From 5G-Advanced to 6G: An Evolutionary Roadmap Towards AI-Native and Cloud-Native Intelligent Networks

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ABSTRACT: The evolution of mobile communication systems continues unabated, with the transition from fifth generation (5G) networks towards sixth generation (6G) marking a significant technological leap. 5G-Advanced, commencing with 3rd Generation Partnership Project (3GPP) Release 18, serves as a crucial evolutionary bridge, enhancing established 5G capabilities while introducing foundational elements for 6G. Key enhancements in 5G-Advanced include the deeper integration of Artificial Intelligence/Machine Learning (AI/ML) for network optimization and initial exploration for air interface improvements, dedicated support for Extended Reality (XR) applications demanding high throughput and low latency, advancements in Non-Terrestrial Networks (NTN) for ubiquitous coverage, and substantial improvements in uplink performance. The vision for 6G anticipates a paradigm shift towards hyper-connected experiences, fusing the physical, digital, and human realms, driven by significantly enhanced Key Performance Indicators (KPIs) and novel capabilities such as integrated sensing and communication (ISAC) and native AI integration. Enabling technologies like Terahertz (THz) communications, Reconfigurable Intelligent Surfaces (RIS), and advanced antenna systems are under intense investigation to realize this vision. Concurrently, network architectures are evolving rapidly, embracing cloud-native principles like microservices and containerization more deeply, and moving towards fundamentally AI-native designs where intelligence is embedded across all network layers. This article provides a comprehensive analysis of this evolutionary trajectory, detailing the features of 5G-Advanced (Release 18 and 19), the requirements and enabling technologies for 6G, the architectural transformations towards cloud-native and AI-native models, a comparative analysis of 5G-Advanced and 6G, and a discussion of the associated research challenges, standardization roadmaps, potential timelines, and societal implications.

KEYWORDS: 5G, 6G, *Artificial Intelligence, Machine Learning, smart city Saudi Arabia, Vision 2030.*

I.   INTRODUCTION

The history of mobile communications is characterized by generational shifts, each introducing transformative capabilities. From the analog voice services of the first generation (1G) to the digital voice and basic data of 2G, the mobile internet access of 3G, the mobile broadband era ushered in by 4G/LTE, and the diverse service pillars of 5G (enhanced Mobile Broadband - eMBB, Ultra-Reliable Low-Latency Communication - URLLC, and massive Machine-Type Communication - mMTC) defined in initial 3GPP releases (Rel-15, Rel-16, Rel-17) , the trajectory has been one of continuous advancement. 5G aimed to connect not just people but also industries and a vast ecosystem of devices, laying the groundwork for digitalization across various sectors.

Building upon this foundation, 5G-Advanced, which officially commenced with 3GPP Release 18, represents a significant phase in the 5G lifecycle. Often described as the "mid-point of 5G standardization" , 5G-Advanced aims to enhance the performance and efficiency of 5G networks, address immediate commercial requirements, expand 5G's reach into new vertical markets, and critically, introduce foundational technologies and concepts paving the way towards 6G. The formal adoption of the "5G-Advanced" logo by 3GPP underscores its significance as a distinct evolutionary phase. This phase is characterized by a strategic balancing act: refining 5G for current market needs, such as improved uplink coverage or cost-effective IoT devices like Reduced Capability (RedCap) , while simultaneously initiating studies and normative work on forward-looking features like AI for the air interface , advanced XR support , and enhanced NTN capabilities , which serve as stepping stones towards 6G.

Looking towards the next decade, the vision for 6G is taking shape, targeting commercial deployments around 2030. 6G promises more than just incremental performance gains; it envisions a "hyper-connected experience for all" , fundamentally fusing the physical, digital, and human worlds into a cyber-physical continuum. This future network is expected to enable truly transformative applications, including multi-sensory extended reality, holographic telepresence, massive-scale digital twins, and intelligent autonomous systems. A defining characteristic of this transition is the shift from 5G's focus on "connected things" to 6G's emphasis on "connected intelligence". This shift is propelled by the anticipated native integration of AI and Machine Learning (ML) not merely as optimization tools, but as fundamental components of the network fabric itself.

Underpinning this functional evolution are two major architectural trends. Firstly, the adoption of cloud-native principles, initiated in the 5G Core (5GC) with its Service-Based Architecture (SBA), is expected to deepen and potentially extend into the Radio Access Network (RAN), bringing increased agility, scalability, and programmability. Secondly, and more profoundly, the architecture is anticipated to become AI-native, designed from the ground up to embed intelligence and support AI workloads across all network domains and layers.

This article aims to provide a comprehensive academic analysis of the evolutionary journey from 5G-Advanced to 6G. It will delve into the key technological enhancements introduced in 3GPP Releases 18 and 19, explore the multifaceted vision for 6G including performance targets (KPIs) and broader value indicators (KVIs), identify and analyze the core enabling technologies being researched, detail the architectural evolution towards cloud-native and AI-native paradigms, offer a comparative perspective on the capabilities of 5G-Advanced versus 6G, and discuss the overarching context encompassing research challenges, standardization efforts, potential deployment timelines, and the potential societal impact of these next-generation networks.

II. 5G-Advanced: The Evolutionary Bridge (Release 18 and beyond)
Overview and Objectives

3GPP Release 18 marks the formal commencement of 5G-Advanced, serving as the first release under this new branding. It represents a crucial phase in the 5G lifecycle, designed not only to refine and enhance the capabilities established in Releases 15, 16, and 17 but also to expand the applicability of 5G technology and lay essential groundwork for the transition towards 6G. The core objectives of 5G-Advanced, starting with Release 18, are multi-faceted: improving network performance and energy efficiency, extending 5G into new vertical industries and supporting diverse use cases (such as advanced IoT, immersive XR, Non-Terrestrial Networks, and Industry 4.0 applications), enhancing existing features like MIMO and mobility, and introducing foundational studies and functionalities that anticipate future 6G requirements. A key characteristic of this phase is the deliberate effort to balance immediate commercial needs and operator priorities (e.g., cost reduction, coverage extension) with the longer-term technological vision leading to 6G.

Key Enhancements in 3GPP Release 18

Release 18 introduces a wide array of enhancements and new features across various aspects of the 5G system. The following subsections detail the most significant developments.

AI/ML Integration

Release 18 represents a significant step in formally integrating AI/ML capabilities into the 5G standard, moving beyond proprietary implementations. This integration occurs across multiple domains:

- **RAN Optimization:** Building upon studies in Release 17 , Release 18 specifies normative work for using AI/ML to optimize RAN operations. Key use cases include network energy saving, load balancing, and mobility optimization. The focus is on enhancing data collection mechanisms and defining signaling support within existing NG-RAN interfaces (like Xn, F1, E1) to facilitate these AI-driven optimizations. For instance, efficient traffic steering and load balancing techniques studied in Rel-17 are advanced to the normative phase. This approach leverages AI to improve the efficiency of established RAN functions without fundamentally altering the existing architecture immediately. Standardization efforts, such as those within ETSI's Experiential Networked Intelligence (ENI) group, also contribute by defining architectures for cognitive network management using AI-driven closed loops.
- **Air Interface Enhancements (Study Item):** Marking a first for 3GPP, Release 18 initiated a dedicated study item (SI) to explore the potential of AI/ML for enhancing the NR air interface itself. This study did not yield normative specifications in Rel-18 but investigated the feasibility and potential benefits of AI/ML in three representative use cases:
    - Channel State Information (CSI) Feedback: Enhancing accuracy and reducing overhead through AI-based compression or prediction.
    - Beam Management: Improving efficiency and accuracy, particularly for high-frequency bands, through AI-based beam prediction.
    - Positioning: Enhancing accuracy, especially in challenging environments (NLOS, multipath), using AI for direct location estimation or assisting traditional methods. The study delved into necessary frameworks, AI model lifecycle management (LCM) aspects (functionality-based vs. ID-based), network-UE collaboration levels, the critical challenge of model generalization across diverse scenarios, and the complexities of testing and validating AI-based air interface features. This exploratory work lays the groundwork for potential normative specifications in subsequent releases (e.g., Rel-19 plans normative work for AI positioning and beam management).
- **Management and Orchestration (MANO):** Recognizing that deploying AI models requires robust management, 3GPP WG SA5 focused on AI/ML management in Rel-18. Building on initial Rel-17 work, a comprehensive study (TR 28.908) was completed, leading to normative specifications in TS 28.105. This work defines an AI/ML operational workflow covering the entire lifecycle: training (including validation), testing, emulation (pre-deployment evaluation), deployment, inference, and monitoring. It specifies management capabilities for each phase, including ML training management, inference function management, performance monitoring, and importantly, AI/ML trustworthiness management (evaluating fairness, robustness, explainability). This framework is crucial for enabling the operational deployment of AI features developed in other groups, particularly in multi-vendor environments where AI models might be implementation-specific.
- **Core Network Analytics:** The Network Data Analytics Function (NWDAF), introduced earlier, continues to evolve. Rel-18 security work addresses aspects of Enablers for Network Automation (eNA) phase 3, including interactions between NWDAF and Management Data Analytics Service/Function (MDAS/MDAF), handling sensitive information, and security aspects for roaming and federated learning scenarios.

The approach in Release 18 towards AI integration appears measured. Normative work targets the optimization of existing, well-understood RAN functions through established interfaces, providing tangible benefits in areas like energy saving and load balancing. Concurrently, the more disruptive application of AI directly to the air interface, which requires fundamental changes and faces significant challenges like generalization and testing, is addressed through a comprehensive study item. This strategy allows for immediate gains while carefully building the foundation for deeper AI integration in future releases. The parallel development of AI/ML lifecycle

management frameworks in SA5 is essential, providing the operational underpinning needed to deploy and manage these AI capabilities reliably and trustworthily as they mature.

Extended Reality (XR) Support

Supporting immersive XR experiences (Virtual Reality - VR, Augmented Reality - AR, Mixed Reality - MR) is a key driver for 5G-Advanced, demanding simultaneous high data rates and very low, bounded latency. Typical requirements include tens of Mbps throughput and end-to-end (motion-to-photon) latency below 20ms, translating to a RAN latency budget of roughly 10-15ms. Release 18 introduces several enhancements specifically targeting these demanding requirements :

- **XR Awareness and QoS:** A core concept introduced is "XR Awareness," enabling the RAN to understand XR traffic characteristics. This leverages mechanisms defined in SA2 (Study FS_XRM, TR 23.700-60), such as PDU Sets (groups of PDUs processed together by the application) and Data Bursts (transmission duration). The RAN can use the PDU Set Integrated Handling Indication (PSIHI) to discard remaining PDUs of a set if one is lost, saving resources. Furthermore, PDU sets can carry an "importance" indication, allowing the RAN to prioritize critical data and potentially discard less important sets during congestion, thereby improving QoS for the essential XR streams.
- **Latency Reduction:** While not introducing fundamentally new low-latency PHY techniques, Rel-18 aims to meet the stringent XR latency targets through optimized scheduling and resource management, enabled by XR awareness. The ability to quickly adapt scheduling based on PDU set readiness (e.g., via SSSG switching mentioned below) contributes to reducing delay. Further latency reduction techniques, such as using packet delay/deadline information for uplink scheduling, are studied for Rel-19.
- **Power Saving:** Given that XR devices are often battery-constrained wearables (glasses, headsets) susceptible to overheating , power saving is a critical enhancement area. Rel-18 focuses on aligning UE Discontinuous Reception (DRX) patterns with the specific periodicities of XR traffic (e.g., 16.66ms for 60fps, 11.11ms for 90fps, 8.33ms for 120fps), which were not optimally handled previously. Key techniques include:
  - PDCCH Monitoring Adaptation: Dynamically adjusting when the UE needs to monitor the control channel (PDCCH) based on XR traffic patterns. Search Space Set Group (SSSG) switching allows rapid transition between sparse and dense monitoring based on PDU set readiness, minimizing delay while saving power during inactive periods. PDCCH skipping allows the UE to enter sleep mode earlier if a data burst ends before the configured DRX active time expires. These power-saving mechanisms are projected to yield gains of 10-30%.
- **Capacity Enhancements:** To handle the high data rates efficiently:
  - Uplink Configured Grant (CG) Enhancements: Allows periodic UL resources with reduced signaling. Rel-18 introduces the ability to configure multiple potential Physical Uplink Shared Channel (PUSCH) occasions within a CG period, providing flexibility.
  - UCI for Unused Resources: UEs can signal via Uplink Control Information (UCI) if allocated CG PUSCH occasions are not needed, allowing the gNB to reallocate them to other users, improving cell capacity and reducing interference. This also saves gNB energy by skipping unnecessary PUSCH detection.
  - Enhanced Buffer Status Reports (BSR): Layer 2 BSRs are enhanced to provide more accurate information on buffered data volume and associated delay/deadline constraints, enabling the gNB to tailor grants more precisely, minimizing padding and delay. Capacity gains from these enhancements are also estimated at 10-30%.

