Bharat 6G Alliance Whitepaper

6G TECHNOLOGY LANDSCAPE SURVEY AND ROADMAP FOR R&D, PLATFORMS & TRIALS IN INDIA



October 2026

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Chapter 1: 6G Overview

Sixth-generation mobile systems, or **6G**, are being shaped as the successor to 5G-Advanced with a broader goal than higher peak speed alone: the industry aims to combine communications, computing, sensing, automation, and resilience into a more intelligent digital infrastructure. 6G is envisioned as the next generation mobile network targeting IMT-2030 deployment around 2030, delivering transformative capabilities including Tbps data rates, sub-1ms latency, ubiquitous intelligence, integrated sensing, and AI-native architecture. The transition from 5G to 6G builds on foundational technologies introduced in Release 18 (2024) through Release 21 (2029). In 3GPP's current roadmap, Release 20 is focused on 6G studies and Release 21 is planned for normative 6G work, with full technology proposals for IMT-2030 expected later in the decade

6G is therefore best understood not as a single radio upgrade, but as a system redesign driven by new service requirements, cloud-native software, tighter AI integration, broader coverage models, and much stronger attention to energy efficiency and trustworthiness. Industry and standards bodies increasingly describe 6G as a platform for digital-physical integration, where networks do more than transport data: they help perceive the environment, coordinate edge intelligence, and adapt services in real time.

Main technology themes

One of the strongest themes in 6G is the move toward AI-native networking. Release 20 studies and industry reports point to AI being embedded across the RAN and Core for tasks such as CSI compression, mobility prediction, scheduling, automation, and operational optimization. This is a step beyond today's analytics-driven automation because the intent is to make intelligence part of the system architecture rather than an overlay function.

A second major theme is Integrated Sensing and Communication, or ISAC. In this model, the radio network not only carries user traffic but also derives information about motion, range, or the physical environment, enabling applications such as industrial automation, smart infrastructure, robotics, and richer contextual services. This is closely tied to the broader 6G vision of digital-physical convergence, where communications and perception increasingly share the same infrastructure.

A third theme is Ubiquitous Coverage through stronger integration of terrestrial and non-terrestrial networks. 6G planning assumes that satellite and cellular systems will work together more seamlessly, supporting service continuity, improved positioning, and broader coverage for remote, mobile, and mission-critical use cases. This is especially important for national strategies that see 6G as strategic infrastructure rather than a purely commercial network refresh.

Additional 6G themes include exploration of higher frequency spectrum, evolution of massive MIMO and beamforming, tighter coupling between communications and cloud computing, security and privacy enhancements, and architectures that are more modular and software-driven than previous generations. Sustainability also appears repeatedly as a design principle, with some reports describing 6G goals in terms of far better energy efficiency per bit and more carbon-aware network management.

Standards and industry direction

The current standards picture is important because it shows that 6G is still in the study phase rather than final specification. According to 3GPP, Release 20 contains the study work for 6G,

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while Release 21 is planned to start the normative specification phase. That means the industry is currently refining service requirements, architecture concepts, and candidate radio approaches rather than implementing a frozen 6G standard.

This timing explains why 6G discussion is strongly influenced by white papers, national roadmaps, and pre-standard collaboration groups. The Next G Alliance, for example, has published overview work covering dozens of candidate technology areas and highlighting research needs across radio, architecture, operations, and trustworthiness. In parallel, governments and industry bodies in countries such as India, Japan, and South Korea have framed 6G as a strategic research and industrial priority tied to domestic capability building, testbeds, and long-term competitiveness.

Because of this, current 6G development is happening through experimental platforms more than commercial deployments. Cloud-native cores, AI frameworks, advanced RF labs, and early sensing or NTN testbeds are serving as the practical bridge between 5G-Advanced and future 6G systems.

Outlook

A realistic view is that 6G will arrive gradually, with many of its first benefits appearing as extensions to 5G-Advanced platforms before full 6G standards are complete. The near-term value will likely come from software-defined upgrades such as better automation, AI-assisted optimization, improved edge integration, and more flexible support for sensing and non-terrestrial connectivity.

Over the longer term, 6G is expected to become the framework for a more unified digital infrastructure in which communication, computation, sensing, and control are orchestrated together. Whether that vision succeeds will depend not only on radio breakthroughs, but also on interoperability, affordability, energy performance, security, and the ability of standards bodies and industry ecosystems to convert ambitious research themes into deployable systems.

Target of the document

As 6G is still under development, there are various programs across the world and industry towards use case identification, R&D on 6G, standardization, prototyping, proof of concepts and planning pilots. A similar exercise is being conducted across India. This document tries to provide a landscape survey of 6G and roadmap for India 6G R&D. The document provides an

- Overview of 6G technology and standardization
- Identifies the key architectural changes over 6G
- Discusses the impact of AI on 6G
- Details the possible 6G technology landscape in the form of a matrix
- Identifies a “Master Strategic Roadmap for Indian 6G R&D”
- Provides a list of potential technology platforms which can be used to create 6G technologies/solutions
- Details the list of potential PoC and trials that can be conducted in India to study 6G technologies, use cases and provide a platform for showcasing India R&D in 6G
- Identifies the current 6G R&D being conducted in India and suggestion on potential list of priority areas requiring attention.
- Lists the areas/aspects/topics to be further studied for the next version of this document
- Brief on the 6G programs across the world to provide context

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Chapter 2: 6G Standardization

6G is being scoped against the ITU-R IMT-2030 framework (Recommendation M.2160, approved in 2023), which defines six usage scenarios. Three are direct evolutions of the IMT-2020 (5G) scenarios — Immersive Communication (from eMBB), Massive Communication (from mMTC), and Hyper-Reliable Low-Latency Communication (from URLLC). Three are new to the 2030 vision — Ubiquitous Connectivity, AI and Communication, and Integrated Sensing and Communication (ISAC). 3GPP has organized its entire 6G work program around this six-scenario structure.

Rather than a single-release jump, 3GPP has deliberately split the path to 6G across two releases. Release 20 is a dual-track release: one track (Rel-20_5GA) continues 5G-Advanced commercial enhancements, while a parallel track (Rel-20_6G) carries out the first formal 6G use-case, requirements, architecture and radio-technology feasibility studies. Release 21 is the first release that will contain normative — i.e., binding, implementable — 6G specifications, including the Stage 3 protocol detail and ASN.1/OpenAPI that chipset and equipment vendors need to build certifiable 6G silicon.

The path to 6G is not a clean break from 5G. Most foundational technologies are already being studied in:

- 3rd Generation Partnership Project Release 18 (5G-Advanced Phase 1)
- Release 19 (5G-Advanced Phase 2)
- Release 20 (Pre-6G Studies)
- Release 21 (Early 6G Standardization)

The overall 6G objective is:

- **Native AI + Native Sensing + Native Digital Twin + Extreme Connectivity + Sustainable Infrastructure**

The transition from 5G-Advanced to 6G is structured across a clear four-release pipeline in 3GPP, moving from normative 5G enhancements to the first concrete 6G specifications.

The timelines of 3GPP releases leading to 6G:

Phase	Timeline	Focus Area	Key 6G-Enabling Technologies
Release 18	Jun 2024	First 5G-Advanced version	AI/ML for air interface, expanded MIMO, sidelink enhancements, network energy savings, XRM, AI/ML services support
Release 19	Dec 2025	5G-Advanced	Advanced AI/ML integration, ISAC study items, ambient IoT, enhanced NTN (non-terrestrial networks)
Release 20	Jun 2027	Final 5G-Advanced release	Mature ISAC, AI-native air interface elements, sub-THz study results, preliminary 6G ideas
Release 21	Mar 2029	First true 6G release	6G architecture definition, AI-native system design, full IMT-2030 compliance
First 6G Commercial Systems	2030		
Large Scale Deployment	2032+		

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- **Release 18 (5G-Advanced Baseline):** Establishes foundational data-driven network automation. Studied AI/ML for air interface and standardized AI/ML for NG-RAN.

- **Release 19 (The 6G Bridge):** Focuses on expanding use cases that serve as technological precursors to 6G. Key milestones include channel modelling for the upper mid-band (7–24 GHz), Advanced Integrated Sensing and Communication (ISAC) studies, low-power Ambient IoT architectures, and phase-3 Non-Terrestrial Network (NTN) enhancements.

- **Release 20 (6G Technical Study Phase):** The definitive pivot to 6G. It runs technical studies spanning the Radio Access Network (RAN) and Service & System Aspects (SA). Release 20 focuses on evaluating candidate waveforms, channel coding schemes, system requirements, and network topologies, without producing normative specifications.

- **Release 21 (First Normative 6G Specifications):** Expected to deliver the first functional, implementable 6G drop. It converts Release 20 Technical Reports (TRs) into normative Technical Specifications (TSs), outlining the IMT-2030 standard for commercial deployment targeting 2030.

Detailed breakup of 5G Advanced and 6G 3GPP Releases

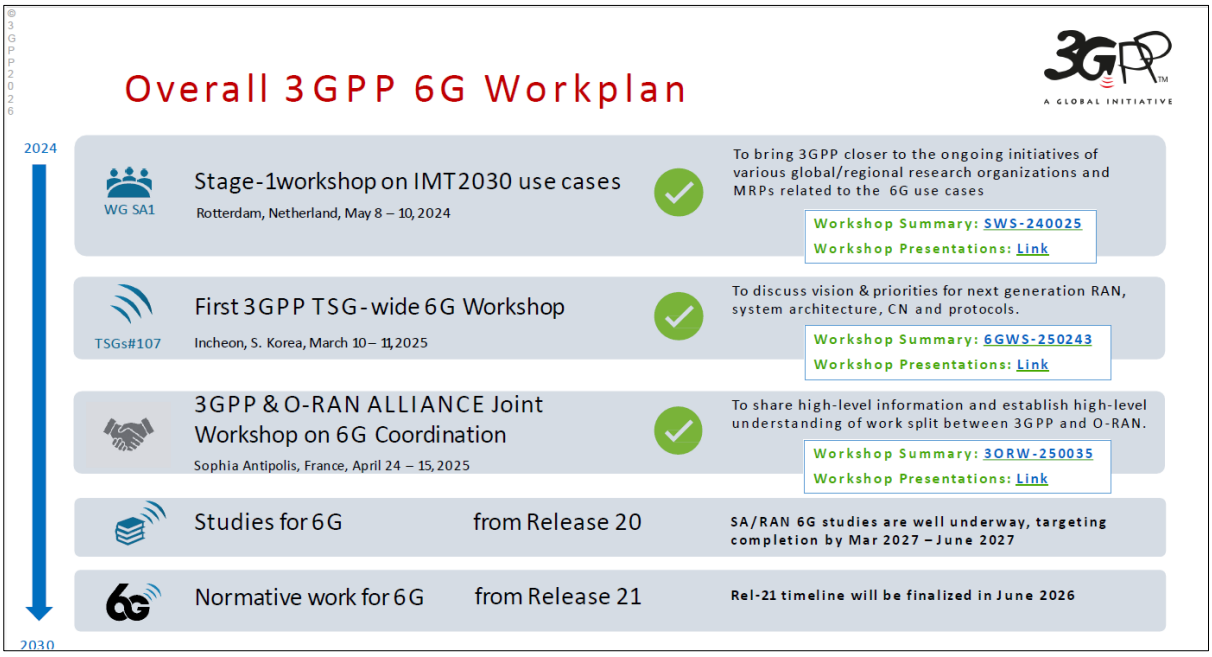

Figure 1.1: Overall 3GPP 6G Workplan (Source: 3GPP)

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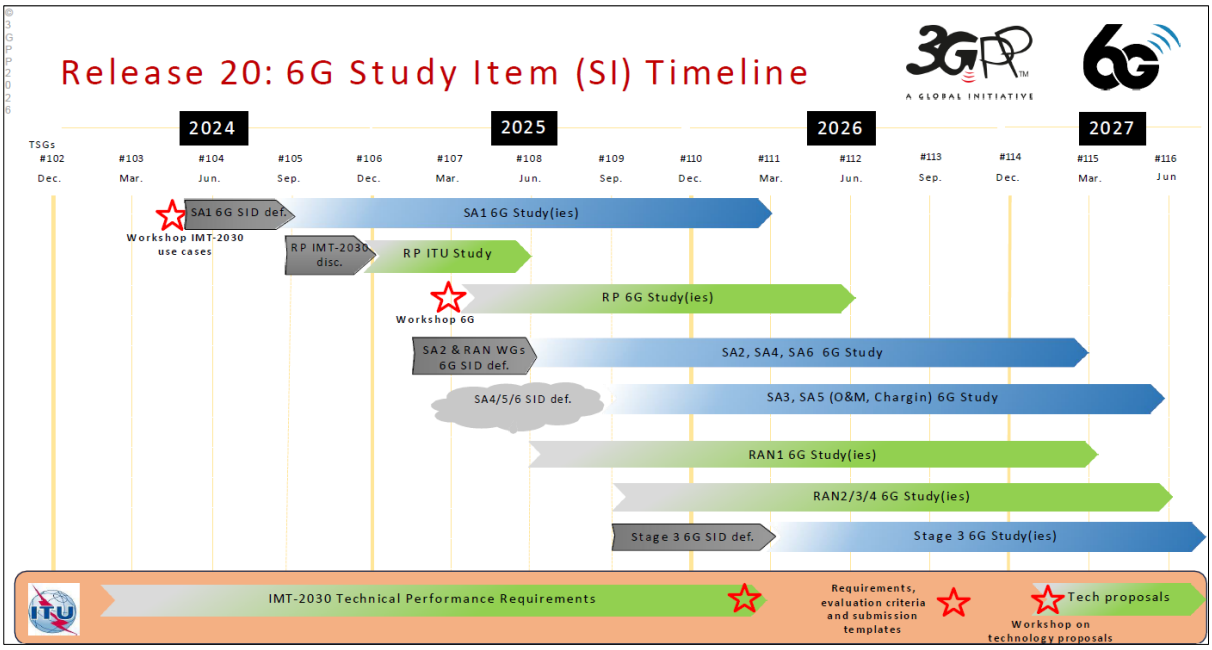

Figure 1.2: 3GPP Release 20: 6G Study Item (SI) Timeline (Source: 3GPP)

3GPP Standardization Roadmap: Release 18 to Release 21

3GPP work is carried out by three Technical Specification Groups — RAN (radio access), SA (services and system aspects) and CT (core network and terminals) — each with several working groups, and is captured in Study Items (SIs, which produce non-binding Technical Reports / TRs) followed by Work Items (WIs, which produce binding Technical Specifications / TSs). The tables below summarize how the SI/WI portfolio evolves from Release 18 through the just-timelined Release 21; they are representative rather than exhaustive — Release 20 alone carries roughly 126 work items and 74 study items in the 5G-Advanced track.

