, the process of connecting virtually everyone and everything that we envisioned is well underway. The globally standardized technologies for the broad range of 5G devices and services are being deployed at a much faster pace than in any previous generation[2]. As shown in Figure 2, 5G is expected to transform our society and enable more than $13.1 trillion in global sales activities by 2035[3].

Figure 2: 5G is expected to deliver on the full economic potential promised by its original vision

[2] Comparing initial-year results: LTE with 4 operators and 3 OEMs vs. 5G with 60+ operators and 40+ OEMs
[3] "The 5G Economy in a Post-COVID-19 Era," an independent study from IHS Markit, commissioned by Qualcomm Technologies, Inc.

5G Advanced will deliver on the 5G promise

Today, the evolution of 5G Advanced is just beginning, bringing a second wave of innovation. Qualcomm and a worldwide ecosystem of 3GPP companies are actively working on 5G NR Release 18, the inaugural standard release of 5G Advanced that will improve existing use cases as well as extend 5G into new devices, services, and industries. 5G Advanced will drive further evolution of mobile broadband and expansion into new verticals, with improvements and new features (see Figure 3). At the same time, our longer-term research looks beyond Release 18 to innovations in subsequent releases of 5G Advanced. This work is laying the technology foundation for 6G, anticipated to support use cases requirements in 2030 and beyond.

Figure 3: 3GPP Release 18 kicks off the 5G Advanced evolution

6G transition will leverage 5G Advanced technologies and deployments

Every new mobile generation is expected to build on the technology foundation of the previous generations. This was the case with 5G, where LTE Advanced Pro (Release 13, 14 and beyond) was not only an essential component of the 5G technology platform, but its broadly deployed networks also anchored the initial 5G rollout.

As we start to envision what's to come after 5G, one big goal is to minimize the impact of introducing a new radio access technology (RAT). The transition from LTE Advanced Pro to 5G, for example, required upgrading 4G equipment to coexist with 5G. For the transition from 5G Advanced to 6G, we consider how to use cloud-native solutions like service proxies to limit the impact on legacy deployments without affecting interoperability.

Naturally, industry and users alike will expect 6G to coexist, complement, and augment existing 5G deployments for a smooth transition in all types of fixed and mobile use cases. It is envisioned that 6G will also make the most out of existing infrastructures and spectrum by sharing cloud, compute, and storage resources. For instance, for hosting the network function at the edge through co-siting and spectrum sharing with multi-RAT spectrum sharing (MRSS) — similar to dynamic spectrum sharing (DSS) during the transition to 5G.

Also, 6G is expected to be AI-native, incorporating AI by design. That opens up the opportunity to bring more intelligence and coordination to radio access networks (RANs) and to the end-to-end system. More intelligent control will improve the performance, coverage, and efficiency of these broader deployments from day one.

Standardization timeline

3GPP is the global standards body in which each generation of mobile technology is established. As shown in Figure 4, current expectations are that official specifications work on 6G standards will start around 2025. It will focus on study items for use cases and foundational aspects such as waveforms and channel coding, as well as AI, sensing, and how to address architecture evolution and migration. Next come the earliest work items leading to the first set of 6G specifications. To support commercial launches beginning in 2030 (approximately ten years after 5G), the first 6G standard will need to be completed and ratified by early 2028. Trials and interoperability testing must be complete before commercial launch.

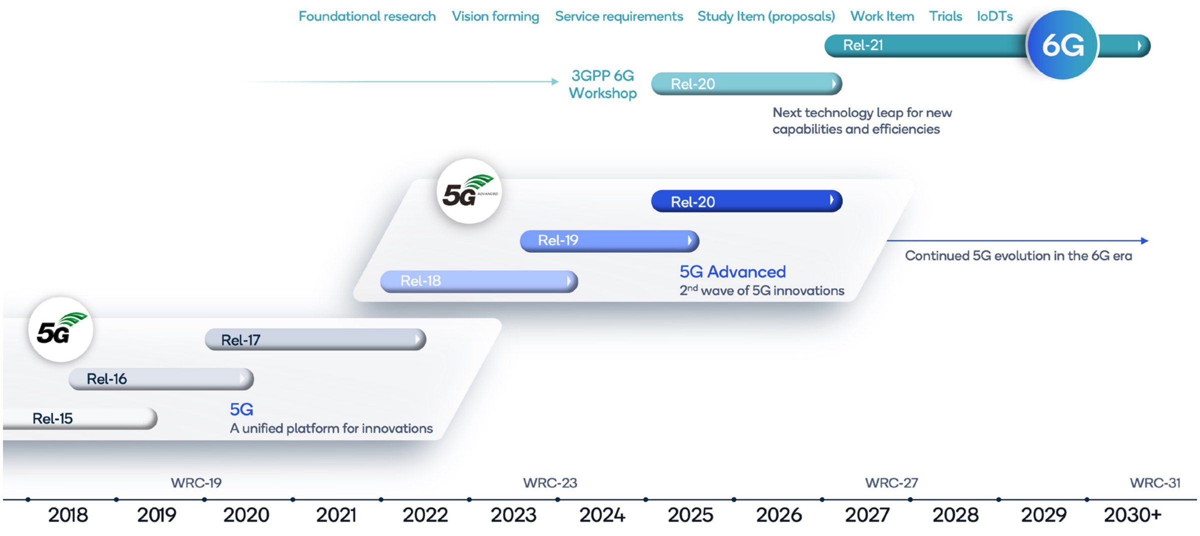


Figure 4: 5G Advanced on the path to 6G

Global initiatives driving toward 6G

Although specifications development and commercialization are some years away, numerous regional initiatives are already underway to drive leadership of 6G technology. They include the Next G Alliance in North America, Hexa-X in Europe, and several more in Asia (see Figure 5). In addition, many academic communities are focusing their research on enabling 6G and presenting at annual events like the Brooklyn 6G Summit and 6G@UT Forum. These regional initiatives are kickstarting the discussions around next-generation technologies that will feed into global 6G standardization efforts. They will fuel the technology narratives as the vision for 6G distills and its enabling technologies come into focus for participants in both academia and industry.

Figure 5: 6G technology leadership is a priority for each geographic region

Market drivers for the next-generation mobile platform

Amid the continuous advancement of mobile technologies during the past 40-plus years, a new generation of mobile network has emerged every decade or so. Each new generation allows the mobile industry to evaluate new requirements and design an enhanced, end-to-end system. 3G, 4G and 5G have all balanced the support for current needs with greenfield innovations that can enable future use cases.

In anticipation of what will come after 5G Advanced, the early vision for 6G is starting to emerge across the mobile ecosystem and broader industries. At Qualcomm, we see three main market drivers for a new mobile platform beyond 5G that will become commercially available around 2030.

Market driver 1: Addressing goals for economic growth and societal sustainability

As the impact of mobile technology is felt across more industries and regions, the next-generation mobile platform has a role to play in addressing goals for economic growth and societal sustainability (see Figure 6). In that vein, the United Nations has established the model of 17 sustainable development goals (SDGs)[4] that all countries should address to achieve peace and prosperity worldwide. As described above, 5G is already contributing significantly to global economic growth, and 6G can provide another meaningful boost by bringing connected intelligence to even more industries and use cases.

Lack of access to connectivity is a factor in inequality and social economics. Connecting more people tends to reduce inequality and improve quality of life, so one goal of 6G should be to make connectivity more accessible, irrespective of income level or geography.

For sustainability, the role of green networks and devices is becoming more important as we head into the 6G era. The highest priority is a more energy-efficient network architecture that generates less pollution. It is also necessary to reduce the environmental impact of billions of devices by producing them in a smaller carbon footprint and designing them to consume less power.

Figure 6: Designing 6G to more effectively address goals of economic growth and societal sustainability

[4] The 17 Goals, Sustainable Development, United Nations, https://sdgs.un.org/goals

Market driver 2: Capitalizing on the latest technology advancements

Through the global 3GPP standardization process, the ecosystem can align on interest areas in the core wireless and adjacent domains and bring them into the scope of the 6G definition. This will facilitate the focused, collaborative research and development (R&D) needed to create the next-generation platform suited to the needs of the next decade. The following are some potential technology building blocks for the new 6G platform:

Radio and baseband:
Supporting even higher bands (e.g., upper mid-band, sub-terahertz), enhanced PHY/MAC performance (e.g., faster switching), more flexibility, and improved efficiency.

Network disaggregation:
Optimizing network architecture for horizontal and vertical ecosystems, for a richer mix of equipment vendors.

Compute topology:
Complementing the growing relevance of the connected intelligent edge with virtualization, containerization, and enablement of hybrid clouds.

Machine learning:
Exploiting the synergies of wireless and distributed artificial intelligence for network automation and optimization.

Silicon and material:
Using advances in semiconductor and material sciences to enable faster and more efficient baseband processing and meta-surfaces.

Power management:
Maximizing performance while lowering power consumption and introducing lower-power or passive devices.

Multimedia and display:
Driving toward higher resolution (e.g., 8K and beyond), richer colors, improved optics, lower latency, and new form factors.

Perception and human interface:
Transforming how we interact with the digital and virtual worlds through advanced perception technologies and even more immersive experiences.

Approximately every two years, 3GPP standardizes a new release of incremental improvements to the current mobile system. However, rolling out major breakthroughs in core technologies efficiently must wait for a generational transition, when a blank-slate design can be introduced. For instance, the flexible framework with scalable numerology in 5G was designed to efficiently support millimeter wave (mmWave) spectrum, but for 4G LTE to support mmWave would have been prohibitive.

6G will comprise both evolutionary and revolutionary advances. Technology areas being studied and included for 5G Advanced will become the evolutionary technology foundation for 6G. Figure 7 illustrates those, along with some of the revolutionary advances envisioned for 6G platform.

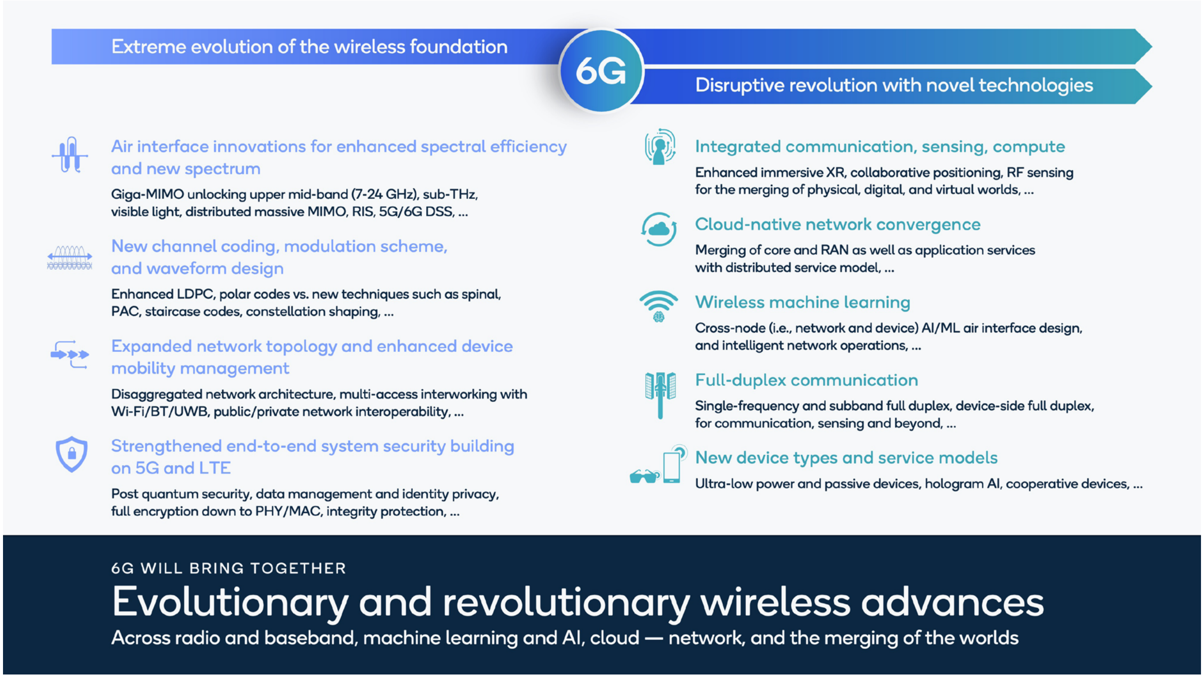


Figure 7: 6G will bring together evolutionary and revolutionary wireless advances

Market driver 3: Enabling enhanced experiences and new categories of use cases

4G brought smartphones into the mainstream. 5G is taking wireless into new services and verticals. And 6G is poised to enable new user experiences at the connected intelligent edge with new classes of devices, services, and deployments. Figure 8 highlights several of those use cases.