The Rel-18 approach to XR support primarily involves making the network cognizant of XR application behavior (traffic patterns, data structures) and using this awareness to optimize existing NR mechanisms like DRX, scheduling, and QoS differentiation. This focus on adapting current frameworks, rather than introducing radical new radio techniques, reflects an evolutionary strategy. The strong emphasis on power saving alongside performance metrics highlights the practical challenge of enabling XR on wearable devices with limited battery and thermal budgets.

Non-Terrestrial Networks (NTN) Enhancements

Building upon the foundational NTN support introduced in 3GPP Release 17 , Release 18 significantly enhances capabilities to enable robust and versatile satellite-based communication, aiming for ubiquitous 5G coverage and supporting new vertical applications. Key areas of enhancement include:

- **Mobility and Discontinuous Coverage (Satellite Access Phase 2):** A major focus is addressing the challenges posed by satellite movement, particularly for Non-Geostationary Orbit (NGSO) constellations, which result in moving cells and potentially discontinuous coverage for UEs. The Rel-18 study "5GC Enhancement for Satellite Access Phase 2" (FS_5GSAT_Ph2, TR 23.700-28) and subsequent normative work investigated solutions for mobility management (including NTN-TN and NTN-NTN handover) and power saving mechanisms when coverage is intermittent. This includes enhancements to paging procedures, mechanisms for the network and UE to determine and coordinate periods of UE unreachability, handling signaling overload due to coverage loss, and improved Conditional Handover (CHO) triggers using time and location criteria relevant to predictable satellite paths. Seamless satellite switching with re-synchronization is also addressed. This work is crucial for making NTN practical for initial NGSO deployments and managing dynamic constellation changes.
- **Satellite Backhaul:** Recognizing the potential of satellites to provide backhaul connectivity in remote areas or for resilient networks , Rel-18 included a study (FS_5GSATB, TR 23.700-27) and normative work (5GSATB). This addresses challenges like dynamic latency in satellite backhaul links, support for deploying User Plane Functions (UPFs) onboard satellites (e.g., GEO satellites with ground-based gNBs) for edge computing or local data switching, and specifying necessary QoS control and charging mechanisms.
- **IoT NTN Enhancements:** Tailored improvements were specified for supporting low-power IoT devices over satellite networks. This includes performance enhancements like configurable HARQ feedback and UE GNSS measurements, mobility improvements using time/location triggers and broadcasting neighbor satellite information via a new System Information Block (SIB), and specific handling for discontinuous coverage (e.g., a dedicated RRC Release cause). Furthermore, new LTE bands (Band 253 - Extended L-band, Band 254 - L+S band) were introduced specifically for IoT NTN use , reflecting the initial focus on leveraging existing NB-IoT/eMTC standards for satellite IoT. Support for NR RedCap devices over NTN is planned for Rel-19.
- **Other Aspects:** Rel-18 also covered NR radio aspects for NTN , guidelines for extra-territorial 5G systems , support for specific use cases like control/video surveillance via satellite , and security considerations (FS_5GSAT_Sec), which concluded that satellite coverage information should primarily come from trusted O&M sources.

The focus of Rel-18 NTN enhancements on practical deployment issues like mobility, discontinuous coverage, and backhauling signifies a maturation of the technology beyond the initial feasibility established in Rel-17. The work reflects the need to make satellite integration robust and operationally manageable. Furthermore, the distinct track for IoT NTN, initially leveraging LTE-based technologies, highlights the strategy of tailoring NTN solutions to different service segments (high bandwidth vs. low-power massive connectivity), mirroring terrestrial network evolution.

Uplink Performance Improvements

Addressing uplink limitations observed in early 5G deployments, particularly coverage bottlenecks and performance constraints at cell edges or in new mid-bands , is a key focus in Release 18. Enhancements span multiple areas:

- **Enhanced MIMO:** Release 18 pushes uplink MIMO capabilities further. Support for more than four UE transmit antennas (e.g., 8 DMRS ports studied) enables transmission of four or more layers per device, specifically targeting devices like Customer Premises Equipment (CPE), Fixed Wireless Access (FWA) units, vehicles, and industrial IoT devices that can accommodate more complex antenna structures. Simultaneous uplink transmission from multiple antenna panels is facilitated, particularly for mmWave and multi-TRP scenarios, benefiting similar device types. Coherent Joint Transmission (CJT) is strengthened through techniques like codebook compression and random channel state hopping , with

support for up to 4 TRPs in sub-7 GHz assuming ideal backhaul. Uplink DeModulation Reference Signals (DMRS) are enhanced to support up to 24 orthogonal ports for better multi-user MIMO performance.

- **Transmit Switching and Waveform Flexibility:** Dynamic switching between CP-OFDM and DFT-S-OFDM waveforms in the uplink is studied, allowing adaptation to channel conditions and potentially improving efficiency or coverage. General uplink transmit (Tx) switching enhancements are introduced to improve coverage and mobility. Chipsets implementing Rel-18 features also mention switched uplink capabilities across FDD and TDD bands.

- **Power Control and Enhancements:** Release 18 introduces dynamic power adaptation mechanisms where schedulers adjust power based on device feedback and data volume. The maximum allowed device power limit is increased when using Carrier Aggregation (CA) or Dual Connectivity (DC). Techniques like Frequency Domain Spectrum Shaping (FDSS) are employed to reduce Maximum Power Reduction (MPR) and Peak-to-Average Ratio (PAR) without requiring spectrum extension, allowing devices to transmit closer to their maximum power more often, thereby improving coverage. Enhanced uplink power control mechanisms are also specified for multi-TRP deployments.

- **Coverage Enhancements:** Building on Rel-17 work, Rel-18 includes further enhancements for uplink coverage, with a specific focus on improving the Physical Random Access Channel (PRACH) performance. This includes allowing multiple PRACH transmissions with the same beam for the 4-step RACH procedure. Power domain enhancements like FDSS also contribute to better coverage.

This comprehensive set of uplink improvements targets multiple dimensions – peak rate, coverage, efficiency, and flexibility – reflecting a holistic strategy to overcome the uplink challenges encountered in real-world 5G networks. The notable emphasis on enhancing uplink for CPE, FWA, vehicular, and industrial devices suggests a growing recognition of the importance of these use cases, which often demand higher and more symmetric uplink performance compared to traditional mobile broadband scenarios dominated by downlink consumption.

Other Notable Features

Beyond the major themes above, Release 18 included significant work in several other areas:

- **Reduced Capability (RedCap) NR:** Following its introduction in Rel-17 , Rel-18 enhances RedCap support, primarily focusing on enabling positioning for these lower-complexity devices. This includes defining accuracy requirements for 1 Rx branch devices and introducing frequency hopping (FH) techniques to allow RedCap devices to measure positioning signals over a bandwidth wider than their own RF capability. Studies also continued on further reducing RedCap device cost and power consumption. Looking ahead, Rel-19 plans to add NTN support for RedCap devices , and a study on ultra-low power Ambient Power-Enabled IoT is also part of Rel-19.

- **Positioning:** Besides RedCap, Rel-18 brought general positioning enhancements including support for bandwidth aggregation across up to three positioning frequency layers (PFLs) for regular UEs, mechanisms for low power and high accuracy positioning (including for industrial IoT), support for carrier phase measurements, and sidelink-based positioning. Rel-19 aims to introduce AI/ML-based localization techniques.

- **Mobility:** To reduce handover latency and overhead, Rel-18 introduces mechanisms for Layer 1/Layer 2 triggered inter-cell mobility within a Central Unit (CU). It also enhances Conditional Handover (CHO) procedures and resolves prior issues where CHO and Dual Active Protocol Stack (DAPS) mobility could not work together effectively. Support for mobile Integrated Access and Backhaul (IAB) nodes, including inter-donor migration, is also defined. Rel-19 plans to extend L1/L2 triggered mobility (LTM) to work between different gNBs (inter-CU) and explore AI/ML for predicting mobility events.

- **Network Energy Savings:** Driven by operator OPEX concerns and sustainability goals , energy efficiency is a major focus. Rel-18 included a study item to define a base station energy consumption model, evaluation methodology, and KPIs. Specific techniques investigated or specified include dynamic power adaptation based on load , spatial adaptation (adjusting antenna ports/chains) , alignment of cell discontinuous transmission/reception (DTX/DRX) with UE DRX , and the introduction of a low-power wake-up receiver (WUR) that allows the main receiver to sleep more deeply. Rel-19 will continue this work with features like on-demand SSB transmission for secondary cells and adaptation of periodic signal transmissions.

- **Security:** Rel-18 introduced numerous security enhancements. For vertical industries, this included security for UE-to-UE relay ProSe, roaming support for AKMA, security for new mission-critical service

features, phase 2 EDGE computing security (e.g., privacy, authentication), and security for subscriber-aware northbound API access (SNAAPPY) in CAPIF. For the 5G Core, work focused on SBA security details (e.g., TLS certificates, OAuth corrections), security impacts of virtualization, home network triggered primary authentication, security for eNA phase 3 (e.g., NWDAF data handling), and network slicing phase 3 security (e.g., roaming slice info, temporary slices). Looking ahead, Rel-19 plans to study and specify countermeasures against potential threats from quantum computing, likely involving 256-bit security algorithms.

- **Other Areas:** Continued MIMO evolution focused on CSI enhancements (especially for mobility), extending the unified TCI framework to multi-TRP scenarios, and enhancing DMRS/SRS. Multicast and Broadcast Services (MBS) phase 2 included support for UEs in RRC_INACTIVE state and simultaneous reception of broadcast and unicast services. Network Slicing phase 3 addressed aspects like roaming UE slice information and temporary slices. Sidelink evolution included support for unlicensed spectrum operation (5/6 GHz bands) and sidelink carrier aggregation. A study on duplex evolution explored subband full duplex and enhancements for dynamic TDD.