Table: 3GPP Release 18-21 Overview:

Release	Timeframe	Status (June 2026)	Primary Character
Release 18 (5G-Advanced Ph.1)	Dec 2021 – Jun 2024	Completed	First 5G-Advanced release. Introduces AI/ML into the air interface as a standardized capability, RedCap Phase 2, Network Energy savings as a first-class feature set, and XR/MBS enhancements.
Release 19 (5G-Advanced Ph.2)	2024 – Dec 2025	Completed	Converts Rel-18 AI/ML study results into normative multi-vendor features, introduces Ambient IoT, advances NTN to regenerative payloads, and runs the first channel-modeling studies (ISAC, 7–24 GHz) that feed directly into 6G.
Release 20 (Dual track)	2025 – Jun 2027	In progress	Rel-20_5GA: further 5G-Advanced commercial enhancements (~126 WIs / 74 SIs). Rel-20_6G: the first formal 6G use-case (TR 22.870), radio-scenario (TR 38.914), architecture (TR 23.801) and protocol (TR 29.84x) studies.
Release 21 (First 6G release)	2027 - Mar 2029	Timeline agreed June 2026 (TSGs#112)	First normative, implementable 6G specifications. Functional freeze targeted December 2028; ASN.1/OpenAPI freeze targeted no earlier than March 2029, opening the window for certifiable 6G silicon and equipment.

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Table: Release 18 – First 5G-Advanced Release (Selected Rel-18 SI/WI relevant to the path of 6G)

Domain	Study / Work Item	Description / Scope
RAN1/ RAN2	AI/ML for NR Air Interface (TR 38.843 → normative)	First standardized ML use cases at the air interface: CSI feedback compression, beam management, and positioning accuracy enhancement, together with an ML model-management lifecycle (training, monitoring, fallback to legacy operation).
RAN1/ RAN4	RedCap Phase 2 / NR-Light	Further reduces UE complexity (e.g., single Rx antenna, narrower bandwidth, lower power class) to widen the reduced-capability device tier for wearables and industrial sensors.
RAN1	Massive MIMO evolution	Enhanced multi-TRP operation, CSI overhead reduction, and uplink coverage/capacity improvements.
RAN2/ RAN3	NR-NTN and IoT-NTN enhancements	Continued integration of satellite access for both broadband and IoT-NTN device classes.
RAN1/ RAN2	Network Energy Savings	Cell DTX/DRX, SSB-less SCell operation for inter-band carrier aggregation, and CSI-based spatial/power-domain adaptation — the first formal energy-saving feature set in NR.
RAN2	XR enhancements (XRM)	QoS handling, capacity and power optimizations tailored to XR and cloud-gaming traffic patterns.
SA2	Multi-SIM and ATSSS enhancements	Improved support for multi-identity devices and multi-access traffic steering, switching and splitting.
SA2/ SA5	Network Slicing Phase 3, eNA Phase 3	Enhanced slicing flexibility and the third phase of enablers for network automation / data analytics (NWDAF evolution).
CT	AI/ML application enablement, NG_RTC	Core-network support for AI/ML service enablement and evolution of real-time communications.

Table: Release 19 — Second 5G-Advanced Release (Selected Rel-19 SI/WI relevant to the path of 6G)

Domain	Study / Work Item	Description / Scope
RAN1/ RAN2	AI/ML for NR Air Interface, Phase 2 (normative)	Extends Rel-18 use cases with multi-vendor model-management refinements and additional CSI/beam scenarios.
RAN2/ RAN3	AI/ML for NG-RAN enhancements	CU/DU exchange of AI model parameters over F1AP/XnAP, AI/ML-based dynamic network-slicing resource allocation, and multi-vendor interoperability validation.
RAN1/ RAN2/ SA2	Ambient IoT — Solutions for Ambient IoT in NR	Battery-less, backscatter-based IoT devices operating on the order of microwatts, targeting asset tracking and environmental monitoring — the first normative ambient-IoT framework, with core-network charging and security aspects defined in parallel.
RAN2/ RAN3	NTN Phase 3: regenerative payloads, GNSS-resilient NR-NTN	gNB-onboard-satellite operation with intra-/inter-satellite-gNB mobility, plus continued NR-NTN operation when GNSS positioning is degraded or unavailable.
RAN1	Channel modeling for ISAC and for 7–24 GHz	Two studies whose channel models feed directly into the 6G upper-mid-band (FR3) and sensing work that follows in Release 20.
RAN2/ RAN3	Multi-hop sidelink relay, mobile IAB enhancements	Extends topology flexibility for coverage extension and wireless backhaul, including mobile-IAB node migration and RACH-less handover.
RAN2	XR Phase 3, Network Energy Savings Phase 3	Further QoS refinement for multi-modal XR traffic and continued network power-reduction work.
SA1	TR 22.837 — ISAC service requirements (5G-Advanced)	Approximately 32 ISAC use cases (object/intruder detection, collision avoidance, automotive navigation, health and sports monitoring) with confidentiality, integrity and regulatory considerations — the direct precursor to the 6G ISAC requirements in TR 22.870.

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Domain	Study / Work Item	Description / Scope
SA1/ SA2	TS 22.137 — Sensing service requirements	Defines terminology and operations for co-located and separated sensing transmitter/receiver configurations within the 3GPP system.
CT	Charging for Ambient IoT, AI/ML model transfer Phase 2	Core-network billing support for the new ambient-IoT device class and continued standardization of ML model distribution.

Release 20 — Dual-Track Release (5G-Advanced + First 6G Studies)

Release 20 runs two parallel tracks under one release: Rel-20_5GA continues commercial 5G-Advanced enhancement, while Rel-20_6G performs the foundational 6G studies whose outputs directly seed Release 21 normative work.

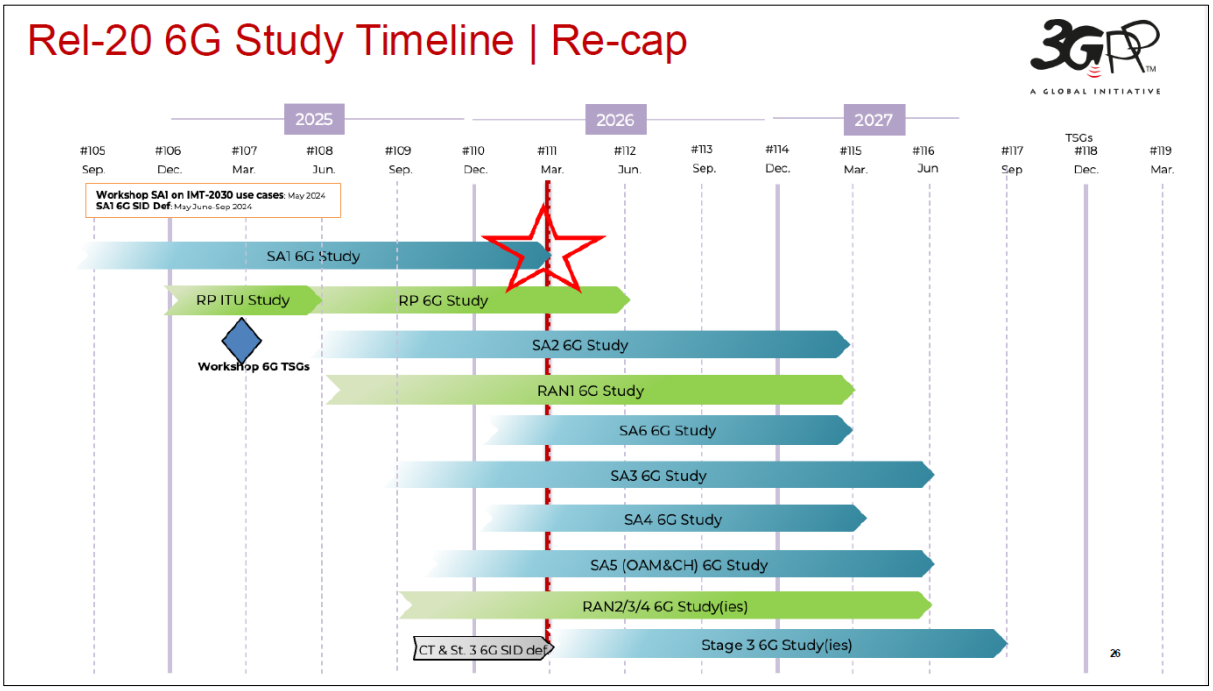

Figure 1.3: 3GPP Release-20 6G Study Timeline (Source: 3GPP)

Track A — 5G-Advanced (Rel-20_5GA) [Selected Release 20 5G-Advanced study and work items.]

Domain	Study / Work Item	Description / Scope
RAN1	MIMO evolution; mono-static sensing integration	gNB-based mono-static sensing using the existing NR PHY, targeting UAV navigation and smart-transportation use cases while minimizing specification impact — a direct bridge into 6G ISAC.
SA2	Satellite Access Phase 4 (FS_5GSAT_Ph4)	Continued maturation of NTN architecture for both consumer and IoT services.
SA2/ SA6	Future Railway Mobile Communication System Phase 6 (FS_FRMCS_Ph6)	Continued migration of railway operators off legacy GSM-R onto 3GPP technology.
SA5	Energy Efficiency as Service Criteria, Phase 2 (FS_EnergyServ_Ph2)	Formalizes energy KPIs as an explicit network performance / service criterion rather than a secondary metric.

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Track B — 6G Studies (Rel-20_6G) [Release 20 6G study items — the foundation for Release 21]

Domain	Study / Work Item	Description / Scope
SA1	TR 22.870 — Study on 6G Use Cases and Service Requirements	Approved at TSG SA#111 (Fukuoka, March 2026); ~161 use cases, 473 potential and 243 consolidated requirements, and 22 KPI tables, organized around System & Operational Aspects, AI, ISAC, Immersive Communication, Ubiquitous Connectivity, Massive Communication, and Industry & Verticals, plus cross-cutting sustainability and computing considerations.
RAN	TR 38.914 — Study on 6G Scenarios and Requirements	Reported ~90% complete at TSGs#111; defines radio-level requirements and 5G→6G migration aspects that will guide RAN working-group technical work in Release 21.
SA2	FS_6G_ARCH / TR 23.801 — Study on Architecture for 6G System	Started August 2025; studies new NAS functionality for connectivity and beyond-connectivity services, enhanced SBA/slicing/user-plane/QoS/policy/exposure frameworks, and deeper non-3GPP access convergence (Wi-Fi, wireline). Working assumption: the 6G core reuses and extends most of the 5G core rather than a clean-slate redesign.
CT	TR 29.840 / 29.841 / 29.842 + CT1 NAS study	First 6G protocol studies: control-plane protocols, user-plane protocol aspects, and resilience/reliability in the 6G core network, plus a study on the NAS protocol — targeted to complete by September 2027.
RAN1/ RAN4	21-month technical study on 6G radio technology options	Active since Q3 2025; evaluates waveform, multi-antenna, duplexing and spectrum candidates (FR3/upper-mid-band) ahead of Release 21 normative work.

Release 21 — First Normative 6G Release [Release 21 timeline, as agreed at 3GPP TSGs#112]

Domain	Study / Work Item	Description / Scope
All TSGs	First normative 6G specifications	Stage 1 service requirements substantially shaped by the consolidated TR 22.870 output; Stage 2 architecture and Stage 3 protocol work spanning roughly March 2027 to end 2028.
All TSGs	Functional freeze	Targeted for December 2028 at TSGs#122.
All TSGs	ASN.1 / OpenAPI freeze	Targeted for no earlier than March 2029 — the point at which chipset and equipment vendors can begin certifiable 6G silicon and system development.
RAN/ SA	ITU-R IMT-2030 submission	Release 21 (potentially complemented by Release 22, mirroring how Release 16 complemented Release 15 for the IMT-2020 / 5G submission) is expected to form 3GPP's candidate technology submission to ITU-R.
Industry	Commercial launch target	Approximately 2029–2030, aligned with the global ITU-R IMT-2030 designation window.

Standardization Timeline

Figure 1.4 shows the 3GPP release plan from Release 18 to Release 21 alongside the ITU-R IMT-2030 process, from the M.2160 framework to the IMT-2030 specifications, on one time axis. Four dates pace the roadmap. The Release 20 6G studies conclude in mid-2027 and define what Release 21 will standardize. The ITU-R proposal window, February 2027 to February 2029, is the period in which candidate technologies are submitted to ITU-R for evaluation. WRC-27 in November 2027 decides the spectrum on which early 6G will operate. The Release 21 ASN.1 freeze, targeted for no earlier than March 2029, is the point from which certifiable 6G silicon and equipment can be developed, leading to the first commercial systems around 2030.

