6G: The Next Horizon

From Connected People and Things to Connected Intelligence

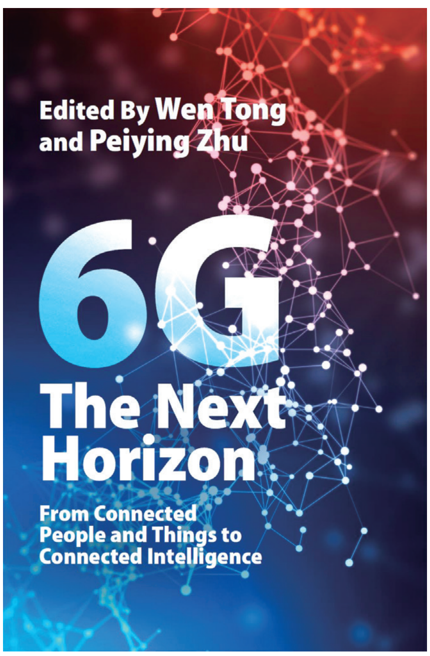
HUAWEI

Envisioning and Defining 6G Together

”Ten years may sound like a long time, but it passes very quickly. Whether or not we will provide a satisfactory answer by 2030 will depend on some crucial factors: Was the process of defining 6G open? Was there broad participation from a diverse range of players? Was there sufficient engagement? Have we delivered an attractive 6G vision? ... We hope that it will inspire more people, companies, and industries to bring broader and deeper perspectives to 6G. Huawei is also ready and willing to engage with our industry peers, with industry verticals, and with enterprises that may need 6G. Let's envision and define 6G together.”

Eric Xu

Deputy Chairman of the Board and Rotating Chairman of Huawei



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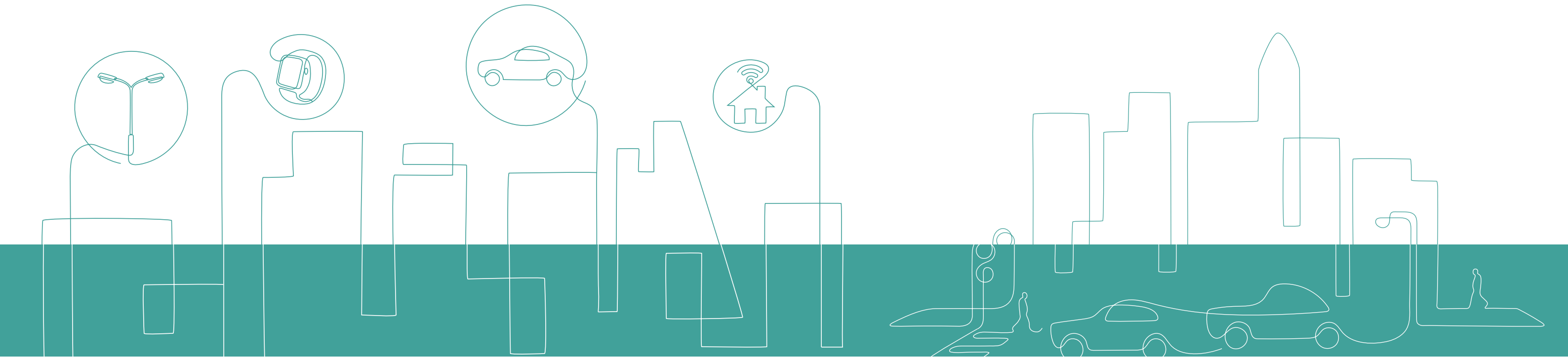

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Abstract

Wireless communication turned its first page in the early 1900s when Marconi transmitted the radio signal across the Atlantic. Since the 1980s, mobile communication has revolutionized the world, transforming every aspect of our lives. With the endless frontiers spanning 5G, we start wondering what 6G will be like. 6G — a more advanced next-generation mobile communication system — will go far beyond just communications. It will serve as a distributed neural network that provides links with integrated communication, sensing, and computing capabilities to fuse the physical, biological, and cyber worlds, ushering in an era of true Intelligence of Everything. Building upon 5G, 6G will continue the transformation from connected people and things to connected intelligence. In essence, it will bring intelligence to every person, home, and business, leading to a new horizon of innovations. In this paper, we present a holistic view of our 6G vision, exploring 6G key capabilities, new use cases and requirements, new building blocks, and paradigm shifts in air interface and network architecture designs. More details are available in our book "6G: The Next Horizon" recently published by Cambridge University Press [1].

Keywords

6G, connected intelligence, native AI, networked sensing, integrated sensing and communication (ISAC), extreme connectivity, integrated terrestrial and non-terrestrial networks, native trustworthiness, sustainability, paradigm shifts

1. Mega-trends and Key Drivers

New generations of mobile communications system emerge roughly every 10 years, while the mainstream services provided by mobile networks and the application of new frequency bands usually take two generations or more to mature. In fact, it took almost four generations to have people connected anywhere and anytime, leading to a connected society. With the rapid global commercialization of 5G starting around 2020, not only will society be better connected with enhanced communication capabilities, but also more devices in all kinds of business scenarios will be connected, moving from an era of connected society to one of connected everything. Following this trend, we envision that 6G will provide better connections for people and things, and will embrace the trend of a smart society, continuing the transformation from connected people and things to connected intelligence. In addition to the ongoing evolution of the three usage scenarios initiated in 5G [2], AI and sensing will become two new usage scenarios in 6G, as suggested in Figure 1. Three key drivers are leading mobile communications toward a new era of connected intelligence, as described below.

Driver 1: New Applications & New Business

In the 6G era, more applications will emerge. Extended reality (XR) cloud services together with haptic feedback and holographic display are likely to become mainstream human-centric applications. The exponential increase in the traffic demand per device, together with strict latency and reliability requirements, will become a major challenge for 6G network design in terms of the massive capacity needed.

At the same time, with the burgeoning numbers of IoT devices and the new capability of wireless sensing providing big data to learning algorithms, AI will become an engine for all types of automation. Big data will therefore become a major driver for the order-of-magnitude increase in 6G network throughput. Furthermore, high-performance industrial IoT applications will impose demanding requirements in terms of deterministic latency and jitter, while also needing guaranteed availability and reliability. Such use cases also drive the extreme and diverse performance that will be a defining feature in 6G.

Driver 2: Proliferation of Intelligence

The mobile industry has profoundly impacted people's life, helped to mitigate the digital divide, and contributed significantly to society's overall productivity and economic growth. This trend will continue into 2030 and beyond. In particular, as pervasive intelligence — supported by massive machine learning (ML), brute-force computing, and big data analytics — becomes the key enabler of business and economic models in the future [3], paradigm shifts in radio technology and network architecture will be driven by the following four critical factors, as shown in Figure 2.

- ### Native AI Support

For 6G, end-to-end (E2E) mobile communications systems will be designed with optimal support for AI and ML — not only as a basic functionality, by also for optimal efficiency. In terms of the architecture, running distributed AI at the edge will achieve ultimate performance while also addressing the concerns of data ownership. Truly pervasive intelligence, combined with deeply converged ICT systems that feature diverse connectivity, computing,

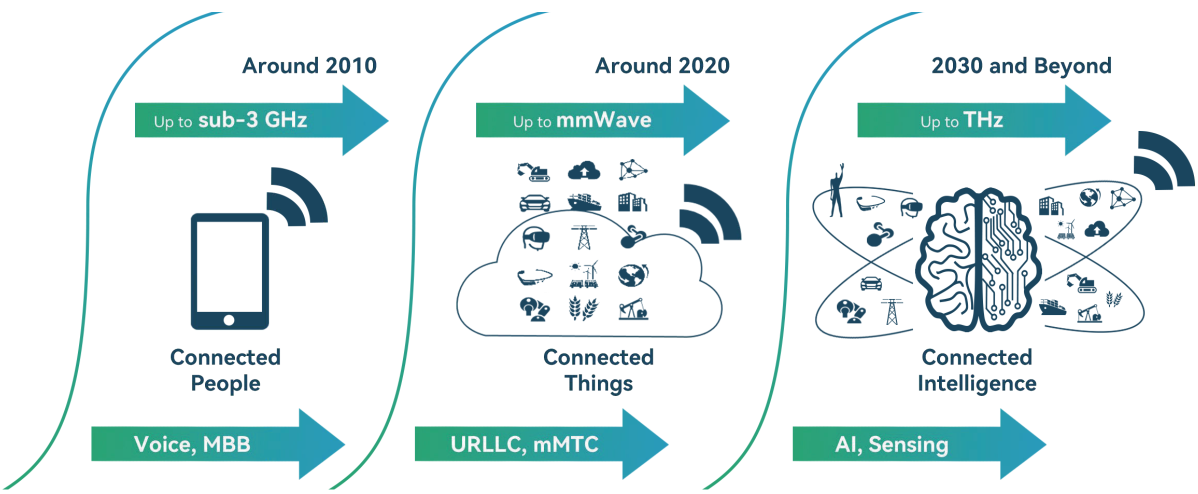

Figure 1 Mega-trends of mobile communications toward 2030 and beyond

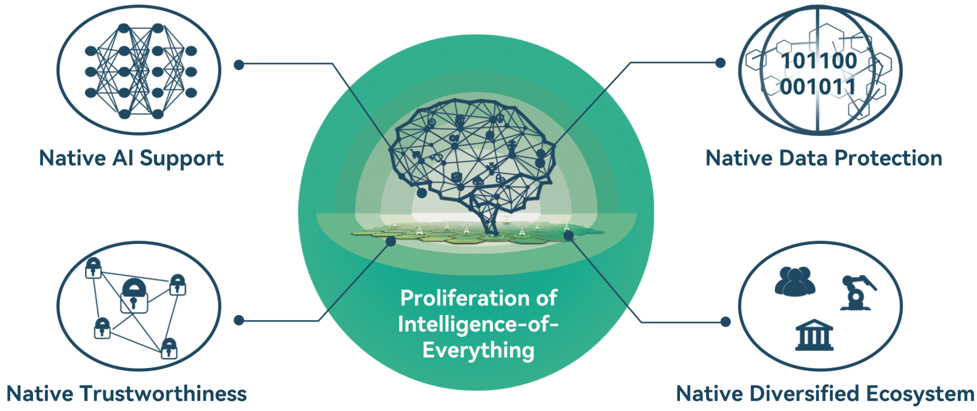

Figure 2 6G features driven by proliferation of intelligence

and storage resources at the edge, will become a native trait. The 6G network architecture with native AI support will bring "Networked AI", moving away from today's centralized "Cloud AI" [3].

- ### Native Data Protection

The protection of privacy in every aspect of 6G networking and data will be essential. We expect that users — which might be people or machines — will be empowered as data owners with control and operation rights. At the same time, the design of 6G should guarantee privacy, ensure the proper rights of data subjects, enable data control and processing, and support policies such as the General Data Protection Regulation (GDPR) [4] in order to establish fundamental guidelines for technology design and usage in the future.

- ### Native Trustworthiness

To support a diverse range of use cases and markets, it is essential to have customized, verifiable, and measurable trustworthiness. Today's nomothetic network ownership and operation will evolve into a many-party, many-player, and many-actor pattern, where an inclusive multilateral trust model — rather than a unilateral one — will be vital. In addition to being future-oriented, the trustworthiness architecture should incorporate security, privacy, resilience, safety, and reliability [5].

- ### Native Diversified Ecosystem

With 5G capabilities gradually expanding, the vertical wireless market is expected to ramp up throughout the 2020s. As we approach the 6G era, a universal ICT framework — one that could offer an overarching perspective for all industries and thereby accelerate the collaboration and convergence of ICT and OT sectors — would be extremely beneficial. The first wave of 6G commercial use is likely to boost both the consumer and vertical markets.

Driver 3: Sustainability & Social Responsibility

With multiple generations of technologies and spectrum deployments coexisting in mobile systems and the increasingly heterogeneous services running on top, there is high demand for sustainable development of 6G innovations. It is expected that deploying, operating, monitoring, and managing 6G networks and services will be cost- and energy-efficient, easy, and automated. Furthermore, 6G should be an enabler for achieving the sustainable development goals (SDGs) [7] of society as a whole.

2. Overall Vision and Capabilities

6G — a more advanced next-generation mobile communications system — will go far beyond just communications. Over the next decade, in addition to continuous wireless innovations, the rise of massive AI and the creation of massive digital twins will be the two major catalysts that fuel more technology breakthroughs. The resulting 6G will be a game-changer in terms of both the economy and society — it will lay a solid foundation for the future Intelligence of Everything.