The breadth of topics addressed in Release 18 clearly demonstrates 5G-Advanced moving beyond the initial 5G focus areas. It tackles practical deployment needs (uplink, mobility, energy saving), expands into new device categories (RedCap) and domains (NTN, Industrial IoT, XR), and initiates foundational work (AI for air interface, duplex evolution) crucial for the path towards 6G. The sustained focus on energy efficiency across multiple releases signals its elevation to a primary design constraint, alongside performance and cost.

Outlook Towards Release 19

3GPP Release 19 serves as the second installment of 5G-Advanced, continuing the evolutionary trajectory established by Release 18. The functional freeze for Release 19 is targeted for Q3 2025, with the ASN.1 freeze expected in Q4 2025. The primary focus of Release 19 is expected to be on further maturing the features introduced in Release 18, addressing critical needs observed in commercial 5G deployments, and continuing the balanced evolution required to bridge the gap towards 6G.

Key technical areas anticipated in Release 19 include :

- **AI/ML Integration:** Moving beyond the Rel-18 study, Rel-19 is expected to specify normative work for AI/ML applications on the air interface, particularly for positioning and beam management. A new study item will explore AI/ML for mobility enhancements, such as predicting the best serving cell. Work on AI for network energy saving and load balancing also continues.
- **Massive MIMO and Beam Management:** Further enhancements are planned, including support for even larger antenna arrays (beneficial for new mid-bands like 6-7 GHz), advancements enabling cost-efficient distributed MIMO (D-MIMO) deployments, and mechanisms to accelerate beam management, such as UE-initiated reporting.
- **Extended Reality (XR):** Building on Rel-18, Rel-19 aims to improve XR capacity through enhanced uplink and downlink scheduling utilizing packet delay information and reducing the impact of measurement gaps on data transmission. Study of multi-modality XR support within a UE is also planned.
- **Non-Terrestrial Networks (NTN):** Evolution continues with objectives like increasing satellite downlink coverage, studying the feasibility of placing a full gNB onboard a satellite, introducing higher power UEs, and crucially, adding NTN support for RedCap devices.
- **Internet of Things (IoT):** A study item focuses on Ambient Power-Enabled IoT, investigating ultra-low power devices potentially using energy harvesting. Normative specifications will be developed for the Low-Power Wake-Up Signal (LP-WUS) and Wake-Up Receiver (WUR) concept studied in Rel-18, aiming for significant device power savings.
- **Energy Efficiency:** Further enhancements building on Rel-18 are planned, including on-demand SSB transmission in secondary cells and adapting the periodicity of signals like SSB, paging, and random access based on network needs. Energy efficiency as a service criterion is also being explored.
- **Mobility:** The L1/L2-triggered mobility (LTM) framework will be extended to support inter-gNB handovers and NR-DC scenarios.
- **Security:** Addressing emerging threats, Rel-19 will explore quantum computing resistant security mechanisms, potentially involving 256-bit algorithms.

Release 19 follows a pattern of consolidating and extending the work of the previous release. Promising concepts studied in Rel-18 (AI for air interface, LP-WUR) are targeted for standardization, while core areas like MIMO, mobility, XR, NTN, and energy saving see continued refinement based on deployment experience and evolving needs. Simultaneously, the inclusion of new forward-looking studies like Ambient Power IoT and AI for mobility prediction demonstrates that 5G-Advanced, even in its second release, maintains its role as a preparatory phase, actively investigating potential building blocks for the 6G future. Release 19, therefore, solidifies 5G-Advanced capabilities while further paving the path towards the next generation.

III. The Vision for 6G: Requirements and Capabilities

As 5G-Advanced continues to evolve, the global research community, standardization bodies, and industry consortia are actively shaping the vision for the sixth generation of wireless networks (6G), anticipated for deployment around 2030. This vision extends far beyond simple performance upgrades, aiming to create a deeply integrated and intelligent communication fabric supporting novel applications and addressing key societal challenges.

Emerging Use Cases and Societal Drivers

The development of 6G is driven by a confluence of anticipated technological capabilities and pressing societal needs. Unlike previous generations primarily focused on enhancing human-centric communication, 6G envisions a seamless integration of the physical, digital, and human worlds , creating a cyber-physical continuum. This convergence is expected to enable a range of transformative use cases:

- **Immersive and Multi-Sensory Experiences:** Going beyond the visual and auditory focus of current VR/AR, 6G aims to enable truly immersive extended reality (XR) incorporating haptic feedback and potentially other senses. Holographic communication and telepresence, creating realistic 3D representations for remote interaction, are frequently cited goals. Massive-scale digital twins – virtual replicas of physical objects, processes, or environments – are envisioned for monitoring, simulation, and control across various sectors.
- **Intelligent Autonomous Systems:** 6G is expected to be a key enabler for advanced robotics and autonomous systems. This includes network-enabled collaborative robots ("cobots") working alongside humans in factories or homes , fully autonomous vehicles and transportation systems requiring hyper-reliable connectivity and sensing , autonomous supply chains , and widespread drone integration for logistics, monitoring, and other services.
- **Ubiquitous Intelligence and Sensing:** A defining feature of the 6G vision is the native integration of AI and sensing capabilities. Networks are expected to provide pervasive AI services, enabling context-aware applications and intelligent automation everywhere. Furthermore, the network itself is envisioned to act as a sensor ("Network as a Sensor" or ISAC), capable of detecting, localizing, and imaging objects in the environment, providing spatial awareness for various applications.
- **Societal Goals and Sustainability:** Critically, the 6G vision is strongly tied to addressing broader societal challenges. Sustainability is a core driver, with explicit goals to align with the UN Sustainable Development Goals (SDGs) and initiatives like the European Green Deal. This includes minimizing the environmental footprint of the network itself (energy efficiency, resource use) and enabling other sectors to become more sustainable. Digital inclusion, aiming to bridge the digital divide and provide connectivity for all, is another central theme. Trustworthiness – encompassing security, privacy, resilience, and safety – is considered paramount given the network's anticipated deep integration into critical infrastructure and personal lives. Enhanced healthcare, remote education, public safety, smart cities, and smart manufacturing are consistently highlighted as key application domains benefiting from 6G. Additionally, 6G is expected to foster economic growth and enable new platform-based business models.

A remarkable aspect of the 6G visioning process is the strong convergence observed across various global initiatives and organizations. Visions articulated by the ITU , European projects like Hexa-X and the 6G Flagship program , North America's NextG Alliance , and major industry players like Samsung , Nokia , and Ericsson all emphasize common themes: the fusion of worlds, native AI, integrated sensing, immersive experiences, and a strong focus on sustainability, inclusion, and trustworthiness. This suggests an emerging global consensus on the high-level ambitions for the next generation of wireless technology, moving

significantly beyond enhancing traditional communication metrics to creating a multi-functional, intelligent platform deeply intertwined with societal goals.

Target Key Performance Indicators (KPIs)

To support the envisioned use cases, 6G networks are expected to deliver substantial improvements in traditional Key Performance Indicators (KPIs) compared to 5G and 5G-Advanced. While specific target values are still under discussion and refinement within standardization bodies like ITU-R and research projects, the general ambition points towards significant, often order-of-magnitude, leaps.

- **Peak Data Rate:** Targets ranging from hundreds of Gbps up to 1 Terabit per second (Tbps) are frequently discussed in research literature , representing a 25-50x increase over the 20 Gbps target of 5G. The ITU-R M.2160 framework provides a more conservative research target range of 50-200 Gbps, acknowledging that achievable rates depend heavily on the specific scenario and frequency band.
- **User Experienced Data Rate:** The data rate reliably available across most of the coverage area is targeted to reach around 1 Gbps , a 10x improvement over the 100 Mbps 5G target. ITU examples suggest targets of 300-500 Mbps or higher.
- **Latency:** Air interface latency is targeted to decrease significantly, with goals of 0.1 milliseconds (100 microseconds) often cited , a 10x reduction from 5G's 1ms target. The ITU range is 0.1-1 ms. Associated jitter targets are around 1 microsecond. The aim is to achieve a perception of virtually zero latency for many applications.
- **Reliability:** Reliability targets are pushed towards "six nines" or even higher, with error probabilities potentially reaching 1×10^{-9}. The ITU range for air interface reliability is $1-10^{-5}$ to $1-10^{-7}$, compared to 5G's baseline of 1×10^{-5}.
- **Connection Density:** To support massive IoT and ubiquitous sensing, connection density targets are increased by at least 10x, aiming for 10^7 devices/km² , with the ITU suggesting a range of 10^6-10^8 devices/km². Some visions mention density in terms of volume, e.g., 100 devices/m³.
- **Mobility:** Support for higher speeds is envisioned, potentially up to 1000 km/h , compared to 5G's 500 km/h target. The ITU range is 500-1000 km/h.
- **Spectrum Efficiency:** Improvements of 1.5x to 3x over 5G are targeted by ITU , while some research aims for higher peak efficiencies (e.g., 60 b/s/Hz vs 5G's 30 b/s/Hz).
- **Area Traffic Capacity:** Significant increases are expected, with research targets like 1 Gb/s/m² mentioned , although ITU examples are more modest at 30-50 Mbit/s/m² , still representing an improvement over 5G's 10 Mb/s/m².
- **Energy Efficiency:** A critical KPI, often targeted for at least a 10x improvement or measured as a significant reduction in energy per bit (e.g., >90% reduction or 1 Tb/J). The ITU emphasizes that efficiency must improve significantly to offset the energy consumption increase from higher capacity and denser networks.
- **Bandwidth:** Supporting Tbps rates necessitates much wider bandwidths. While 5G uses up to 100/400 MHz component carriers (FR1/FR2) and Rel-17 allows aggregation up to 2 GHz , 6G envisions utilizing contiguous bandwidths of tens of GHz , potentially aggregating up to 100 GHz, primarily available in the THz spectrum.

It is important to recognize the variability in these target values, reflecting the ongoing research and standardization process. Official targets set by bodies like ITU-R tend to be more conservative or provide ranges compared to ambitious goals stated in some research papers. This difference highlights the necessary reconciliation between visionary goals and practical constraints related to technology maturity, cost, and deployment feasibility that occurs during standardization. Nonetheless, the scale of improvement aimed for across nearly all KPIs underscores the need for disruptive technological and architectural innovations beyond the incremental evolution of 5G. Achieving Tbps rates, sub-millisecond latency, and massive connection density simultaneously necessitates the exploration of new spectrum (THz), advanced spatial processing (UM-MIMO, RIS), novel functionalities (ISAC), and fundamentally different network paradigms (AI-native, deeper cloud-native integration).

ITU IMT-2030 Framework: New Capabilities

The formal framework for 6G development, Recommendation ITU-R M.2160 "Framework and overall objectives of the future development of IMT for 2030 and beyond" , introduces several new capabilities alongside enhancements to existing 5G KPIs. These new capabilities signify a fundamental expansion of what constitutes a mobile generation, moving beyond pure communication metrics to encompass broader functionalities and societal values. The six entirely new capabilities defined are:

1. **Coverage:** Defined as the ability to provide access to communication services within a desired service area. Unlike previous implicit assumptions, coverage is now an explicit capability, often measured by the cell edge distance achievable via link budget analysis. This directly addresses the societal goal of ubiquitous connectivity and bridging the digital divide. M.2160 defines it conceptually without setting a specific target distance.