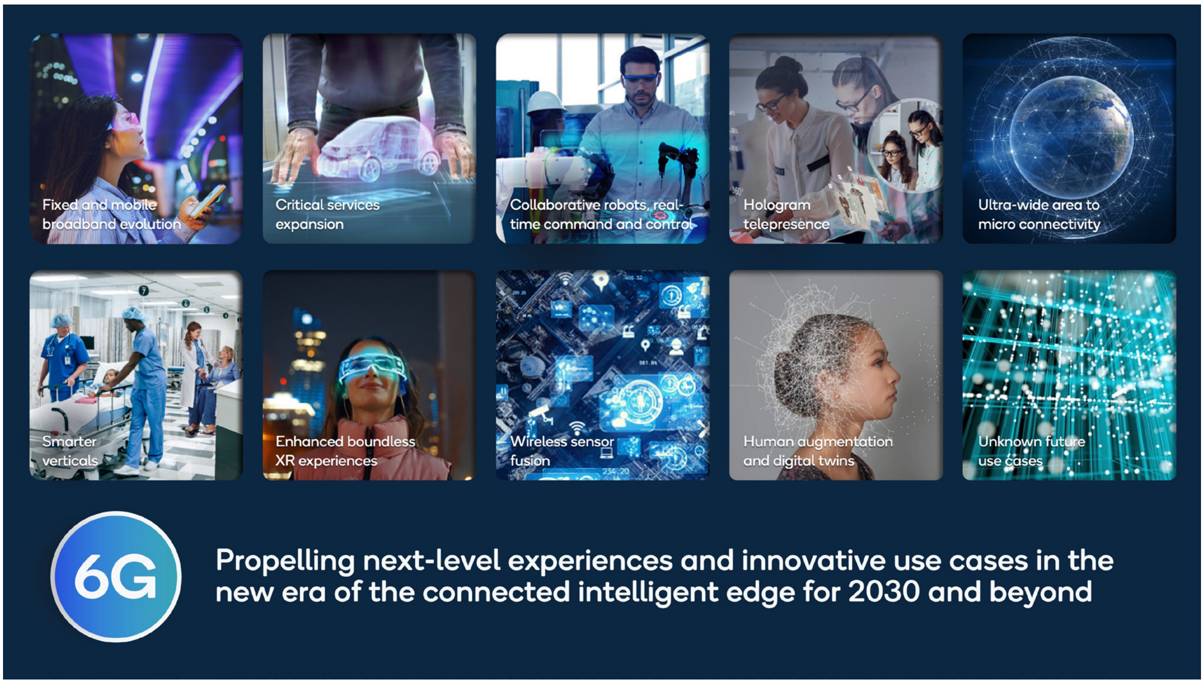


Figure 8: 6G will bring new and enhanced user experiences across the connected intelligent edge

6G will deliver an evolution path for fixed and mobile broadband with more capacity, higher throughput, and lower latency. It will provide more pervasive access through higher-density connections and ubiquitous coverage, and it will expand mission-critical services through higher reliability and availability.

6G will also support enhanced services and new use cases, as shown in Figure 9. Envisioned use cases include hologram telepresence, collaborative robots, human augmentation, deeper immersion to the digital and virtual worlds, and advanced sensing. 6G will serve as the innovation platform for devices, experiences, and use cases that emerge around 2030 and beyond.

A smarter wireless platform to

support enhanced services and new use cases

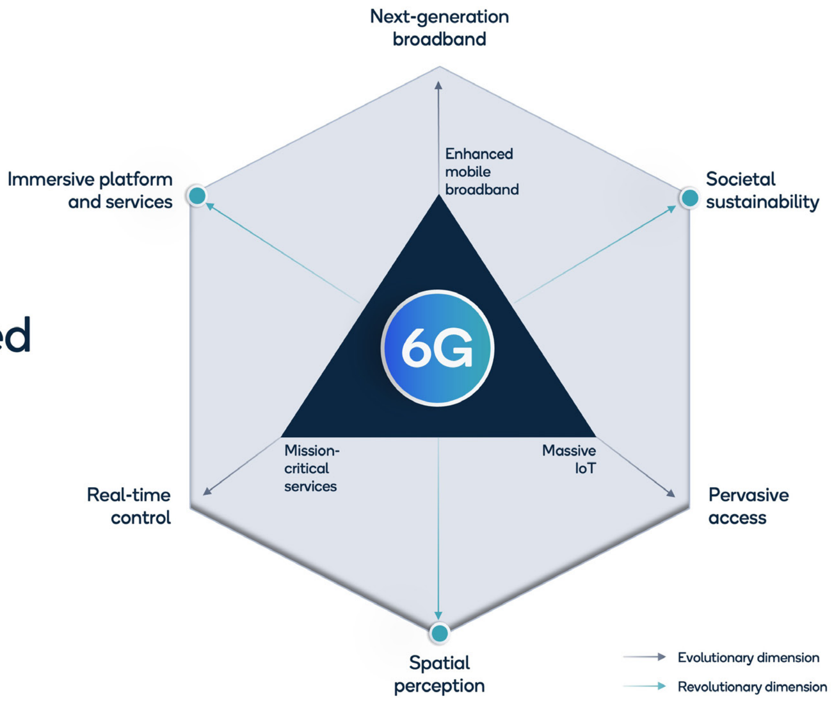


Figure 9: 6G will enhance existing use cases and expand into new ones

Next-generation broadband:
Taking fixed and mobile broadband experiences to the next level. With lower latency, seamless mobility, and higher peak and average throughput, 6G will drive the evolution of form factors and performance in devices such as smartphones, laptops, and customer-premises equipment. Its new capabilities will empower novel use cases and applications like holograms.

Real-time control:
Going beyond the ultra-reliable, low-latency communications made possible with 5G, into areas like collaborative robots. This class of services will demand even lower latency, greater reliability, higher availability, and stronger end-to-end system security. It will also facilitate machine learning that spans central cloud, edge cloud and devices.

Pervasive access:
Enabling mobile connectivity virtually everywhere — down to micro-connectivity and into space — by supporting ultra-dense deployments and low-complexity devices such as those used in passive, zero-energy IoT. Hyper-scalability in 6G will require optimizing device management and enabling easy, seamless onboarding.

Societal sustainability:
Meeting greener goals and bridging the digital divide. Mobile connectivity is the essential ingredient of tomorrow's connected intelligent society. 6G will be designed to address the requirements of high performance, complex use cases, but it will also be environmentally sensitive, accessible, and cost-efficient.

Immersive platform and services:
Exploiting the full potential of the metaverse. While boundless extended reality (XR), including virtual reality and augmented reality, is the focus of current innovation, new opportunities for human-machine interface (HMI) can bring even more-immersive experiences to life. 6G will focus on exploring enhanced boundless XR use cases in the metaverse.

Spatial perception:
Developing new capabilities in wireless positioning and sensing. Wireless sensing, both active and passive, can bring new efficiencies like better beam management to the core operations of 6G networks and devices. It can also unlock new use cases in a variety of industries.

6G system capabilities and design targets

To realize the new use cases described in the preceding section, 6G will incorporate a diverse set of foundational wireless and adjacent technologies, depicted in the triangles in Figure 10.

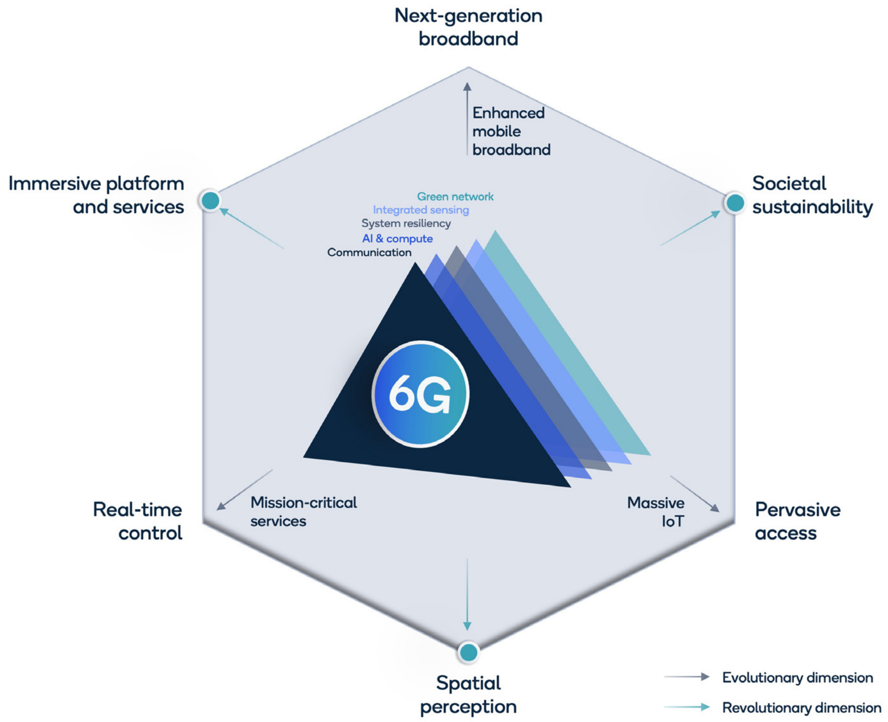


Figure 10: 6G will be a smarter platform that goes beyond communication

Communication:
6G will connect more people and things, delivering next-generation voice and data. It will bring an opportunity to revolutionize the way we approach fixed and mobile communication.

AI and compute:
AI will be used to design, deploy, operate, and optimize 6G networks, devices, and services. The AI-native system will collect information from end to end, then it will apply dynamically distributed computing for improved performance and new capabilities in devices, infrastructure, networks, and clouds.

System resiliency:
6G as envisioned will be more flexible, as it is expected to be capable of connecting a broader range of things. Building on the security foundation established by 5G, security, data management, and privacy need to be reimagined. It sets the stage for a variety of new features such as multifaceted trust, configurable security and post-quantum cryptography.

Integrated sensing:
The precision of cellular-based positioning will increase in 6G and appear in new devices and services, along with joint communications and sensing. Sensor fusion (across both RF and non-RF sensors) can deliver values and insights for new use cases in localization, gesture recognition, imaging, and environmental detection.

Green network:
As noted above, 6G will be designed from the outset with sustainability in mind. Also envisioned is the possibility of energy-harvesting technologies that can reduce or eliminate the need for a battery in certain devices and applications.

To support the range of envisioned devices and services, the 6G platform needs to be adaptable to large variations in system requirements like throughput, mobility, coverage, latency and reliability. It will need to provide pervasive access in remote, rural areas and in space while also providing extreme mobile broadband in densely populated areas like stadiums and city centers. Not all 6G deployments will need to support all use cases at once, but the end-to-end system design must be capable of supporting them. That means that each category of 6G use cases will be driven by a broad set of extreme key performance indicators (KPIs) and corresponding targets, which have yet to be formally established.

Figure 11: Key use cases drive the extreme 6G system requirements

6G is being designed to meet IMT-2030 performance targets that the ITU-R is defining by target 6G service areas. It is expected that the new 6G targets will push existing KPIs further in areas such as throughput, latency, and mobility. They will also likely include new KPIs for measuring quality of service (QoS) of new use cases and deployments.

Spectrum considerations

Spectrum is the lifeblood of all wireless communications. Like previous generations of the mobile technologies, 6G will also operate in all spectrum bands and support all available regulatory frameworks, e.g., licensed, unlicensed, and shared (see Figure 12).