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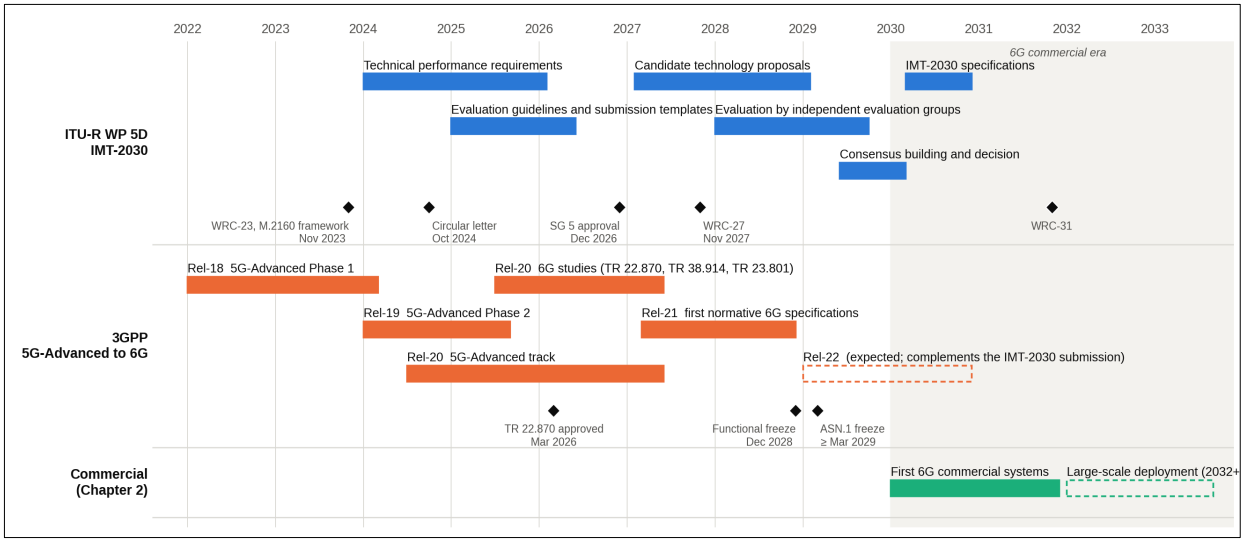

Figure 1.4: 3GPP and ITU-R IMT-2030 standardization timelines, 2022 to 2033. Sources: 3GPP TSGs#112 Release 21 timeline (June 2026); ITU-R WP 5D timeline for IMT-2030 and Circular Letter 5/LCCE/115. Dashed bars are expected but not yet scheduled.

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Chapter 3: 6G Use Cases, Technologies, and Key Architectural Changes

This chapter surveys the technologies, use cases and products that are expected to define 6G. It begins with the key enabling technologies and the nine technology pillars identified by one6G, and with the new product classes and primary use cases that follow from them. It then presents the 6G use cases as seen by the three international bodies whose work shapes the standard, namely the NGMN and one6G industry studies, the ITU-R IMT-2030 framework, and the 3GPP release studies on 6G use cases and service requirements.

The second half of the chapter follows the structure of a 6G network. It describes the major technology domains, then the 6G air interface, the 6G core network and the end-to-end system design, and ends with the deployment architecture. The technologies introduced here are the raw material for the technology landscape matrix in Chapter 5, where the same items are placed by network domain and by level of integration, and for the roadmap, platforms and trials in Chapters 6 to 8.

6G Technologies

6G Technology Landscape

6G Application Layer				
XR	Metaverse	Industry 5.0	Robotics	AI Agents
Digital Twin		Autonomous Mobility		Holographic Communicatior

6G Service Platform		
AI Services	Positioning	Sensing
Security	Data Market Place	Twin Services

6G Core	
AI Native Core	Intent Driven Networking
Compute Orchestration	Digital Twin Controller
Data Fabric	

6G AI-Native RAN/ Air Interface		
Massive MIMO	Distributed MIMO	Cell-Free Networks
ISAC	Semantic Comm	AI PHY

6G Radio/ Sensing/ Compute		
Sub-7GHz	FR3 (7-24 GHz)	mmWave
Sub-THz	Reconfigurable Surfaces	NTN

Key Enabling Technologies

- **Upper Mid-Band and Sub-THz Communications:** Exploiting the 7–24 GHz (FR3) and 100–300 GHz (Sub-THz) spectrum blocks to achieve extreme data rates and ultra-

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low latency, requiring highly accurate near-field propagation and spatial non-stationarity modelling.

- **Integrated Sensing and Communication (ISAC):** Turning the radio access network into a radar system. The air interface simultaneously transmits data and gathers situational awareness data (range, velocity, and positioning) from reflections.

- **Ambient IoT:** Low-power, battery-free, or energy-harvesting tracking devices that scavenge RF energy from environmental signals to power ultra-low-cost sensor ecosystems.

6G Technology Pillars (9 Enabling Technologies as per one6G)

1. THz frequencies
2. 6G Radio Access (AI-native, ISAC-integrated)
3. Next-generation MIMO (Ultra-massive 1024+, cell-free, RIS-enabled)
4. Integrated Sensing and Communication (Joint radar-comm functionality)
5. Non-terrestrial networks (Satellite-HST-UAV convergence)
6. Multimodal sensing-computing-communication-control (Remote operation)
7. Distributed federated AI (Privacy-preserving decentralised ML)
8. Intelligent user plane (In-network computing, semantic comm)
9. Flexible programmable infrastructures (Cloud-native, disaggregated)

New Types of 6G Products and Solutions

- **AI-Native Active Antenna Units (AAUs):** Next-generation massive MIMO arrays featuring integrated, low-latency edge accelerators capable of dynamically running real-time neural networks directly on the baseband.

- **Holographic & Extended Reality (XR) Terminals:** Lightweight, high-compute UEs optimised for split-rendering processing architectures with stringent jitter and deterministic transport demands.

- **Cell-Free Massive MIMO Distributed Units (DUs):** Coordinated base station topologies that eliminate traditional cell borders, turning inter-cell interference into macro-diversity gains.

Primary Use Cases

- **Immersive Telepresence & Digital Twins:** High-fidelity real-time replication of physical assets with extreme throughput and ultra-low latency.

- **Unified Terrestrial/Non-Terrestrial Orchestration:** Continuous, deterministic satellite-to-terrestrial roaming for logistics, maritime, and public safety across low Earth orbit (LEO) constellations and high-altitude platforms (HAPS).

- **Autonomous Industrial Swarms:** Closed-loop, sub-millisecond robot-to-robot control loops operating across distributed edge-compute domains.

The use cases that 6G is expected to serve have been described by three international bodies, and the next three sections present each view in turn. The NGMN Alliance gives the operator view. The ITU-R gives the IMT-2030 framework of usage scenarios and capabilities against

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which candidate 6G technologies will be evaluated. 3GPP turns these into service requirements for the standard through its Release 20 study on 6G use cases.

6G Key Use Cases based on one6G Whitepaper and NGMN Studies

NGMN, the Next Generation Mobile Networks Alliance, is the forum in which leading mobile operators, together with vendors and research institutes, set out what they expect from each new generation. Its 6G work started with 6G Drivers and Vision in 2021, followed by 6G Use Cases and Analysis in 2022 and the 6G Position Statement in 2023. NGMN groups 6G use cases into four classes, namely enhanced human communication, enhanced machine communication, enabling services and network evolution, and asks that 6G be introduced as an evolution of 5G rather than as a replacement. The table below consolidates the NGMN use cases with those of the one6G industry association. For each category it lists the 6G enablers, which are the technologies from the previous sections that the use case needs and that 5G cannot supply. A small set of technologies recurs across almost every row. These are sub-THz and THz spectrum, ISAC, native AI, NTN convergence, cell-free MIMO and deterministic communication.

Category	Use Cases	6G Enablers
Immersive Communications	Holographic telepresence, XR/MR, VR/AR	THz (holograms), ultra-low latency, precise localisation
Tactile Internet	Remote haptic operation, tele-surgery	<0.1ms latency, multimodal sensing-control
Digital Twins	High-fidelity industrial DT, massive twinning	ISAC, real-time bidirectional updates, AI processing
Remote Operation	Uncrewed facilities, AMR factory control, remote driving	Multimodal teleoperation, cooperative robotics
AI Agent Interactions	Autonomous AI agents, multilateral ecosystems	Native AI, AI-as-Service
Sensing-Assisted Comm	Vehicle radars, environmental monitoring, e-health	ISAC at THz, chemical analysis, medical imaging
Ubiquitous Connectivity	Rural/indoor coverage, in-flight/in-train entertainment	NTN convergence, RIS enhancement
Industry 4.0/5.0	Factory automation, smart cities, smart metering	THz Tbps, cell-free MIMO, deterministic comm

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Use Cases based on IMT-2030

The ITU-R is the body that decides what a generation of mobile technology must achieve before it can carry the IMT label. Its Working Party 5D approved the IMT-2030 framework as Recommendation ITU-R M.2160 in November 2023. Rather than listing applications, the framework describes 6G through usage scenarios and capabilities, to which WP 5D added minimum technical performance requirements in 2026. Figures 3.1 to 3.4 summarise these elements and the timeline on which they are being completed.

Figure 3.1 is the IMT-2030 usage-scenario wheel. Three scenarios extend those of IMT-2020. Enhanced mobile broadband becomes immersive communication, massive machine-type communication becomes massive communication, and ultra-reliable low-latency communication becomes hyper-reliable and low-latency communication. Three scenarios are new to 6G, namely ubiquitous connectivity, AI and communication, and integrated sensing and communication. The outer ring carries four overarching aspects that apply as design principles to all six scenarios. These are sustainability, connecting the unconnected, ubiquitous intelligence, and security and resilience.

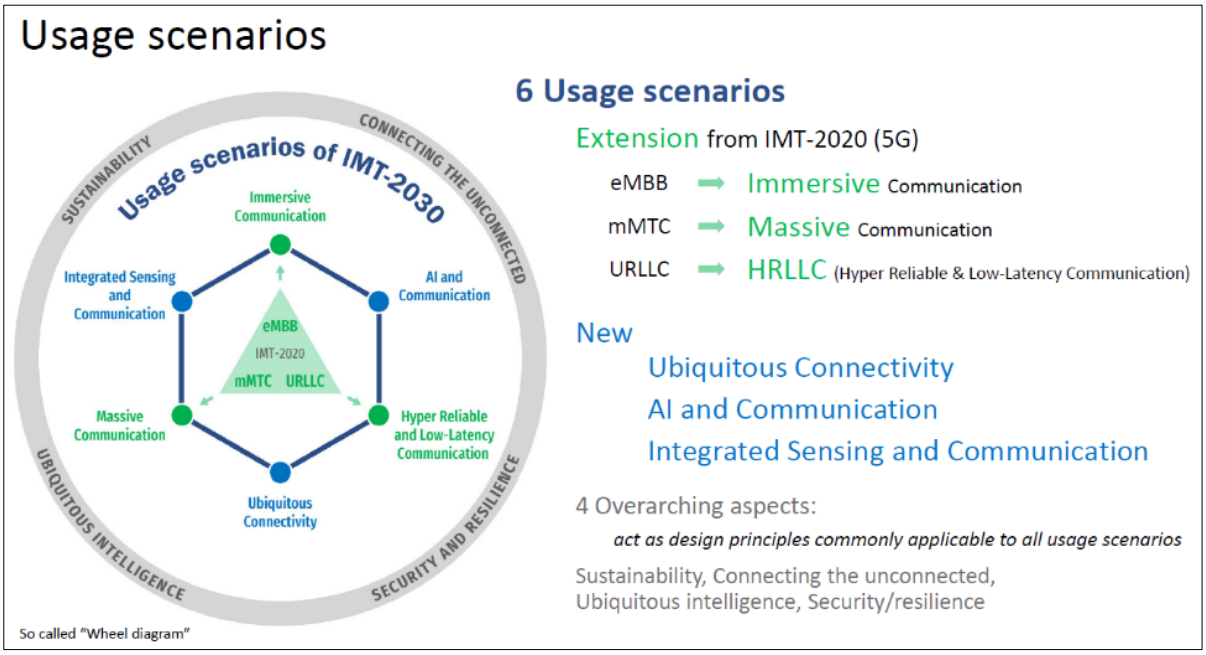

Figure 3.1: Usage scenarios of IMT-2030, the ITU-R wheel diagram. (Source: ITU-R M.2160, WP 5D)

Figure 3.2 is the capabilities palette. The lower half shows nine capabilities carried over from IMT-2020 with enhanced target ranges, including peak and user-experienced data rate, spectrum efficiency, area traffic capacity, connection density of one million to one hundred million devices per square kilometre, mobility up to 1000 km/h, latency of 0.1 to 1 ms, and reliability up to one error in ten million. The upper half shows six capabilities new to IMT-2030, namely coverage, sensing-related capabilities, applicable AI-related capabilities, sustainability, interoperability, and positioning to between 1 and 10 cm. The ranges are research targets. The values that apply to each usage scenario will be fixed in later ITU-R reports.

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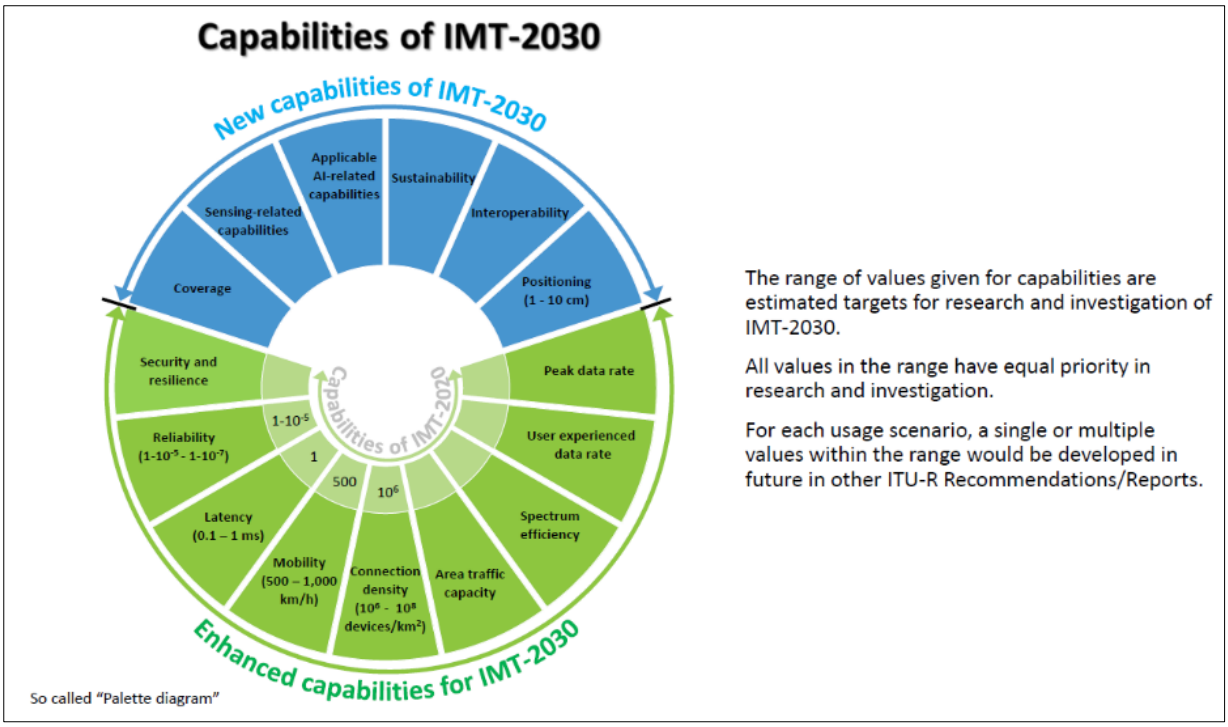

Figure 3.2: Capabilities of IMT-2030, the ITU-R palette diagram. Source: ITU-R M.2160, WP 5D.