We envision that 6G will enable the transformation from connected people and things to connected intelligence. Compared with its predecessor, 6G will offer extreme performance and realize major improvements in terms of key performance indicators (KPIs). Furthermore, it will be a key enabler in achieving the full-scale

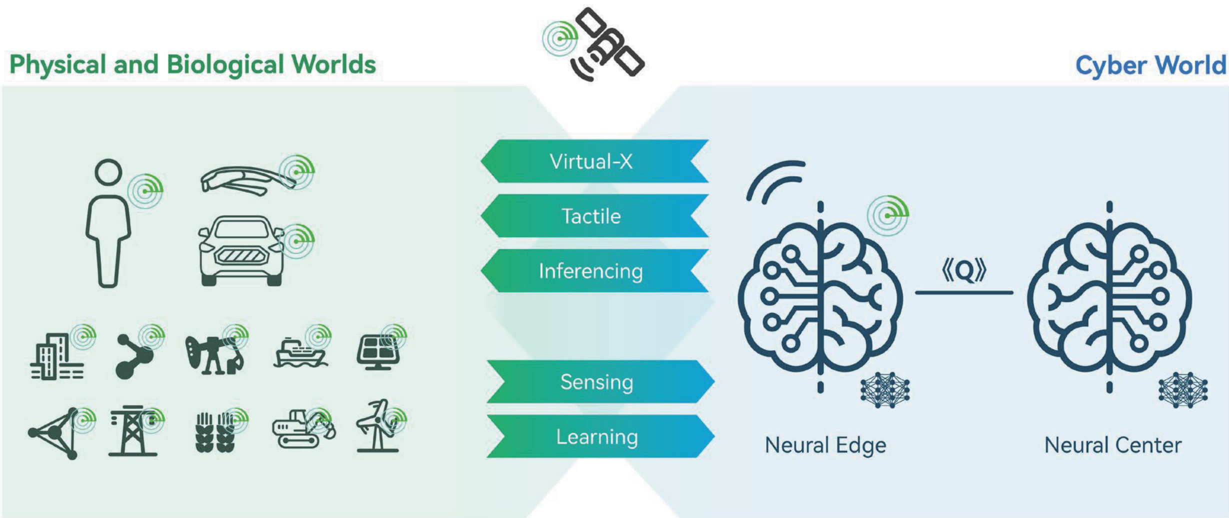

Figure 3 Fusion of physical, biological, and cyber worlds

digital transformation of all vertical businesses. More importantly, we believe that 6G will serve as a distributed neural network, providing links with integrated sensing, communication, and computing capabilities. This will fuse the physical, biological, and cyber worlds, ushering in an era where everything will truly be sensed, connected, and intelligent.

Figure 3 provides an overview of how the 6G network functions as the fabric of the converged physical and cyber worlds. First, from the cyber world to the physical world — this is a typical downlink channel — the primary service will be all kinds of XR, which, enhanced by tactile communication and new human-machine interface, creates immersive experience when interacting with the digital world. Meanwhile, the continuous deep learning in the digital world serves as AI engine for the physical world, providing real-time inferences to facilitate all kinds of decision making. This imposes major challenges on the radio interface design, requiring extremely high throughput and ultra-low latency. Second, from the physical world to the cyber world — this is a typical uplink channel — the primary application is sensing and the collection of big data for ML. How to compress and transmit the huge amount of data (or model parameters in the neural networks) for massive ML poses a new challenge. 6G will be a network of sensors and ML, where data centers will become neural centers, and ML tasks will spread over the entire network, from neural center to deep neural edges (e.g., base stations or even mobile devices).

In the following sections, we discuss the six fundamental technology pillars that will shape 6G, that is, the six technical directions for 6G, as shown in Figure 4.

Pillar 1: Native AI

6G will boast a native AI capability, which is neither an add-on nor an over-the-top feature. One of the primary objectives for 6G is to support AI everywhere. AI will be both a service and a native feature in the 6G communication system, and 6G will be an E2E system that supports AI-based services and applications. Specifically, 6G air interface and network designs will leverage E2E AI and ML to implement customized optimization and automated operation, administration, and management (OA&M). This is known as "AI for Network (AI4NET)", as shown in the upper half of Figure 5. In addition, each 6G network element will natively integrate communication, computing, and sensing capabilities, facilitating the evolution from centralized intelligence in the cloud to ubiquitous intelligence on deep edges. This is the concept of "Network for AI (NET4AI)" or "AI as a Service (AIaaS)", as shown in the lower half of Figure 5. For AIaaS, 6G functions as a native intelligent architecture that deeply integrates communication, information, and data technologies, as well as industry intelligence, into wireless networks, serving all types of AI applications with large-scale distributed training, real-time edge inference, and native data desensitization.

To achieve this vision, it is necessary to address three key challenges.

- 6G should be the most efficient platform for AI. This presents new challenges in terms of how to realize minimum cost for both communication and computation, each of which is a KPI for future study. To minimize communication costs, it is necessary to design a 6G system that can transfer massive big

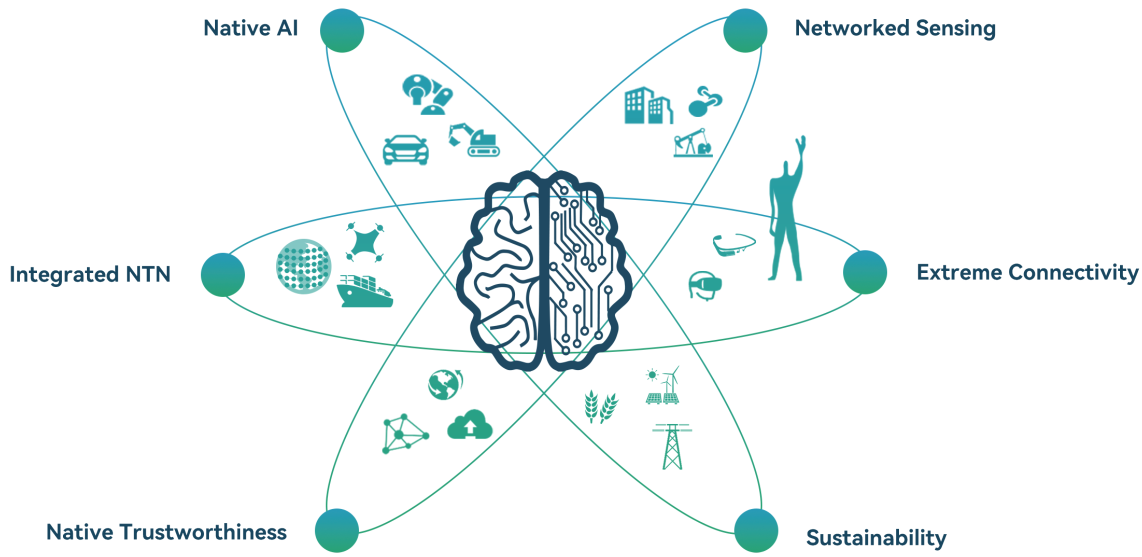

Figure 4 Six pillars of 6G key capabilities

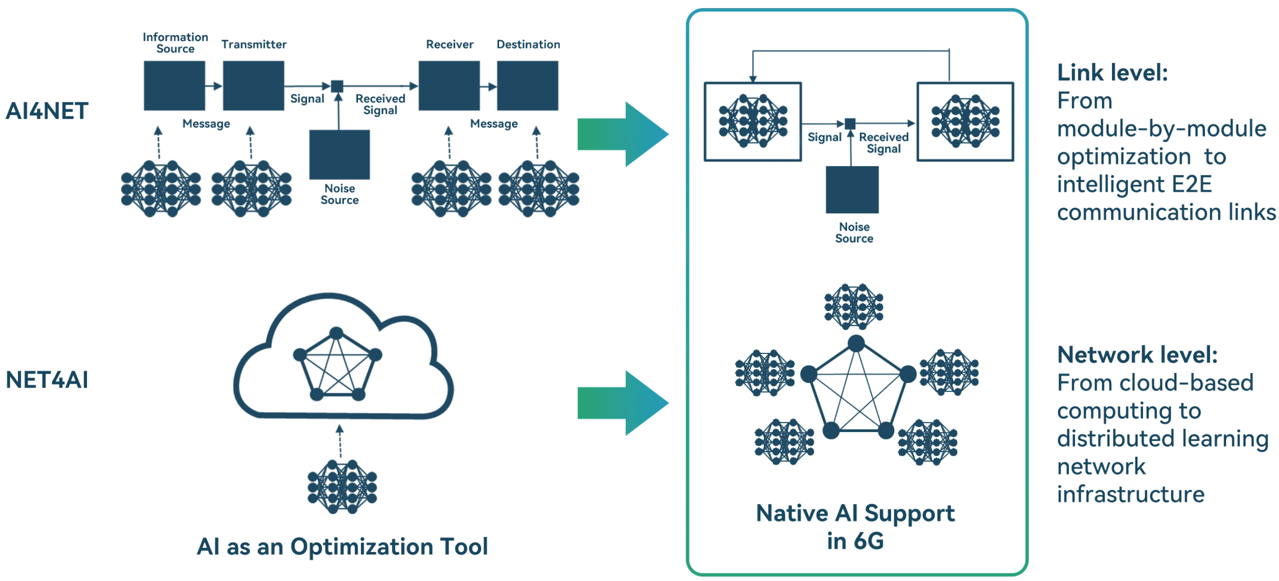

Figure 5 AI4NET and NET4AI

data for AI training using minimal capacity resources. To minimize computation costs, it is necessary to implement optimally distributed computing in the networks, where we can best leverage mobile edge computing.

- In order to support ML, 6G will need to enable the collection of massive data from the physical world (millions of times more data than at present) so that a cyber world can be created. This, however, poses another major challenge for 6G. As such, how to effectively compress training data based on information and learning theory becomes a new and essential topic in 6G research.

- An efficient and distributed collaborative learning architecture will be vital for reducing the computational load involved in large-scale AI training. Data split and model split for AI will be incorporated into the 6G network architecture. Furthermore, leveraging distributed and federated learning will help optimize computing resources, local learning, and global learning, and help meet the new data local governance requirements. In this sense, 6G core network functions will be pushed toward a deep-edge network, while cloud-based software operations will shift toward massive ML. In addition, with the frequent transfer of large amounts of data and models from deep edges (devices), the 6G radio access network (RAN) will shift from downlink-centric to uplink-centric.

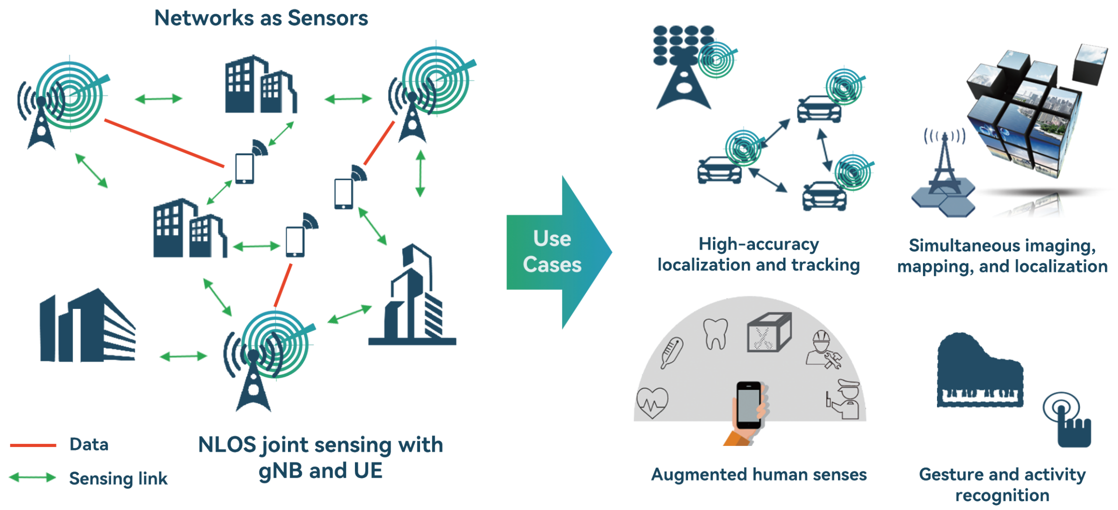

Figure 6 Networked sensing enables new services beyond communication

Pillar 2: Networked Sensing

6G will feature the networked sensing capability. Higher frequency bands (from mmWave up to THz), wider bandwidth, and denser distribution of massive antenna arrays in future 6G systems will enable a single system to integrate wireless signal sensing and communication, each of which mutually enhancing the other. The communication system as a whole can serve as a sensor, exploring radio wave transmission, reflection, and scattering in order to sense and better understand the physical world, ultimately providing a broad range of new services. This is known as "Network as a Sensor". Four categories of use cases that can be supported by 6G sensing are shown in Figure 6 and described later in Section 3. In terms of sensing, it enables high-accuracy localization, imaging, and environment reconstruction capabilities that could help improve communication performance — for example, more accurate beamforming, faster beam failure recovery, and less overhead to track the channel state information (CSI). This is known as "sensing-assisted communication". Moreover, as a foundational feature for 6G, sensing is a "new channel" that observes, samples, and links the physical and biological worlds to the cyber world. Real-time sensing is therefore essential to make the concept of digital twin — a true and real-time replica of the physical world — a reality in the future.

Traditionally, sensing is a standalone function with a set of dedicated devices and equipment, such as radar, lidar, computed tomography (CT), and magnetic resonance imaging (MRI). Mobile phone positioning in mobile systems, assisted by air interface signaling and device-based measurements, is an elementary sensing-like capability. Compared with the traditional methods of providing sensing functionality, the integrated sensing and communication (ISAC) design in the 6G network has two targets and potential benefits: to significantly reduce the cost of additional sensing equipment, and to leverage the large-scale cooperation between widely deployed base stations and user devices for improved sensing performance.

The ISAC functions can happen at different levels, ranging from loosely coupled to fully integrated and from shared spectrum and hardware to shared signal processing and protocol stacks. It can even include cross-module, cross-layer information sharing. Such integration will bring mutual benefits. Furthermore, it will enable technological innovations on new system KPIs and fundamental limits, new channel model and evaluation methodologies, joint waveform design, hardware co-design, new frameworks of protocols and procedures, cooperative sensing and data fusion, AI-assisted sensing, sensing-assisted ML, and much more.