Figure 12: 6G will be designed for all spectrum types and bands

Licensed, exclusive-use spectrum will continue to be the priority for mobile network operators, because it can guarantee the QoS required for the most demanding services that operate over long ranges (e.g., kilometers). Unlicensed spectrum offers bandwidth for lower-power, flexible, opportunistic uses that operate over smaller areas (e.g., meters). New, more robust, and dynamic spectrum sharing approaches are currently being researched. They will allow different users and multiple network operators to share limited spectrum resources efficiently, including for future satellite-based connectivity solutions. It is anticipated that MRSS technologies will enable early 6G deployments so that 6G can be rolled out in 5G spectrum without delay.

6G will support all bands used by 5G and previous generations, and it will use new spectrum bands:

Upper mid-band spectrum:
The bands between 7 and 16 GHz (potentially up to 24 GHz) are currently not used by mobile network operators. By opening up bands in this range for mobile communications, 6G operations would combine the best of both worlds: the wide-area coverage of sub-7 GHz spectrum and the extreme capacity of mmWave. The new 6G radio technology that is being designed to operate in this frequency range will take advantage of advanced antenna systems to compensate for larger RF signal losses to provide coverage comparable to lower mid-band spectrum in the 3 to 4 GHz range. To support future capacity needs for immersive use cases like boundless XR, each mobile operator will need access to at least 1 GHz of bandwidth in the upper mid-band spectrum range.

Sub-terahertz (sub-THz):
Further expansion beyond 100 GHz is expected for 6G, up to at least 150 GHz and potentially up to approximately 300 GHz. The wireless industry is making great strides overcoming the hurdles to using sub-THz bands in existing and new deployments.

Long-term research vectors and enabling technologies

Qualcomm Technologies' foundational wireless research never stops. Today, we are driving technology advances that may become part of 5G Advanced (Release 18 and beyond) while others will become the building blocks of the 6G platform.

Broadly, six main research vectors will form the foundation for 6G.
They are enabling technologies for:

- Merging of physical, digital, and virtual worlds
- AI-native, end-to-end (E2E) communications
- Scalable network architecture
- Air interface innovations
- Expanding into new spectrum bands
- Communications resiliency

The following subsections focus on selected technologies in each vector.

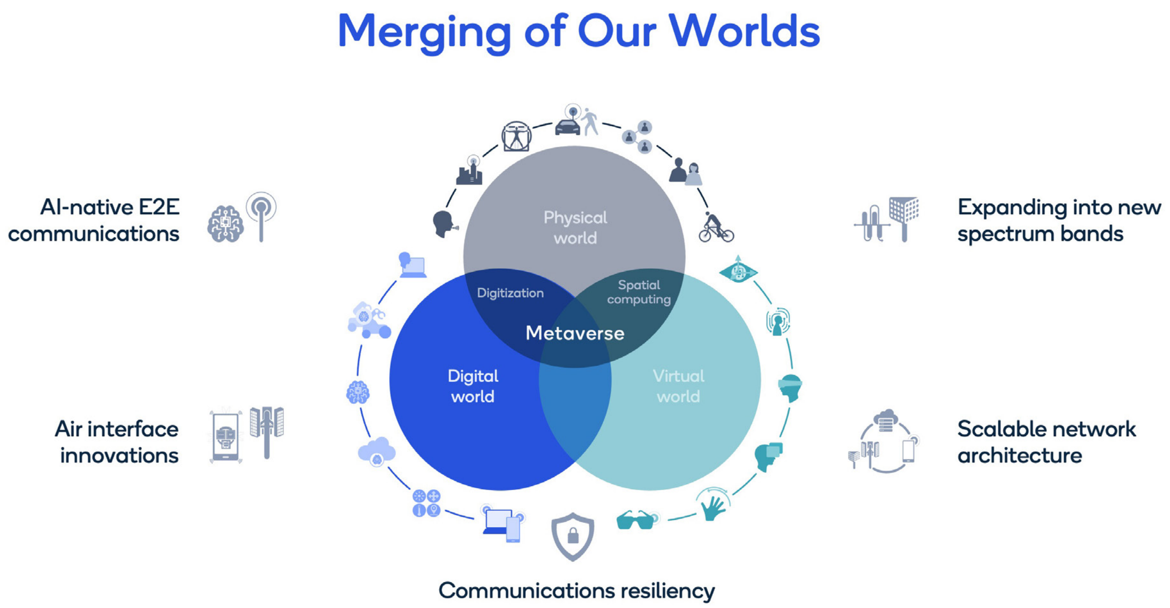


Figure 13: Long-term research vectors that will enable 6G

Merging of the physical, digital, and virtual worlds

6G has the potential to usher in the era of XR, as depicted in Figure 14, when XR glasses will become the next compute platform.

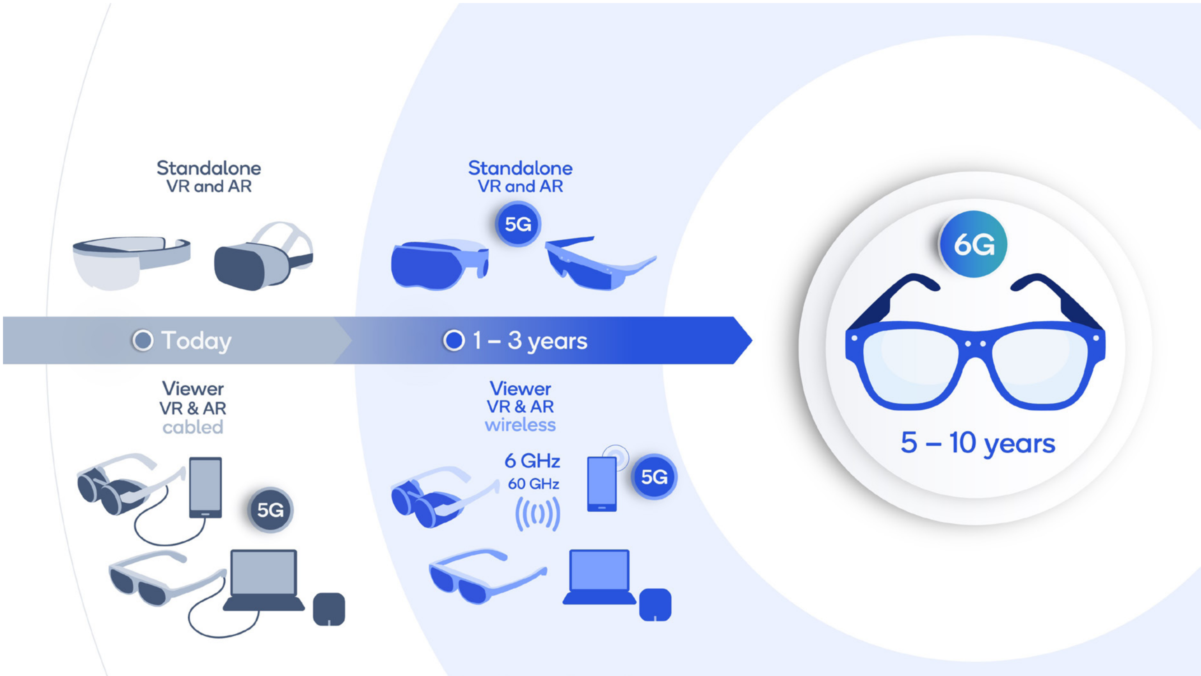


Figure 14: XR will become a mass-market compute platform

As XR devices become pervasive, their requirements for connection density, capacity, and coverage will approach those of current smartphones. Immersive experiences will be enabled by the fusion of the physical, digital, and virtual worlds, forming the building blocks of the metaverse. This section of the paper examines five metaverse-enabling technologies.

Digital twin and spatial compute

The complex physical world will be digitized. The resulting digital twin will evolve continuously through location, sensing, and 3D maps generated by a variety of XR devices, cameras, and sensors. The digital twin will make it possible to monitor, design, simulate, analyze, optimize, and predict the behavior of physical systems (see Figure 15). With common spatial anchors, location, and mapping shared across multiple devices, the possibility arises for shared, immersive experiences such as holographic conferencing and virtual collaboration.

Figure 15: Digital twins and spatial computing will fuel the future of boundless XR

6G will also usher in an era of spatial computing. Perception algorithms like six-degrees-of-freedom (6DoF) head/hand/eye tracking will evolve to work seamlessly in any environment, regardless of lighting and mobility conditions. Display and optics technology will make a generational leap, with higher display resolution and improved field of view (FOV). Graphics rendering, enabling photorealistic effects, will continue to improve by including volumetric (3D) content and avatar representation with higher frame rates and more pixels, accompanied by immersive spatial audio.

Note that digital twins and spatial computing will require higher data rates, ranging from 100 Mbps to 10 Gbps depending on applications. The overall network capacity requirement will be 100 times that of 5G systems. To meet those requirements, native 6G support will be needed for seamless switching and aggregation across bands (sub-THz, mmWave, upper mid-band, sub-7 GHz, and unlicensed, shared spectrum), based on user location, available spectrum, and coverage.

Native support for distributed compute

Design requirements for sleek XR glasses will constrain battery size and on-device power. Modem-RF power consumption needs to be approximately 100 mW to improve the form factor, and graphics rendering with photorealistic visuals also requires high-performance CPU and GPU resources. Power requirements will naturally lead to a distributed compute architecture, as shown in Figure 16.

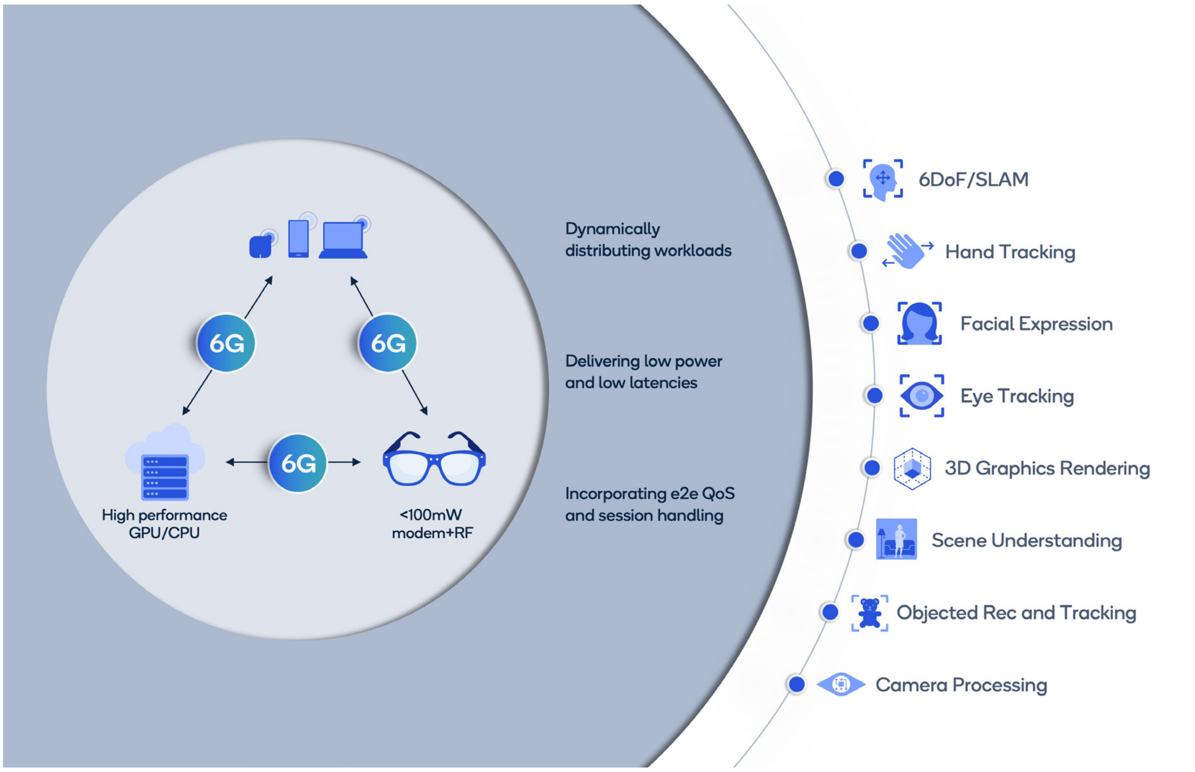


Figure 16: 6G protocols natively supporting distributed compute

Processing, such as rendering, will be spread across XR glasses, an edge compute device (e.g., a smartphone), and the cloud. That architecture already exists and will become native for 6G with built-in protocols fusing distributed compute and communication, incorporating session handling, media processing requirements, and end-to-end QoS.