2. **Positioning:** This capability refers to the network's ability to determine the location of connected devices. While 5G offered positioning, 6G elevates it to a core capability with significantly higher accuracy targets. Positioning accuracy is defined as the difference between the estimated and true position (horizontal/vertical). The target accuracy range for research and investigation is 1 to 10 centimeters , a substantial improvement aimed at enabling new location-aware services and addressing GNSS limitations in challenging environments like indoors or dense urban canyons.

3. **Sensing-related capabilities:** This represents a major functional expansion, defining the ability of the radio interface itself to perform sensing tasks such as estimating range, velocity, and angle of objects, detecting their presence, and potentially enabling localization, imaging, and mapping functionalities. Performance would be measured using metrics relevant to sensing, like accuracy, resolution, detection probability, and false alarm rate. This capability underpins the ISAC use case scenario. M.2160 describes the types of functionalities rather than setting specific numerical targets at this stage.

4. **Applicable AI-related capabilities:** This capability signifies the network's native ability to support AI-enabled applications by providing functionalities distributed throughout the system. These functionalities include distributed data processing, distributed learning (e.g., federated learning), AI model execution, and inference. This capability is crucial for realizing the vision of ubiquitous intelligence and AI-native networks. Like sensing, it is defined functionally in M.2160 without specific numerical targets.

5. **Sustainability:** Formally recognized as a key capability, sustainability encompasses minimizing negative environmental impacts (energy consumption, resource use, GHG emissions) throughout the network and device lifecycle, as well as enabling positive societal and economic sustainability. Energy efficiency (measured in bit/Joule) is highlighted as a quantifiable aspect that needs to improve significantly alongside capacity growth to ensure overall power consumption does not escalate uncontrollably. Alignment with global goals like the UN SDGs and the Paris Agreement is emphasized.

6. **Interoperability:** Defined as a principle ensuring the radio interface is based on member-inclusivity and transparency, enabling functionality between different entities within the system. This promotes open ecosystems and avoids vendor lock-in, fostering innovation. It is presented as a design principle rather than a quantifiable metric.

The explicit inclusion of these six new capabilities within the ITU's IMT-2030 framework marks a pivotal moment in the evolution of mobile communications. It signals a shift from networks solely defined by communication performance to multi-functional platforms designed with integrated sensing, native intelligence, high-precision positioning, and core societal values like sustainability and ubiquitous coverage at their heart. The fact that several of these capabilities are initially defined conceptually or functionally, rather than by strict numerical targets (with the exception of positioning accuracy), suggests that the initial focus is on establishing their intended role and purpose within the 6G ecosystem. The detailed performance metrics and evaluation methodologies for these novel capabilities are expected to be developed during the subsequent Technical Performance Requirements (TPR) phase of the ITU-R process.

Key Value Indicators (KVIs): Beyond Performance Metrics

Complementing the enhanced KPIs and new technical capabilities, the 6G vision incorporates a strong emphasis on Key Value Indicators (KVIs). KVIs represent a deliberate effort to move beyond purely technical performance metrics and explicitly integrate broader human, societal, and environmental values into the design, development, and evaluation of 6G systems. This value-based approach aims to ensure that 6G technology not only delivers

advanced performance but also contributes positively to global challenges and societal well-being, aligning with frameworks like the UN SDGs.

Major European research initiatives like Hexa-X and the Smart Networks and Services Joint Undertaking (SNS JU) have been prominent in defining and promoting KVIs, often grouping them into three core categories :

- **Sustainability:** This is perhaps the most emphasized KVI, encompassing three dimensions:
  - Environmental Sustainability: Minimizing the negative environmental impact across the entire lifecycle of 6G technology. This includes improving energy efficiency (reducing energy consumption per bit), reducing the overall network energy footprint, minimizing CO_2 emissions (towards Net Zero goals), promoting circular economy principles (material efficiency, recycling, reducing e-waste), and considering impacts on biodiversity. It also includes the "enablement effect" – how 6G can help other sectors reduce their environmental impact.
  - Societal Sustainability: Ensuring 6G benefits society broadly and equitably. Key aspects include digital inclusion (bridging the digital divide), accessibility for all (including vulnerable groups), affordability, positive impacts on health, safety, education, job creation (vs. displacement), and cultural preservation.
  - Economic Sustainability: Supporting long-term economic growth and viability. This involves ensuring the affordability of services, enabling new business models and ecosystems, improving cost efficiency (e.g., Total Cost of Ownership - TCO reduction), fostering innovation, and ensuring the economic viability of the 6G ecosystem for all stakeholders.
- **Trustworthiness:** This KVI addresses the need for secure, reliable, and privacy-preserving 6G networks, crucial given their expected pervasiveness. It encompasses:
  - Security: Protecting against malicious attacks (confidentiality, integrity, availability). This includes addressing new threats from AI, quantum computing, and distributed architectures.
  - Privacy: Safeguarding sensitive user and system data from unauthorized access or leakage.
  - Robustness/Resilience: Ensuring the network can withstand and recover from unintentional faults, environmental disturbances, or system malfunctions.
  - Safety: Protecting users and the environment from harm potentially caused by the network or its applications.
- **Inclusion/Inclusiveness:** This value focuses on ensuring equitable access to 6G technology and its benefits for everyone, regardless of location, socioeconomic status, gender, culture, health, or other factors. It directly relates to bridging the digital divide and making advanced services accessible and affordable globally.

The introduction of KVIs represents a significant evolution in network design philosophy, embedding societal and ethical considerations alongside technical performance from the very beginning. However, operationalizing KVIs presents considerable challenges. Many KVIs are inherently qualitative, multi-dimensional, and potentially conflicting (e.g., enhancing coverage for inclusion might increase energy consumption). Measuring progress requires interdisciplinary approaches, combining quantitative metrics (mapping KVIs to measurable KPIs where possible) with qualitative assessments. Developing standardized definitions and evaluation methodologies is crucial. Initiatives like the SNS JU Test, Measurement, and Validation (TMV) Working Group are actively working on consolidating KPI/KVI definitions, target values, and validation methods based on input from various research projects, aiming to create a common framework for assessing 6G systems holistically. Frameworks like the Hexa-X-II methodology (mapping goals to KVs to KVIs, distinguishing Use Case vs. Enabler KVIs) provide structured approaches for integrating these value considerations into the technology development lifecycle.

IV. Enabling Technologies for 6G

Realizing the ambitious vision and meeting the demanding KPIs and KVIs of 6G necessitates the development and integration of several key enabling technologies. While some are evolutionary extensions of 5G concepts, others represent more radical departures.

Terahertz (THz) Communications (0.1-10 THz)

The THz frequency range, broadly defined as 0.1-10 THz, is widely considered a cornerstone technology for achieving the multi-gigabit and potentially terabit-per-second (Tbps) data rates envisioned for 6G.

- **Potential:** The primary allure of THz lies in the vast swaths of contiguous bandwidth available – potentially tens or even hundreds of GHz – far exceeding the bandwidths available in current cellular bands. This enormous bandwidth is the key enabler for extreme data rates required by applications like high-fidelity holographic communication and immersive XR. Additionally, the short wavelengths offer high spatial resolution, making THz bands promising for integrated sensing and high-accuracy positioning applications.

- **Challenges:** THz communication faces significant physical hurdles. Signals suffer from severe free-space path loss, which increases quadratically with frequency. Compounding this is molecular absorption loss, where atmospheric gases (primarily water vapor) absorb energy at specific resonant frequencies within the THz band, creating transmission "windows" interspersed with high-attenuation peaks. This effect is both frequency- and distance-dependent. The extremely short wavelengths also make THz signals highly susceptible to blockage by common objects, often necessitating line-of-sight (LoS) paths for reliable communication. Reflection and scattering losses are also very high for non-LoS (nLoS) paths. Hardware implementation remains challenging, requiring efficient and cost-effective components (power amplifiers, mixers, antennas) capable of operating at these high frequencies and handling multi-GHz bandwidths. The need for very narrow beams to overcome path loss creates significant challenges in beam alignment and tracking, especially for mobile users. Furthermore, the large electrical size of antenna arrays needed can lead to near-field propagation effects in typical deployment distances, requiring different beamforming strategies than traditional far-field approaches. Channel modeling must account for these unique THz phenomena, including sparsity, the beam split or squint effect due to wide bandwidths, and potential pulse distortion (temporal broadening) within absorption regions.

- **Solutions and Advancements:** Research is actively addressing these challenges. Ultra-massive MIMO (UM-MIMO) arrays with a very large number of antenna elements are proposed to provide sufficient beamforming gain to counteract path loss. Advanced beamforming techniques, including beamfocusing and potentially wavefront engineering using non-Gaussian beams (e.g., Bessel, Airy) are being explored for near-field scenarios. Reconfigurable Intelligent Surfaces (RIS) are considered a key complementary technology to bypass blockages and create virtual LoS paths. Progress in semiconductor technology (e.g., III-V compounds like InP, GaN; SiGe BiCMOS) and novel materials like graphene is pushing the performance boundaries of THz transceivers and antennas. Spectrum allocation strategies that are distance-aware (e.g., DAMC) and modulation techniques that adapt to absorption peaks (e.g., DA-APM) aim to optimize spectrum usage. True-time delay (TTD) based beamforming is proposed to mitigate the beam squint effect inherent in wideband phase-shifter-based arrays. The unique propagation effects are also being explored for potential benefits, such as using high absorption for secure short-range communication or exploiting temporal broadening for security.

Given the significant propagation challenges and hardware complexities, THz communication is often seen as crucial for achieving the peak 6G data rate targets but may initially be deployed in more constrained scenarios, such as short-range indoor links, fixed wireless access, or specific industrial applications, rather than providing ubiquitous mobile coverage.

Reconfigurable Intelligent Surfaces (RIS)

RIS technology, also known as Intelligent Reflecting Surfaces (IRS), represents a paradigm shift in wireless system design, moving from solely optimizing transmitters and receivers to actively engineering the propagation environment itself.

- **Principles:** An RIS is typically a planar surface composed of a large number of small, low-cost, passive or nearly passive elements. Each element can independently alter the phase (and potentially amplitude) of an incident electromagnetic wave before re-radiating it. By coordinating the response of all elements via a software controller (often connected to a base station), the RIS can collectively shape the reflected wavefront, for instance, to steer the signal towards a desired receiver, cancel interference, or create specific multipath conditions. This transforms the wireless channel from a passive, uncontrollable medium into a

partially controllable, smart radio environment (SRE).

- **Hardware:** RIS implementations are often based on metasurfaces, which are artificial, thin electromagnetic materials. A common architecture involves three layers: an outer layer with metallic patches that interact with the incident wave, a middle copper plate to prevent signal leakage, and an inner control circuit board. Tunability of elements is achieved using components like PIN diodes, varactor diodes, or liquid crystals, controlled electronically via an external controller (e.g., FPGA or MCU). While the basic concept involves passive reflection, research is also exploring variations like RIS with limited amplification, integrated sensing capabilities, surfaces that can simultaneously transmit and reflect (STAR-RIS), dynamic metasurface antennas (DMA), and stacked intelligent metasurfaces (SIM).
- **Role in 6G:** RIS is envisioned as a key enabler for overcoming propagation challenges, particularly in higher frequency bands (mmWave/THz) where signals are prone to blockage and high path loss. By intelligently redirecting signals, RIS can improve coverage, enhance received signal strength, and increase link reliability. They can also be used to improve spectral and energy efficiency, suppress interference, enhance MIMO capacity through engineered multipath, improve localization accuracy, and bolster physical layer security by directing signals away from eavesdroppers. RIS can be integrated synergistically with other technologies like NOMA, MEC, SWIPT, UAVs, and massive MIMO.
- **Challenges:** Despite the promise, practical deployment faces hurdles. A major challenge is acquiring the accurate channel state information (CSI) needed to optimally configure the large number of RIS elements, especially since passive elements cannot easily transmit pilot signals themselves. Optimizing the phase shifts of thousands of elements in real-time is computationally complex. Effective deployment strategies (where to place RISs for maximum benefit) need to be developed. While potentially cheaper and more energy-efficient than active relays, the cost, power consumption (of control circuitry), and scalability of very large RIS implementations remain areas of investigation.