It is also worth mentioning that recent developments in semiconductor technology have bridged the "Terahertz (THz) band gap" (caused by the lack of THz hardware enablers). These developments are expected to stimulate various THz sensing applications [8]. In addition to ultra-high resolution imaging, given the range of wavelengths and properties of molecular vibration, THz sensing can perform spectrogram analysis to identify the constituent parts of different types of food, medicine, and air pollution. Furthermore, due to its compact form-factor and non-ionizing safety, THz sensing can be integrated into mobile devices and even wearables to identify the number of calories in food and help detect hidden objects. As a result, 6G sensing devices will become a gateway for realizing numerous innovative AI applications.

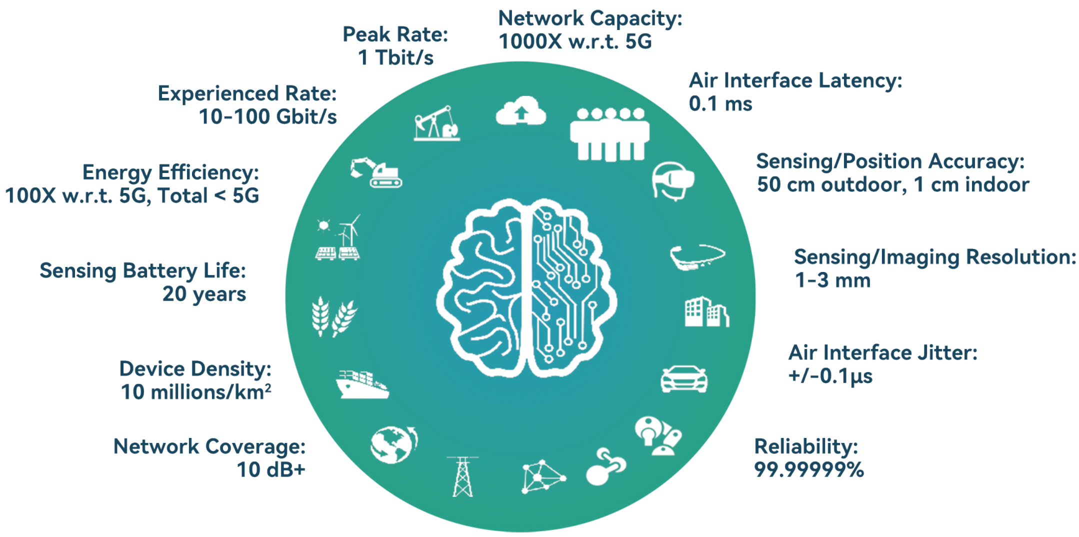

Figure 7 RAN KPIs for extreme connectivity

Pillar 3: Extreme Connectivity

6G will provide universal high-performance wireless connections and ultimate experience with speeds comparable to optical fiber. The major KPIs for the 6G RAN are shown in Figure 7. Up to Tbit/s peak rate, 10–100 Gbit/s experienced rate, sub-millisecond level latency, a tenfold increase in the density of 5G connections, centimeter-level localization, millimeter-level imaging, and E2E system reliability based on controllable error distribution will not only enable human-centric immersive services in the future, but also accelerate full-scale digital transformation and productivity upgrade of vertical industries.

The increase in wireless traffic drives the need for wider spectrum that usually comes with higher frequency, while the mobile communications system infrastructure favors the lower frequency spectrum for ubiquitous coverage. After several generations of wireless evolution, more and more new frequency bands are deployed for network upgrades. 6G will use not only the millimeter wave (mmWave) spectrum, but also the THz or even visible light spectrum, potentially using the entire spectrum for the first time in order to deliver ultimate extreme connectivity.

THz communication is a new wireless technology that involves numerous challenges. Research is currently exploring the design of high-power devices, new materials for antennas, radio frequency power transistors, THz transceiver on-die architecture, channel modeling, and array signal processing [9]. Whether THz technology is successfully adopted in 6G depends on the engineering breakthroughs in THz-related components such as electronic, photonic, and hybrid transceivers and on-die antenna arrays.

Communication through visible light is a potential radiation-free transmission technology that enables connectivity without an electromagnetic field (EMF). However, a large-scale micro-LED array technology will be required to attain data rates reaching tens of Tbit/s for short-distance communications with low power consumption, small form factors, and low-cost devices. In addition, visible light communication (VLC) [10] can access large amounts of unlicensed spectrum, but several challenges in terms of uplink transmission, mobility management, and high-performance transceivers must be overcome before VLC can be successfully utilized in 6G.

Pillar 4: Integrated NTN

6G will integrate terrestrial networks and non-terrestrial networks (NTNs) to deliver complete coverage worldwide, connecting the unconnected. As the cost to manufacture and launch satellites decreases, huge fleets of low- or very low-earth orbit (LEO/VLEO) satellites will become reality in NTNs — it is a strong possibility that 6G will integrate VLEO satellite mega constellations. A VLEO satellite system, in addition to delivering worldwide coverage, offers a number of new capabilities and advantages. For example, it eliminates the issue with communication latency inherent in conventional geostationary earth orbit (GEO) and medium earth orbit (MEO) satellite systems. It can also provide coverage to areas uncovered by terrestrial networks, offering complementary radio access. VLEO satellite systems can also provide more accurate positioning, which is critical for autonomous driving and important for earth sensing and imaging. Figure 8 shows some preliminary region characterization where using mega-LEO satellite constellation would achieve lower

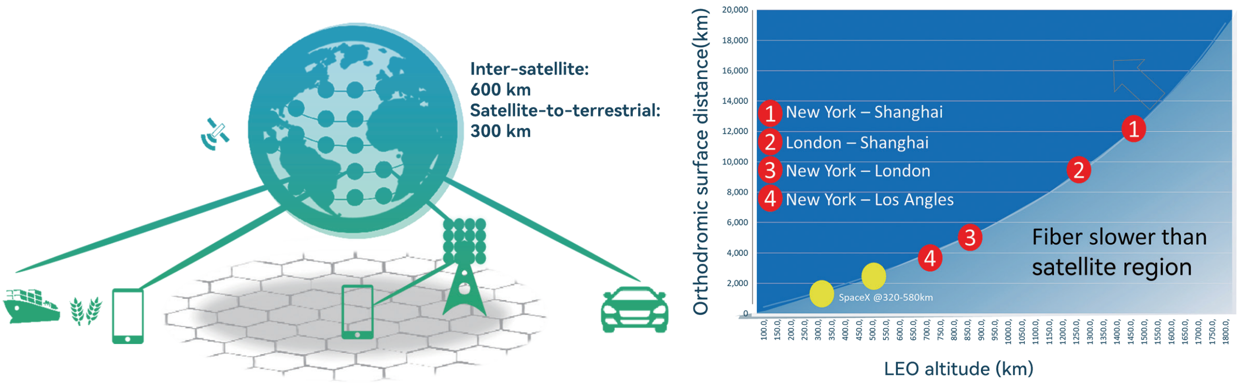

Figure 8 Integrated NTN for low-latency long-distance communication

transmission latency than traditional fiber over long-distance communication.

In addition to satellite communications, new radio nodes such as drones, unmanned aerial vehicles (UAVs), and high-altitude platform stations (HAPSs) will be an integral part of 6G, functioning as either mobile terminals or temporary infrastructure nodes. By integrating both terrestrial and non-terrestrial networks, 6G will stand apart from its predecessors.

NTNs are currently designed and operated separately. In the 6G era, however, their functions and operations, along with their resources and mobility management, are expected to be tightly integrated. Such an integrated system will identify each user terminal with a unique ID, unify billing processes, and continuously provide high-quality services via optimal access points. Moreover, with a virtualized air interface, the addition and deletion of a non-terrestrial access point would be transparent to user equipment (UE). Given that the deployment, maintenance, and energy source of satellites differ completely from those of terrestrial networks, it is expected that new operating and business models will emerge.

Pillar 5: Native Trustworthiness

The 6G network will integrate various capabilities such as communication, sensing, computing, and intelligence, making it necessary to redefine the network architecture. The novel network architecture should be capable of being flexibly adapted for tasks such as collaborative sensing and distributed learning to proliferate AI applications on a large scale, where trustworthiness should be guaranteed as a native feature. The concept of "trustworthiness" here covers topics including security, privacy, resilience, safety, and reliability [5].

Data, as well as the knowledge and intelligence derived from it, is the driving force behind 6G network architecture redesign, wherein new features will be developed to enable E2E native trustworthiness. These features include new data governance architectures that support data compliance and monetization, as well as advanced privacy protection and quantum attack defense technologies.

From a technology perspective, the security, privacy, and resilience established by cryptography and defense technologies are usually referred to as the three pillars of trustworthiness, which are underpinned by ten blocks (three in security, two in privacy, and five in resilience), as shown in Figure 9. The design objectives with regard to the three pillars and ten blocks are summarized as follows:

- **Balanced security:** Different protected assets or properties may require a different level of protection or different weight in each facet of integrity, confidentiality, and availability, depending on different scenarios.

- **Permanent privacy protection:** The identity and behavior of users are protected so that only those parties authorized by users are able to interpret the content of information transferred among them.

- **Smart resilience:** In order to provide and maintain an acceptable level of service while operations face various faults and challenges, situation awareness and big data analytics are leveraged to identify and then avoid or transfer risks. If this is not possible, the consequences must be controlled and only the residual non-harmful risks accepted [11].

Among the enabling technologies, the following two are of note:

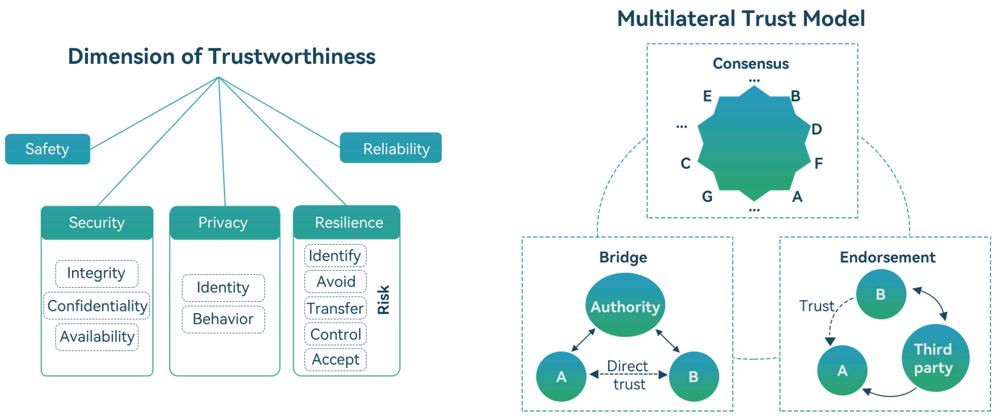

Figure 9 Dimensions of trustworthiness and the multilateral trust model

- **Multilateral trust model:** An inclusive multilateral trust model (including modes such as bridge, consensus, and endorsement) will serve as the foundation of future security systems. Because the 6G network architecture will trend toward a distributed nature, a consensus-based model may be the most important mode in the multilateral trust model. For this purpose, distributed ledger technologies (such as blockchain-like technologies) will be developed after new challenges in wireless networks are addressed. Such challenges center on how to achieve low latency, high availability, high reliability, strong privacy protection, and digital sovereignty.

- **Post-quantum cryptography:** As quantum computing continues to develop, challenges arise with regard to classical cryptography, which is based on mathematical problems such as large prime factorization and discrete algorithms. Key generation and exchange algorithms are two indispensable elements involved in cryptography. In 6G, one-time pad (OTP) encryption can be used with full-duplex communications at the physical layer in order to safeguard against quantum computing–based attacks. When quantum computing becomes reality, quantum communication technologies are expected to be more secure and have lower latency due to quantum entanglement. Lightweight cryptographic algorithms and privacy-compliance-related algorithms are some potential areas in this regard that warrant further research.

Pillar 6: Sustainability

Green and sustainable development is the core requirement and ultimate goal of network and terminal designs in 6G. By introducing the green design concept and native AI capability, 6G aims to improve the overall energy efficiency (defined in bits per Joule) 100-fold across the network and keep the total energy consumption (in unit of Joules) lower than 5G while also ensuring optimal service performance and experience. As the core infrastructure of the digital economy, 6G will have to make unique contributions to the sustainable development of humankind.

In terms of the research directions for E2E green 6G network design, the potential technologies to realize energy efficiency span architectures, materials, hardware components, algorithms, software, and protocols. Industry consensus needs to be established on the methodology used to evaluate sustainability across the entire ecosystem. Dense network deployment (leading to a shorter propagation distance), centralized RAN architecture (resulting in fewer cell sites and higher resource efficiency), energy-aware protocol design, and cooperation between users and base stations are some factors that need to be carefully considered in order to achieve an energy-efficient 6G communication system. In addition, renewable energy and radio frequency (RF) energy harvesting technologies as well as backscattering communication techniques (with no active RF power) should also be considered. As we move toward using higher and higher frequencies, finding innovative ways to deal with the reduced power amplifier (PA) efficiency becomes a major challenge [12], as shown in Figure 10-a.