Figure 3.3 is the WP 5D timeline for IMT-2030. The framework and technology-trends reports were completed between 2021 and 2023. Technical performance requirements, evaluation criteria and submission templates follow between 2024 and 2026. Candidate technology proposals are invited from February 2027 to February 2029, are evaluated by registered independent evaluation groups through 2029, and the IMT-2030 specifications are expected in 2030. The two World Radiocommunication Conferences, WRC-23 and WRC-27, are the spectrum decision points.

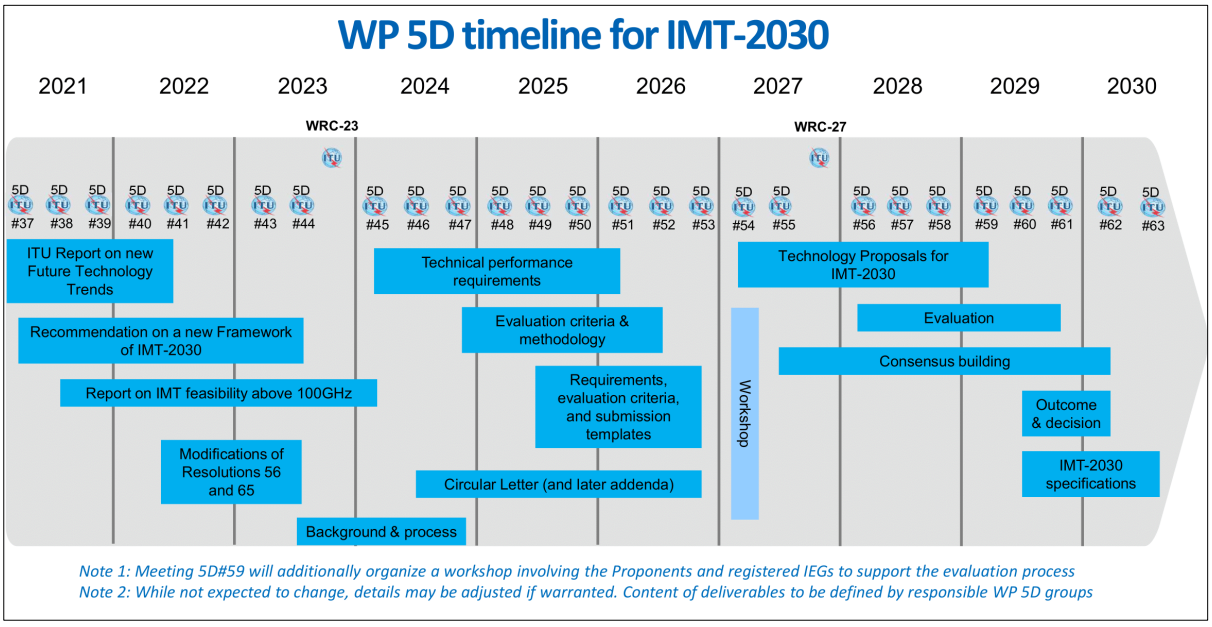

Figure 3.3: WP 5D timeline for IMT-2030. Source: ITU-R WP 5D.

Figure 3.4 lists the twenty minimum technical performance requirements of IMT-2030, drafted by WP 5D in February 2026 for Study Group 5 approval in December 2026. Thirteen are carried over from IMT-2020, from peak data rate and spectral efficiency through latency,

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reliability and bandwidth. Seven are new and mark the change in what a 6G radio must do. They are a composite requirement, link distance, positioning accuracy, sensing-related requirements, an AI-related requirement, energy efficiency for sustainability, and resilience and extended connectivity. These requirements are the yardstick against which every candidate 6G radio technology, including any submitted through 3GPP, will be judged.

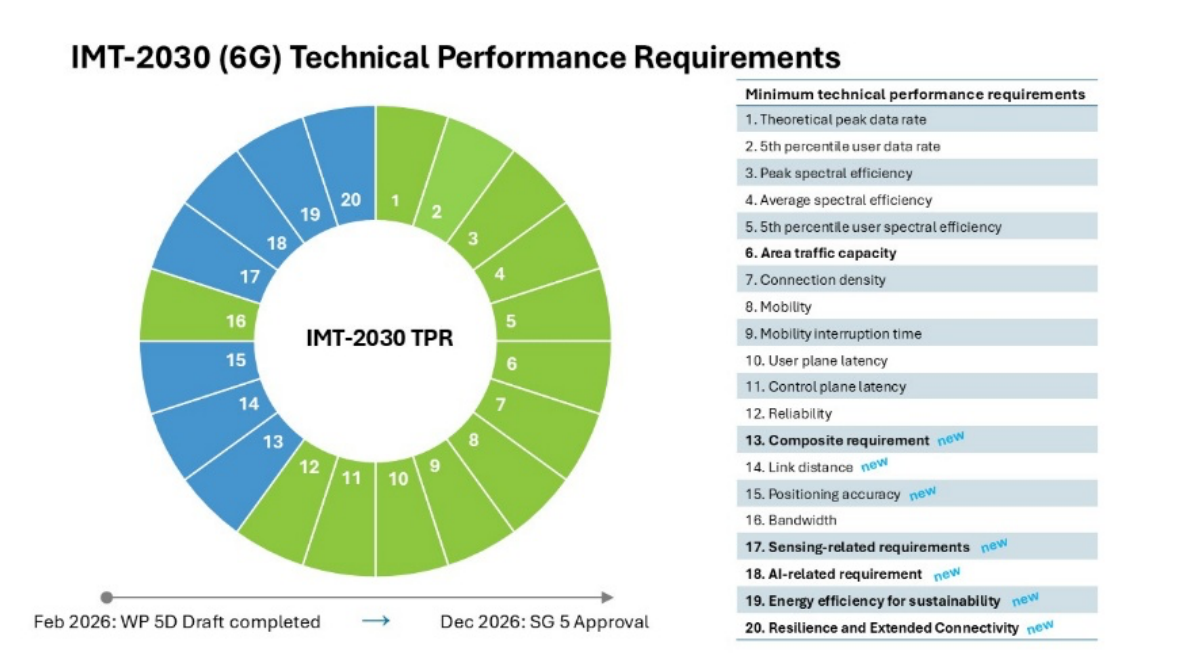

Figure 3.4: IMT-2030 minimum technical performance requirements. Source: based on the ITU-R WP 5D draft report, February 2026.

Use Cases based on 3GPP Release

3GPP is where use cases become requirements. Its Release 20 study on 6G use cases and service requirements, TR 22.870, was approved in March 2026 after consolidating about 160 use cases contributed by operators, vendors and verticals into a set of service requirements and key performance indicator tables that will drive the Release 21 specifications. The table below groups the 3GPP use cases into six categories. Four of them, AI-native 6G, ISAC, ubiquitous connectivity and immersive communication, correspond directly to the IMT-2030 usage scenarios of Figure 3.1, which is by design, since the 3GPP submission has to be evaluated against them. The remaining two, massive communication and industry and vertical applications, carry forward the machine-type and private-network use cases that 5G introduced and that 6G is expected to serve at larger scale and lower device complexity.

Category	Use Cases
AI-Native 6G	Network Optimisation, End-to-end AI for connected Cars, Personalised Health Monitoring
Integrated Sensing and Communication (ISAC)	Public Safety and Disaster Response, Transportation, Industrial Automation, Health Monitoring
Ubiquitous Connectivity	Satellite-Based Communication, Resilient Connectivity, Positioning and Timing

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Category	Use Cases
Immersive Communication	Holographic Conferencing, Spatial Collaboration, Cloud Gaming and Streaming, Education and Guided Tours
Massive Communication	Wide-Area Coverage, Low-Complexity Devices
Industry and Vertical Applications	Localised Networks, Mission-Critical Services, Robotics

Major 6G Technology Domains

The use cases above are served by a small number of technology domains rather than by a long list of individual features. The table below describes six of them, namely AI-native communications, ISAC, cell-free massive MIMO, distributed MIMO, semantic communications and digital twin networks. For each domain it shows the starting point in Releases 18 and 19, the expected evolution through Releases 20 and 21, and the intended 6G end state.

SN	Title	Description	Remarks
1	**AI-Native Communications**	**Release-18/19 Foundations** • AI for CSI feedback • AI beam management • AI mobility optimisation • AI energy saving **Release-20/21 Evolution** • AI-designed waveforms • AI schedulers • AI PHY optimisation • AI RAN control loops	6G End State: AI becomes part of protocol stack
2	**Integrated Sensing and Communications (ISAC)**	**Network becomes a radar.** **Use Cases** • Traffic monitoring • Drone tracking • Human detection • Industrial automation • Smart city sensing **New Hardware** • Radar-capable gNB • Joint radar-communication antenna arrays	ISAC is expected to become a flagship 6G capability.
3	**Cell-Free Massive MIMO**	5G: UE → One Cell 6G: UE ← Multiple Distributed Radio Nodes **Expected Benefits:** • Uniform coverage • Reduced interference • Better edge throughput	Likely one of the largest architectural shifts
4	**Distributed MIMO**	• Evolution of COMP • Multiple Radio Units combine to have joint beamforming. **Required sub-technologies** • Fronthaul synchronisation • Cloud-RAN • AI-Coordination	
5	**Semantic Communications**	• **Current 5G:** Transmit Bits • **Upcoming 6G:** Transmit Meaning **Examples:** • AI Model updates • Object descriptors • Scene information	Expected to dramatically reduce traffic volume

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SN	Title	Description	Remarks
6	**Digital Twin Networks**	Every network entity has a digital twin. **Examples:** • UE twin • Cell twin • Factory twin • City twin **Applications:** • Predictive optimisation • Network simulation • Autonomous operations	

6G Air Interface

This section provides a brief on the 6G air interface being studied in 3GPP RAN1 and RAN4 since the third quarter of 2025 and is evaluating the new waveform, multi-antenna, duplexing and spectrum candidates ahead of the Release 21 normative work. The section also provides a walkthrough of the spectrum strategy, multiple access, reconfigurable intelligent surfaces, the AI-native physical layer, ISAC at the physical layer and native non-terrestrial integration, and then summarises the design characteristics, the physical-layer technologies, the key hardware components and the overall air-interface landscape in four tables.

Spectrum strategy

- FR1 continuity: sub-6 GHz spectrum remains the coverage backbone, carried forward from 5G NR.
- Upper mid-band / FR3 (roughly 7–24 GHz): identified as a key new 6G band (with key focus on 7.125 – 15GHz); Release 19's 7–24 GHz channel-modelling study directly influences this work.
- Sub-THz (100–300 GHz): targeted for ultra-high-capacity, short-range links, with cmWave (7 - 24GHz) also drawing significant interest as an intermediate band.

Waveform and multiple access

- AI-based waveform optimization, replacing static, rule-based configuration with self-learning adaptation to channel and traffic conditions.
- Orthogonal Time Frequency Division Multiplexing (OTFDM) is among the candidate waveforms studied as a successor to OFDM, enabling simultaneous transmission of reference signals and data with lower peak-to-average power ratio and reduced overhead.
- Continuation of NR's flexible, scalable numerology, plus exploration of non-orthogonal multiple access (NOMA) and fluid-antenna multiple access (FAMA) for denser connectivity.

Multi-antenna evolution

- Ultra-massive MIMO (umMIMO) and distributed / cell-free massive MIMO (D-MIMO, CF-mMIMO), which replace fixed cell boundaries with user-centric clusters of distributed access points to reduce inter-cell interference and improve uniform coverage.
- Structural MIMO (S-MIMO), using highly directional beams and structural antenna-panel arrangements to deliver 360-degree azimuth/elevation coverage beyond what conventional 5G MIMO panels achieve.

Reconfigurable Intelligent Surfaces (RIS)

- RIS introduces a new, largely passive network node — a surface of many reconfigurable elements that reshapes the propagation environment to improve coverage, positioning and sensing without significant added energy consumption. Standardization is still working through near-field channel modeling and how to integrate RIS elements that may be owned by third parties rather than the mobile network operator.

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Full-duplex and flexible duplexing

- 6G studies are evaluating a move beyond fixed TDD/FDD allocation toward dynamic, sub-band full-duplex operation, allowing simultaneous transmit/receive on adjacent resources to improve spectral efficiency and reduce latency.

AI-native physical layer

- Release 18 established three founding AI/ML air-interface use cases — CSI feedback compression, beam management, and positioning accuracy enhancement — together with a model-management lifecycle (training, monitoring, fallback to legacy behavior). Release 19 extended these into normative, multi-vendor-validated features. The 6G ambition is to move from "AI as an add-on to the PHY" to a PHY that is AI-native by design, with inference treated as a first-class signal-processing function rather than an optional enhancement.

Integrated Sensing and Communication (ISAC) at the physical layer

- ISAC requires joint waveform design so that the same transmission simultaneously carries communication data and supports radar-like sensing (object detection and tracking, environment monitoring, motion monitoring), using mono-static, bi-static or multi-static receiver configurations, optionally assisted by RIS. The Release 19 ISAC service-requirements study (TR 22.837, ~32 use cases) and Release 20's mono-static sensing work using the existing NR PHY are the direct precursors to a native 6G ISAC air interface.

Native non-terrestrial integration

- Regenerative satellite payloads (gNB functionality onboard the satellite), direct-to-device connectivity, and store-and-forward operation for intermittently connected areas — all matured through Release 19 NTN work — are expected to be designed into the 6G air interface as native capabilities rather than a terrestrial-network add-on.