RIS offers a fundamentally new tool for wireless engineers – the ability to control the channel. Its potential to improve performance cost-effectively and energy-efficiently, especially at higher frequencies, makes it a strong candidate technology for 6G. However, overcoming the system-level challenges of CSI acquisition, control signaling, and optimization is critical for realizing its full potential.

Integrated Sensing and Communication (ISAC)

ISAC represents a significant functional evolution for wireless networks, aiming to merge radar-like sensing capabilities with traditional communication functionalities within a unified framework.

- **Concepts:** The core idea is to utilize the same hardware platform, frequency spectrum, and potentially waveforms for both transmitting/receiving communication data and sensing the surrounding environment (e.g., detecting objects, estimating their range, velocity, angle). This integration is driven by the increasing similarities between modern communication and radar systems (use of high frequencies, large arrays, sophisticated signal processing) and the potential for significant gains in spectral efficiency, energy efficiency, hardware cost reduction, and reduced signaling overhead compared to deploying separate systems. Beyond resource sharing, ISAC enables synergistic benefits, where sensing information can aid communication (e.g., location-aware beamforming, blockage prediction) and communication signals can be exploited for sensing tasks. ISAC is recognized as one of the six key usage scenarios for IMT-2030/6G , transforming the network into an active sensor of the physical world.
- **Techniques:** Realizing ISAC involves innovations across multiple layers:
  - Waveform Design: Approaches include communication-centric (adapting communication waveforms like OFDM for sensing), sensing-centric (embedding communication data onto radar waveforms), or joint design (creating new waveforms optimized for both functions).
  - Signal Processing: Algorithms are needed for jointly estimating communication channel parameters and sensing parameters (e.g., target parameters from echo signals), managing interference between the two functions, and fusing data from potentially distributed sensing nodes.
  - Networking: Efficient allocation of shared resources (time, frequency, spatial beams, power) between sensing and communication tasks is crucial. Network architectures need to support different sensing modes (monostatic where Tx/Rx are co-located, bistatic/multistatic with separate Tx/Rx) and enable the collection, processing, and utilization of sensing data across the network.
- **Challenges:** Designing waveforms that perform well for both communication (high data rate, low error rate) and sensing (high resolution, accuracy) involves inherent trade-offs. Managing mutual interference

between communication signals and sensing echoes is complex. Hardware design, especially for monostatic ISAC which benefits from full-duplex transceivers to transmit and receive simultaneously, is challenging. Estimating channels for both functions can be difficult as they may have different requirements (e.g., sensing often needs finer angular/delay resolution). Achieving synchronization across nodes for distributed/multistatic sensing is non-trivial. Perhaps most significantly, ISAC introduces new security and privacy vulnerabilities: sensing data (location, activity) can be eavesdropped, and communication signals used for sensing could be intercepted by malicious targets. Addressing these security and privacy concerns is critical for commercial viability.

ISAC fundamentally expands the role of wireless networks from mere information conduits to active participants in perceiving and interacting with the physical environment. This aligns strongly with the 6G vision of fusing physical and digital worlds. While the potential benefits are substantial, overcoming the technical complexities in waveform design, signal processing, resource management, and particularly security/privacy is essential for ISAC to become a practical reality in 6G.

Advanced Antenna Systems and Spatial Processing

The evolution of antenna systems and spatial processing techniques remains a critical path for enhancing performance in 5G-Advanced and is expected to continue playing a central role in 6G.

- **Evolution Beyond Massive MIMO:** 5G introduced massive MIMO, and 5G-Advanced (Rel-18/19) continues to refine it with enhanced CSI acquisition, better support for multi-TRP coordination (extending the unified TCI framework), and increased uplink MIMO capabilities (more layers, more orthogonal DMRS ports). 6G is expected to push this further.
- **Scaling to Higher Frequencies and Larger Arrays:** The move towards higher frequency bands (upper mid-band, mmWave, THz) necessitates even larger antenna arrays (in terms of element count) to compensate for increased path loss and enable highly directional beamforming. Concepts like extreme massive MIMO (xMIMO) or ultra-massive MIMO (UM-MIMO) with potentially thousands of antenna elements are being researched. The smaller wavelengths at higher frequencies allow packing more elements into a given physical aperture.
- **Distributed Architectures:** There is a growing trend towards distributed antenna systems, moving away from the traditional cellular structure. Distributed MIMO (D-MIMO) and Cell-Free Massive MIMO concepts, where many geographically distributed access points cooperatively serve users, are gaining significant interest. 3GPP Release 19 includes work items aimed at enabling cost-efficient D-MIMO deployments. These architectures promise benefits like improved macro-diversity gain, enhanced coverage consistency (eliminating cell edges), higher reliability, and better support for multi-perspective localization and sensing.
- **AI-Driven Spatial Processing:** The complexity of managing extremely large arrays, coordinating distributed access points, performing rapid beamforming/tracking (especially at high frequencies), and optimizing CSI feedback necessitates the integration of AI/ML. AI is already being studied in 5G-Advanced for beam management, channel prediction, and CSI enhancement , and is expected to become an integral part of the 6G air interface and RAN control plane.
- **Emerging Concepts:** Research is also exploring more futuristic concepts like Holographic MIMO or intelligent surfaces acting as continuous apertures, potentially offering further gains in spatial resolution and efficiency.

The continuous evolution towards larger, potentially distributed, and more intelligent antenna systems is fundamental to achieving the capacity, coverage, reliability, and new sensing/positioning capabilities envisioned for 6G. However, this increasing complexity in the spatial domain demands sophisticated management and optimization, making AI/ML integration not just beneficial but likely essential for practical operation.

Other Potential Enablers

While THz, RIS, ISAC, and advanced spatial processing are frequently highlighted, the 6G technology landscape includes other important research directions:

- **Quantum Technologies:** The primary driver for considering quantum technologies in 6G is security. The anticipated advent of powerful quantum computers poses a threat to current public-key cryptography algorithms. Therefore, research is underway on quantum-resistant cryptography (QRC) algorithms and potentially Quantum Key Distribution (QKD) mechanisms to secure 6G communications. 3GPP Rel-19 includes plans to explore 256-bit security algorithms as a step towards quantum resilience.
- **Ambient IoT / Zero-Energy Devices:** To connect the anticipated trillions of devices in the 6G era, many of which may be simple sensors or tags, ultra-low power operation is essential. Research into Ambient IoT explores devices that harvest energy from their surroundings (e.g., radio waves, light, heat) and communicate using extremely low power techniques, potentially including backscatter communication. 3GPP Rel-19 includes a study item on Ambient Power-Enabled IoT and will specify the Low-Power Wake-Up Signal/Receiver (LP-WUS/WUR) concept , enabling devices to sleep deeply while remaining reachable.
- **Advanced Duplexing Schemes:** To improve spectral efficiency, particularly in TDD bands, advanced duplexing techniques are being investigated. 3GPP Rel-18 included a study on Subband Full Duplex (SBFD), where transmission and reception occur simultaneously in different parts of the band, and enhancements for dynamic/flexible TDD operation. Full Duplex, while challenging due to self-interference, remains an area of interest.
- **Semantic Communications:** Moving beyond transmitting raw bits, semantic communications aims to transmit the meaning or intent behind the data, leveraging AI/ML to extract and reconstruct relevant information at the receiver. This could lead to dramatic improvements in communication efficiency, especially for applications involving complex data like video or sensor streams, by transmitting only the essential semantic information required for a specific task.
- **Blockchain and Distributed Ledger Technologies (DLT):** These technologies are being explored primarily for enhancing security, privacy, and trust in distributed 6G environments. Potential applications include secure identity management, decentralized trust frameworks, tamper-proof data logging, and managing spectrum sharing or network slicing agreements.

This broader range of enabling technologies indicates that 6G development is pursuing multiple avenues simultaneously. Some technologies, like quantum security and zero-energy devices, address fundamental long-term challenges related to trustworthiness and sustainability. Others, like semantic communications, offer potentially disruptive ways to improve efficiency beyond traditional methods. The successful integration of a subset of these diverse innovations will likely shape the final form of 6G networks.

Technology	Principle of Operation	Potential Role/Benefit in 6G	Key Research Challenges
Terahertz (THz) Comms (0.1-10 THz)	Utilizes ultra-wide bandwidths in high-frequency spectrum for data transmission.	Extreme data rates (Tbps), high-resolution sensing/positioning.	Severe path/absorption loss, blockage, hardware maturity (efficiency, cost, bandwidth), beam alignment, near-field effects, channel modeling complexity.
Reconfigurable Intelligent Surfaces (RIS)	Software-controlled metasurfaces manipulating EM waves (phase/amplitude) to engineer the radio channel.	Enhance coverage/mitigate blockage (esp. high freq.), improve capacity/energy efficiency, interference suppression, localization/sensing aid.	CSI acquisition for passive elements, real-time optimization complexity, deployment strategies, scalability, hardware cost/power.
Integrated Sensing & Communication (ISAC)	Merges sensing (radar-like) and communication functions using shared resources (hardware, spectrum, waveform).	Improved spectral/energy/hardware efficiency, mutual S&C benefits (e.g., sensing-assisted beams), new location/environment-aware services.	Waveform trade-offs, interference management, hardware complexity (e.g., full duplex), joint channel/target estimation, network sync, security/privacy vulnerabilities.

Advanced Antenna Systems / Spatial Processing	Evolution to larger arrays (UM-MIMO), higher frequencies, distributed architectures (D-MIMO/Cell-Free), AI integration.	Higher capacity/spectral efficiency, improved coverage/reliability (esp. high freq.), enhanced sensing/localization, complex spatial multiplexing.	Hardware complexity/cost/power (large arrays), channel estimation/feedback overhead, distributed coordination/synchronization, AI model training/complexity.
Quantum Security	Utilizes quantum-resistant algorithms (QRC) or quantum phenomena (QKD) for secure communication.	Protect against threats from future quantum computers, ensure long-term data confidentiality/integrity.	Algorithm maturity/standardization, QKD implementation challenges (distance, infrastructure), key management complexity.
Ambient IoT / Zero-Energy Devices	Devices harvest ambient energy (RF, light, etc.) and communicate using ultra-low power (e.g., backscatter).	Enable massive deployment of simple sensors/tags with long lifetimes, support ubiquitous sensing, reduce battery dependence/e-waste.	Energy harvesting efficiency, communication range/reliability, interference management, integration with network protocols.
Semantic Communications	Transmits the meaning/intent of data rather than raw bits, using AI for encoding/decoding.	Potential for massive efficiency gains (bandwidth, power), task-oriented communication, improved resilience to noise/errors.	Defining/quantifying semantics, AI model complexity/training, lack of theoretical foundation, interoperability.