Workloads to be distributed include 6DoF pose, simultaneous location and mapping (SLAM), hand/eye tracking, facial expression recognition, scene understanding, object recognition and tracking, camera frame processing, and 3D graphics rendering. The distribution will need to be seamless across the system, and it must consider latency, power, capacity, and spectrum. The best user experiences will require highly reliable, low-latency communication across the XR device, edge compute devices, and cloud, approaching the range of 1 to 10 milliseconds. Zero-interruption handovers are also needed to maintain highly immersive experiences.

Fusion of perception, wireless, and multimedia

In the metaverse, the best user experiences will demand tight synergies among wireless, multimedia, and perception.

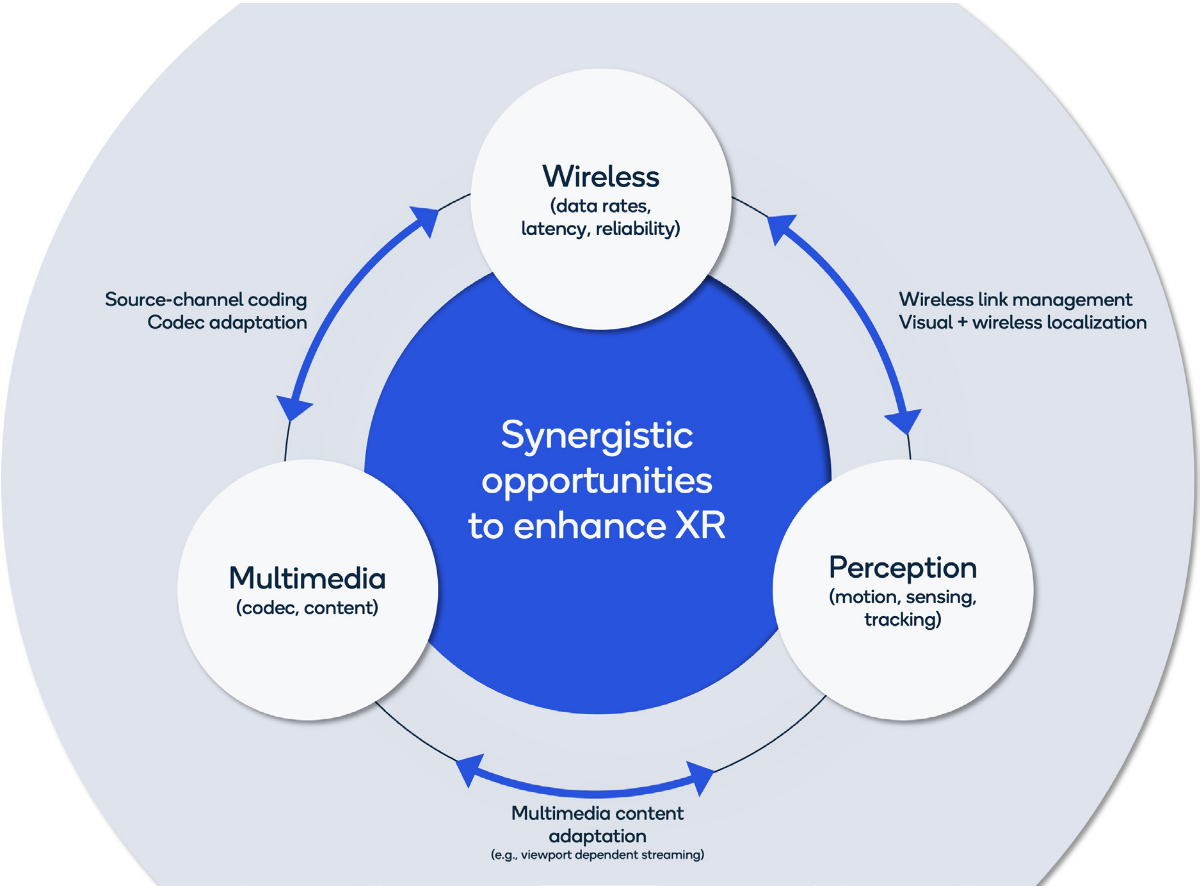


Figure 17: 6G can exploit synergies across perception, multimedia, and wireless

Multimedia:
Codecs can adapt based on dynamically changing wireless conditions. 6G systems can be natively designed to provide applications and multimedia codecs with application programming interfaces (APIs) on radio link conditions. Joint source and channel coding concepts need to be revisited for the low-power and high-reliability requirements of XR.

Perception:
Sensor inputs (camera and IMU), for an accurate pose of the device, and a depth map, for the observed environment, can be fused with wireless measurements. The result will be an accurate RF map that improves beamforming (e.g., for mmWave). While visual localization techniques can provide centimeter-level accuracy, their robustness can vary depending on lighting conditions, inadequacy of visual features, and size of search space.

Wireless:
Precise positioning and sensing can complement and improve overall localization. 6G can provide native support for fusing visual and wireless localization. It also presents an opportunity to standardize localization and mapping data formats essential for interoperability across XR devices, servers, and phones paired with glasses. That will enable users to have shared context, as desired by location owner and user preferences, including privacy.

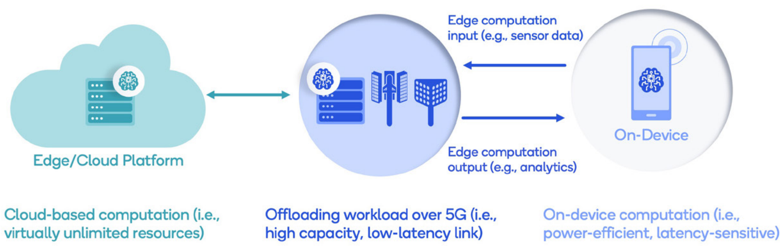
Advanced human interfaces

Given the potential for XR devices to evolve into the next compute platform, the way in which humans interact with those devices will evolve as well. Unlike smartphones, XR glasses do not have a screen that can be manipulated with fingers. Voice commands and gesture recognition can provide reasonable interfaces in some use cases. Since users already wear devices on their head, brain-computer interface (BCI) is another promising area for the HMI with XR devices. These advances need to be monitored so that 6G can provide native support.

Services beyond data communication

The role of wireless in enabling the metaverse expands beyond data communication. To optimize the performance of this new class of services, we are evolving the connected intelligent edge, powered by on-device AI, edge cloud processing, and mobile connectivity in 5G and 6G. Areas of current focus include precise positioning, sensing, relative ranging, and time resiliency.

The left side of Figure 18 shows the system architecture for supporting services beyond data communication. In a device-only model, the device can support such services as performing measurements and computation independently, without relying on the network. In a hybrid model, the device and the network can both collect and process the data to support the non-data service, with either one taking the lead and the other assisting. An example is 5G precise positioning, in which the device can measure positioning reference signals (PRS) and the computation can be done either on the device or in the network. To optimize the system for non-data services, we can develop new interfaces across cloud, network, and device platforms. They can facilitate efficient, horizontal scaling, and they can level the playing field for new entrants to a market with large, vertical incumbents. A hybrid cloud and device platform can offer the greatest flexibility for meeting diverse service requirements. In most cases, a service orchestration trade-off is necessary (see right side of Figure 18).



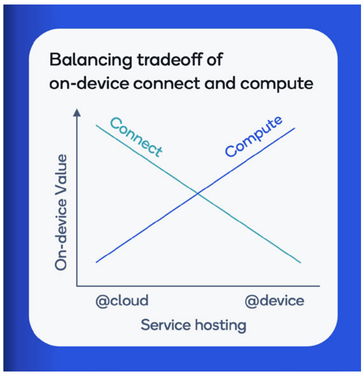


Figure 18: Dynamically partitioning functionality to balance system performance and power consumption

AI-native, end-to-end (E2E) communications

During the development of 5G, research began into the use of machine learning (ML) to improve the performance, efficiency, user experience, and operation of wireless systems. 6G will be AI-native, with AI being a core part of the 6G system design from the start. It is expected that AI will be distributed in the end-to-end system, operating autonomously among the cloud, network, and devices across all protocols and layers. 6G moves away from the traditional, model-driven design for communications and network, toward a data-driven design, with joint training, model sharing, and distributed inference across networks and devices. Federated learning, a distributed learning concept, will be able to scale fully with the 6G platform.

The following section outlines some of the main research areas foundational to 6G system design.

Network architecture and procedure enhancements

Figure 19 shows that the initial deployments of wireless ML appear in 5G as an overlay. Overlay ML is implemented independently, either on the device or in the network, as an optimization of existing functions such as QoS enhancement, energy saving, and beam management. It is left to the device or infrastructure vendor to implement wireless ML as proprietary functions, including proprietary model development and management. Overlay ML supports only single-sided models in which inference is performed either on the device or in the network. The features rely on proprietary and standardized data collection used as input for training, as in the self-organizing network and minimization of drive test (SON/MDT) features in 5G NR Release 16 and beyond.

Figure 19: Continuing evolution of wireless ML into 6G

Although overlay ML does not support collaboration between the network and the device for end-to-end performance optimization, the cross-node ML envisioned for 5G Advanced does support it. As with overlay ML, cross-node ML supports proprietary models, but new procedures enabling standardized interfaces, including model development and management, can facilitate jointly optimized performance. For instance, features like positioning, beam management and channel state feedback (CSF) are being considered for joint optimization between the device and network. Besides single-sided models supported by overlay ML, cross-node ML introduces the possibility of running two-sided models, with joint inference performed sequentially; for example, at the device then the network, or vice versa. Cross-node ML may define further data collection based on new use cases as input to training. It may also introduce monitoring procedures that allow the network and device to track ML performance and enable coordinated model selection and configuration.

Native ML is the natural next step, in which ML is integrated across all protocols and layers to operate autonomously between the device and the network. Native ML will support integrated ML across all procedures to train for improved performance and adapt to different deployment environments and device types. In addition, data fusion will require new data collection that is integrated into ML lifecycle management for further autonomous operation.

Data-driven communication and network design

One anticipated benefit of AI-native design is that the end-to-end system can be dynamically optimized for the specific deployment site, radio environment, and user context. ML-based models can be initially trained with synthetically generated data on a digital twin of the physical environment, then transferred to the network and devices for live operation. That allows the models and algorithms to be hyper-optimized for each deployment site, radio condition, and device/user context, resulting in improved performance, QoS, and robustness.

In that type of optimization, it will be important to address the “sim-to-real” gap, or the potential degradation in ML performance due to the discrepancy between synthetic and real data. Transfer learning and fine-tuning of the ML model may be needed upon deployment; domain expertise can help minimize the sim-to-real gap and facilitate that fine-tuning. Federated learning over a large number of deployed devices can also reduce the time needed for fine-tuning. Additionally, federated learning enables personalized operation and lifelong adaptation of the ML models, while efficiently utilizing network bandwidth and minimizing data privacy concerns. Reinforcement learning based on end-to-end, system-level metrics and long-term KPIs may be further applied toward life-long adaptation of the deployed models. The resulting, predictive (rather than reactive) power of ML-based designs is useful in improving the performance and robustness of 6G systems.

In AI-native design, one ML agent resides in the network and another on the device. They interact with each other by means of distributed inference. One example is the ML-based CSF for joint channel compression and reconstruction in 5G Advanced. Similar ML operations across peers, such as modulation/demodulation, channel encoding/decoding, peer transmission control protocol (TCP) entities, and source encoding/decoding, can also benefit from ML.

Specifying the ML operational frameworks but not the ML design is a way of allowing the specification to be forward-compatible. It ensures that rapid advances in ML-based communication and network design can be made without changing the specification, a process that usually takes two years. Similarly, AI-native design allows the ML algorithms to adapt, whether through online training or offline re-training.