The 6G physical layer moves away from rigid frame designs in favour of adaptive, software-defined, and AI-optimized radio structures:

- **Waveform and Numerology:** Evaluating alternatives to traditional CP-OFDM—such as Orthogonal Time Frequency Space (OTFS) to mitigate severe Doppler shifts in high-mobility and sub-THz scenarios, alongside multi-carrier waveforms tailored for dynamic spectrum sharing.

- **Advanced Modulation and Coding:** Integration of AI-designed constellation mapping alongside advanced Low-Density Parity-Check (LDPC) and Polar code variants to approach the Shannon capacity limit under non-linear RF impairment conditions.

The 6G air interface is purposefully designed with these core characteristics:

1. **AI-Native Architecture:** Built around compression and adaptation with native AI/ML integration

2. **Coverage Optimization:** Extended coverage from existing (mmWave) and new bands

3. **Efficiency Centrality:** Energy, spectrum, and implementation complexity optimization

4. **Backward Compatibility:** 5G-compatible with spectrum sharing capabilities

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Technical Architecture of 6G

6G AI-Native Air Interface Architecture	
THz Layer (0.1 – 10THz)	Ultra-Massive MIMO (1024+)
RIS Assisted Beamforming	Near-Field MIMO Processing
AI-Driven PHY/MAC	Compression-Adaptation Core
ISAC Joint Processing	Semantic Communication

Physical Layer Technologies

Technology	Description	Target Performance
Terahertz (THz) Communication	Carrier frequencies 100-300 GHz (sub-THz to THz)	100 Gbps to 1+ Tbps data rates
Ultra-Massive MIMO	1024+ antenna elements with phased-array antennas	Approx. 5x spectrum efficiency improvement
Reconfigurable Intelligent Surfaces (RIS)	Programmable metasurfaces for beam control	Energy-efficient ultra-massive MIMO enablement
Advanced Waveform & Coding	New OFDM variants, adaptive coding schemes	Optimized for THz channel characteristics
Near-Field MIMO	Addressing mutual coupling effects at THz	Enhanced coverage for short-range THz[j]

Key Components of 6G Air Interface

Component	Function	Technology
THz Transceivers	100s Gb/s transmission	CMOS/InP/GaAs/SiGe/GaN chipsets
Phased-Array Antennas	Dense beamforming	1024+ element arrays
RIS Panels	Environment reconfiguration	1-bit to multi-bit metasurfaces
AI PHY Processor	Native AI inference	Neural network accelerators
ISAC Engine	Joint sensing-comm	Radar-communication fusion

6G Air Interface Landscape

SN	Title	Description	Remarks
1	**Waveforms**	**Current Waveforms:** • OFDM **Future Waveforms:** • Enhanced OFDM • AI-generated waveforms • OTFS variants • Delay-Doppler systems	
2	**Spectrum**	**Sub-7 GHz** • Coverage layer. **FR3** • 7-24 GHz • Most likely primary 6G deployment band. **Benefits**: • Wider bandwidth, Better propagation than mmWave **mmWave** • 24-100 GHz • High-capacity hotspots **Sub-THz** • 100-300 GHz: Research phase.	

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SN	Title	Description	Remarks
		• Applications: Holographic communication, Tbps links	
3	**Intelligent Surfaces**	Also called: Reconfigurable Intelligent Surface (RIS)	Walls become passive beamformers
4	**Joint Communications and Sensing (JSAC/ISAC)**	• Same waveform • Communication + Radar + Localization	Network becomes a sensor
5	**Cell-Free Architecture**	• Traditional: Cell-centric • Future: User-centric	
6	**AI-Native RAN**	New blocks: • AI Scheduler • AI Beam Controller • AI Mobility Controller • AI Energy Manager	
7	**Native NTN**	Integration of Terrestrial Networks and • GEO satellites • MEO satellites • LEO satellites • HAPS	
8	**Extremely Large MIMO**	• Current: 64T64R, 128T128R • Future: 256+, 512+, 1024 Element Arrays	

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6G Core (6GC)

Unlike the air interface, the working assumption emerging from 3GPP SA2's 6G architecture study (TR 23.801, started August 2025) is evolutionary rather than revolutionary: the 6G Core is expected to reuse and extend most of the 5G Service-Based Architecture (SBA) rather than start from a clean sheet.

Extending the Service-Based Architecture

- 5G Release 15 introduced SBA, decomposing the legacy Evolved Packet Core into a larger set of smaller, independently scalable, cloud-native Network Functions. 6G Core work is expected to extend this modularity rather than replace it — including enhanced network slicing, network sharing, user-plane architecture, QoS framework, policy framework, and network-exposure framework, all explicitly in scope for TR 23.801.

New non-access-stratum (NAS) functionality

- TR 23.801 studies whether and how to introduce new NAS functionality to support connectivity and "beyond-connectivity" services — such as Sensing-as-a-Service, Compute-as-a-Service and AI-as-a-Service — without disrupting existing NAS functions that 5G devices already rely on.

Converged multi-access

- The study also examines deeper support for non-3GPP access (Wi-Fi, wireline) and simultaneous multi-access data connections spanning 3GPP and non-3GPP access — continuing the direction set by 5G-Advanced ATSSS enhancements in Release 18–19 toward a genuinely converged access fabric.

AI-native control plane

- 6G Core is attempting to move AI from a support function layered on top of the Core to a foundational part of how the core operates. This includes evolution of 5G's Network Data Analytics Function (NWDAF) toward closed-loop, intent-driven automation, and SA5 standardization of AI model lifecycle management, telemetry ingestion and orchestration interfaces. Early proposals submitted into SA2 — for example an AI-native Core using SRv6-based dynamic routing with reinforcement-learning policy control — report on the order of 40% improvement in session-processing efficiency over GTP-based fixed-path architectures in initial trials, illustrating the direction of travel even though such proposals remain under discussion rather than agreed.

Network–compute convergence

- 3GPP SA leadership has framed the 6G promise as going "beyond communication service to deliver everything as a service" — Sensing-as-a-Service, Compute-as-a-Service, AI-as-a-Service — which requires the core to jointly orchestrate compute and connectivity resources rather than treating compute purely as an edge-application concern sitting outside the network.

Protocol-layer studies (TSG CT)

- TR 29.840 — Control-plane protocols in the 6G Core network.
- TR 29.841 — User-plane protocol aspects in the 6G Core network.
- TR 29.842 — Resilience and reliability in the 6G Core network.
- A CT1 study on the NAS protocol for the 6G system.

All four are targeted to complete by September 2027, feeding Release 21 Stage 3 core specification work.

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Security and trust

- Post-quantum cryptography (PQC) readiness and zero-trust architectural principles are being designed into the Core from the outset under SA3, rather than retrofitted later — a direct response to the long service life expected of 6G infrastructure relative to the maturing threat of quantum-capable cryptanalysis.

Sustainability as a core design criterion

- Energy efficiency, formalized as a service criterion in Release 20 5G-Advanced work (FS_EnergyServ_Ph2), carries forward into 6G Core design as a first-class KPI alongside throughput, latency and reliability.

The 6G Core architecture shifts from virtualized service-based designs to a fully cloud-native, decentralized, and microservice-driven environment:

- **Semantic Communication & Knowledge Spheres:** The Core network shifts from routing raw bitstreams to orchestrating intent and semantic meanings, drastically optimizing data transmission efficiency across distributed nodes.

- **Distributed Ledger-Driven Slicing:** Multi-operator slicing, roaming settlement, and cross-domain zero-trust authentication managed via decentralized consensus mechanisms.

- **Deterministic Mesh Routing:** Dynamic, ad-hoc Core routing capability where intermediate topological nodes (including gNBs or edge compute hosts) can provision short-lived core user-plane microservices

Aspect	5G Core	6G Core Evolution
Architecture	Cloud-native SBA	AI-native Extended SBA
AI Integration	Limited AI/ML support	Native AI with MLOps infrastructure
Computing	Edge computing (MEC)	In-network computing + Cloud-edge-federation
Sensing	Not integrated	ISAC-native with sensing exposure
Security	Classical encryption	Post-quantum + Quantum-safe infrastructure

Key 6G Core Functions

6G Core Network Architecture		
Service Exposure Layer: AI Services	Sensing Services	XaaS
Core Network Functions: • AMF (Access & Mobility) + AI Mobility Engine • SMF (Session Management) + AI Resource Orchestrator • PCF (Policy) + AI Policy Analyzer • NRF (Discovery) + AI Service Discovery • UDM (Data) + Federated Learning Manager		
AI/ML Infrastructure • Network-hosted MLOps (Training/Inference/Testing) • UE & 3rd-party AI service on-demand • Distributed AI Federation Engine		
Data & Computing Fabric: • Unified Data Repository + Digital Twin Store • Edge Cloud + In-Network Computing Plane • Federated Data Fabric		

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The Core Network Design Principles for 6G as proposed by NGMN in its Architecture Evolution Study is listed below:

1. **Enable Innovation**: Support IMT-2030 capabilities (sensing, AI/ML, computing, security)
2. **Modular Deployment**: On-demand feature deployment without compromising connectivity
3. **AI/Agentic-AI Automation**: Autonomous intelligent network management
4. **Cloud-Native Extension**: Full SBA extension with cloud-native NF implementations
5. **Network as a Service**: Computing-as-Service, Data-as-Service, AI-as-Service
6. **Smooth Migration**: 5G SA to 6G seamless transition
7. **Sustainability**: Cross-layer energy optimization from design

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6G System Design

IMT-2030 System Requirements: The ITU-R IMT-2030 framework defines three new usage scenarios and six critical capabilities:

New Usage Scenarios:

1. Ubiquitous Connectivity: Coverage enhancement (remote/rural/indoor)
2. AI and Communication: Native AI integration
3. Integrated Sensing and Communication: Joint sensing-comm functionality

New Critical Capabilities:

1. Coverage: Enhanced connectivity scale
2. Sensing-related: Positioning, environmental awareness
3. AI-related: Ubiquitous intelligence
4. Sustainability: Energy/carbon efficiency
5. Interoperability: Multi-network convergence
6. Positioning: cm-level accuracy

6G system design spans well beyond any single interface or network function — it is being scoped as an end-to-end system covering terrestrial, aerial and satellite domains, with AI and sensing woven through every layer.

End-to-end, multi-domain design philosophy
SA2 architecture work targets unified authentication, session continuity, and traffic steering across macro terrestrial, aerial and satellite layers — building toward what industry analysis describes as a single global 6G coverage fabric rather than separate terrestrial and non-terrestrial systems.

Use-case taxonomy as a system design input
TR 22.870's organization of the 6G use-case space — System & Operational Aspects, AI, ISAC, Immersive Communication, Ubiquitous Connectivity, Massive Communication, and Industry & Verticals, plus cross-cutting sustainability and computing considerations — is itself a system design input: it tells architecture groups which capabilities must be designed as native system functions versus optional services.

"Everything as a service"
Sensing-as-a-service, compute-as-a-service and AI-as-a-service are positioned as native 6G system capabilities, exposed and monetized through evolved network-exposure frameworks (the 6G-era evolution of today's NEF, CAPIF and SEAL/SEALDD enablers), rather than bolted-on application-layer features.

Network digital twins
High-fidelity, physically accurate simulation of complete 6G systems — from a single tower to city scale — is emerging as both a design/validation tool and, looking further ahead, a candidate input to real-time network operations and self-optimization.

AI agents as system-level actors
TR 22.870 formally defines an AI agent as an automated, intelligent entity capable of interacting with its environment, acquiring contextual information, reasoning, self-learning, decision-making, and executing tasks autonomously or in collaboration with other AI agents to achieve a specific goal. Treating AI agents as first-class system actors — rather than passive applications — introduces new system-design requirements around agent-to-agent communication, authentication, and governance..

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Cross-domain standardization coordination

6G system design requires tight coordination across working groups operating in parallel: RAN1 (physical layer, sub-THz, ISAC), RAN2 (protocols, scheduling), RAN3 (architecture, NTN), RAN4 (RF performance), SA1 (use cases), SA2 (architecture, slicing, compute), SA3 (security), SA5 (management, AI orchestration, energy), SA6 (application enablement), and CT (protocols, conformance). Cross-TSG sessions — such as the one held at TSGs#111 that cleared the way for the Release 21 timeline agreement at TSGs#112 — are how 3GPP keeps these parallel tracks aligned.

A measured pace toward "real" 6G

Independent industry commentary on TR 22.870 cautions that, as an intentionally broad Stage 1 study, much of its catalog reflects evolution of existing 5G-Advanced capability rather than a genuinely new requirement. The most defensible case for 6G — as opposed to continued 5G-Advanced evolution — rests on the handful of areas where current architectures fall short structurally: native ISAC, AI-native closed-loop control, and unified terrestrial/non-terrestrial mobility chief among them.

6G System Design

- **Cell-Free Spatial Architectures:** Transitioning from cell-centric grids to user-centric topologies. Devices are served by a dynamic cluster of coordinated transmission-reception points (TRPs), flattening the network edge.

- **Native Compute-Network Integration:** Blending computational resources into routing fabrics. The network treats compute capacity as a routable metric alongside bandwidth and latency, dynamically allocating workloads to the optimal execution node.

- **Zero-Trust Quantum-Safe Security:** Integrating Post-Quantum Cryptography (PQC) across control planes and utilizing Quantum Key Distribution (QKD) principles to protect the transport backplane against future decryption threats.

6G Deployment Architecture

6G System Deployment Architecture
Application Layer: • Immersive Communications (Holographic/XR) • Tactile Internet / Remote Operation • Digital Twins (High-fidelity industrial) • AI Agent Interactions
Network Exposure Layer: • Management/Automation Exposure • Service Exposure (AI/Sensing/Computing) • Analytics Exposure
Network Layer (6G RAN + 6G Core): • 6G RAN: THz + mmWave + RIS + NTN • 6G Core: AI-native SBA + ISAC + In-Network Computing • Interfaces: 6UE (UE-RAN), RAN-CN (RAN-Core)
Supporting Functions Layer: • Cloud Infrastructure & Management • Transport Network (deterministic, wide-area sync) • Data Pipeline & Federated Data Fabric • Common Platform Functions (Digital Twin, MLOps)

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Chapter 4: Artificial Intelligence (AI) in 6G

6G treats AI not as an add-on feature, but as a foundational design element built into every layer of the architecture. 6G is envisioned as an AI-native platform with systematic capabilities to exploit high data volumes from within/outside the network. AI is treated differently in 6G than in any prior generation: not as an optimization layer added on top of a fixed network, but as an architectural primitive present in the air interface, the RAN, the core and the management plane simultaneously.