Table 1 : Overview of Key 6G Enabling Technologies

V. Evolution of Network Architecture Towards 6G

Parallel to the development of new radio technologies, the underlying network architecture is undergoing a profound transformation, driven by the adoption of cloud-native principles and the nascent integration of artificial intelligence as a core component. This evolution is essential to provide the flexibility, scalability, automation, and intelligence required to support the diverse and demanding services envisioned for 6G.

Cloud-Native Foundation: From 5GC SBA to 6G

The architectural shift towards cloud-native design began significantly with the 5G Core (5GC). Unlike previous monolithic, hardware-centric core networks, the 5GC is based on a Service-Based Architecture (SBA). In the SBA, network functionalities are decomposed into modular Network Functions (NFs) that expose their capabilities and consume services from other NFs via standardized Service-Based Interfaces (SBIs), typically using web-based protocols like HTTP/2 and RESTful APIs. This decoupling allows NFs to be developed, deployed, scaled, and upgraded independently, fostering agility and flexibility. The SBA inherently supports key 5G concepts like Network Slicing and Control and User Plane Separation (CUPS), enabling customized logical networks and optimized data paths.

The SBA is designed to be implemented using cloud-native technologies, marking a convergence of telecom and IT practices. Key cloud-native principles adopted include:

- **Microservices:** Decomposing monolithic NFs into smaller, independent, and stateless (where possible) microservices. This enhances modularity, resilience (failure of one microservice doesn't bring down the entire NF), and allows for independent scaling and faster development cycles.
- **Containerization:** Packaging microservices and their dependencies into lightweight containers (e.g., Docker), enabling consistent deployment across different environments and efficient resource utilization compared to traditional Virtual Machines (VMs).
- **Orchestration:** Using platforms like Kubernetes to automate the deployment, scaling, management, and lifecycle of containerized NFs.
- **Continuous Integration/Continuous Deployment (CI/CD):** Employing DevOps practices and CI/CD pipelines to enable rapid testing, integration, and deployment of new features and updates.

This cloud-native foundation, built upon the evolution of Network Function Virtualization (NFV) , provides significant benefits in terms of agility, scalability, resilience, and operational efficiency.

Looking towards 6G, this cloud-native paradigm is expected to become even more deeply entrenched and pervasive. The trend is towards further disaggregation, potentially extending the SBA and microservice concepts beyond the core network into the Radio Access Network (RAN). Research on Service-Based RAN architectures explores decomposing RAN functions (e.g., CU-CP, CU-UP, DU functions) into microservices communicating via SBIs, aiming to bring similar flexibility and programmability to the access network. While challenges exist in applying cloud-native techniques to the real-time, performance-critical domain of the RAN , the potential benefits in terms of customization, efficiency, and enabling edge computing are significant drivers. Tools like service meshes, which manage communication between microservices, are becoming integral but also introduce challenges like latency overhead that require optimization. Overall, the cloud-native architecture established by 5GC provides the essential underpinning for the complex, dynamic, and software-driven network envisioned for 6G, enabling the integration of AI and supporting diverse service requirements. However, adapting and optimizing these cloud-native techniques for the specific demands of telecom networks, particularly the RAN and latency-sensitive applications, remains an ongoing process.

AI-Native Architecture: Principles and Design

While 5G-Advanced introduces AI/ML as optimization tools and subjects of study, the vision for 6G embraces a more fundamental integration, often termed "AI-native". This signifies an architectural paradigm where AI/ML is not merely applied to the network, but is intrinsically woven into its design, operation, and service capabilities across all layers and domains – from devices and the air interface through the RAN and Core, up to management and orchestration.

- **Concept and Principles:** An AI-native network is designed from the outset to leverage AI and be optimized for AI workloads. Key principles include:
  - AI Enablement: The network infrastructure (compute, storage, communication) must efficiently support the demands of AI training, inference, and data handling, potentially across a distributed cloud-edge-device continuum.
  - AI for Network Optimization: AI/ML algorithms are used pervasively to automate and optimize network functions, aiming for enhanced performance (throughput, latency, reliability), improved resource efficiency (spectrum, energy), self-healing/self-optimization capabilities, and enhanced security.
  - Network for AI Services: The network acts as a platform to facilitate and deliver AI-based services to end-users and applications, potentially offering AI capabilities "as a Service" (AIaaS).
  - Data-Centricity: Robust mechanisms for data collection, management, sharing, and processing across network domains are essential to fuel AI models.
  - Lifecycle Management: Automated and integrated management of the entire AI model lifecycle (data preparation, training, deployment, monitoring, updating, retraining) is required.
  - Trustworthiness and Explainability: AI components must be secure, robust, reliable, and ideally explainable to ensure trust and facilitate debugging.
  - Sustainability: AI operations themselves should be energy-efficient and contribute to overall network sustainability goals.
- **Architectural Implications:** Realizing an AI-native vision necessitates architectural evolution. Proposals include:
  - New Architectural Planes: Some visions suggest dedicated planes for data handling (Data Plane) and intelligence/decision-making (Smart Plane or Network Intelligence Stratum) alongside the traditional control and user planes.
  - Enhanced Analytics Functions: Building upon 5G's NWDAF, 6G requires more sophisticated, potentially distributed, data analytics and AI coordination functions. ETSI ENI provides a framework for cognitive management using closed AI loops.
  - Data Infrastructure: Native support for data collection, aggregation, storage, and secure sharing across domains, potentially managed by dedicated data prosumer capabilities.
  - AI Orchestration: Frameworks for managing distributed AI tasks, coordinating models across layers (e.g., Network Intelligence Orchestration - NIO), and managing the AI lifecycle.
  - Integration with Digital Twins: Utilizing network digital twins for AI model training, validation,

simulation, and real-time network management.
  ○ Advanced AI Models: Leveraging foundation models, Large Language Models (LLMs), or Large Communication Models (LCMs) for complex network understanding and intent-based management.

The shift to an AI-native architecture represents a deeper integration than seen before. It moves beyond using AI for specific optimization tasks towards embedding intelligence as a fundamental network capability, enabling continuous adaptation, automation, and the creation of novel AI-driven services. However, this vision faces substantial challenges. Ensuring reliable access to high-quality, diverse data across potentially siloed domains while respecting privacy is critical. Managing the complexity of distributed AI systems, coordinating models across the cloud-edge-device continuum, and ensuring efficient lifecycle management requires sophisticated orchestration frameworks. Furthermore, establishing trust in AI-driven decisions, ensuring explainability, and guaranteeing robustness against adversarial attacks are paramount for critical network infrastructure. Addressing these challenges through architectural design and standardization is key to realizing the AI-native 6G promise.

AI Integration in RAN and Core

The integration of AI is envisioned across both the Radio Access Network (RAN) and the Core Network (CN), but with different focuses reflecting their distinct roles and operational constraints.

- **AI in RAN:** The RAN, being highly dynamic and computationally intensive, is a prime area for AI-driven optimization and potentially fundamental redesign.
  ○ Automation and Optimization: AI/ML is targeted for automating complex RAN tasks traditionally handled by heuristics or complex algorithms. This includes dynamic resource allocation and scheduling (predicting traffic, optimizing for slice SLAs) , intelligent beam management (beam prediction, tracking, selection, especially for massive MIMO and high frequencies) , mobility optimization (handover prediction, trajectory-aware resource management) , interference coordination and mitigation , network energy saving (predictive cell sleep modes) , and dynamic RAN slicing.
  ○ AI-Native Air Interface: A more radical concept involves embedding AI directly into the physical (PHY) and MAC layers, potentially replacing or augmenting traditional signal processing blocks (e.g., channel estimation, decoding, waveform design) with learned components. This aims for optimized performance tailored to specific conditions but faces significant challenges in training, standardization, and interoperability.
  ○ Architectural Enablers: The Open RAN (O-RAN) architecture, with its disaggregation and introduction of the RAN Intelligent Controller (RIC), is seen as a key enabler for AI in the RAN. The RIC (near-RT and non-RT) provides standardized interfaces (E2, A1, O1) and platforms (xApps, rApps) for deploying AI/ML applications from multiple vendors to monitor and control RAN elements. Initiatives like the AI-RAN Alliance further promote research and blueprints for AI in the RAN. The concept of AI-and-RAN explores dynamically sharing infrastructure between RAN processing and other AI workloads (like generative AI inference) for better resource utilization.
- **AI in Core Network:** AI integration in the CN typically focuses on network-wide analytics, orchestration, and management.
  ○ Advanced Analytics: Building on 5G's Network Data Analytics Function (NWDAF) and Management Data Analytics (MDA) concepts, 6G core analytics will likely be more sophisticated, distributed, and predictive. AI can provide deeper insights into network traffic patterns, user behavior, service quality, and potential anomalies.
  ○ Intelligent Orchestration: AI can optimize end-to-end network slicing (resource allocation, lifecycle management) , automate service provisioning and assurance, optimize traffic steering across domains, and enhance security through intelligent threat detection and response.
  ○ Cognitive Management: Emerging concepts involve using advanced AI models like Large Language Models (LLMs) or AI agents within the core network management plane to interpret high-level intents, automate complex configuration tasks, and provide natural language interfaces for network operations.
- **Cross-Domain Coordination:** Effective AI-native operation requires coordination across RAN, Core,

and Management domains. This necessitates frameworks for end-to-end AI orchestration, managing the lifecycle of AI models deployed across different domains, and establishing secure and efficient data pipelines for collecting and sharing information needed for training and inference.

While both RAN and Core benefit from AI, the nature of integration differs. RAN AI often deals with real-time or near-real-time radio resource optimization and potentially PHY/MAC layer functions, demanding low latency and tight integration with RAN elements. Core AI typically operates on longer timescales, performing network-wide analysis and orchestration based on aggregated data. Open architectures like O-RAN are particularly significant for enabling innovation and deployment of AI applications in the complex RAN domain by providing standardized data access and control interfaces.

Distributed AI Frameworks

Centralized AI approaches, where data is aggregated in a central cloud for training and inference, face significant limitations in the context of 6G due to massive data volumes, stringent latency requirements for real-time control, data privacy regulations, and communication overhead. Consequently, distributed AI frameworks, which push intelligence closer to the network edge and end devices, are considered essential for realizing the AI-native 6G vision.

- **Motivation:** Key drivers for distributed AI include:
  - Latency Reduction: Performing inference and potentially training closer to the data source (at the edge or on-device) reduces the delay associated with backhauling data, crucial for real-time applications like autonomous driving or industrial control.
  - Privacy Preservation: Techniques like Federated Learning allow models to be trained collaboratively on distributed data without centralizing sensitive raw data, addressing privacy concerns.
  - Bandwidth Efficiency: Processing data locally reduces the amount of data that needs to be transmitted across the network, alleviating backhaul congestion.
  - Scalability: Distributing the computational load across numerous edge nodes and devices can be more scalable than relying solely on centralized cloud resources.
  - Context Awareness: Local AI models can better adapt to specific local conditions and context.
- **Concepts and Techniques:** Distributed AI encompasses various approaches:
  - Edge AI: Deploying AI models and performing inference/training at network edge nodes (e.g., base stations, MEC servers).
  - On-Device AI: Running AI models directly on user equipment (smartphones, vehicles, IoT devices).
  - Federated Learning (FL): A collaborative learning paradigm where devices train local models on their data, and only model updates (e.g., gradients, weights) are sent to a central server for aggregation, preserving data privacy. Statistical FL (StFL) is proposed for resource prediction in network slicing.
  - Distributed Inference: Splitting large AI models across multiple nodes (e.g., device and edge) for inference.
  - Multi-Agent Systems: Utilizing autonomous software agents (e.g., Belief-Desire-Intention agents) distributed across the network to perform learning and decision-making collaboratively.
  - Hierarchical AI: Combining local AI at devices/edge nodes with higher-level coordination and aggregation at central controllers or cloud platforms.
- **Architectural Support:** Enabling distributed AI requires specific network capabilities and architectural support:
  - Compute Continuum: A flexible architecture spanning cloud, edge, and end-device compute resources.
  - Efficient Communication: Optimized protocols and potentially dedicated network planes (e.g., Data Plane) for exchanging model parameters, updates, or intermediate results efficiently.
  - Orchestration Frameworks: Systems to manage the deployment, coordination, and lifecycle of distributed AI models and workflows (e.g., Network Intelligence Orchestration , integration with platforms like Kubeflow).
  - Service Mesh Optimizations: Addressing potential latency overheads introduced by service meshes

used for inter-microservice communication in cloud-native environments.