Another significant challenge centers on computing power consumption due to the rise of AI. We can speculate that, on average, the human brain achieves data rates of 20,000 Tbit/s and can store 200 TB of information while consuming only 20 Watts. Conversely, the computing power of AI is doubling every two or three months, far in excess of Moore's Law. For a neural center to achieve the same capabilities as the human brain, there is a 1,000 times gap at a point of time near the end of Moore's

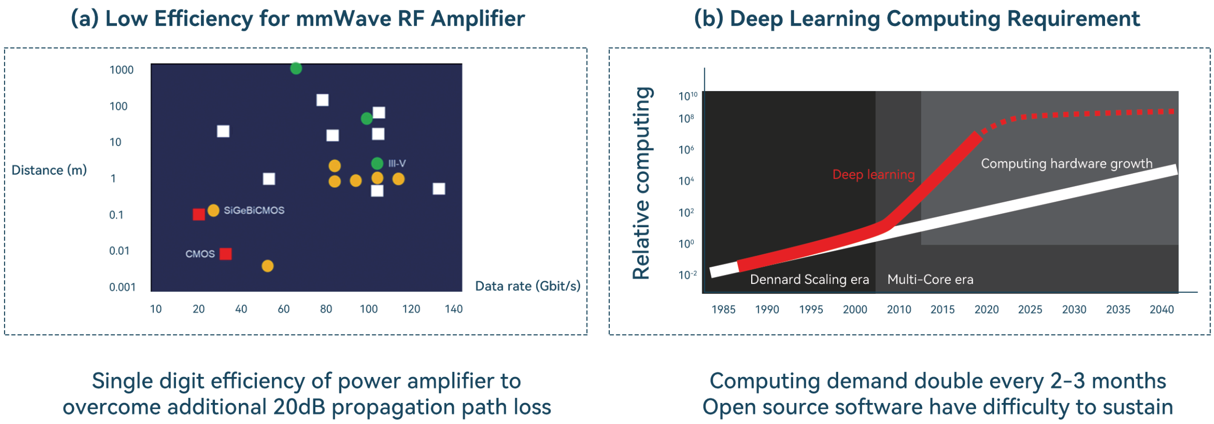

Figure 10 Two typical challenges for low power consumption in the 6G era

Law, as shown in Figure 10-b. In order for neural centers to replace data centers and fully leverage the potential of AI, it is imperative to use significantly advanced ML technologies that facilitate sustainable AI-based 6G [13]. A standardized approach to implementing a distributed computing architecture and software orchestration will enable the 6G network to be an efficient platform for a diversified ecosystem.

3. Use Cases and Requirements

There is a tendency to overestimate what can be done in two years but underestimate what can be done in ten years. As new technologies become more widely adopted in wireless communications systems, within the lifecycle of 6G, many aspects of our daily lives will be augmented by ultra-high speed and ultra-reliable wireless connections, native AI, and advanced sensing technologies. Based on the key capabilities required, we have identified five major categories of usage scenarios, as shown in Figure 11. Among these categories, eMBB+, URLLC+, and mMTC+ are extensions and combinations of the usage scenarios defined in 5G, while sensing and AI are two new usage scenarios that will flourish in 6G. In the following section, we explore these categories and provide examples of use cases and requirements under each category.

Usage Scenario 1: eMBB+

This usage scenario is the continuous evolution of enhanced mobile broadband (eMBB) for human-centric communication use cases. It will enable extremely immersive experience and multi-sensory interactions in XR applications — including augmented reality (AR), virtual reality (VR), and mixed reality (MR) — and telepresence. eMBB+ will pose much higher requirements on the peak data rate, user-experienced data rate, low E2E latency, and large system capacity (i.e., high throughput and supported connections). Furthermore, it will enable a range of use cases in entertainment, education, manufacturing, and

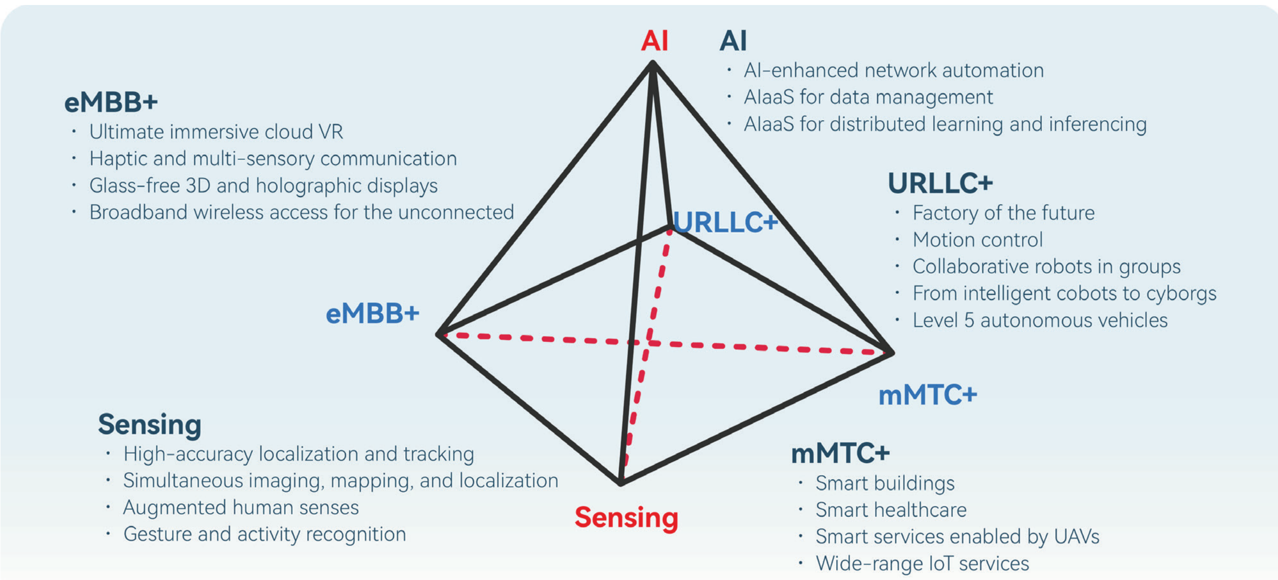

Figure 11 Overview of typical 6G use cases

navigation, transforming the way we live, learn, work, and travel. Both indoor and outdoor cases are needed, where seamless user experience in the target activity areas must be guaranteed along the E2E routes of activities, regardless of the high mobility in extreme cases. The user-experienced data rate in remote areas and on planes and ships must be maintained to support ubiquitous high-quality connections. Some examples of the corresponding use cases are discussed below.

• Ultimate immersive cloud VR

360° extremely immersive XR is an evolution of current XR services, offering an even higher resolution and video frame rate close to the limit of human perception. It provides an extremely low interactive latency, delivering the optimal immersive visual experience. For example, it will enable people to play football virtually with friends anywhere and at any time, or watch a live football match from the referee's perspective. To enable extended periods of use without making users experience dizziness, motion sickness is an important consideration in cloud VR. The target motion-to-photon (MTP) latency, close to the limit of human perception, is approximately 10 ms, which is half that of current VR requirements. In addition to requiring extreme video resolution and color depth, ultimate VR is expected to require more than a 100-fold increase in the raw data rate. Furthermore, an architecture that enables pure remote rendering is more suitable for devices that have limited computing capabilities — user devices often have strict constraints in terms of power and weight. In this case, a stringent transmission latency (an RTT of less than 2 ms) and higher data rate will be required.

• Haptic and multi-sensory communication

Haptic communication involves the exchange of real-time haptic information, including surface, touch, actuation, motion, vibration, and force information. This information is transmitted over the network along with audiovisual information. For example, haptic clothing can make a virtual football game feel more realistic, enabling the wearer to experience the texture, weight, and pressure of the virtual ball, or it can allow the wearer to receive a virtual hug from a family member far away.

Among haptic applications, teleoperation with interactive feedback (such as tele-surgery, tele-diagnosis, and tele-motion-control) in highly dynamic environments is the most challenging. In these cases, haptic feedback is important to stimulate the human brain and help users adjust their operation time, stress, gesture, and so on. This type of interactive teleoperation requires very low latency, with the RTT requirement for air interface transmission being as low as 0.1 ms. Furthermore, teleoperation imposes strict requirements on the relative transmission latency between audio, video, and haptic information, as well as on reliability and throughput.

• Glass-free 3D and holographic displays

While wearing VR devices, users always focus on the screen regardless of whether the displayed object is close or far away. Because this affects users' ability to perceive depth correctly, they may experience dizziness or other unwanted effects. Glass-free 3D displays based on visual accommodation are expected to be the next game-changing solution, relying on techniques such as light field and holographic display. Such displays would allow users to see far-away family members up close without the need to wear glasses, delivering an immersive and true-to-life experience. Allowing users to experience this anywhere and anytime requires support from the 6G mobile system. New applications such as mobile 3D navigation will require 3D images to be transmitted over mobile networks, giving rise to extremely high requirements in terms of network bandwidth. The raw data rates, depending on image size, resolution, color, and so on, will vary from sub-1 Tbit/s to a few hundred Tbit/s [14]. Research on compression techniques that can reduce the bandwidth consumption is ongoing.

• Broadband wireless access for the unconnected

Today, about 40% of people around the world lack access to mobile networks. Ambitious plans to integrate terrestrial and non-terrestrial networks in the 6G era aim to increase the coverage rate to nearly 100% worldwide, even in sparsely populated areas, expanding financial and social inclusion. For people in remote unconnected areas or ships, non-terrestrial networks can serve as relay links to terrestrial base stations.

Directly connecting non-terrestrial networks and mobile phones is an attractive prospect, as it ensures seamless switchover between different access services. For instance, it is important for people on the move to have a broadband connection. The integrated 6G system should provide optimal, scenario-specific MBB coverage for people in cars, trains, planes, and ships.

Furthermore, with the integration of terrestrial and non-terrestrial networks, 6G will be resilient against natural disasters, ensuring continuity of services.

Usage Scenario 2: URLLC+

6G will accelerate the comprehensive digital transformation of vertical industries. This usage scenario is the continuous evolution of ultra-reliable low-latency communications (URLLC) for critical machine-type communication (MTC) in Industry 4.0 and beyond [15]. It also applies to new applications enabled by the ubiquitous utilization of robots, UAVs, and new human-machine interfaces (HMIs) in manufacturing, public service, autonomous driving, and household management. To be more closely adapted to all kinds of vertical applications, the requirements on low latency and high reliability may be strict in first-order statistics (e.g., mean number of errors in a period) but controllable in the distribution or higher-order statistics (e.g., distribution of errors in a period).

• Factory of the future

Unlike traditional assembly lines, which are suited to mass production, factory of the future aims to implement full automation and flexibility, meeting the demands of mass customization. To enable this revolution, the 6G network will play a key role. The precondition for modules to freely move around in order to instantly form a customized assembly line is the use of ultra-high performance radio links, which untether machines from interconnection cables. Furthermore, with AI and digital twins, it will be possible to accumulate and share manufacturing experience and knowledge among machines and robots, helping optimize the evolving manufacturing process. 6G could also bring many other benefits to the factory of the future. For example, a ubiquitous RF sensing system would enable proactive maintenance of the entire production environment and processes. And, as the factory of the future requires no human onsite, lights-out manufacturing would significantly lower the OPEX and carbon footprint.

• Motion control

In addition to being one of the most challenging use cases, motion control is the core logic in the automation field [16]. It is responsible for controlling every aspect of a machine's movements in a well-defined manner. This type of operation already exists in modern manufacturing, but it is implemented via wired technologies such as industrial Ethernet. In order to realize a truly flexible production line, communication needs to be transformed from wired to wireless — for example, 6G. This requires ultra-high reliability (e.g., greater than 99.9999%) and low-latency (e.g., sub-ms or even μs) deterministic communication capabilities so that precise and reliable control can be achieved.

• Collaborative robots in groups

In the factory of the future, most of the major work will be performed by robots instead of humans. During production, numerous types of robots — such as automated guided vehicles (AGVs) and drones — will transport raw materials, spares, and accessories from the warehouse to the production line. For large or heavy parts, multiple robots will collaborate to transport them — this is known as collaborative carrying [16]. To achieve safe and efficient cooperation among these robots, a cyber-physical control application will be used to control and coordinate their movement. For example, carrying rigid or fragile parts requires precise coordination, whereas flexible or elastic parts allow a certain degree of freedom for higher efficiency. To maintain the level of accuracy needed for complex collaborative work, it will be necessary to leverage the synchronization, latency, and localization accuracy capabilities provided by the 6G network. In this case, a localization accuracy of 1 cm, an E2E latency of approximately 1 ms, and reliability greater than 99.9999% may be desirable.

• From intelligent cobots to cyborgs

Recently, collaborative robots — known as cobots — have appeared in the manufacturing industry. Unlike traditional robots that work in separate and restricted regions, cobots can collaborate and interact with people in close proximity. Like co-workers, they are expected to be intelligent (allowing them to understand the dynamic environment and tasks), cautious to human safety, proactive to actions and risks, and reliable in functionality. To achieve all of this, it is necessary to integrate AI, ICT, and OT. Furthermore, the high-performance sensing and communication technologies integral to 6G are essential to support cobots' mobility and interaction with humans.

Cyborgs, a concept laid out in 1960 [17], are the next evolutionary step of cobots. They are cybernetic organisms — humans enhanced with machines. For example, cyborgs could be used to enhance a person's strength or sensory abilities, or help someone overcome physical disabilities. With the development of neuroscience, 6G will be the key for cyborg interconnection.

- ### Level 5 autonomous vehicles

In terms of technical requirements, autonomous driving is the most challenging use case of smart transportation. The initial level of autonomous vehicles (typically used in scenarios such as mining, quarrying, construction, and agriculture) requires remote human driving and teleoperation.

Level 5 autonomous vehicles are a more advanced use case, which will redefine the meaning of traveling by car. As autonomous vehicles completely take over driving and route planning, journeys in such vehicles could be relaxing, enjoyable, and productive, while retaining the advantage of a private space. To deal with unforeseen situations, sensing and AI capabilities provided by 6G, as well as ultra-low latency, high reliability, and precise localization, will be essential.