Two complementary tracks: AI for Network, Network for AI

3GPP's own Release 19 feature grouping captures this duality directly, labelling work as either "AI for Network" (using AI/ML to operate the network better — predictive RAN intelligence, NWDAF-style analytics) or "Network for AI" (the network as infrastructure that delivers AI services — distributed training and inference, AI agent communication). Both tracks continue and deepen into 6G.

AI-native Air Interface
The air-interface AI story runs in a clear line: Release 18 establishes three founding use cases (CSI feedback compression, beam management, positioning); Release 19 turns these into normative, multi-vendor interoperable features; Release 21 is expected to make AI inference a built-in PHY/MAC capability rather than a feature that can be toggled off.

AI-native Core and Management
In the core, AI moves "from support function to system core": SA2 architecture proposals explore AI-driven, intent-based session and traffic control, while SA5 standardizes the surrounding lifecycle: AI model deployment, telemetry ingestion, and orchestration across multi-vendor RAN and core deployments.

AI Agents and Agentic Communication
TR 22.870 defines an AI agent as an automated intelligent entity capable of interacting with its environment, acquiring contextual information, reasoning, self-learning, decision-making, and executing tasks — autonomously or in collaboration with other AI agents — to achieve a specific goal. Catalogued use cases include built-in intelligent communication assistants (enhancing IMS-based calling), AI-native networks with flexible UE-network coordination, and AI/ML training and inference hosted in the network (for example, in agricultural applications). Standards work, including early IETF drafts, is already exploring protocols for agent-to-agent and agent-to-tool communication carried over 6G.

AI-RAN: AI compute meets radio access
A wave of 2025–2026 industry moves is building the AI-RAN bridge from AI-enhanced 5G-Advanced to AI-native 6G: NVIDIA's strategic partnership and $1 billion investment in Nokia to co-develop AI-RAN products; NVIDIA's AI Aerial platform — including the Aerial Omniverse Digital Twin and the Sionna neural radio framework — adopted by Ansys, Keysight, Samsung and other ecosystem partners; Samsung's virtualized RAN running on Intel Xeon silicon; and a broader AI-RAN Alliance that has drawn more than 100 members. T-Mobile, BT, Elisa, NTT DOCOMO and Vodafone are among the operators conducting early AI-RAN field trials beginning in 2026, ahead of any finalized 6G standard.

Small, efficient models for network-embedded AI
Because RAN, Edge and Core AI functions must run under tight latency and power budgets, research attention is turning to compact, efficient "tiny" language and reasoning models for AI-

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native network functions, rather than relying solely on large centralized models — reflecting a practical constraint as much as a design preference.

Open questions and risks

- The genuine bottleneck for many AI use cases is often compute, energy, data availability and governance rather than the network itself - current 5G already supports substantial edge-AI inference.

- Multi-agent coordination (e.g., cross-agent data fusion for robotics) is rated only medium-low priority in early market-prioritization exercises, reflecting real concerns about ecosystem maturity and governance.

- AI/ML security — model integrity, adversarial robustness, training-data privacy — is an explicit, ongoing SA3 workstream rather than a solved problem, and will need to mature in step with AI-native deployment.

AI-Native Air Interface

Traditional physical-layer blocks—such as channel estimation, equalizer blocks, beamforming management, and CSI feedback compression—are replaced or optimized by end-to-end deep learning models. In Release 20/21, standardizing two-sided AI models ensures multi-vendor interoperability, defining exactly how neural networks from different infrastructure suppliers interact across the air interface.

Network Automation & Predictive LCM

AI drives the closed-loop lifecycle management (LCM) of the network. Predictive Radio Resource Management (RRM) analyzes temporal and spatial trends to pre-emptively optimize coverage, adjust beam directions, and shift loads. Network infrastructure components dynamically enter ultra-deep sleep states based on predictive traffic models, optimizing overall energy efficiency.

Distributed Collaborative Inference (Edge AI)

The system architecture natively supports split-inference pipelines. Large AI models are dynamically divided between the device, the distributed unit, and edge data centres. This allows low-power UEs to leverage heavy network compute resources via dedicated, low-latency data conduits.

Aspect	5G-Advanced	6G AI-Native
AI Integration	Selected aspect improvements	Native incorporation from onset
Scope	PHY/MAC limited	Full stack: PHY -> MAC -> RAN -> Core ->Transport
Architecture	Cloud-native + AI add-ons	AI deeply embedded in architecture
Autonomy	Assisted automation	Agentic-AI for autonomous networks

Release	AI Milestone
Release 18	AI/ML for air interface (first standardization)
Release 19	Advanced AI/ML integration, ISAC-AI fusion
Release 20	AI-native air interface elements matured
Release 21	Full AI-native 6G architecture standardized

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The below diagram provides a pictorial representation of AI Architecture in 6G System.

AI Architecture in 6G System
AI Services Layer: • AI-as-Service (on-demand customizable AI) • 3rd-party AI applications • UE-integrated AI models
Network-hosted MLOps Infrastructure: • Training Cluster (distributed GPU/TPU) • Inference Engine (real-time AI processing) • Testing & Validation Platform • Model Version Management
Distributed AI Federation: • Federated Learning Manager (privacy-preserving) • Decentralized Offloading Decisions • Resource-aware FL Optimization • Client Selection & Discovery
Native AI Air Interface: • AI-driven PHY (compression-adaptation architecture) • Deep Learning for THz Ultra-Massive MIMO • ML-based Channel Modeling (scenario ID, prediction) • Semantic Communication Engine
AI-Enabled Network Management: • Agentic-AI Autonomous Operations • Network Digital Twin (predictive maintenance) • QoS Prediction (distributed) • Energy Optimization (cross-layer)

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Chapter 5: 6G Technology Landscape Matrix

In this chapter, we define the 6G technology landscape matrix that is used in the subsequent chapters of this report. The matrix places each 6G technology in one of five network domains (UE, RAN, Core, Transport, and Applications & Services) and at one of five levels of integration, from key technology block up to deployed system. Chapter 7 uses the matrix to identify the platforms required, Chapter 8 the trials required to demonstrate the technologies, and Chapters 9 and 10 map the Indian R&D programmes against it to identify gaps. The chapter closes with the cross-cutting technology threads that the matrix reveals and the conclusions that follow for India.

Structure of the Matrix

The columns of the matrix are the five network domains: User Equipment (UE), Radio Access Network (RAN), Core Network, Transport Network, and Applications & Services. The rows are five levels of integration, and each entry in the matrix belongs to exactly one level:

- **Key Technology Blocks:** the fundamental techniques that distinguish 6G from 5G, such as AI-native PHY, ISAC or cell-free MIMO. This is the unit of research.
- **Subsystems:** an engineered assembly of technology blocks that performs one function inside a product, such as a modem-RF subsystem, a RAN Intelligent Controller or a fronthaul transport subsystem. This is the unit of a development project.
- **Chipsets:** the silicon and hard IP on which subsystems are realized. This is the unit of fabless design and foundry access, and is expanded per domain in the chipset tables that follow the matrix.
- **Platforms:** reference designs, open/closed-source software stacks and testbeds on which subsystems are integrated and validated. This is the unit of a shared national facility (Chapter 7).
- **Systems:** complete deployable products or networks built from platforms and chipsets, such as a 6G base station, a 6G Core or a holographic telepresence service. This is the unit of a trial (Chapter 8).

How to Read the Matrix

The matrix is read in two directions. Reading down a column gives the complete product stack of one domain, from the research-level technique to the deployable system; this is the view a product or platform team needs. Reading across a row gives what one level of integration requires across all five domains; this is the view a funding programme needs, because programmes are usually organized by level (a chipset scheme, a testbed scheme, a trials scheme) rather than by domain.

Two views are provided. The headline matrix compresses each cell to its two or three defining entries and is intended for presentations and executive readers. The detailed matrix is the full inventory and is the reference for Chapters 7 to 10.

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6G Technology Landscape at a Glance

The headline view below shows the two or three defining entries in each cell. The full inventory, which Chapters 7 to 10 draw on, follows on the next pages.

Level \ Domain	User Equipment (UE)	Radio Access Network (RAN)	Core Network	Transport Network	Applications & Services
Key Technology Blocks	• Multi-band FR1 / FR3 / sub-THz operation • AI/ML air interface on the device • ISAC, ambient IoT and PQC on the device	• AI-native PHY / MAC • Cell-free ultra-massive MIMO, RIS and ISAC • FR3 / sub-THz spectrum and native NTN access	• AI-native SBA with closed-loop NWDAF • Compute-as-a-service and network exposure • PQC / zero-trust security	• Deterministic xHaul (TSN / DetNet) • 800G / 1.6T coherent and sub-THz wireless xHaul • NTN feeder and inter-satellite links	• Immersive XR / holographic communication • Digital twins and sensing-as-a-service • AI agents, autonomous robotics and V2X
Subsystems	• Multi-band modem-RF subsystem • AI-inference and sensing subsystems • Ambient-IoT harvesting / backscatter	• RU / DU / CU • Ultra-massive MIMO array, FR3 / sub-THz front-end • RIC, ISAC and NTN payload subsystems	• 6G NF set (AMF / SMF / UPF evolution) • NWDAF, NEF and charging • Slicing / MEC orchestration, PQC security	• Fronthaul (eCPRI / RoE) and optical (OTN / DWDM) • IP / SR core and synchronization • Satellite gateway and ISL	• XR rendering and split compute • Digital-twin synchronization • AI-agent orchestration and LLM inference
Chipsets	• 6G modem SoC and sub-THz RFIC • AI-native NPU and sensing SoC • PQC security element, ambient-IoT ASIC	• O-DU L1 SoC and DPU • ELAA beamforming and FR3 / sub-THz RFIC • NTN payload SoC, RIS IC, ISAC ASIC	• Server CPU + DPU for cloud-native NFs • UPF acceleration SmartNIC • AI accelerators and PQC HSM	• 800G / 1.6T coherent DSP • TSN switch and SRv6 router silicon • Timing ASIC, Inter-Satellite Link (ISL) optics, sub-THz xHaul	• Edge AI-inference chipsets • XR-rendering GPUs • LLM-serving accelerators
Platforms	• Device reference platforms • Open-source UE stacks and SDR prototyping • XR and ambient-IoT development kits	• Open RAN stacks (O-RAN SC, srsRAN, OAI) • AI-RAN compute and RAN digital twin • FR3 / sub-THz and RIS testbeds	• Cloud-native 6G-ready core (vendor, free5GC / Open5GS) • Kubernetes telco cloud and MLOps • Network digital-twin simulation	• SDN / segment-routing controllers • Optical and TSN testbeds • Satellite–NTN integration	• XR / metaverse SDKs • Application digital-twin platforms • AI-agent and robotics frameworks
Systems	• 6G smartphones, XR glasses, wearables • Ambient-IoT, UAV / robotics, V2X terminals • 6G CPE / FWA terminals	• Cell-free, AI-RAN base stations • Sub-THz small cells and RIS environments • Integrated terrestrial–NTN access	• 6G Mobile Core (telco cloud) • MEC and AI-native OSS / BSS • Network digital-twin systems	• Converged xHaul networks • Terrestrial–NTN transport (LEO / MEO / GEO) • Sub-THz / FSO wireless backhaul	• Holographic telepresence • ISAC smart-city / industrial systems • Autonomous multi-agent robotics

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Detailed 6G Technology Landscape Matrix

Level \ Domain	User Equipment (UE)	Radio Access Network (RAN)	Core Network	Transport Network	Applications & Services
Key Technology Blocks	• Multi-band operation across FR1, FR3 (7–24 GHz) and sub-THz • AI/ML air interface on the device (CSI compression, beam prediction, positioning) • ISAC on the device (sensing with the communication waveform) • Ambient IoT (battery-less / energy-harvesting devices) • Post-quantum cryptography (PQC) for identity and security • Multi-access convergence (3GPP + non-3GPP) on the device	• AI-native PHY / MAC (ML-based CSI, beam, scheduling, positioning) • Ultra-massive, cell-free / distributed MIMO • New spectrum: FR3 upper mid-band (7–24 GHz) and sub-THz (100–300 GHz) • Reconfigurable Intelligent Surfaces (RIS) • ISAC: joint waveform and sensing receiver • Native NTN access (regenerative payloads, direct-to-device) • AI-RAN: shared accelerator compute for L1/L2 and AI workloads	• AI-native Service-Based Architecture (intent-driven, modular NFs) • Converged 3GPP / non-3GPP access (TR 23.801) • NWDAF evolution to closed-loop automation • Compute-as-a-service and edge compute in the core • Network exposure and monetization APIs for verticals • PQC / zero-trust security framework • Network digital twin for network management	• Deterministic xHaul (TSN / DetNet evolution) • 800G / 1.6T coherent optical transport • Sub-THz and free-space-optical wireless xHaul • SRv6 dynamic routing • Precision time synchronization (PTP / SyncE evolution) • NTN feeder and inter-satellite links (ISL) • Energy-aware transport orchestration	• Immersive XR / holographic communication • Application digital twins and sensing-as-a-service • AI agent-to-agent (A2A) communication • Autonomous robotics / V2X orchestration • Vertical application enablement (industry, health, mobility)
Subsystems	• Modem-RF subsystem (multi-band PA / LNA, beamforming module) • AI-inference subsystem (NPU + memory) • Sensing (radar-like) receive subsystem • Ambient-IoT energy-harvesting and backscatter subsystem • Sub-THz power-management subsystem • Multi-SIM / identity and secure-element subsystem	• RU / DU / CU subsystems • Ultra-massive MIMO antenna-array and beamforming subsystem • FR3 / sub-THz radio front-end subsystem • RAN Intelligent Controller (Near-RT / Non-RT RIC) • RIS panel and controller subsystem • ISAC sensing-function subsystem • NTN gNB payload subsystem (Doppler / delay compensation) • Energy-management subsystem (sleep modes, renewables)	• AMF / SMF / UPF evolution (6G NF set) • NWDAF / network-data-analytics subsystem • NEF and charging / monetization subsystem • Slicing and compute-orchestration (MEC) subsystem • AUSF / UDM security subsystem with PQC • Network digital-twin subsystem	• Fronthaul transport subsystem (eCPRI / RoE evolution) • Optical transport (OTN / DWDM) subsystem • IP / MPLS-SR core transport subsystem • Synchronization subsystem (PTP / SyncE) • Satellite–terrestrial gateway and ISL subsystem	• XR rendering and split-compute subsystem • Digital-twin synchronizatio n subsystem • AI-agent orchestration and LLM-inference subsystem • Robotics / V2X control subsystem • Vertical application-enablement subsystem
Chipsets	• 6G baseband / modem SoC • Sub-THz RFIC and front-end • AI-native NPU • Sensing and GNSS-free positioning SoC • Security element (PQC eSIM / eUICC) • Ambient-IoT ultra-low-power ASIC	• O-DU L1 SoC • Ultra-massive MIMO / ELAA RF and beamforming chipset • FR3 / sub-THz RAN RFIC and PA • DPU / SmartNIC for DU • NTN gNB payload SoC • RIS control IC • ISAC ASIC	• Server CPUs for cloud-native NFs (with DPU) • UPF acceleration DPU / SmartNIC • AI accelerators for NWDAF and control plane • PQC HSM	• 800G / 1.6T coherent DSP • TSN / DetNet switch silicon • SRv6 router silicon • Timing / sync ASIC (PTP grandmaster) • LEO ISL optical terminal ASIC • Sub-THz xHaul transceiver	• Edge AI-inference chipsets (GPU / NPU edge servers) • XR-rendering GPUs • LLM-serving inference accelerators