The move towards distributed AI is thus a fundamental requirement for practical and scalable AI integration in 6G. It addresses key limitations of centralized approaches regarding latency, privacy, and bandwidth. However, implementing distributed AI introduces its own complexities, including managing distributed resources, ensuring model consistency, handling communication overhead for model updates, and developing robust orchestration frameworks. The network must evolve into an active platform that facilitates these distributed AI operations, rather than just being a passive pipe for data.

Zero-Touch Network and Service Management (ZSM)

Zero-Touch Network and Service Management (ZSM) represents the pinnacle of network automation, aiming to enable networks that can largely manage themselves throughout their lifecycle with minimal or zero human intervention. It is considered a crucial component for managing the anticipated complexity, scale, and dynamism of 6G networks and services.

- **Concept:** ZSM envisions largely autonomous networks capable of self-configuration, self-monitoring, self-healing, and self-optimization. Operations are driven by high-level policies and intents (expressing business goals or service requirements) rather than low-level manual commands. The goal is full end-to-end automation across multiple network domains and potentially multiple vendors.
- **Role of AI/ML:** AI and ML are fundamental enablers for ZSM. Data-driven analytics, predictive modeling, and intelligent decision-making algorithms are required to interpret network state, predict future conditions, diagnose problems, and determine optimal actions within closed automation loops. AI is essential to handle the complexity and achieve the level of autonomy targeted by ZSM.
- **ETSI ZSM Framework:** The European Telecommunications Standards Institute (ETSI) Industry Specification Group (ISG) ZSM, formed in 2017, is defining a reference architecture and solutions for zero-touch automation. Key elements include:
  - Architecture: Defines management domains, end-to-end service management, integration fabric, and data services.
  - Closed Loops: Employs closed-loop control mechanisms (Observe-Orient-Decide-Act model) at different levels (resource, service, business) for automation.
  - Intent-Based Interfaces: Supports interfaces where management systems receive high-level intents and translate them into concrete actions.
  - Interoperability: Aims to enable automation across multi-vendor and multi-domain environments through standardized interfaces and data models. The feasibility of the ETSI ZSM framework is being validated through various Proofs of Concept (PoCs).
- **Relevance to 6G:** ZSM is seen as indispensable for managing 6G networks due to their expected scale (massive IoT, ubiquitous connectivity), complexity (integration of NTN, sensing, diverse slices), and agility requirements (on-demand service creation, dynamic adaptation). It is particularly crucial for efficiently managing massive network slicing ecosystems envisioned for 6G. By automating operations, ZSM promises significant improvements in operational efficiency (reducing OPEX), service agility (faster time-to-market), and network resilience.

ZSM effectively embodies the application of AI-native principles to the specific domain of network and service management. It leverages AI/ML within a structured architectural framework to achieve unprecedented levels of automation. The development of standardized frameworks like ETSI ZSM is vital for ensuring that this automation can be realized in a practical, interoperable manner across the complex, multi-faceted 6G ecosystem.

VI. Comparative Analysis: 5G-Advanced vs. 6G

The transition from 5G-Advanced (Rel-18/19) to the envisioned 6G represents both a quantitative leap in performance and a qualitative shift in capabilities and architectural philosophy.

Capabilities and Performance Targets

A direct comparison reveals the scale of ambition for 6G relative to the enhancements brought by 5G-Advanced over the initial 5G baseline.

- **Quantitative Leap in KPIs:** As summarized in Table 2, 6G targets substantial, often order-of-magnitude, improvements over 5G/5G-Advanced across most traditional KPIs. Peak data rates aim for Tbps levels (vs. 5G's 20 Gbps), user experienced rates target the Gbps range (vs. 100 Mbps), air interface latency aims for the 100-microsecond level (vs. 1 ms), connection density targets increase by 10-100x, and reliability potentially improves by several orders of magnitude. Mobility support is also expected to double to 1000 km/h. While 5G-Advanced introduces enhancements (e.g., improved uplink MIMO , lower latency for XR , increased energy efficiency), these are generally incremental improvements within the 5G framework, whereas 6G targets represent a fundamental step-change requiring disruptive technologies.
- **Qualitative Expansion of Capabilities:** Beyond enhancing existing metrics, 6G introduces fundamentally new capabilities, as formalized in the ITU IMT-2030 framework. While 5G-Advanced improves positioning (e.g., bandwidth aggregation, RedCap support), 6G targets centimeter-level accuracy as a native capability. Integrated sensing becomes a core network function in 6G , moving beyond communication. AI is envisioned to be natively integrated across the 6G architecture , whereas 5G-Advanced applies AI primarily for optimizing existing functions or studies its use for the air interface. Sustainability and ubiquitous coverage are elevated to explicit capability goals in 6G , reflecting a broader scope than the primarily performance-driven goals of 5G/5G-Advanced.
- **Integration of Key Value Indicators (KVIs):** The 6G vision explicitly incorporates KVIs like Sustainability, Trustworthiness, and Inclusion as core design principles and evaluation criteria. This represents a significant philosophical shift from the predominantly KPI-focused development of 5G and 5G-Advanced, aiming to align technological progress with broader societal and environmental goals from the outset.

Indicator/Capability	5G (IMT-2020 Target/Baseline)	5G-Advanced (Rel-18/19 Enhancements/Goals)	6G (IMT-2030 Target/Vision)
Peak Data Rate	20 Gbps	Enhanced MIMO, CA/DC power limits	50-200 Gbps (ITU examples) , up to 1 Tbps (research target)
User Experienced Rate	100 Mbps	Uplink improvements, XR QoS	300-500+ Mbps (ITU examples) , up to 1 Gbps (research target)
Latency (Air Interface)	1 ms	Reduced latency for XR (~10-15ms RAN budget) , L1/L2 mobility	0.1 - 1 ms (ITU range) , 100 µs (research target)
Reliability (Air Interface)	1×10^{-5}	URLLC enhancements, NTN resilience	1×10^{-5} to 1×10^{-7} (ITU range) , up to 1×10^{-9} (research target)
Connection Density	10^6 devices/km²	RedCap evolution, IoT NTN	10^6 - 10^8 devices/km² (ITU range) , 10^7 devices/km² (research target)
Mobility	500 km/h	L1/L2 mobility, enhanced CHO/DAPS	500 - 1000 km/h (ITU range) , 1000 km/h (research target)
Area Traffic Capacity	10 Mbit/s/m²	MIMO/UL enhancements	30-50 Mbit/s/m² (ITU examples) , 1 Gb/s/m² (research target)
Spectrum Efficiency	~30 bps/Hz (peak DL)	Enhanced MIMO/CSI, CJT	1.5x - 3x improvement over 5G (ITU target) , 60 bps/Hz (peak DL research target)
Positioning Accuracy	Meter-level (Rel-16+)	Enhanced accuracy (BW agg, carrier phase), RedCap support	1 - 10 cm (ITU target)
Energy Efficiency	Baseline	Dedicated study, WUR, dynamic adaptation	Significant improvement (e.g., >10x, >90%/bit), core sustainability goal

Integrated Sensing	Not natively supported	Initial studies/related tech (e.g., positioning)	**New Capability:** Native radio sensing (range, velocity, angle, imaging)
Native AI Support	Limited (e.g., NWDAF)	AI for RAN optimization (normative), AI for air interface (study)	**New Capability:** Deep integration across all layers, AIaaS support
Ubiquitous Coverage	Goal, limited by deployment	NTN enhancements for broader reach	**New Capability:** Explicit goal, leveraging terrestrial/NTN integration
Sustainability (KVI)	Secondary consideration	Increased focus on energy saving	**New Capability/KVI:** Core design value (Environmental, Societal, Economic)
Trustworthiness (KVI)	Security focus	Security enhancements (Rel-18/19)	**KVI:** Holistic view (Security, Privacy, Resilience, Robustness, Safety)
Inclusion (KVI)	Implicit benefit	Efforts to reduce device cost (RedCap)	**KVI:** Explicit goal to bridge digital divide, ensure equitable access

Table 2 : KPI and Capability Comparison: 5G vs. 5G-Advanced vs. 6G

Architectural Approaches

The architectural evolution also highlights key differences:

- **Cloud-Native Adoption:** 5G-Advanced builds upon the cloud-native 5GC SBA introduced in initial 5G releases, focusing on maturing its implementation and potentially extending some principles towards the RAN (e.g., vRAN). 6G is expected to adopt cloud-native principles more deeply and pervasively, potentially realizing fully service-based architectures end-to-end, including the RAN. This implies a more complete transformation towards software-defined, disaggregated, and automated infrastructure.
- **AI Integration:** 5G-Advanced integrates AI primarily as an application or optimization layer on top of the existing architecture (e.g., AI for RAN optimization using existing interfaces, NWDAF for analytics). 6G envisions an AI-native architecture where AI is a fundamental building block, potentially requiring new architectural planes (intelligence/data planes), native support for AI workflows (training, inference, lifecycle management), and deep integration into PHY/MAC layers.
- **Network Function Design:** 5G-Advanced largely works within the NF structure defined for 5G SBA. 6G may involve further decomposition of functions into finer-grained microservices and introduce new types of network functions related to sensing, AI orchestration, and data management.
- **Management and Orchestration:** 5G-Advanced utilizes evolving MANO frameworks, incorporating initial AI-driven analytics (NWDAF) and automation (SON evolution). 6G aims for full Zero-Touch Network and Service Management (ZSM), relying heavily on AI/ML for intent-driven, autonomous operations across complex, sliced, multi-domain environments.

In essence, 5G-Advanced represents an optimization and extension phase within the fundamental 5G architectural framework, introducing AI and other precursors cautiously. 6G, conversely, aims for a more radical architectural transformation, natively embedding intelligence and cloud principles throughout the network to support a significantly expanded set of capabilities and use cases.

VII. 5G-Advanced as an Evolutionary Step Towards 6G

5G-Advanced is not merely an incremental upgrade to 5G; it serves a critical role as an evolutionary stepping stone towards the realization of 6G. Several technologies, concepts, and architectural principles introduced or significantly enhanced during the 5G-Advanced phase (Releases 18 and 19) provide the necessary foundation upon which 6G capabilities will be built.