Usage Scenario 3: mMTC+

6G will continue the journey started by 5G to connect everything, but it will do so with a broader variety of devices, new HMIs, higher density of connections, and native trustworthiness. This usage scenario is the continuous evolution of massive machine type of communication (mMTC), which is characterized by the massive number of lightly connected devices with sporadic traffic in smart cities, healthcare, buildings, transportation, manufacturing, and agriculture. The required data rate could range from very low to medium, and the packet arrival time interval could range from a day to a few milliseconds. A key requirement is for sensors to have a long lifetime, but this may differ significantly depending on their energy harvesting capabilities. In some cases, zero-power backscattering-based passive IoT devices would also be applied as an option for extremely low-cost connections.

- ### Smart buildings

Smart building refers to managing and controlling a building as intelligent entities with seamless information flowing among related parties, including electronic products, smart materials, control systems, and users. Integration is the first step in making a building smart. As a complex ecosystem, one building might contain many different subsystems, including surveillance cameras, elevator control, air conditioning, and electrical power. The usage of 6G in the smart building industry should enable a common infrastructure with high efficiency and intelligence to be built. In addition, due to the massive number of sensors installed in a smart building, they will need to support large-scale connectivity and low energy consumption. The second step is to interconnect buildings. In the future, mobile communication infrastructure will provide the digital foundation for cross-platform trustworthiness.

- ### Smart healthcare

Pervasive and customized healthcare services, free of geographical constraints, is the vision for smart healthcare in the future. As the mobile communications system develops, it will enable various new use cases to emerge, including dynamic monitoring of personal health, tele-diagnosis and pathology inference, holographic medical and recovery training, and tele-surgery. In particular, with the new sensing and AI capabilities in 6G, real-time analysis on patient data could prove extremely beneficial. Furthermore, use cases such as tele-diagnosis and tele-surgery will significantly reduce the pressure in an aging society, especially in regions that lack sufficient medical resources.

- ### Smart services enabled by UAVs

UAVs, commonly known as drones, come in a wide variety of sizes and weights, and they can be used in various sectors [18]. UAV applications may cover many fields, such as unmanned inspection for mining and exploration, and aerial filming for media and entertainment. However, the more advanced communication, sensing, and AI capabilities delivered by 6G will see UAV applications evolving to take more responsibilities in our daily lives. For instance, UAVs in 6G can act as mobile base stations and provide on-demand, high-capacity coverage to deliver live streaming of XR services and high-accuracy positioning services. And with autonomous driving capabilities, massive UAVs are expected to be utilized in future logistics to deliver packages over long distances. It is not beyond the realm of possibility that such UAVs could land on top of cars or buses to recharge during a long-distance delivery.

- ### Wide-ranging IoT services

Another area that will significantly benefit from 6G's global seamless coverage is wide-range IoT services. For example, 6G could enable the collection of information from buoys in the oceans to report container status during ocean transportation or from sensors in forests or deserts to forecast and prevent natural disasters in a timely manner. Wide-ranging IoT services will be extended to such unconnected locations to better protect the world.

Usage Scenario 4: Sensing

Networked sensing creates a new type of usage scenario beyond communication. It covers a range of use cases such as localization for device-based or even device-free targets, imaging, environment reconstruction and monitoring, and gesture and activity recognition [19]. The sensing usage scenario adds new performance dimensions to the International Mobile Telecommunications (IMT), such as detection probability, and sensing resolution and accuracy (in terms of range, velocity, and angles). The requirements of these dimensions vary from application

to application. For localization and reconstruction applications in the future, high sensing accuracy and resolution are required, whereas for imaging applications, ultra-high resolution is the key. And for gesture and activity recognition, detection probability becomes the top priority.

- ## High-accuracy localization and tracking

Empowered with sensing capabilities, the 6G network will be able to provide positioning services for device-based targets (similar to 5G) and localization services for device-free objects (similar to radar use cases). Latency, Doppler, and angular spectrum information from scattered and reflected wireless signals can be processed to extract coordinates, orientation velocity, and other geometric information in a physical 3D space. High-accuracy 3D localization and tracking down to the centimeter level enables meaningful association between cyber information and the locations of physical entities. As such, this will make various applications feasible, spanning from factories to warehouses, hospitals to retail shops, and agriculture to mining. For example, this could enable robots in an automated factory to easily retrieve parts on a warehouse shelf and install them accordingly [20].

In addition to high-accuracy absolute localization, applications such as automatic docking and multi-robot cooperation also pose high requirements on relative localization. When a swarm of robots collaboratively lift and carry a complex-shaped mechanical part or a drone docks with a moving vehicle that has a small landing margin, it is critical for each robot or drone to determine its locations with respect to others.

Further empowered by AI, future systems could also provide semantic localization with context awareness and dynamic address resolution according to service context. This would enable robots in restaurants to function similar to human waiters. For instance, a robot could deliver a glass of wine to a customer sitting by the window without requiring coordinates from a human.

- ## Simultaneous imaging, mapping, and localization

With simultaneous imaging, mapping, and localization, three sensing capabilities are mutually enhanced. The

imaging function captures images of the surrounding environment, and the localization function obtains locations of surrounding objects. The mapping function then uses these images and locations to construct a map, which in turn helps the localization function improve the inference of locations.

Simultaneous localization and mapping (SLAM) applications in the mmWave or THz bands enable sensing devices to construct 3D maps of the surroundings in unknown environments. In the context of 6G, sensing devices could be 6G base stations or terminals, including cars, drones, and robots. Compared with the traditional lidar and optical camera systems, SLAM via 6G wireless signals enables autonomous vehicles to obtain ultra-high resolution and accuracy in all weather conditions and the capability to see what is around the corner. Similar functions for indoor scenarios would allow robots and AGVs to move around freely even in crowded environments.

- **Augmented human senses**

Augmented human senses aim to provide a safe, precise, and low-power sensing capability superior to that of the human eye. With the THz ISAC technology that leverages the mmWave band, such capability could be integrated into a portable or wearable device, or even used in an implant.

The "seeing beyond eyes" concept — enabled by ultra-high resolution imaging — can be applied in daily life to find pinprick leaks in water pipes or implement contactless flaw detection and quality control in smart factories. This concept also means making the invisible visible. By utilizing the penetration characteristics of electromagnetic waves, applications such as security scans on packages or detection of cables in walls could be performed on portable devices or even smartphones. The larger radio frequency range being explored in 6G opens up the possibility to see through materials such as skin, subcutaneous fat, suitcases, and furniture. Spectrogram recognition is another part of this concept and is based on identifying targets through the spectrogram sensing of their electromagnetic or photonic characteristics. The unique absorption characteristics of different materials can be characterized by THz signals. Typical applications include food calorie detection and environmental PM2.5 analysis [21].

One of our prototypes, showcased at EuCNC2021 virtual booth (virtual.eucnc.eu), has demonstrated the feasibility of implementing THz imaging on portable devices. Leveraging communication waveforms, this prototype can sense and image a hidden object with mm-level resolution. More details can be found in [22].

- **Gesture and activity recognition**

Device-free gesture and activity recognition using ML is the key to promoting next-generation human-computer interfaces. It allows users to conveniently interact with devices through gestures and actions. Such recognition is divided into two types: macro and micro. Macro recognition refers to body movements. One example of this is to automatically supervise patient security in future smart hospitals — for example, to detect falls or monitor rehabilitation exercises. Compared with traditional camera-based monitoring, one of the key benefits of ISAC is privacy protection. Micro recognition refers to gestures, finger movements, and facial expressions. Imagine playing pianos and drawing pictures in the air but hearing real music and seeing real pictures created by XR at the same time. This will make it possible to truly create art anywhere anytime.

Usage Scenario 5: AI

This usage scenario aims to intelligently connect distributed intelligent agents in order to proliferate large-scale deployment of AI in all industries. Spectrally efficient, high-capacity, and low-latency transmission for distributed learning — including data and model parameter exchange among large numbers of intelligent agents — is expected for real-time AI. Native trustworthiness, with the support of native security and local data privacy, is a key enabler for this usage scenario.

- ### AI-enhanced network automation

Today, mobile networks require large workforces for network operation, administration and maintenance (OA&M). AI has great potential to relieve this major labor and financial burden. For instance, the network system itself could implement, operate, and manage network configurations and function deployment. Manual passive OA&M will evolve into zero-touch proactive OA&M — for example, by using predictive network analytic services and E2E system OA&M across all technical domains. AI in 6G will adapt to environmental changes and optimize both the communication and computing resources for optimal solutions that meet diversified requirements.

- ### AIaaS for data management

Huge volumes of data will be generated, collected, and exchanged in future mobile communications networks. Such data will be used to perform and optimize various network services related to operation and management tasks (e.g., for configuration management, fault management, and SLA assurance). Moreover, knowledge extracted from raw data could be exchanged with other systems or business sectors in order to generate a broader scope of value. Data is an essential asset for AI, but not all the raw data is high quality or usable. As such, it is necessary to support efficient data processing while reducing computational complexity and energy consumption. In this regard, AIaaS could be used to select high-quality data from vast amounts of raw data.

- ### AIaaS for distributed learning and inference

In the 6G era, software generation will be transformed from Software 1.0 (human coding) to Software 2.0 (data coding), in which massive data is provided to deep learning algorithms in order to generate deep neural network (DNN) models for each application. Following this trend, in 10 years, AI model providers will be field-specific OTTs or carriers, while AI inference capabilities will be delivered to individuals and vertical industries by public service carriers or operators. A mobile communications system that provides AIaaS for distributed learning and inference applications will be the key to meeting the real-time and large-scale learning and inference requirements of society and vertical industries in the future. In terms of distributed learning and inference services, the mobile communications network is not simply a big pipe to transmit bits and bytes; instead, it is a platform with integrated connectivity and computing capabilities designed to provide optimal resource scheduling in order to support learning tasks and achieve fast learning convergence. The benefits of this will go beyond the superior performance (e.g., ultra-low latency) achieved by bringing AI services closer to end users, while also meeting local privacy protection requirements.

4. New Elements

To meet the challenging requirements discussed earlier, in addition to the developments made in wireless transmission technologies, the 6G system will encompass many new elements such as new spectrum, new channels, new materials, and new devices. In this section, we discuss the candidates and challenges in each of these aspects.

New Spectrum

As the primary resource, spectrum is the main consideration for each generation of wireless communication technology — more spectrum is needed to support higher data rates. Furthermore, a globally unified process for spectrum allocation is critical for greater economies of scale and more convenient global roaming, both of which are important factors in realizing a successful industry on a global scale. As mobile communication technologies evolve to new generations, the use of spectrum continues to expand to higher frequency bands. While 5G was the first to use mmWave frequency bands, 6G is expected to explore even higher frequency bands, such as (sub-)THz. Although low- and mid-band frequencies are important for mobile communication systems to achieve wide coverage, 6G will apply the concept of a multilayered frequency band framework, as illustrated in Figure 12 and described later.

- **Low- and mid-bands remain the most cost-effective way for wide coverage.** Low bands (from 700 to 900 MHz) and mid-bands (from 3 to 5 GHz) play a crucial

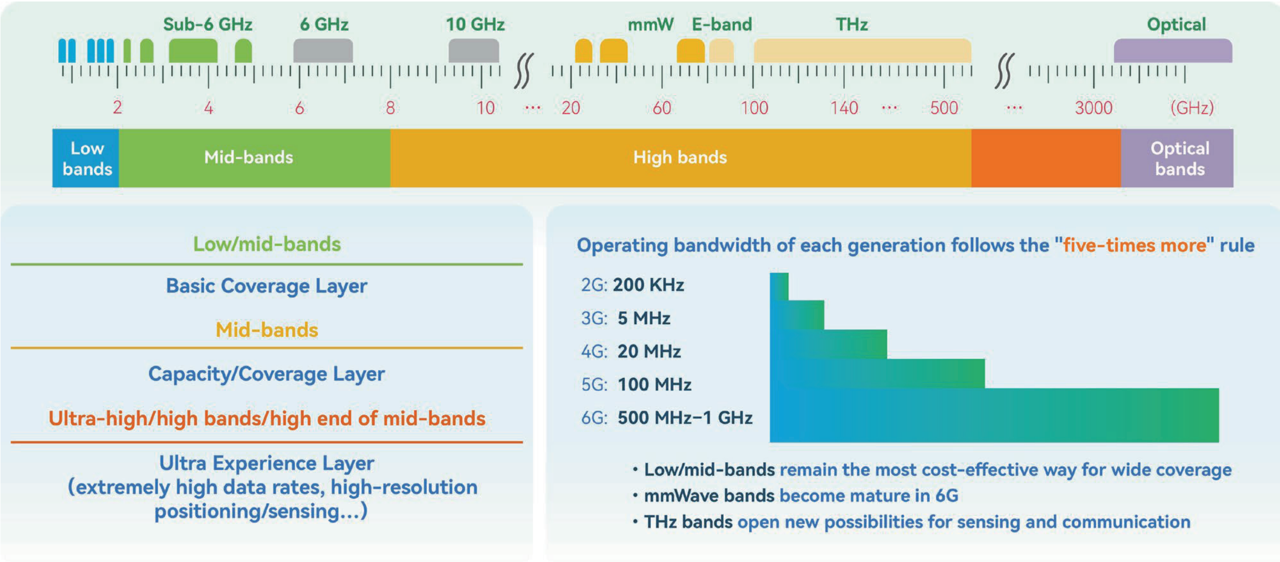

Figure 12 Multilayered frequency band framework

role in 5G and are expected to be vital in 6G as well. Toward 2030 and beyond, at least 1 to 1.5 GHz of additional mid-band spectrum is needed to support the continued growth of traffic, especially when considering multi-operator coexistence. The 6 GHz (i.e., 5925–7125 MHz) and 10 GHz (i.e., 10–13.25 GHz) bands are competitive candidates. Compared with 3.5 GHz, propagation attenuation will be increased in an acceptable range while path loss will be further reduced by more advanced radio technologies.