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Level \ Domain	User Equipment (UE)	Radio Access Network (RAN)	Core Network	Transport Network	Applications & Services
Platforms	• 6G device reference platforms (chipset-vendor research designs) • Open-source UE stacks (OpenAirInterface UE, srsUE) • SDR-based UE prototyping platforms • XR device development kits • Ambient-IoT tag reference designs	• Open RAN software platforms (O-RAN SC, srsRAN, OpenAirInterface 6G branches) • AI-RAN compute platforms (GPU-accelerated stacks, RAN digital-twin simulators) • vRAN platforms on COTS servers • FR3 / sub-THz radio testbeds and channel sounders • RIS testbeds	• Cloud-native 5GC / 6G-ready core platforms (vendor SBA stacks; open-source free5GC / Open5GS evolution) • Kubernetes-based telco-cloud platforms • MLOps / model-orchestration platforms • Network digital-twin simulation platforms	• SDN / segment-routing controller platforms • Optical and TSN transport testbeds • Satellite–NTN integration platforms	• XR / metaverse platform SDKs • Application digital-twin platforms • AI-agent orchestration platforms • Robotics / V2X frameworks (e.g. ROS 2)
Systems	• Smartphones, XR glasses, wearables with AI-native 6G connectivity • Ambient-IoT battery-less sensor systems • UAV / robotics 6G terminals • Automotive 6G / V2X terminals • 6G CPE / FWA terminals	• 6G macro / micro base stations (cell-free AP clusters, AI-RAN accelerated) • Sub-THz small-cell / hotspot systems • RIS-assisted smart radio environments • Integrated terrestrial–NTN access systems	• 6G mobile-core systems (telco-cloud data centres) • Multi-access edge computing (MEC) systems • AI-native OSS / BSS systems • Network digital-twin systems	• Converged fronthaul–midhaul–backhaul networks • Terrestrial–NTN converged transport (LEO / MEO / GEO, feeder and ISL) • Sub-THz / FSO wireless backhaul systems	• Holographic telepresence systems • ISAC-enabled smart-city / industrial systems • Autonomous robotics / multi-agent systems • Application digital-twin services (sensing-as-a-service, AI-as-a-service)

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Chipset View by Domain

The following tables expand the Chipsets row of the matrix for each network domain, giving the target chip and representative vendors for each technology block. Only chipsets with an established commercial vendor base are listed. FR3 / sub-THz RF front-end silicon, sub-THz xHaul transceivers and ambient-IoT ASICs are kept in the matrix as required items as the vendor base is still evolving and is itself a finding for Chapter 10.

UE Domain: Chipsets

Technology Block	Chipset Examples / Targets
6G baseband / modem SoC	• Target: 6G modem + application-processor fusion SoC • Qualcomm Snapdragon X-series modem path, MediaTek M-series, Samsung Exynos modem, Apple C-series
AI-native NPU	• Target: AI tile integrated in the modem SoC, or a separate co-processor • Arm Ethos-N, CEVA NeuPro-M, Synopsys ARC NPX6
Sensing and GNSS-free positioning SoC	• Target: sensing / positioning engine fused with the modem • Qorvo UWB, NXP Trimension
Security element (PQC eSIM / eUICC)	• Target: 6G eSIM / eUICC with post-quantum cryptography • Infineon OPTIGA, NXP EdgeLock

RAN Domain: Chipsets

Technology Block	Chipset Examples / Targets
O-DU L1 SoC	• Target: L1 accelerator SoC for 400 MHz bandwidth with ISAC support • Marvell OCTEON 10 Fusion, AMD/Xilinx RFSoC, Intel Agilex 7 with vRAN Boost, Qualcomm X100, Picocom PC802
Ultra-massive MIMO / ELAA RF and beamforming chipset	• Target: 1000+ element active antenna system with distributed beamforming • TI AFE79xx path, ADI RadioVerse
DPU / SmartNIC for DU	• Target: inline L2/L3 offload and xApp hosting for AI-native RAN • NVIDIA BlueField, Marvell OCTEON, Intel IPU E2100
NTN gNB payload SoC	• Target: regenerative satellite payload with Doppler and delay compensation • STMicroelectronics, Airbus / CNES
RIS control IC	• Target: controller ASIC for surfaces with thousands of elements • Greenerwave, NTT DOCOMO metasurface IC, Pivotal Commware
ISAC ASIC	• Target: joint communication and sensing baseband on one chip •

Core Domain: Chipsets

Technology Block	Chipset Examples / Targets
UPF acceleration DPU / SmartNIC	• Target: 1.6 Tbps UPF on a single DPU with AI-driven QoS in the data plane • AMD Pensando, Intel IPU, NVIDIA ConnectX / BlueField
AI accelerators for NWDAF and control plane	• Target: AI server hosting 6G analytics and closed-loop control • NVIDIA Grace Hopper, Intel Xeon with AMX, AMD Instinct MI300
PQC HSM	• Target: hardware security module with post-quantum root of trust • Marvell LiquidSecurity, Thales HSM, Rambus PQC cores
Server CPUs for cloud-native NFs (with DPU)	• Target: telco-cloud server CPU paired with a DPU for compute-as-a-service • Intel Xeon, AMD EPYC, Arm Neoverse

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Transport Domain: Chipsets

Technology Block	Chipset Examples / Targets
800G / 1.6T coherent DSP	• Target: 200+ Gbaud coherent DSP for xHaul and sub-THz RAN feed • Acacia (Cisco) CIM-8, Nokia PSE-6s, Infinera ICE7, Huawei oDSP
TSN / DetNet switch silicon	• Target: sub-100 µs jitter switch integrated with the 6G core • Marvell Prestera, Microchip SparX-5i, Intel TSN reference designs
LEO ISL optical terminal ASIC	• Target: space-grade optical inter-satellite link terminal • Mynaric CONDOR Mk3, Tesat LCT, Honeywell
SRv6 router silicon	• Target: 800G-class SRv6 router ASIC for xHaul aggregation and core • Broadcom Jericho / Tomahawk, Cisco Silicon One, Nokia FP5
Timing / sync ASIC (PTP grandmaster)	• Target: PTP grandmaster / boundary clock with sub-100 ns accuracy • Microchip, Renesas, SiTime

Cross-Cutting Technology Threads

Seven technology threads appear in more than one column of the matrix. They are the defining technologies of 6G in the sense that each one changes what has to be built in several domains at once, and they are therefore the natural units around which platforms (Chapter 7), trials (Chapter 8) and the Indian R&D gap analysis (Chapter 10) should be organized. The table below traces each thread across the five domains. A dash indicates that the thread has no specific entry in that domain.

Thread \ Domain	User Equipment (UE)	Radio Access Network (RAN)	Core Network	Transport Network	Applications & Services
AI-native networking	On-device AI/ML air interface and NPU	AI-native PHY / MAC, RIC, AI-RAN compute	AI-native SBA, NWDAF closed-loop automation	Energy-aware transport orchestration	AI agents, edge LLM inference
Integrated sensing and communication (ISAC)	Sensing receive chain, positioning SoC	Joint waveform, sensing function, ISAC ASIC	ISAC network function	Low-latency inter-site links for cooperative sensing	Sensing-as-a-service, smart-city / industrial systems
New spectrum (FR3)	Multi-band front-end and FR3 RFIC	FR3 radio, ELAA, small cells	–	Sub-THz / FSO wireless xHaul / backhaul	–
Cell-free MIMO and RIS	Multi-band antenna and beam management	Distributed MIMO, RIS panels and controllers	–	Fronthaul capacity and sync for coherent APs	–
Native NTN	Direct-to-device connectivity	Regenerative payload gNB, NTN SoC	Converged access and mobility	Feeder links, ISL, satellite gateway	–
PQC and zero-trust security	PQC secure element, eSIM	–	AUSF / UDM with PQC, PQC HSM	–	–
Digital twins	–	RAN digital-twin simulation	Network digital twin	Network digital-twin simulation platforms	Application digital twins

System-Level Chipset Evolution Path

1. 2026-2027: Rel-20 study phase. First 6G IP prototypes. D-band RFIC samples, AI-RAN NPU FPGA, PQC test chips.
2. 2028-2029: Rel-21 spec freeze. First 6G baseband tape-outs on N2. NTN SoC with Doppler IP. DPU with 6G UPF offload.
3. 2030: Commercial chipsets. UE SoC: modem+AP+AI+NPU+sub-THz. RAN: O-RU with 1024-ELAA + JCAS ASIC. Core: 1.6T DPU with PQC.

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Standards-to-Silicon Gap: 3GPP Rel-21 is expected to be finalized by Mar 2029. Chipset vendors need 18-24mo from freeze to device. Hence, first 6G phones will mostly not be available before H2 2030.

Open Issues Impacting Silicon

1. Waveform: If a new JCAS waveform is selected vs CP-OFDM reuse, needs new FFT/radar IP.
2. Migration: SA-only vs NSA-like 6G impacts dual-connectivity modem complexity.
3. Spectrum: 7-24 GHz + sub-THz requires multi-band RFIC or chiplet approach.

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Conclusions

A single reference frame. The matrix gives the report one common frame. Chapters 7 to 10 place platforms, trials and funded projects on the same five-by-five grid and use the same vocabulary for the key technologies, such as ISAC, ultra-massive MIMO, sub-THz and PQC. Any new item introduced in a later chapter is first given a cell in the matrix, so that the report stays consistent as it grows.

Seven threads organise the landscape. The detailed matrix lists more than a hundred items, but they group into seven cross-cutting threads: AI-native networking, ISAC, new spectrum, cell-free MIMO and RIS, native NTN, PQC and digital twins. Planning platforms and trials by thread, with at least one platform and one trial per thread, keeps the Indian 6G programme coherent and makes progress easy to track.

Silicon is a clear opportunity. The chipsets listed in the four domain tables come today from global vendors, and the first commercial 6G devices and networks in India will build on them. At the same time, three blocks that 6G requires do not yet have an established vendor base: FR3 / sub-THz RF front-ends, sub-THz xHaul transceivers and ambient-IoT ASICs. These are areas where Indian fabless design companies and research groups, supported by the national semiconductor and design-linked incentive programmes, can aim for an early position by building on existing strengths in RF design and low-cost devices.

Platforms are where work can start now. The existing Platforms row is built largely on open-source stacks (OpenAirInterface, srsRAN, O-RAN SC, free5GC, Open5GS) and on testbeds. The large OEMs will have their own internal proprietary platforms for 6G. These need engineering effort and shared facilities rather than foundry access. Indian institutions and start-ups already active in 5G open-source software and testbeds can extend that work to 6G ahead of the Release 21 freeze, and contribute to the standard in the process.

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Chapter 6: Master Strategic Roadmap for 6G Ecosystem Development in India

This chapter sets out the phased roadmap for building the 6G ecosystem in India. The roadmap is aligned with the international standardization calendar, so that each phase delivers what the next 3GPP or ITU-R milestone requires.

Roadmap Phases

The four phases below are aligned to these milestones: Phase 1 to the Release 20 study period, Phase 2 to the Release 21 drafting period and the opening of the ITU-R proposal window, Phase 3 to the Release 21 freeze and IMT-2030 evaluation, and Phase 4 to the IMT-2030 specifications and first commercial deployment.

Phase	Timeline	Technology Blocks to Develop	Target TRL
Phase 1: Foundation & Revolutionary Tech	2024–2027	• **Air Interface:** FR3, massive MIMO radios, RFIC, ISAC waveform IP, AI-native RAN L1/L2, RIS panels and their controllers, NTN RAN • **Core:** AI-native Service Based Architecture (SBA 2.0), Post-Quantum Cryptography (PQC), compute-aware SMF/UPF, data exposure for sensing • **System:** Zero-touch intent orchestration, network digital twin, NTN-terrestrial convergence • **Devices / sub-systems:** RF front-ends for RRH, baseband SoCs, IoT devices	TRL 2-4
Phase 2: System Integration & PoC	2027–2028	• **Advanced Radio:** Distributed MIMO field trials, FR3 (7–24 GHz) systems, sub-THz xHaul, Inter-Satellite Link (ISL) for LEO/MEO/GEO • **E2E Integration:** 6G protocol stack on cloud-native telco cloud, AI-NWDAF + RIC fusion, deterministic TSN xHaul • **Security:** E2E PQC, AI-driven security, privacy for sensing data • **Energy:** Zero-energy IoT, network energy per bit better than 5G • **Standards:** Indian contributions into Rel-21 drafting and the ITU-R IMT-2030 proposal window; WRC-27 spectrum positions	TRL 4-6
Phase 3: Large-Scale Trials & Standardization	2028–2029	• **Pre-Commercial Systems:** Full 6G gNB + Core + NTN, single-drop spec validation against the Rel-21 freeze • **Showcase:** National 6G showcase in 2029/30 on pre-commercial systems • **Vertical Pilots:** Automotive, health, smart cities, industry	TRL 6-8

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Phase	Timeline	Technology Blocks to Develop	Target TRL
		• **Sovereignty:** Hybrid multi-technology 6G telco cloud, pan-India testbed	
Phase 4: Early Deployment	2030 onward	• **Commercial:** Initial 6G deployment in 2030 on Rel-21 equipment, aligned with the IMT-2030 specifications • **Scale:** Large-scale deployment from 2032 • **Standards:** Rel-22 features and support for the IMT-2030 submission	TRL 8-9

Target TRL uses the nine-level Technology Readiness Level scale: TRL 2 to 4 covers concept and laboratory validation, TRL 5 to 6 a prototype validated and demonstrated in a relevant environment, TRL 7 to 8 a system demonstrated and qualified in an operational environment, and TRL 9 a system proven in commercial operation.