New and expanded use cases based on awareness

Data-driven design opens up opportunities for better system performance and new use cases in several areas.

Radio-/Situation-awareness:
To adapt to current conditions, ML algorithms can incorporate real-time awareness of radio and user context through environmental and contextual sensing. Examples include intelligent beamforming for improved throughput and robustness, more efficient spectrum access and scheduling, device and network power management, optimized network traffic, improved mobility, and better detection of and defense against security threats. ML-based contextual sensing will help in detecting objects, gestures, and movement.

Semantic awareness:
Algorithms that are semantically aware of the data source can improve system performance. Applications like holographic video, metaverse, and collaborative robots are expected to boost data volume, and data-driven designs can compress and recover source information in a semantically aware, goal-oriented manner. That will make bandwidth utilization more efficient while preserving source information that is meaningful for perception and for desired actions at the destination.

System-level awareness:
Data-driven design also provides system-level awareness within the network and across devices. Jointly trained and continuously optimized over time, ML models can adapt to system entity behaviors to improve performance and efficiency in areas like beam management, link adaptation, power saving, and mobility.

Data management enhancements

Data analytics will play a prominent role in new and enhanced mobile experiences as data is collected from the end user and other data sources, then processed. Each network entity managing the data is subject to different regional regulations in areas like privacy and consent. Therefore, 6G systems must comply with requirements related to collecting, accessing, and processing user data across the central and edge clouds, as shown in Figure 20. They must extend that compliance to infrastructure functions and to data sources ranging from IoT devices to smartphones. Data must be managed throughout its lifecycle, from collection to processing, with security and privacy procedures that ensure data ownership, provenance, and governance.

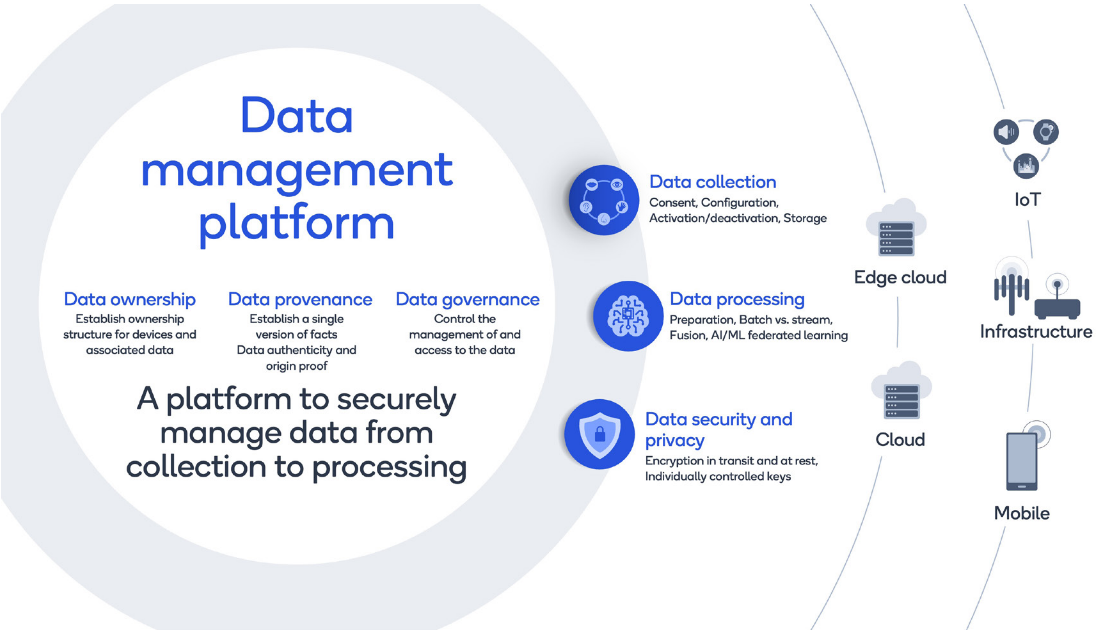


Figure 20: 6G data management platform

Scalable network architecture

Efficiently addressing the growing demand for data and 5G services will entail disaggregating and distributing cloud processing across the connected intelligent edge, closer to the user. Simultaneously, initiatives like the open RAN (O-RAN) have moved mobile network architectures toward new topologies featuring disaggregation and virtualization for scalability, cost-effectiveness, and performance.

6G will bring more technologies to make the end-to-end system scalable and adaptive. This section examines the evolution of a network architecture that can support an even broader set of devices, use cases, and deployment topologies.

Further network disaggregation in 6G

Since 3G, cellular system architecture has gradually evolved from monolithic to split. The transition from 3G to 4G introduced the notion of control and user planes split at the core network, with a flat RAN architecture and separate security between RAN and core network on the control plane. In the transition from 4G to 5G, the split between user and control planes was extended to the RAN, to include flexible location of core functions. A further attempt to enable cloud and virtualized networks was the introduction of service-based architecture, which for 5G has been limited to the core network.

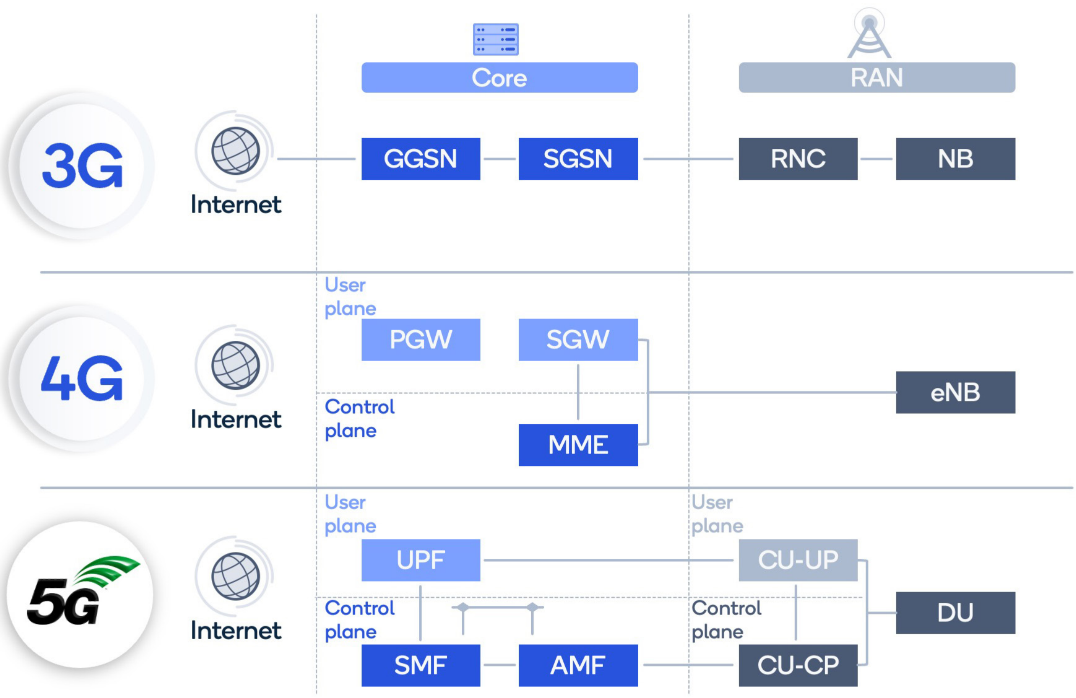


Figure 21: Increasing disaggregation of network from 3G to 5G

The 5G core platform also separated control plane functions and connected them in a service-based architecture, including edge computing. Features introduced on the RAN platform, spanning 3GPP and O-RAN, included RAN virtualization functions and the definition of disaggregated RAN with horizontal separation of control and user planes. 5G RAN also introduced a vertical split of protocol stack functions across the central unit (CU), distributed unit (DU), and radio unit (RU).

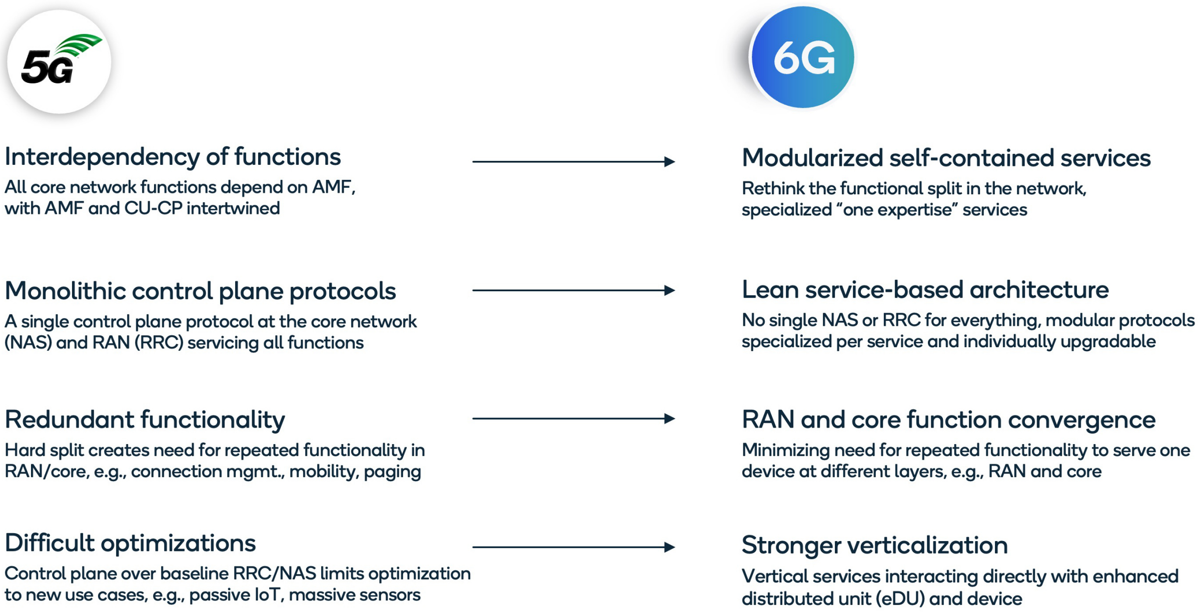


Figure 22: 6G system design builds on a foundation of 5G technology

The evolution across generations has trended toward splitting functions in the network, with initial attempts at cloud-based solutions in 5G. However, the existing architecture still has limitations, so the 6G system will be flexible and cloud-native to allow for faster adoption of new features and verticals.

Cloud-native system development principles emphasize modularity; for instance, services and microservices are created with little interdependence. A limitation to enabling fully cloud-native implementations in 5G and previous system architectures is the interdependence among network functions that works against those principles. For example, in 5G systems, all control plane functions depend on access and mobility management (AMF) and the central unit control plane (CU-CP) for routing; therefore, any new feature or function will require an upgrade to the AMF and CU-CP. Moreover, control plane upper-layer protocols are monolithic: the non-access stratum (NAS) protocol carries all information between the device and the core network, and the radio resource control (RRC) is the all-encompassing control protocol between the RAN and the device.

For 6G, two main design drivers can address such limitations. The first is to modularize network functions into self-contained modular services by rethinking the functional split in the network and defining a series of specialized, "one expertise" services such that each service can evolve or even be replaced independently of other services. The second is to introduce modular protocols for each service over a lean, end-to-end, service-based architecture. That architecture should make it possible to remove or at least minimize redundant functionality like connection/context management, mobility, and paging between RAN and the core network. The architecture would also facilitate the introduction of new features and services through stronger verticalization.

6G network architecture can enable a single cloud platform to host services for application, core, and RAN, extending the benefits of service-based architecture to RAN. Its end-to-end, cloud-native approach improves such characteristics as scalability, resiliency, elasticity, agility, reuse, visibility, automation, and failover. A cloud-native solution can also allow each service across RAN and core network to scale independently by increasing or decreasing resources allocated across functions independently.

For 6G networks to take full advantage of a cloud-native solution, the functional split between core network and RAN needs to be refactored to fully leverage the flexibility of moving functionality between the edge and central cloud. 5G inherited the functional hierarchy from 3G and 4G, based on the requirements of an appliance-centric architecture assuming a relatively static deployment of centralized and edge functionality. 6G should revisit these assumptions with an eye to how the cloud is being deployed to allow traditional core and RAN functions to be located anywhere as long as latency and processing requirements are supported. Cloud platforms enable a redistribution of core network and RAN service, which will simplify protocols and reduce functional duplication while maintaining QoS requirements. Additionally, applications can share the common platform and directly access services anywhere in the network, whether deep in the cloud or at the edge.