- **mmWave becomes mature in the 6G era.** Compared with low- and mid-bands, the mmWave band is more challenging due to more severe radio propagation characteristics. However, new drivers will emerge in the 6G era. First, a significant volume of available bandwidth in the mmWave bands is essential for the ultra-high data rates required in 6G. Second, mmWave bands are the key spectrum that can achieve a centimeter-level sensing resolution, which is especially important for mapping with network infrastructures. This is difficult for mid-bands due to practical limitations such as available bandwidth and antenna aperture size. Third, the evolution of more advanced radio techniques can also improve the utilization of the mmWave bands. E-bands (71–76 and 81–86 GHz) are prime candidates to support larger contiguous blocks in the future, where integrated access and backhaul (IAB) would be a key technology for efficient spectrum utilization.

- **THz bands open new possibilities for sensing and communication.** One of the most notable features of the THz bands is the potential to provide ultra-wide bandwidth. About 230 GHz of spectrum has been allocated to mobile services in the THz range of 100 to 450 GHz. This makes it possible to support very high data rates for short-distance (less than 10 meters) and mid-distance (e.g., 200 meters) communication. In addition, THz bands bring enhanced sensing resolution thanks to ultra-wide bandwidth and shorter wavelengths. In the future, smart phones integrated with THz sensing technology will be able to augment human senses — for example, they will detect calories in food, find pinprick leaks in water pipes, facilitate security checks, or monitor the skin and subcutaneous vascular health.

New Materials and Antennas

The tremendous evolution of digital communication over the past few years can be attributed to the remarkable progress made in semiconductor technologies. With 6G on the horizon, new material technologies will continue to evolve, facilitating the application of new spectrum and new antennas for new usage scenarios.

• Silicon advancement toward THz

Silicon technologies, which inherently have low cost, high yield, small geometry, and low power, have been used to continuously drive next-generation applications in communication, imaging, computing, and more. Based on the existing silicon platform — one that is already mature — advanced process features are added to enable new capabilities. For example, unlike the standard complementary metal-oxide-semiconductor (CMOS), the SiGe-BiCMOS platform can now successfully perform many applications simultaneously, such as imaging, spectroscopy,

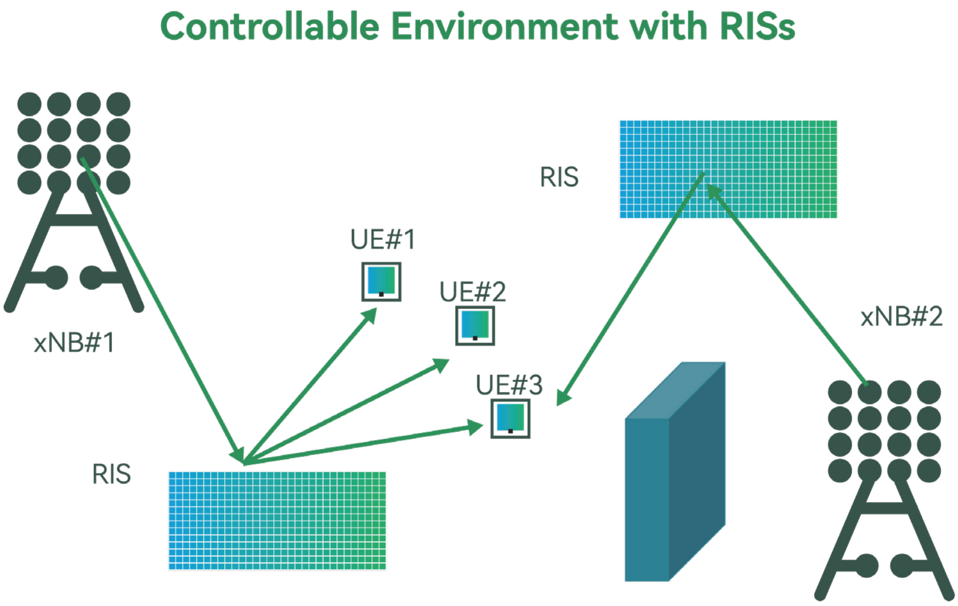

Figure 13 Use case example of RISs enabled by reconfigurable materials

and communication. Advanced processes allow for a more efficient and compact hybrid integration of both photonic and electronic components on the same silicon, something that is predicted to be realized in the near future.

Silicon technology, however, has fundamental limitations for photonic use due to its indirect bandgap. Type III–V semiconductors such as InP and GaAs with a direct bandgap were therefore proposed to overcome these limitations. But the high cost involved in such semiconductors has prevented their wide adoption across the market. To overcome the limitations of silicon while leveraging photonic features, heterogeneous integration of silicon with III–V semiconductors has emerged, combining the advantages of both. Integrating III–V materials on the same silicon wafer in a standard lithography process has shown great potential in many photonic applications.

The advancements of semiconductor technologies have made it possible for us to achieve a THz integrated circuit (IC). We can now fabricate ICs up to 700 GHz through SiGe heterojunction bipolar transistor (HBT) technology. Estimates indicate that the performance limit of SiGe HBT may reach or even exceed 1 THz in the near future [23]. Silicon THz ICs hold several advantages, such as low cost, compact size, high yield, and easy integration. A convenient way to implement a THz antenna involves directly integrating it with the frontend circuit on a silicon substrate. However, on-chip antenna design is challenging due to the surface wave generated in substrates. The surface wave will interfere with the antenna radiation and result in poor performance. Antenna-in-package is another possibility, although the interconnection loss between antennas and monolithic microwave integrated circuits (MMICs) is high. At THz frequencies, it is both desirable and challenging to realize the design and implementation of efficient and low-loss THz antennas.

- ## Reconfigurable materials and intelligent surfaces

Tuning of materials' electrical properties is desired in many cases because it allows for devices with more functions, smaller dimensions, and reduced costs. As such, various tunable materials have been proposed and embedded into systems for flexible and dynamic control. This tuning feature has enabled reconfigurable intelligent surfaces (RISs), which are controlled through a digital platform. RISs can manipulate the incident electromagnetic waves to desired outputs through carefully designed electromagnetic scatterers (meta-atoms), which are designed to induce phase or amplitude changes (or both) on the incident waves and can therefore perform beamforming and steering. These scatterers can be made of tunable materials and controlled electronically or thermally. For example, graphene, liquid crystal, and phase change materials have been used for such surfaces and demonstrated feasible for realizing dynamic control.

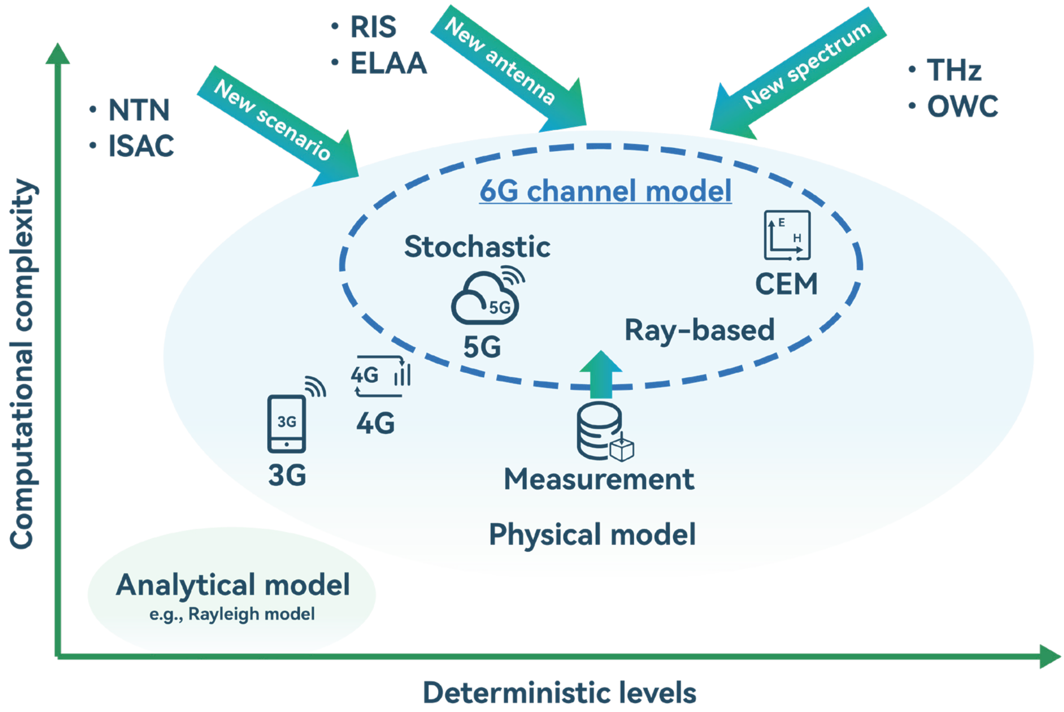

Figure 14 New challenges in channel modeling for 6G

Figure 13 shows a use case example of RISs enabled by reconfigurable materials [24]. The RISs can be used to extend the coverage from outdoor or indoor base stations to users, vehicles, or AGVs in cases where there is no direct link between them or the link is blocked by obstacles. By tuning the phases of elements, the RISs can direct their beams to the target end users dynamically and relay information to the desired locations with attenuation compensation. Beamforming at a base station and reflecting phase control at the RISs can be jointly optimized to maximize multi-user performance. In addition, the potential large apertures may help enhance resolutions in sensing applications.

New Channels

Radio wave propagation is a fundamental part of wireless communications. Before constructing and operating real-world systems, we must understand the principles of radio propagation and develop the associated channel models. These models represent the key propagation processes and allow for meaningful evaluation of and comparison between different systems [25].

The methodology of channel modeling is roughly divided into three categories: deterministic, stochastic, and hybrid. In deterministic models, the physical propagation parameters are fixed, meaning that the real physical channels in specific scenarios can be reconstructed using techniques such as computational electromagnetics (CEM), ray tracing, and measurements. Stochastic models are usually built upon the distribution of scattered clusters, which are randomly generated by a specified probability density function. Hybrid models (also known as quasi-deterministic models) are a combination of the other two models — they typically combine the dominant paths calculated by deterministic models and scattering paths generated by stochastic models.

In terms of large-scale system-level evaluation, stochastic models, as adopted in 3GPP, are usually simpler and more efficient than deterministic models. However, these models cannot express the deterministic parameters related to a specific system or scenario. For example, they cannot express geometrical information related to multipath channel parameters or locations of communication devices or scatterers. Deterministic models are usually applied when precise characterization of the channel environment is needed, but this increases computational complexity. From 3G to 5G, research on the channel model tended to focus on improving the deterministic levels under limited complexity.

In 6G, channel modeling faces new challenges introduced by the potential new spectrum, antennas, and scenarios, as illustrated in Figure 14. A single type of channel modeling scheme may not be sufficient to meet the evaluation requirements of all usage scenarios in 6G. In contrast, usage scenario-dependent channel modeling might be a viable option, while a potential hybrid model that achieves a good trade-off between accuracy and complexity is

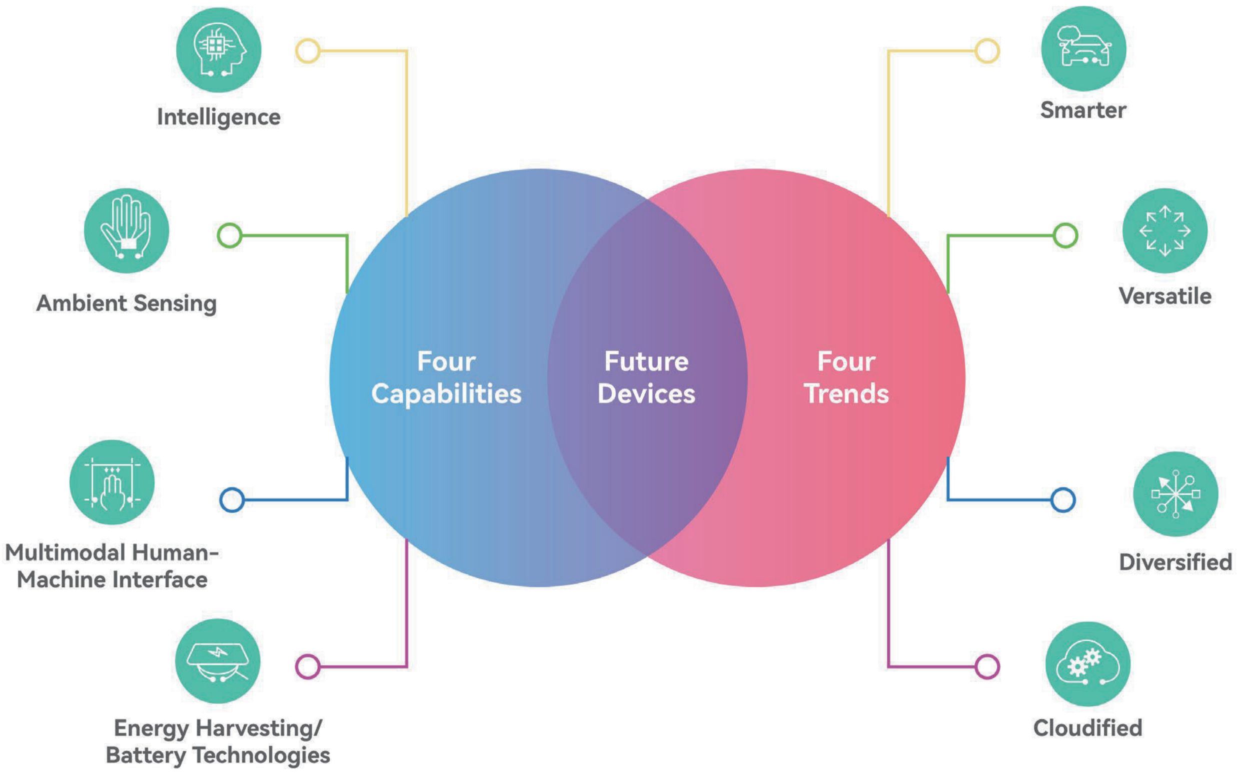

Figure 15 Capabilities and trends for future devices

worthy of investigation. Some examples and challenges are discussed below.