- **AI/ML Foundation:** The work initiated in Rel-18/19 on AI/ML integration is paramount. Applying AI for RAN optimization (energy saving, load balancing, mobility) provides practical experience and validates data collection/signaling mechanisms. The exploratory studies on AI for the air interface (CSI, beam management, positioning) identify key challenges, potential gains, and necessary frameworks (lifecycle management, testing), directly informing future 6G normative work. The development of AI/ML management frameworks in SA5 and the evolution of core network analytics (NWDAF/MDA) establish the operational and analytical infrastructure needed for more pervasive AI in 6G. 5G-Advanced essentially de-risks and prepares the ground for the AI-native 6G architecture.
- **XR Support:** The enhancements for XR in Rel-18/19 (XR awareness, power saving, QoS mechanisms) address the stringent requirements of immersive applications. While 6G aims for even more advanced multi-sensory experiences, the work in 5G-Advanced provides the initial network capabilities and understanding needed to support this class of demanding services.
- **NTN Evolution:** Building on the basic NTN support in Rel-17, 5G-Advanced tackles crucial operational aspects like mobility, discontinuous coverage, and IoT integration. This makes satellite integration more practical and robust, paving the way for the truly ubiquitous coverage envisioned for 6G, which will likely rely on seamless interworking between terrestrial and non-terrestrial components.
- **Cloud-Native Maturation:** 5G-Advanced drives the further adoption and refinement of cloud-native principles (microservices, containers, SBA) in operational telecom networks. Experience gained in deploying and managing cloud-native 5GC and exploring vRAN concepts provides essential learning for the deeper, end-to-end cloudification anticipated in 6G.
- **Advanced Radio Technologies:** Continued evolution in areas like MIMO (higher ranks, multi-TRP, D-MIMO enablers) , positioning (cm-level accuracy goal approached) , sidelink (unlicensed spectrum, relaying) , and duplexing studies in 5G-Advanced pushes the boundaries of radio performance and introduces techniques that will likely be integral parts of the 6G radio interface.
- **Focus on Sustainability:** The explicit introduction of energy saving as a key work area in 5G-Advanced establishes the methodologies and mindset required for addressing the broader sustainability KVI that is central to the 6G vision.

Therefore, 5G-Advanced acts as a crucial preparatory phase. It allows the industry to gain experience with key foundational technologies (AI, cloud-native, advanced radio techniques), address immediate market needs, and progressively introduce capabilities that bridge the gap between 5G's initial offerings and the transformative potential of 6G.

VIII. Challenges, Standardization, Timelines, and Societal Impact

The development and deployment of both 5G-Advanced and 6G involve significant technical challenges, complex standardization processes, ambitious timelines, and potentially profound societal impacts.

Research Challenges

- **Technical Hurdles for 6G Enablers:** Realizing the potential of key 6G technologies faces major obstacles. THz communications must overcome severe propagation losses and hardware limitations. RIS requires practical solutions for CSI acquisition and large-scale, low-cost deployment. ISAC needs effective waveform design, interference management, and robust security/privacy mechanisms. Scaling antenna arrays to UM-MIMO levels and managing distributed systems presents significant complexity.
- **AI Integration Complexity:** Building truly AI-native networks requires addressing data acquisition and privacy , developing scalable and efficient distributed AI frameworks (e.g., FL orchestration) , ensuring AI model trustworthiness, explainability, and robustness against adversarial attacks , and managing the entire AI lifecycle automatically.
- **Network Architecture:** Designing flexible, scalable, and efficient architectures that integrate cloud-native principles end-to-end (including RAN), support diverse services (slicing), incorporate native AI and

sensing, and manage distributed resources effectively is a major challenge. Ensuring low latency and high reliability in highly virtualized and disaggregated environments remains critical.

- **Security and Trustworthiness:** The expanded threat surface of 6G (massive IoT, AI integration, distributed systems, NTN, open interfaces) requires new security paradigms. Addressing privacy concerns related to pervasive sensing and AI data collection is crucial. Developing quantum-resistant cryptography is essential for long-term security. Building trust across multi-vendor, multi-domain ecosystems requires robust mechanisms (e.g., ZTA, DLT).
- **Energy Efficiency and Sustainability:** Meeting ambitious performance goals while drastically improving energy efficiency and minimizing environmental impact across the lifecycle requires fundamental breakthroughs in hardware, software, and network operation. Balancing performance KPIs with sustainability KVIs is a key design challenge.
- **Spectrum:** Identifying and allocating sufficient new spectrum, particularly in mid-bands (e.g., 7-15 GHz) and potentially THz bands, is critical but faces challenges of coexistence with incumbent services and complex regulatory processes. Efficiently utilizing existing and new spectrum through sharing and advanced techniques is vital.

Standardization Efforts and Timelines
The evolution is guided by international standardization bodies, primarily 3GPP and ITU-R.

- **5G-Advanced (Rel-18 & Rel-19):**
  - Rel-18: Functional freeze occurred in Q1 2024 (SA/CT#103), ASN.1/protocol freeze in Q2 2024 (SA#104). Implementations are emerging.
  - Rel-19: Work is ongoing. Functional freeze targeted for Q3 2025 (SA/CT#109), ASN.1 freeze Q4 2025 (SA#110). Expected to further mature 5G-Advanced features.
- **6G (IMT-2030):**
  - **ITU-R Process:**
    - Vision/Framework: Completed in Nov 2023 with Recommendation ITU-R M.2160 ("IMT-2030 Framework").
    - Requirements/Evaluation: Defining Technical Performance Requirements (TPRs) and evaluation methodologies (2024-2026).
    - Technology Submission: Call for proposals expected around early 2027.
    - Evaluation/Consensus: Evaluation of proposals and consensus building (approx. 2027-2029).
    - Specification Approval: Final approval of IMT-2030 standards targeted around 2030.
  - **3GPP Process:**
    - Early Studies: Initial requirement studies (use cases, RAN requirements) started in Rel-19 (2024) and continue into Rel-20. Technical studies in WGs planned to start Q3/Q4 2025 (Rel-20) and last ~21 months.
    - First Normative Release (Rel-21): Expected to contain the first set of 6G specifications and form the basis for 3GPP's submission to ITU-R IMT-2030. Decision on Rel-21 timeline expected by June 2026, with ASN.1 freeze no earlier than March 2029. Completion target likely end of 2028 to align with ITU process.
    - Future Releases (Rel-20+): Rel-20 will likely handle both 5G-Advanced evolution and initial 6G studies. Subsequent releases beyond Rel-21 will further evolve 6G specifications.
- **Spectrum Allocation:** Crucial decisions on new spectrum bands for 6G (especially in upper mid-band 7-15 GHz, potentially 4.4-4.8 GHz, 14.8-15.35 GHz, and THz ranges) will be made at World Radiocommunication Conferences (WRC), primarily WRC-27 and potentially WRC-31. Studies for WRC-27 are already underway. Timely allocation is critical for 6G deployment.
- **Deployment Projections:** Initial commercial 6G deployments are widely expected around the year 2030, potentially with early launches starting 2028-2029. Pre-commercial trials are anticipated from 2028 onwards.

Societal Impact

The transition to 6G holds the potential for significant societal impact, both positive and negative, demanding careful consideration.

- **Economic Growth and Innovation:** 6G is expected to drive economic growth by enabling new industries (autonomous systems, immersive experiences, pervasive AI), enhancing productivity in existing sectors (manufacturing, healthcare, agriculture), and creating new business models based on data, sensing, and AI services.
- **Bridging the Digital Divide:** A core goal of 6G is to achieve ubiquitous connectivity, potentially leveraging NTN integration to bring high-speed access to remote and underserved areas, thereby reducing inequalities in access to education, healthcare, economic opportunities, and information. Affordability remains a key factor for true inclusion.
- **Sustainability:** 6G aims to contribute positively to environmental sustainability, both by reducing the energy footprint of the ICT sector itself and by enabling efficiency gains and monitoring capabilities in other sectors (smart grids, precision agriculture, smart cities). However, potential rebound effects (increased usage due to higher capacity) and the lifecycle impact (e-waste from device turnover) need careful management.
- **Enhanced Quality of Life:** Applications in telemedicine (remote diagnostics, surgery), immersive education and collaboration, safer transportation (autonomous vehicles), and improved public safety services promise to enhance well-being and safety.
- **Privacy and Security Concerns:** The increased data collection (especially through sensing), pervasive AI, and massive connectivity inherent in 6G raise significant privacy and security concerns. Risks include heightened surveillance, data breaches, misuse of AI, and sophisticated cyberattacks targeting critical infrastructure. Building trustworthiness is paramount.
- **Societal Equity and Control:** Issues like potential job displacement due to automation, algorithmic bias in AI systems, cultural hegemony in digital content, and digital sovereignty concerns need careful consideration to ensure equitable outcomes and avoid exacerbating existing societal divides.

Navigating these impacts requires proactive engagement from policymakers, industry, researchers, and society at large to steer 6G development responsibly, maximizing benefits while mitigating risks.

IX. Conclusion

The evolution from 5G through 5G-Advanced to the envisioned 6G represents a continuous yet transformative journey in wireless communications. 5G-Advanced, spearheaded by 3GPP Releases 18 and 19, serves as an indispensable bridge, enhancing the capabilities of 5G networks to meet immediate commercial demands while strategically introducing and maturing foundational technologies critical for the 6G era. Key advancements in AI/ML integration for network optimization, dedicated support for demanding XR applications, practical enhancements for NTN deployment, and significant uplink performance improvements characterize this phase, broadening 5G's applicability and preparing the ecosystem for the next generation.

The vision for 6G, targeting deployment around 2030, transcends traditional performance metrics. While promising substantial quantitative leaps in KPIs like data rate, latency, reliability, and connection density, 6G fundamentally aims to create an intelligent, multi-functional platform fusing the physical, digital, and human worlds. This is reflected in the introduction of new capabilities within the ITU IMT-2030 framework, such as integrated sensing, native AI support, centimeter-level positioning, and the explicit elevation of sustainability, coverage, and interoperability as core design goals. The concurrent emphasis on Key Value Indicators (KVIs) – Sustainability, Trustworthiness, and Inclusion – signals a paradigm shift towards value-based design, aligning technological development with broader societal imperatives.

Realizing this vision hinges on overcoming significant research challenges associated with key enabling technologies like THz communications, Reconfigurable Intelligent Surfaces, Integrated Sensing and Communication, and advanced antenna systems. Furthermore, the architectural evolution towards deeply integrated cloud-native principles and fundamentally AI-native designs presents substantial complexities related to data management, distributed AI orchestration, lifecycle management, and ensuring trustworthiness.

The standardization process, led by ITU-R and 3GPP, provides a structured roadmap, with 5G-Advanced specifications finalizing in the mid-2020s and the first 6G specifications (3GPP Release 21) expected around 2028-2029, enabling initial commercial deployments circa 2030. Crucial decisions regarding spectrum allocation, particularly in new mid-bands, will be made at upcoming WRCs.

Ultimately, the journey towards 6G is not merely a technological race but an opportunity to shape a future where connectivity is more intelligent, pervasive, efficient, and aligned with human and planetary well-being. Successfully navigating the technical, architectural, and societal challenges will require sustained research investment, global collaboration in standardization, proactive spectrum planning, and a conscious effort to embed values like sustainability, trustworthiness, and inclusion into the fabric of the next generation of wireless networks. 5G-Advanced provides the crucial momentum and foundational elements for this ambitious undertaking, setting the stage for the connected intelligence era promised by 6G.

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