Another important step in 6G is to move all real-time link management to the RAN edge. Adaptation at the DU allows more efficient activation and selection of features based on requirements for user experience towards a more native AI functionality.

The new 6G system architecture can minimize interdependence among services through a vertical convergence of functions. For example, a core network function like NAS and a central unit function like RRC, that span DUs, can converge into specialized services. Intra-DU functions involving both CU and DU can converge and be managed at the enhanced DU (eDU) itself, based potentially on a request or information received from network services (see Figure 23).

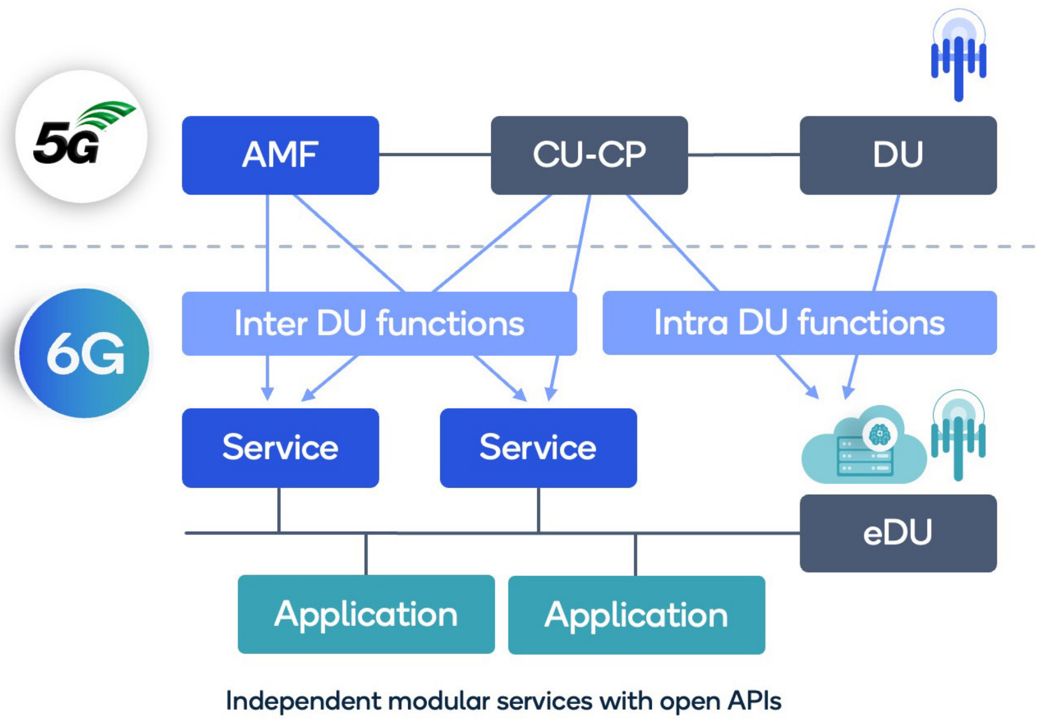


Figure 23: Functional split from 5G to 6G, with vertical convergence and horizontal split

Complementing that vertical convergence is the horizontal split of functions into self-contained, specialized services interacting directly with devices, eDUs, and one another. The eDU itself would be part of the service-based architecture, offering configuration APIs to the services that require such functions.

Air interface innovations

Every new mobile generation brings with it a new air interface. The design for 6G physical and media access control layers (PHY/MAC) is expected to deliver a significant leap in performance and spectrum efficiency over 5G in existing sub-7 GHz and mmWave bands. Furthermore, it is expected to allow for the expansion into new 6G bands, such as upper mid-band and sub-THz.

From the start, the 6G air interface will enable broader devices and services. It will also support the continuing evolution of wireless innovation in the next decade. Fundamental PHY building blocks like waveform, multiple access, and channel coding will efficiently address rapid data growth even as device and network hardware becomes more complex and power demands increase. PHY/MAC design improvements like new duplexing schemes (e.g., full duplex) and new MIMO technologies (e.g., Giga-MIMO) will boost data rate per user and over the entire network. The foundational design will enable ubiquitous 6G coverage across all accessible bands in terrestrial networks (TN) and non-terrestrial networks (NTN).

Cross-disciplinary technologies like AI and RF sensing have emerged as new tools for physical layer design. As described in "Data-driven communication and network design" above, a data-driven methodology will be native for 6G air interface design.

Waveform, modulation, multiple access, and channel coding for sustainable data growth

The rapid growth in data demand over the past several decades is reflected in the growth of peak data rates across communication standards such as cellular, Wi-Fi, and Ethernet (see Figure 24). That growth has largely been facilitated by advances in semiconductor technologies (i.e., Moore's law) and the evolution in RF, analog, and baseband algorithms.

Given the growth rate in mobile data, it is expected that throughput will approach 1 Tbps by the end of the next decade. New 6G algorithmic and PHY architecture will need to support scaling to wider bandwidths and higher-order MIMO to sustain that growth over the ensuing decade. At such high data rates, metrics like power efficiency and area capacity efficiency will become increasingly important, along with traditional metrics like spectral efficiency, gap to capacity, and peak data rate.

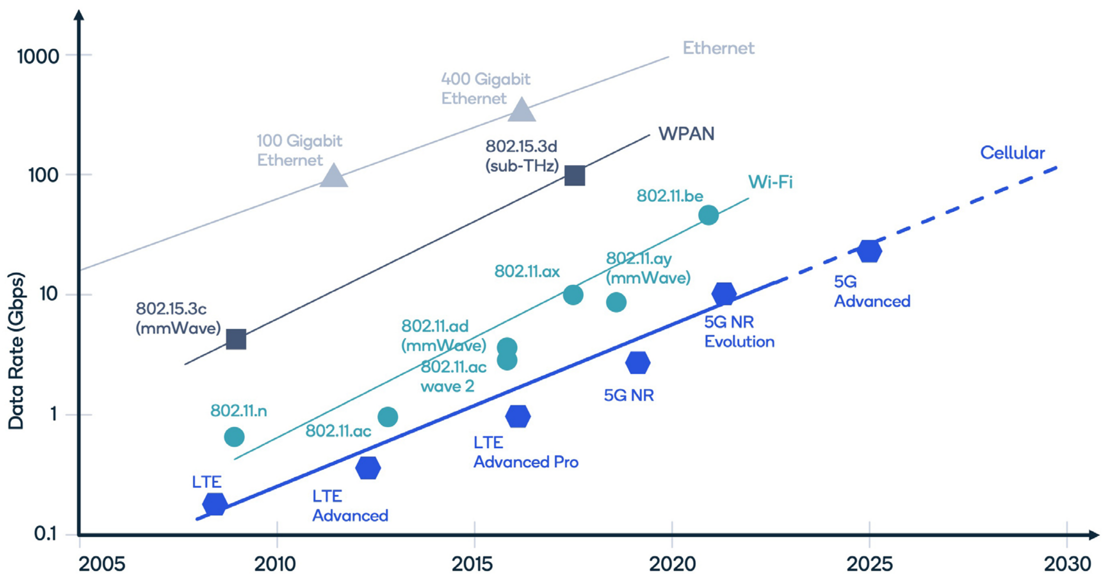


Figure 24: Growth of data rate in communication standards

From the point of view of waveform and multiple access design, the orthogonal frequency division multiple access (OFDMA) standard provides an efficient, low-complexity framework for resource allocation that works perfectly with MIMO. In scenarios where the link budget is limited, discrete Fourier transform spread (DFT-S) complements OFDMA with its low peak-to-average power ratio (PAPR) property while maintaining compatibility to the OFDMA resource grid. It is expected that OFDMA will facilitate a higher data rate in 6G and expand into new use cases. From the design perspective of coding, modulation, and MIMO transmission, new designs facilitating low-complexity demodulation and decoding will become as important as achieving high spectrum efficiency.

Besides supporting envelope scaling, a unified 6G PHY/MAC design needs to address KPIs across all 6G bands. It must be scalable with channel bandwidth and MIMO order, and flexible enough to serve new communication and non-communication services across downlink, uplink, and sidelink. The new RAN design in 6G also plays a role in reducing the cost and complexity of RF and baseband hardware; it will enable technologies such as reconfigurable intelligent surface (RIS) for a robust and cost-efficient massive IoT ecosystem.

Advanced MIMO technologies for continuous spectrum efficiency scaling

6G MIMO technologies will evolve with other fundamental PHY building blocks such as waveform, coding, modulation, and multiple access. The result will be improved user experience in 6G across existing bands with the full potential of new 6G bands.

As described in "Spectrum considerations," 6G is expected to expand into upper mid-band spectrum (7-24 GHz) to achieve higher data rates. Giga-MIMO, an advanced form of 5G massive MIMO, will come to the fore as 6G targets spectrum above 7 GHz. Operating in higher frequency bands (e.g., 13 GHz), Giga-MIMO can utilize a similar form factor for antenna panels to that of 5G massive MIMO at lower frequencies (e.g., 3.5 GHz) because the number of elements scales substantially with shorter wavelength. Giga-MIMO is able to generate narrow beams with a large number of antenna arrays and multiple RF chains. It will achieve nearly self-contained, orthogonal multiple access not only over time and frequency domains, but also over the spatial domain by forming narrow beams.

Another technology, distributed massive MIMO, can improve user experience in both wide-area and local deployments. Distributed massive MIMO antennas can be jointly processed from the same site or from multiple sites, depending on the level of coordination across RUs and the processing capability of DUs. Based on cloud RAN (C-RAN) architecture, a centralized DU can jointly process uplink and downlink transmissions across multiple remote radio units (RRUs). That will eliminate cell-edge boundaries, leading to improved user experience and greater system capacity. Moreover, spectrum efficiency will no longer be the only driving metric in 6G RAN design; distributed massive MIMO based on C-RAN could save power through more flexible management of RRU switching and beamforming control. Distributed massive MIMO can efficiently densify the network, increasing system capacity and expanding mobile communication into higher bands.

Advanced duplexing and all-band spectrum aggregation

To support diverse spectrum, deployment, and use cases, duplexing schemes in 6G are expected to be more flexible and to adapt efficiently to specific needs.

Duplexing can be regarded as a special form of multiple access, in which the uplink and downlink of a device are multiplexed to share available radio resources. As illustrated by the example in Figure 25, frequency division duplex (FDD) and time division duplex (TDD) enable multiple access in the frequency and time domains, respectively. Thanks to state-of-the-art RF and baseband technologies, full-duplex communication has been successfully prototyped and demonstrated in over-the-air environments. Technology advances in RF, analog, antenna, and interconnect hardware will further improve spatial and frequency domain isolation and suppression of interference. Continued development of techniques for self-interference and crosslink-interference estimation, cancellation, and avoidance will mitigate the impact of transceiver nonlinearities.

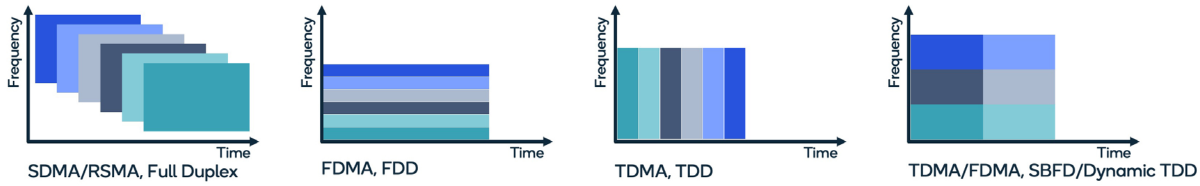


Figure 25: Multiple access and duplexing schemes

Additionally, 6G will support simultaneous communication across multiple bands. While that can significantly increase radio and baseband complexity, it creates an opportunity for devices to optimize power management across antenna, RF chains, analog filters, and baseband processing. As a result, devices can deliver next-level user experiences.