- **New spectrum:** As the spectrum goes beyond 100 GHz into the THz bands, the free space path loss increases accordingly. To compensate for this impact, more advanced beamforming technologies would be needed; otherwise, the applied range will be limited. One challenge in particular for the THz band is the so-called molecular absorption phenomenon. This is where THz signals excite gas molecules in the atmosphere, converting part of the signal power into kinetic energy of the gas molecules. In terms of small-scale fading, measurement results [26][27] show that, similar to mmWave signals, THz signals also exhibit multipath propagation characteristics especially in indoor scenarios, enabling multi-stream transmission in THz bands.

- **New antennas:** With the development of ultra-massive MIMO, new antenna structures such as extremely large aperture arrays (ELAAs), RISs, and orbital angular momentum will significantly affect channel modeling and performance evaluation. For instance, ELAAs bring new channel features, such as near-field spherical waves and non-stationary channels, which need to be characterized. For RISs, in addition to the near-field effects, scattered models such as cross-polarization rates, incidence-angle-dependent phase shifters, and non-ideal impairments will be important features that need to be modeled in order to determine the beneficial application scenarios of RISs.

- **New scenarios:** New scenarios such as ISAC depend heavily on the surrounding environment, especially for scatterer distribution, which is difficult to describe through stochastic models. In this case, deterministic models related to some specific geographical areas are preferred. Which type of model to use for sensing-assisted communication is still an open question. In addition, for NTN scenarios with satellites, the upper atmosphere and clutter loss in the propagation model need to be considered, while for drones serving as base stations, new channel models with moving base stations would be developed.

New Devices

The next revolution of mobile devices, like smartphones replacing feature phones in the past 20 years, is expected to occur in the 6G era. It is anticipated that future devices will adopt new capabilities — such as sensing and imaging, haptic communications, holographic display, and AI — that are enabled by the 6G communications system. These new capabilities may also include human-level perception,

ambient sensing, multimodal human-machine interaction, and energy harvesting, as shown in Figure 15. Such capabilities will transform today's devices, which function as "intelligent assistants connecting physical and cyber worlds" into ones that function as "hyper terminals in a converged physical-cyber world". In the following section, we discuss the four major trends that are driven by the development of these new capabilities.

- **Smarter:** This refers to not only making smartphones smarter, but also augmenting realities to automate everything. In the future, mobile devices will be able to implement AI capabilities and offload computationally intensive tasks to edge clouds. With AI/ML and the development of short-range communication technologies in 6G, devices in the future will have greater intelligence. They will also automate more aspects of our life, improving our service experience and productivity.

- **Versatile:** This refers to not only providing connectivity, but also offering novel sensing capabilities to open up new possibilities for future mobile applications. In the future, devices with multi-sensory capabilities could be integrated into humans to advance the human race, forming cybernetic organisms. Novel sensing capabilities will create the potential for mobile devices to support many new functions, such as imaging, spectroscopy, healthcare monitoring, and gesture recognition.

- **Diversified:** This refers to not only smartphones, but also various types of devices that act as sensors and actuators. In the future, a wide range of human-centric and industrial devices will emerge, integrating advanced sensors, new display technologies, and AI — for example, wearable devices, implantable medical devices, automobiles, robots and cobots, and smart factory equipment. The explosive growth of diversified devices will pose higher requirements on interconnectivity. Anchor devices will help to provide a seamless and consistent user experience.

- **Cloudified:** This refers to not only physical devices, but also virtual devices that enable privacy protection and new business models. In the future, each 6G device will have a virtual counterpart in the cloud acting as its proxy. Such devices are shared in public places and used on demand. With virtual devices in the cloud, users can access desired services anytime and anywhere via shared devices.

In addition to devices, the interfaces between them and humans will also evolve. The brain-computer interface

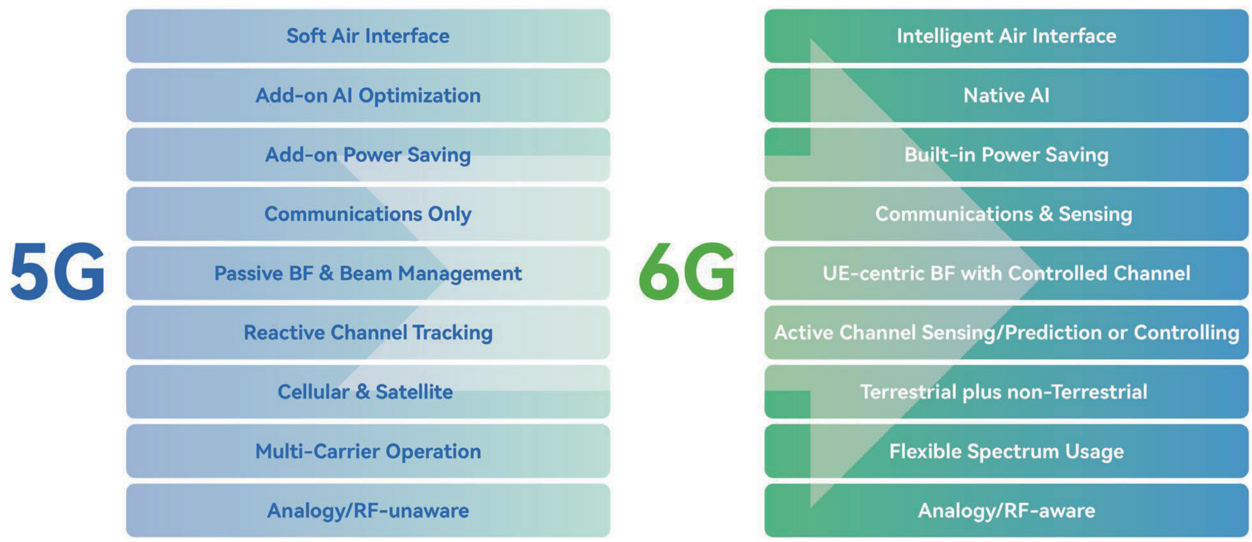

Figure 16 Paradigm shifts of future air interface design

(BCI) concept, first introduced in the 1970s, has undergone significant development. Today, with the help of better neural knowledge and novel neural sensors, implantable multimode sensory neurochips (integrating touch, smell, sight, hearing, and taste functions) are not far from reality. This will enable the human brain to communicate directly with devices in the future, a quantum leap from today's interaction via a screen and keyboard on smartphones.

5. Enabling Technologies and Architectures

In this section, we focus on the paradigm shifts in air interface and network architecture designs. More detailed discussions on the enabling technologies and architectures are provided in [1].

Paradigm Shifts in the Air Interface Design

To serve the diversified use cases discussed in Section 3 and meet the challenging goals toward an era featuring connected intelligence, revolutionary breakthroughs are required in 6G air interface design, triggering paradigm shifts in the design philosophy, as highlighted in Figure 16.

• From soft air interfaces to intelligent air interfaces

The 6G air interface design, powered by a combination of model- and data-driven AI capabilities, is expected to enable tailored optimization of air interfaces for different users. The personalized air interface can customize the transmission scheme and parameters at the UE-level to enhance experience without sacrificing system capacity. Furthermore, it can be scaled easily to support the near-zero-latency URLLC. In addition, a new signaling mechanism — one that is both simple and agile — will minimize the signaling overhead and delay.

• From add-on AI optimization to native AI

For 6G, AI will be a built-in feature of air interfaces, enabling intelligent physical layer (PHY) and media access control (MAC). Rather than being limited to network management optimization (such as load balancing and power saving), it will also replace some non-linear or non-convex algorithms in transceiver modules, or compensate for deficiencies in the non-linear models. AI will not only make 6G PHY more powerful and efficient, it will also facilitate the optimization of PHY building blocks' parameters. Furthermore, it will help provide new sensing and positioning capabilities, which in turn will significantly change the design of air interface components. AI-assisted sensing and positioning will also make it possible to implement low-cost and highly accurate beamforming and tracking. In addition, intelligent MAC will provide a smart controller based on single- or multi-agent ML, including cooperative ML for network and UE nodes. For example, with multi-parameter joint optimization and individual- or joint-procedure training, enormous performance gains can be obtained in terms of system capacity, UE experience, and power consumption.

- **From add-on power saving to built-in power saving**

Minimizing power consumption for both network nodes and terminal devices should be a key requirement in the design of 6G air interfaces. Unlike the power saving mechanism used in 5G, where power saving is an add-on feature or optional mode, power saving in 6G will be a built-in feature and default operation mode. With intelligent management of power utilization, an on-demand power consumption strategy, and other new enabling technologies (such as the sensing- and positioning-assisted channel sounding scheme), we anticipate that both the network and terminals in 6G will feature significantly improved power utilization efficiency.

- **From communication only to integrated sensing and communication**

The communication network as a whole can serve as a sensor with high resolution and good coverage. It can be viewed as a sensing network that generates useful information (such as locations, Doppler, beam directions, and images) for new services such as localization, tracking, and environment monitoring while also functioning to assist communications. In addition, the sensing-based imaging capability on terminal devices offers new device functions such as imaging. A new design requirement for 6G involves building a single network that integrates both sensing and communication functions under the same air interface design framework. We hope that a carefully designed communication and sensing network will offer full sensing capabilities, while also meeting all communication KPIs more effectively.

- **From passive beam management to UE-centric beam operations with controlled channel**

Beam-based transmission is important for high frequencies such as mmWave. Major efforts are needed in order to generate and maintain the precise alignment of the transmitter and receiver beams. Beam management in 6G, however, is likely to be more challenging due to the exploration of even higher frequency ranges. Fortunately, with the help of new technologies such as sensing, advanced positioning, and AI, we can replace the conventional beam sweeping, beam failure detection, and beam recovery approaches with proactive UE-centric beam generation, tracking, and adjustment schemes. In addition, "handover-free" mobility can be realized at the physical layer, at the very least. New intelligent UE-centric beamforming and beam management technologies will enhance UE experience and overall system performance. Moreover, the emerging RIS and moving nodes such as drones make it possible for us to shift from passively dealing with channel conditions to actively controlling them. In this case, the radio transmission environment can be changed to create the desired transmission channel conditions for optimal performance.

- **From reactive channel tracking to active channel sensing/prediction or controlling**

In order to achieve highly reliable wireless communications, it is imperative to have accurate channel information. But, due to the delay involved in measurement and reporting, and the pilot overhead (especially for high-speed mobile UEs), obtaining real-time channel information is difficult. Sensing- and positioning-assisted channel sounding powered by AI can transform pilot-based channel acquisition into location-aware channel acquisition. With the information obtained from sensing/positioning, we can dramatically simplify the beam search process. Furthermore, proactive channel tracking and prediction can provide real-time channel information and eliminate channel aging. In addition, new channel acquisition technology minimizes both channel acquisition overhead and power consumption for network nodes and terminal devices.

- **From cellular plus satellite systems to integrated terrestrial and non-terrestrial systems**

Recent 5G standard releases have been extended to include satellite networks but as separate systems [28]. As a step further, by integrating terrestrial and non-terrestrial systems, it is expected that 6G will achieve universal coverage and on-demand capacity. In 6G, the satellite constellation will be viewed as a new type of network node due to the tight integration of terrestrial and non-terrestrial systems. Combining the designs of both systems will make multi-connection joint operations more efficient, functionality sharing more flexible, and cross-connection switching faster. This will go a long way in helping 6G achieve global coverage and seamless global mobility with low power consumption.

- **From multi-carrier operations to super-flexible spectrum utilization**

Intelligent spectrum utilization and channel resource management are important design aspects in 6G. More frequency bands, as mentioned in Section 4.1, will be explored to provide larger bandwidths, which will support the unprecedented data rates required by 6G. However, higher frequencies suffer from greater path loss and atmospheric absorption. As such, we must consider how to effectively utilize these new spectrums together with lower frequency bands when designing 6G air interfaces. Furthermore, even though full duplex has been promoted in 5G, it is eagerly anticipated to become more mature in 6G.

- **From analog- and RF-unaware to analog- and RF-aware**

Baseband protocols and algorithms are usually designed without carefully considering the features of analog and RF components. This is because it is difficult to model the impairments and non-linearity of such components. In 6G, the design of the baseband physical layer is expected to account for RF impairments and restrictions. And, given 6G's native AI capability, joint RF and baseband optimization and design may be possible.

Paradigm Shifts in the Network Architecture Design

In addition to offering the conventional range of connectivity services, 6G systems could also serve as distributed platforms for executing user workloads in all industry scenarios. This is possible because the 6G network will be built based on a decentralized and user-centric architecture that integrates native AI capabilities. With new enabling technologies, 6G will shift traditional paradigms toward a novel architecture that meets new requirements and integrates new capabilities, as shown in Figure 17.