Evolution of the topology of the radio access network

6G will be designed for capabilities beyond those of 5G and 5G Advanced, so the end-to-end system topology must evolve. The topology will be integral to better communication performance and support new features like sensing and positioning.

Figure 26 illustrates an example of next-generation RAN topology. A traditional base station operating in mid-band or upper mid-band provides wide-area coverage, and local coverage expansion is serviced in the high bands of mmWave or sub-THz.

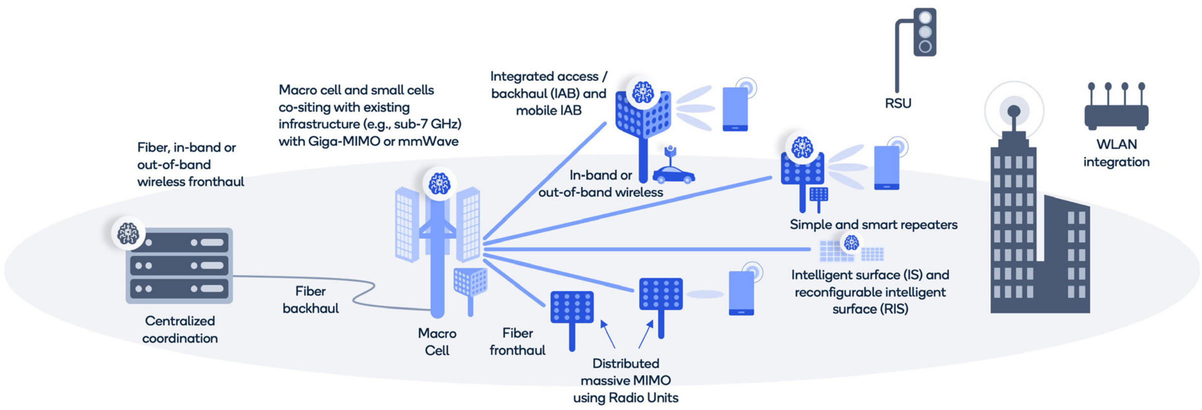


Figure 26: 6G will drive diverse deployment topologies and technologies

Radio units:
The RAN is intelligently and centrally coordinated, and the distributed RUs are connected to the eDU for joint processing.

Repeaters:
Simple and smart repeaters, along with the evolution of integrated access and backhaul (IAB — fixed and mobile) technologies, expand network coverage efficiently.

Open RAN:
Technology components of O-RAN that started in 5G are expected to continue playing a role in 6G. The main aspects of RAN disaggregation and O-RAN are separation of RU and DU by lower layer split, separation of intelligence functions by RAN intelligent controllers (RIC), and separation of software and hardware with industry-standard hardware. O-RAN will likely grow in importance as the diversity of services expands in 6G.

Passive devices:
Progress in basic materials, device science, and advanced manufacturing capability will affect end-to-end system design in 6G. One example is the emergence of passive infrastructure and devices, such as RIS and passive IoT devices. These devices not only improve user experience (no need to charge battery) and network performance (extended coverage) but also improve energy efficiency with low deployment cost.

Design of radio protocols

The goals of achieving better system performance and ensuring seamless interworking with other communication layers (e.g., RAN/core convergence) prompt a new look at the design of the radio protocol layer.

One factor is the future of cloud and the AI-native network architecture. 6G system design will need to revisit the strict separations between the core NAS and RAN access stratum (AS), and between L2 and L3 within the AS. For example, for features with both NAS and AS functions, such as mobility and security, a single protocol signaling can be developed in a converged RAN/core architecture. Similarly, the separation of L2 and L3 may not be necessary for all 6G functions.

6G should support foundational functions supported by 5G radio protocols but also incorporate the AI and cloud aspects mentioned above. For the control plane, that includes basic features such as connection setup, access control, security, reconfiguration, mobility, and exchange of device capability. For the user plane, 6G MAC and above layers should support QoS, random access, buffer status report, in-order delivery, retransmission, header compression, and segmentation.

In 5G, much of RRC signaling design included the configuration of physical layer parameters, complemented by L2 signaling to activate physical layer features. For 6G, a streamlined signaling approach would improve agility and robustness and take AI into consideration.

Another area for evaluation is the design of service data adaption protocol (SDAP), packet data convergence protocol (PDCP), and radio link control (RLC). Those layers need to support very high data rates and low latency, suggesting that many time-critical components should be performed in hardware or in parallel. But 6G will also strive to support devices with zero or very low power consumption, potentially leaving such devices unable to support full protocol layers due to power limitations.

Expanding into new spectrum bands

As noted above, 6G will expand into new spectrum bands as well as operate in the same bands currently used by 5G and 4G systems, as shown in Figure 27. Upper mid-band spectrum in the 7 to 24 GHz range is being explored for 6G deployments, with a focus on the lower 9 GHz portion, from 7 to 16 GHz, which is well suited to provide high throughput and wide-area coverage. We believe at least one third of the 7 to 16 GHz swath of spectrum should be opened for licensed, exclusive use for 6G mobile terrestrial operations. 6G also is expected to use the sub-THz bands to support new, short-range use cases and applications that require extreme capacity.

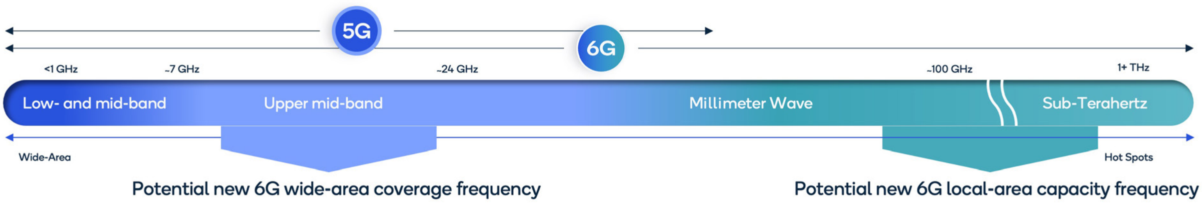


Figure 27: 6G is expected to improve utilization of existing bands and expand into new bands

Wide-area capacity in the upper mid-band

The main advantage of 7-16 GHz band is that wider bandwidth is available and signal propagation properties are more favorable than in higher, mmWave bands. The upper mid-band offers a balanced capacity/coverage trade-off, suitable for wide-area deployments, and it provides opportunities for new 6G technologies.

Active Antenna Systems (AAS) is a promising technology suitable for the upper mid-band. AAS technology allows for practical deployments with an extremely large number of antenna elements. Thanks to the shorter wavelengths in the upper mid-band, more antennas can be packed in the same aperture size. This is what we refer to as Giga-MIMO, an extremely large MIMO system that contains even more transmitter and receiver antenna elements than the 5G massive MIMO. The additional antenna elements can be utilized to effectively compensate for most of the attenuation due to higher frequency. In favorable propagation conditions, they can also increase the chances for supporting higher-rank transmissions and increased capacity.

Together with the potential availability of large bandwidths, lower phase noise, and higher power amplifier efficiency, advanced Giga-MIMO design at upper mid-band offers the high capacity of mmWave and the wide coverage of mid-bands. It also enables high timing/angular resolution for sensing and positioning. Topology enhancements can compensate for any increase in propagation losses and improve coverage. For instance, the introduction of RIS and smart repeaters can efficiently densify the network in providing broader coverage.

New bandwidth frontier in the sub-terahertz (sub-THz) bands

6G is poised to expand into even higher spectrum, including sub-THz bands between 100 and 300 GHz. The abundant bandwidth in sub-THz brings terabit-per-second (Tbps) throughput and sub-millisecond latency into the realm of possibility.

This spectrum range suffers inherently from severe path loss. To a considerable extent; however, that can be offset by high-gain narrow beams. The new bands allow for an extremely large number of antenna elements in the same or comparable form factor as lower bands.

Radio waves in high-frequency bands can enable use cases like communication and RF sensing, creating new business opportunities once 6G is deployed at scale.

Wireless fronthaul | Wireless data center | Wireless fiber to the home | Ultra-precise positioning | RF sensing

Figure 28: Sub-THz can enable new and enhanced use cases

Multi-RAT spectrum sharing

Traditionally, new spectrum needs to be allocated before the rollout of each generation of mobile communication, and vacating and refarming the existing spectrum can take years. The flexibility of OFDMA enables a much faster rollout in the existing bands by allowing multiple radio access technologies to share the same spectrum dynamically. For example, DSS is used to speed up the rollout of 5G in existing 4G bands. Cyclic prefix (CP) OFDMA serves as a common multiple access framework for both RATs to dynamically share time and/or frequency resource on the same carrier. More efficient spectrum sharing is expected for the migration from 5G to 6G, thanks to the forward-compatible design of 5G NR. In addition, systems with narrow beamwidth transmission and reception can enable spatial sharing mechanisms even across technologies and lead to new opportunities for sharing of spectrum.

Advanced spectrum sharing

If bands are not cleared for 6G operations specifically, spectrum sharing solutions should be explored to ensure that 6G deployments do not cause harmful interference to incumbent services while they achieve the desired 6G QoS. Co-existence with other services will have to be studied and evaluated, depending on the services discussed and their technical and operational parameters. Besides traditional sharing techniques that have been the cornerstone of service co-existence like exclusion zones, 6G's core technological advancements may introduce additional sharing scenarios. For example, with regard to satellite services, the use of AAS may allow 3D beamforming that can minimize interference to a satellite receiver. Suitable AAS design trade-off can minimize the base station's equivalent isotopically radiated power (EIRP) above the horizon by main lobe down-tilting and sidelobe suppression, which can meet the protection criteria in place. Similarly, sharing with incumbent radar systems may require static exclusion zones around low-power radars, and more dynamic sharing with high-power radars can allow for more efficient use of the spectrum.

Use case consideration for 6G spectrum

When 5G spectrum was allocated, communications-related requirements such as throughput, latency, and coverage were important. Given the expectation that 6G will support new capabilities beyond communication, such as RF sensing, it is important to keep new requirements in mind when considering suitable spectrum.

Table 1 illustrates sample use cases for sensing. To enhance ranging and angular resolutions, wider bandwidths and more antennas are beneficial. In higher-frequency bands, not only is bandwidth more abundant, but it also allows for more antennas in the same or comparable form factor as in lower-frequency bands.

Example of sensing use case families	Representative Requirements				
	Max range (m)	Max velocity (m/s)	Range resolution (m)	Doppler resolution (m/s)	Bandwidth (GHz)
Smart manufacturing / IIoT	200	9	0.1	0.5	3-5
Traffic maintenance, smart transportation	300	<70	0.1	High	0.4
Environmental monitoring	500	N/A	5	N/A	0.15
Human presence/ fall detection	<20	4	0.1	0.1	0.4
Gesture, activity, proximity detection	<2	<10	0.01	High	3-5
Remote sensing	500	40	1	5	0.15

Table 1: Sample use cases for sensing, with corresponding requirements

Communications resiliency

As mobile technology use cases broaden and connectivity becomes nearly ubiquitous, the end-to-end system — from cloud to network to device — requires greater resiliency in areas like security, privacy, and availability. 5G provides strong privacy protection (e.g., encryption of subscription permanent identifier, strict temporary identifier reallocation policy), authentication, user-plane integrity protection, slice-specific authentication and authorization, and service-based interface security. This section summarizes some of the research areas for communications resiliency in 6G (see Figure 29).

Figure 29: 6G security landscape

Native security

6G will enable a broader range of services than 5G, deployed or enabled at different locations across different network entities. Securing those services may involve different requirements at different protocol layers. For example, services like positioning may require more security for signaling at the physical layer, whereas edge services may rely on application-layer security. At the same time, IoT services that consume more power and edge services that are sensitive to latency may need different security to avoid unnecessary processing. It is expected that 6G will natively support security across all protocol layers and offer security configurations that adapt to different services.

5G introduced to the core network a service-based architecture that will likely expand toward the RAN. Service-based architecture facilitates zero-trust security with fine-grained service authentication and authorization. In 6G, both RAN and core network will benefit from advantages in scaling and service deployment of cloud-native architecture. That requires cloud-native security with DevOps (software development and IT operations) and a continuous integration/continuous deployment (CI/CD) pipeline integrated natively to the 6G system.

Best practices in cloud-native architecture[5] and in software supply chains (e.g., based on a software bill of materials or SBOM)[6] will enhance security of the 6G system, as depicted in Figure 30.
In particular, when integrated with DevOps and CI/CD pipeline, the SBOM containing the details and supply chain relationships of components will help identify and avoid known vulnerabilities on deployment. It will also streamline the software update/patch process.

[5] Cloud Native Security Whitepaper, Cloud Native Computing Foundation
[6] Framing Software Component Transparency: Establishing a Common SBOM, NTIA

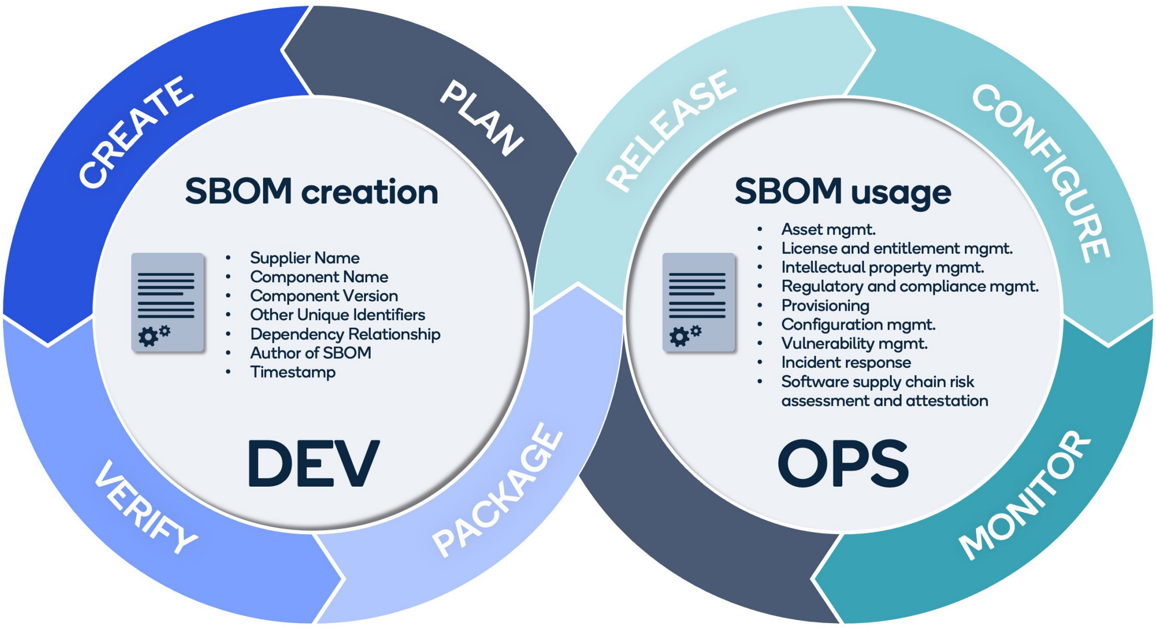


Figure 30: Software supply-chain security

Data security and privacy

6G provides a platform for compute-intensive tasks and collaborative intelligence like federated learning, relying on AI for network and service optimization and for user services.

An essential component of AI is the data collected from sources such as network entities, devices, and application services (see Figure 31). The data needs to be protected in transit and at rest and made available only to authorized entities; in particular that holds for data containing personally identifiable information (PII). 6G should include a robust data management framework that controls access to the data based on strong authentication and authorization. As regulations and use cases evolve, the user consent framework in 6G will enhance the framework in 5G for finer granularity and more dynamic consent.

The robustness of AI relies on the quality of the data used for training. Guarantees of data provenance — authenticity and proof of origin — ensure the quality of that data, including its veracity. AI applications using sensitive and/or private data should employ techniques like federated learning, homomorphic encryption, secure multi-party computation, confidential computing, and differential privacy.

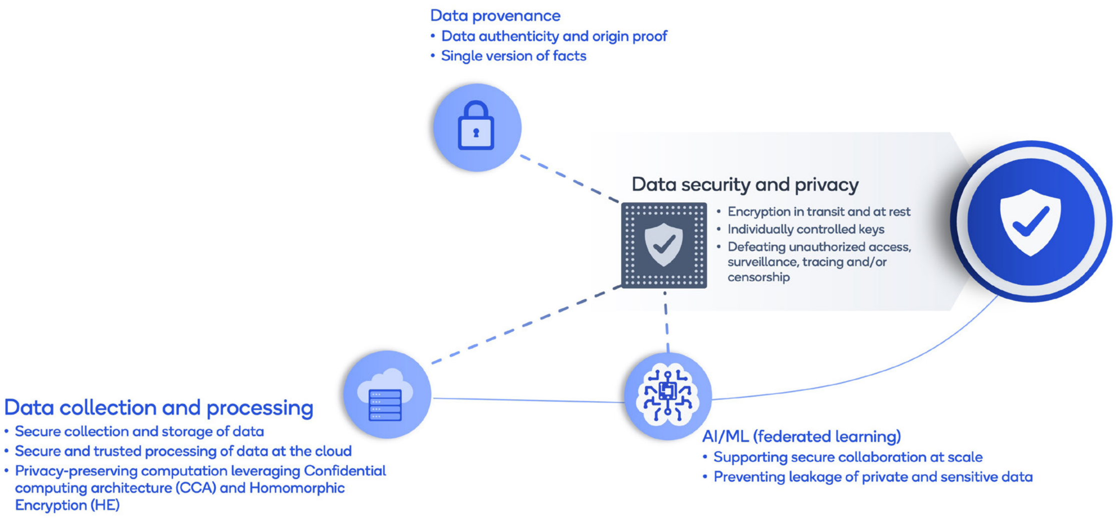


Figure 31: Data security and privacy techniques

Robust trust

As the 6G system becomes more disaggregated, comprises more entities, and introduces more services, it becomes necessary to establish trust among entities. For some operations, assuming implicit trust may lead to security breaches, so a secure and verifiable root of trust is essential for interactions between devices and network services, between network elements, and between devices. Beyond device authentication and remote attestation based on hardware, trust among entities can be hardened by using evidence endorsed by trust anchors like certificate authorities, reputation system, crowdsourcing, and multifactor authentication.

Zero trust in the architecture and security of the 6G system involves architectural support of continuous authentication and authorization. It also depends on rigid execution of authorization for the service and for resources accessed by devices, network entities, and other services. Zero-trust security is significant not only in service operations but also in onboarding network equipment and functions in the cloud, where virtualized network functions from different suppliers are continuously updated and added.

Post-quantum security

Quantum computing offers the potential to solve difficult problems beyond the abilities of classical computers. But some of those problems are deliberately difficult to solve. For example, quantum computing has proved capable of breaking widely used public-key cryptographic algorithms such as RSA and ECC[7], and of halving the security level of symmetric-key algorithms like AES[8].

For 6G, it is imperative to develop and support post-quantum security technologies because communication security needs to be unconditionally resilient to the advances of quantum computing technology. 6G systems will adopt quantum-safe cryptographic algorithms (e.g., NIST-selected algorithms) and choose those best suited to use cases and device/system capabilities. Also, cryptographic algorithms such as Quantum Key Distribution (QKD) and Quantum Random Number Generation (QRND) incorporate properties useful in protecting communication links and in offering communication resiliency.

[7] P. W. Shor, "Algorithms for quantum computation: discrete logarithms and factoring," Proceedings 35th Annual Symposium on Foundations of Computer Science, 1994, pp. 124-134
[8] Grover, Lov K.. "A fast quantum mechanical algorithm for database search". Proceedings of the Twenty-Eighth Annual ACM Symposium on Theory of Computing. STOC '96.
[9] https://csrc.nist.gov/projects/post-quantum-cryptography

Next steps

For the mobile and broader vertical ecosystems, it is full steam ahead toward 6G. On this path, 5G will evolve into 5G Advanced in the second half of the 5G decade, bringing new features and enhancements to realize the full potential of 5G. While the world is still at the very beginning of the journey to 6G, by all accounts 6G will be more than just a new radio technology. It will be a new, intelligent fabric that not only connects people and things, but also allows intelligence to scale across networks and devices at the connected intelligent edge. Along with new AI, compute, sensing, and green technologies, 6G will broaden its reach to every corner of the earth across land, sea, air, and beyond.

The roadmap of new technologies in 5G Advanced is rich, with the expected completion of Release 18 in 2023/24, followed by Release 19 around 2025. The technical foundation of 6G in many areas will be designed and prototyped as part of the evolution of 5G Advanced. As the vision for 6G is firming up and the world progresses toward the middle of the 5G decade, 3GPP is expected to begin its formal study on 6G around or after Release 20, focusing first on Study Items. Release 21 is anticipated as the official start of the 6G specifications, considering all system design requirements and design targets. As each previous generation has evolved over a decade, 6G is meant to evolve throughout the 2030s as an innovation platform supporting a wide range of devices, use cases, spectrum, and deployments.

At Qualcomm, we are working on all fronts to make 5G Advanced and 6G a reality, conducting advanced research and collaborating with leaders in mobile and vertical industries. The early vision of 6G is just starting to form, but the foundational research and early discussions on use cases and system design targets are already taking place. It is an exciting time for the world as the mobile communication ecosystem continues its quest to drive cutting-edge mobile technologies forward.

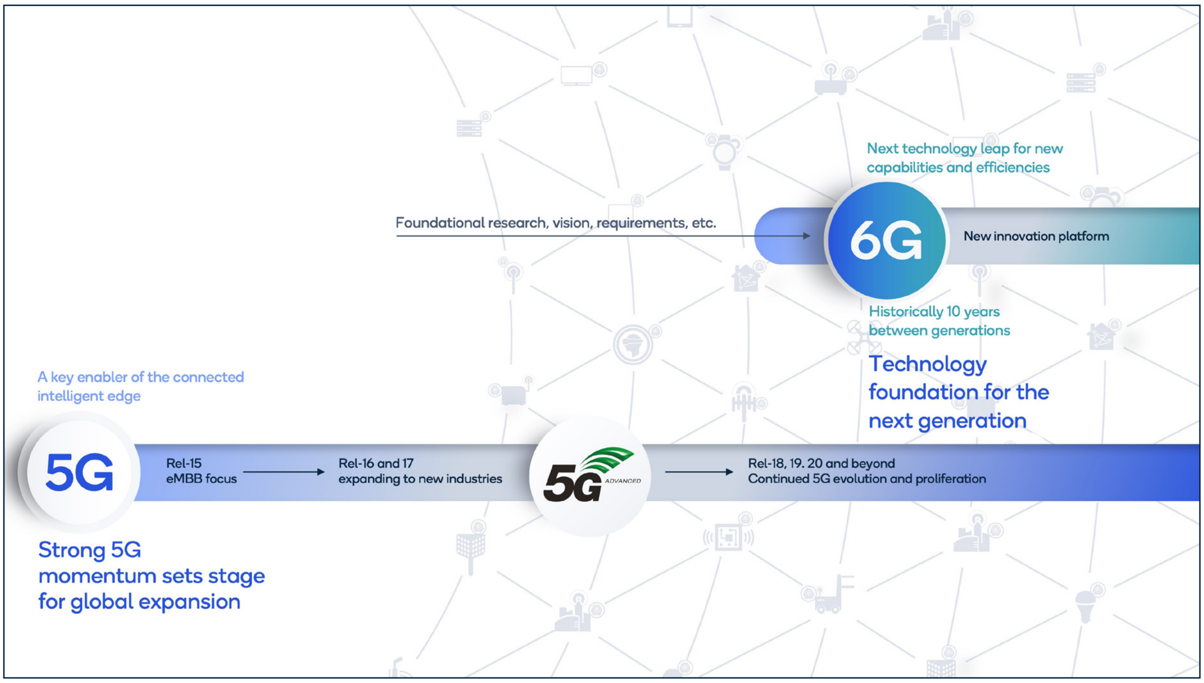


Figure 32: Path to 6G – enabling a connected intelligent future

To learn more about 5G evolution on the path to 6G, please visit:

https://www.qualcomm.com/research/5g

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