- **From cloud-centric AI to native AI**

In today's networks, AI services are located in a central cloud at the application layer. In the 6G era, however, network architecture and AI will go hand in hand. Put differently, native AI support will be one of the fundamental factors that drive innovation in the network architecture. As such, deeply converged communication and computing resources with a fully distributed architecture will lead to a transformation from cloud AI to network AI. The benefits of this will go beyond the superior performance (e.g., ultra-low latency) achieved by bringing AI services closer to end users — privacy concerns could also be locally

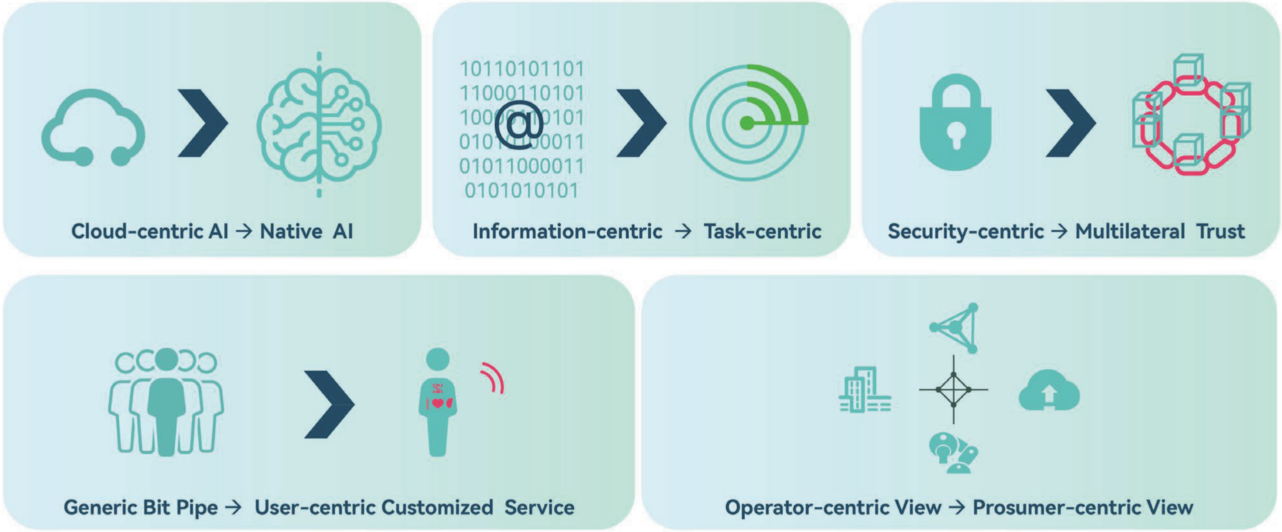

Figure 17 Paradigm shifts of future network architecture design

resolved. This is one of the primary drivers of development in terms of the 6G network architecture. However, the architecture will be significantly impacted by privacy and data governance requirements such as GDPR [4], which advocates for the self-sovereign management of personal data. This means that data ownership should be returned to end users without any intervening authority. Network AI holds especially true in terms of realizing real-time AI functions, because training big data for ML and executing AI inference are inefficient within the centralized cloud AI.

• From information-centric connection to task-centric connection

Conventional communication systems, originally driven by voice and then data communication, mainly focus on information-centric connections. The communication source and destination are clearly defined by end users and the services they intend to use or the other users with whom they intend to communicate. As such, the entire communication mechanism (e.g., session management and mobility management) is designed to provide sufficient support for this connectivity model. Conversely, the 6G system is expected to consist of numerous distributed nodes (e.g., terminals, radio access nodes, and network equipment) with intelligent features that provide native support for intelligent services or that utilize intelligence for self-improvement. AI and sensing are two of the key services that 6G will provide. In order to provide these services, the same task may be executed across numerous distributed nodes in a coordinated manner. This is referred to as task-oriented communication. In the future, wireless communications technology should support diversified device types and time-varying topologies in order to deliver optimal performance for task-oriented communication.

• From security-centric architecture to multilateral trust architecture

5G security, implemented through a standalone framework, is distinct from other network services. In 6G, one of the major paradigm shifts is the transition from simple security to native trustworthiness. This shift involves dealing with the security-by-design framework and a wide range of topics, such as the trust model and security thread from the promising development of quantum computing and application of new technologies (e.g., AI and ML) in security design. To guide the design of a trustworthy 6G architecture and define the corresponding key capabilities, new use cases that yield new requirements, as well as new enabling technologies, should be taken into account.

• From generic bit-pipe to user-centric customized service

From a functional perspective, the network manages the state of each UE or end user. In this regard, the network is essentially a large distributed state machine, meaning that it maintains consistent states across different network functions. This requires the complex exchange of signaling messages, potentially limiting the extent to which network performance can be improved (e.g., latency). More importantly, it may also lead to increased attack points (e.g., an increased attack surface). As the numbers of connected devices and users increase, monolithic network functions (both physical and virtual) also become potential sources of serious bottlenecks. Because the network inherently manages the state of each UE or user, we can understand why a network design based on the per-UE or per-user perspective is needed. Specifically, a user-centric design is capable of providing a virtual private network (VPN) for each user, and such per-user VPNs deliver network services such as mobility management, policy control, session control, and personal data management. In addition, signaling overhead and the corresponding network performance can be optimized at the per-user level.

• From operator-centric view to prosumer-centric view

6G will bring about a paradigm shift as it drives economic and social changes with advances in virtualization and AI. 6G networks will have intelligence at their foundation, enabling a participatory approach to networking and service provisioning. This will redefine the smart connectivity infrastructure as a dynamic pool that contains the resources of all participating users. It is a radical paradigm shift from the conventional operator-centric view to an inclusive prosumer-centric one, where a "prosumer" is a combination of a "producer" and a "consumer". Through a collaborative model bringing together many networks, key aspects such as multilateral ownership, data ownership and privacy, and trust models of involved players must be designed as built-in features rather than add-on ones. Furthermore, in order to achieve

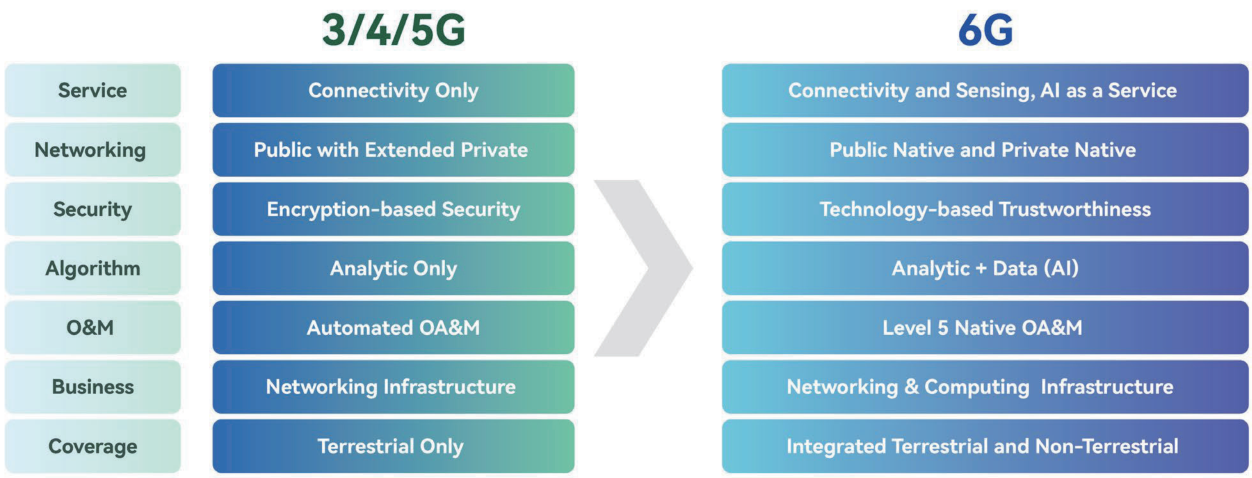

Figure 18 Summary of paradigm shifts in 6G

local data governance and network sovereignty, 6G will adopt new trust and security technologies. In an inclusive prosumer-centric model, every system participant can both contribute and consume resources and services. Moreover, AI and ML technologies will enable autonomous OA&M of 6G networks, involving little to no manual intervention and allowing such networks to flexibly adapt to everyone's needs. In this regard, 6G networks will be tailored rather than proprietary, giving rise to the concept of "my network".

6. Summary and Roadmap

As Guglielmo Marconi said in 1932, it is dangerous to put limits on wireless. Over the last four decades, the wireless revolution has reshaped our lives. Now, the next horizon of innovation will drive new paradigm shifts. In the last part of this article, we summarize the paradigm shifts and lay out the expected timeline of 6G standardization in ITU-R and 3GPP. Open, collaborative, and patient research will be the key to the success and long-lasting value of 6G.

Summary of Paradigm Shifts

Here, we summarize the paradigm shifts the following aspects, as shown in Figure 18:

- Services in 6G will change from connectivity only to connectivity plus sensing and AI.
- Private networking will be supported from the extension of public networking to native design from day one.
- Encryption-based security will transform toward technology-based trustworthiness with multilateral trust architecture and post-quantum cryptography.
- Algorithms in each layer of the communication system will change from analytic only to simultaneous model- and data-driven ones, leveraging AI and ML to couple with practical conditions that are hard to model analytically.
- Level of automation in network OA&M will be further upgraded toward fully touchless "level 5" native automation.
- To natively support intelligence in the system and provide AI as a service for third parties, the networking infrastructure will become converged networking and computing infrastructure.
- With the construction of mega-LEO constellations, the networking infrastructure will extend from terrestrial only to integrated terrestrial and non-terrestrial.

6G Roadmap

Since 2018, numerous initiatives have been launched for 6G research. Industry and academic circles in Europe, China, Japan, South Korea, and the USA have been engaged in identifying the typical application scenarios, key capabilities, and potential technologies for the next-generation wireless network. As the leading international organization, ITU-R is initiating a new cycle toward 2030 and beyond. ITU-R Working Party 5D has started the study of Future Technology Trend and VISION for next-generation IMT standards.

According to the current schedule, ITU-R will complete the VISION study in mid-2023, before World Radio Congress 2023 (WRC23) commences. It will provide a framework and overall objectives for 6G, including usage scenarios and key capability requirements. As further study in the industry continues to fully analyze how these requirements

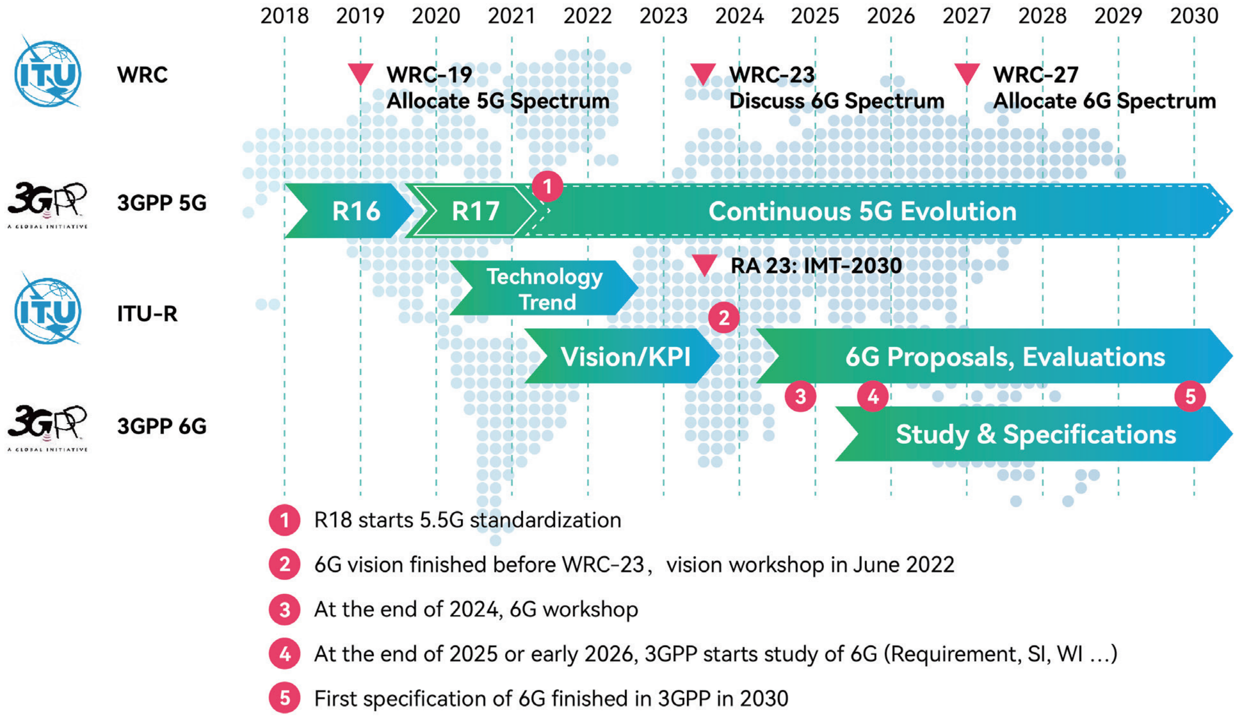

Figure 19 Expected timeline for 6G standardization

will affect the design of wireless communication systems, 3GPP may initiate an overall study into 6G, possibly around the end of 2025 (R20). At present, we expect the first version of 6G standardization to be released sometime around 2030.

The mobile communications industry — from 1G to 5G — has become relatively mature, and its growth has slowed significantly. Unified standards have become more important than ever for achieving economies of scale. As with 4G and 5G, ensuring that 6G is a success requires industry, academic, and ecosystem players to work together. Huawei firmly believes in and is actively contributing to the continuous global cooperation in the development of 6G. The standardization of 6G worldwide will undoubtedly be the path to success for decades to come.

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