The phases are cumulative. The technology blocks matured in Phase 1 are integrated in Phase 2, trialed at scale in Phase 3 and deployed in Phase 4, and the platforms and trials that carry them are set out in Chapters 7 and 8.

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Chapter 7: Proposed 6G Platforms

6G Use-cases and the underlying 6G technologies are implemented using products and platforms using existing and newly build components/subsystems. This chapter provides a list of the most probable platforms/products that will need to be built to enable 6G services.

While designing the platforms/solutions, the operator forum NGMN has specified the critical design principles that has to be used for creating the technologies/solution and are listed below:

- **AI/Agentic-AI native** for autonomous networks
- **Cloud-native extended SBA** with full modularity
- **Sustainability from design** cross-layer energy optimization
- **Trustworthiness** with quantum-safe security
- **Smooth 5G-to-6G migration** avoiding unnecessary complexity
- **Network as Service** Computing/Data/AI-as-Service

Expected Major 6G Product Categories (2030 – 2040)

Product Category	Examples
6G AI Smartphones	On-device foundation models
XR Glasses	Persistent AR
Industrial Robots	Real-time AI control
Digital Twin Platforms	Factory twins
Cell-Free Base Stations	Distributed radio grids
AI-RAN Platforms	Shared AI/RAN infrastructure
Sensing Base Stations	Communication + Radar
NTN Gateways	Space-terrestrial integration
Edge AI Clouds	Telecom AI inference
Autonomous Network Controllers	Zero-touch operations
6G Core	Standards-Compliant 6G Core, AI-Native Core
6G End-to-end Network Management Systems	

6G Product Development Roadmap

The table below provides the mapping of the major 3GPP releases from now till 2030 and the list of potential products that can be built

Timeframe	Product Milestone
2024-2026 (Release 18-19)	• AI/ML air interface prototypes, • ISAC study testbeds, • THz channel measurement systems, • RIS prototype (1024 elems at 26 GHz)
2027-2028 (Release 20)	• THz base station prototypes (100+ Gbps), • Ultra-massive MIMO testbeds, • 6G architecture reference designs, • NTN-terrestrial integration prototypes

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Timeframe	Product Milestone
2029-2030 (Release 21 + IMT-2030)	• Commercial THz base stations, • 6G Smartphones • RIS commercial deployment, • ISAC systems (vehicular/industrial), • 6G Core network products
2030+	• Mass-market 6G deployment, • Holographic XR products, • Digital twin industrial systems, • Remote operation platforms, • AI-native network services • 6G smartphones with THz,

6G Platforms

Platform Type	Purpose	Remarks on Technologies/ Subsystems/ APIs/ Segments	Examples from SNS JU & Global forums for reference
1. 6G-Sandbox / Open Testbeds	Multi-vendor, end-to-end validation of 6G enablers	• SDR + sub-THz, • NTN Emulation, • AI/ML Pipeline, • Digital Twin, • Open APIs. • NTaaS “Network Testbeds as a Service”	• EU: 6G-SANDBOX, 6G-BRICKS, 6G-XR • US: PAWR, POWDER + Colosseum • Japan: NICT testbeds
2. Telco Cloud Continuum	Host AI-native 6G Core, edge, RIC	• K8s, • Service Mesh, • AI inference, • P4/DPUs, • unified device-edge-cloud	• EU: SOVEREIGN-6G hybrid Telco Cloud • US: Linux Foundation O-RAN SC
3. Vertical Trial Platforms	Real-world vertical validation	• Live ports, • Hospitals, • Factories, • Stadiums. • SLA measurement, business model validation	• EU: Stream D trials: 6G-CARE health, GENIUS logistics, 6G-Holonet media
4. NTN Integration Labs	Satellite-terrestrial convergence	• LEO Emulators, • Doppler/delay test, • Multi-orbit, • Multi-band, • ISL optical	• EU: 6G-NTN, 6G-NTN2 Nexus • ESA-NICT 5G/6G NTN Projects: Trantor, 5G-STARDUST
5. Open Software Ecosystems	Avoid fragmentation, ensure sovereignty	• ETSI SDGs, • LF Networking, • CAMARA APIs. • Federated, not centralized	• open source for cloud-edge, telco APIs, 6G, agentic AI
6. Microelectronics Pilots	Chip sovereignty for 6G	• RF-So • RISC-V architecture based SoC for RU, DU, CU, Core • sub-THz Indium Phosphide (InP) RF, • PQC HSM, • Photonic ICs	• SNS JU Stream A/B: TERA6G, 6GTandem, FLEX-SCALE

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Chapter 8: Proposed 6G Trials

Together, these demonstrators cover nearly all major Release 20–21 study areas and would provide a complete bridge from today's 5G-Advanced systems to first-generation commercial 6G deployments

Trial Theme	Timeline	Verticals	Technologies Demonstrated	Lead Regions/ Programs
T1. AI-Native RAN & JCAS PoC	2027 Q4	R&D, Defense	• AI-Native RAN • AI beamforming, • Sub-THz channel sounding, • ISAC radar+comms, • Integrated Sensing	• EU: Hexa-X-II, • Japan: NTT Docomo, • US: Keysight
T2. FR3 Upper-Midband E-MIMO	2028 H1	Industry, Operators	• 7-24 GHz E-MIMO antenna + IC • 4x 5G capacity	• EU: 6GTandem
T3. NTN Direct-to-Device & ISL	2027 Q4	Emergency, Maritime, Rural	• LEO 5G/6G NTN, • Multi-backhaul, • Optical ISL, • Global roaming,	• EU-ESA-Japan, Hispasat Trantor
T4. Digital Health & Holographic	2028	Health, Culture	• 6G-CARE: AI health, wearables, holographic comms • 6G-Holonet: volumetric live events	• EU SNS JU Stream D
T5. Industrial & Logistics	2028	Manufacturing, Ports, Airports	• Industry 5.0 Smart Factory • 6G logistics for efficiency/emissions • AI-driven network for resilient factories • Goal-oriented semantic AI • Digital Twin	• EU: SIXG, OPTIMUS-6G, • PRIME-6G • MAGIC-6G
T6. IoT-ZERO & Underground/ Underwater	2028-2029	Utilities, Mining, Ocean	• near-zero-energy IoT + satellite industrial/ underground/ underwater IoT	• EU SNS JU • IoT-ZERO • PIONEERS-6G:
T7. System-Level Integration	2029 H1	All	• Simplified 6G architecture • Agentic6G autonomous multi-agent AI	EU 2027 Flagship Call €230M PROSPERO SOVEREIGN-6G pan-EU testbed
T8. Showcase	2028 Jul-Aug	Media, Public Safety, Transport	• Live immersive broadcast, • City-Scale Digital Twin, • GNSS-free positioning, • AI-NTN coverage • Connected Mobility Corridor	• US Next G Alliance target
T9. Global Interop & Security	2029	All	• PQC core network, • AI-enhanced security,	• EU-US TTC, EU-Japan, EU-Korea. • PAISES-6G • SHIELD-6G EU-US joint vision validation

Funding Model: EU SNS JU: €630M since 2021, +€270M 2026-2027. US: $2.5B commitment. Japan: $2B. Korea: 440.7B won 6G R&D.

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Delivery Principles for the trials:

1. Real users validate in live environment
2. Mix of 4G/5G and 6G networks to assess improvements of new technologies
3. Use standard test and measurement equipment along with smartphones to verify results. Identify domain-specific KPI to assess impact.
4. Create multi-disciplinary task-forces to enable cross-fertilization of ideas. Involve multi-disciplinary, multi-industry task forces to bring in meaningful and impactful pilots/trials.
5. Have more than one trial for each theme and also handled by different teams for risk management.

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Chapter 9: 6G R&D in India: Key funded programs

This chapter provides an overview of the R&D programs funded by various Government agencies and tries to map them as per the 6G analysis matrix identified in chapter 5.

The key programs funding the R&D related to 6G:

1. DOT's Telecom Technology Development Fund (TTDF) 1.0 scheme
2. MEITY CC&BT program
3. DST IIIT-COMET programs

This document current analyses only the DOT funded projects right now. The other programs along with the major schemes will be analyzed/added in the next major revision or another report from B6GA.

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Analysis of DOT/TTDF 1.0 funded projects

This section attempts to map the current funded projects against the 6G Technology analysis matrix created in the earlier section. The attempt is to identify areas requiring attention.

Table 1: Key Technology Blocks

Architectural Layer (Rows) / Domains (Columns)	6G User Equipment (UE) & Edge Devices	Radio Access Network (RAN)	Network Core	Transport / Backhaul / Quantum	Applications & Vertical Use Cases
Key Technology Blocks *(Algorithms, waveforms, channel models, materials, semantic learning, protocol frameworks)*	**Semantic & AI Radio:**	**Waveform & Signal Processing:**	**Core Network Logic & AI:**	**Quantum Comm & Fiber Theory:**	**Specialized Physical Media Blocks:**
	#25 AI-Native Radio for Semantic Chips	#46 THz Novel Waveform	#8 Sustainable AI-ML Energy-Aware Network	#5 Novel Optical Fiber Quantum Technology	#68 Molecular Comm for NanoBio Things
	#48 EMI Mitigation for CMOS	#56 Radar-Comm Waveform	#30 Secure Decentralized Deep Learning	#11 Indigenous Quantum Sources (Room Temp)	#92 Under-water Acoustic Comm
	#61 Semantic Implications	#67 AI/ML Waveform 6G Air Interface	#47 Advanced ML Anomaly/Fraud Detection	#121 Post-Quantum Cryptography Algorithms	
	#78 cGAN Resource Allocation	#98 Short Packet Waveforms	#55 DARPAN AI Digital Twin		
	#82 AI-driven Semantic Comm		#65 Digital Twin + LLM Semantic Comm		
			#66 Quantum Core Algorithms		
			#106 Automated Service Mgmt AI		
			#127 5GSec Core Threat Detection		
	Security:	**Channel Modeling & Estimation:**			
	#70 FL-Auth Protocol	#15 HAPS Channel Modeling			
	#122 IoT Lightweight Protocols	#16 THz Channel Modeling & AI Transceiver			
		#58 Joint Channel Estimation/Feedback			
		#76 CSI Prediction Deep Learning			
		#81 IRS Channel Estimation			
		Spectrum Sensing:			
		#52 Wideband Sensing & Sharing			
		#116 Sub-Nyquist Wideband Sensing			
		Beam/Access Optimization:			
		#27 AI/ML Initial Access & Beam Mgmt			
		#37 Semantic learning-based architecture			
		#90 Spectrum Sharing & Multi-link			

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Table 2: Subsystems

Architectural Layer (Rows) / Domains (Columns)	6G User Equipment (UE) & Edge Devices	Radio Access Network (RAN)	Network Core	Transport / Backhaul / Quantum	Applications & Vertical Use Cases
Subsystems *(Antennas, RF fronts, analog modules, converters, optical/RF blocks)*	**Device Front Ends:**	**Antennas & Metasurfaces (RIS):**	**Core Encryption Modules:**	**Photonic & Optical Subsystems:**	**Vehicle/Drone Subsystems:**
	#32 210-255 GHz Analog Front End	#24 RIS Joint Localization/Comm	#108 Hardware/Software Post-Quantum Secure Platforms	#10 Photonic Generation D-band signal	#45 Deep Learning Multipath Profiling V2V
	#85 Nano and Dot Antennas	#34 High-purity OAM Antennas		#33 Silicon Photonic Chip NxN Switches	
		#38 Active Reconfigurable Antennas & Fluid Cells		Quick Wideband Spectrum Sensing Photonics	
		#50 Advanced Antenna System		#51 Wired THz Fiber Design	
		#54 Fluid Cell Antennas		#114 XGS-PON OLT and ONU Prototype	
		#57 Vehicular Wideband Antennas			
		#59 3D Printed Fluid Antennas			
		#71 RIS Integrated Sensing & Comm			
		#79 Timed Antenna Array for Beam Steering			
		#83 Fluid Antenna for 6G Wireless			
		#86 IRS for IoT Ubiquitous Connectivity			
		#88 Graphene Beam forming Antenna			
		#93 Smart MIMO Antenna Prototyping			
		#94 D-Band Antenna for THz			
		#120 Multiport Switch Cover 2G-5G			
		#126 Base Station Antenna Rural Network			
		#133 OAM Antennae			
		RF Front Ends & Hardware:			
		#21 GaN Power Amplifier (F Band)			
		#44 THz Topological Photonic Passive Devices			
		#112 mmWave Power Amplifier Chips IP			

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Table 3: Chipsets

Architectural Layer (Rows) / Domains (Columns)	6G User Equipment (UE) & Edge Devices	Radio Access Network (RAN)	Network Core	Transport / Backhaul / Quantum	Applications & Vertical Use Cases
Chipsets *(Silicon components, RFICs, dedicated ASICs, integrated transceivers)*	**Edge/Sensor Chips:**	**Transceiver Chipsets & RFICs:**	**Security/Compute Processors:**	**Satellite & Network Chipsets:**	*N/A (Chipsets map primarily to the device/physical access or transport layers).*
	#131 Chip based CV-QRNG	#60 High-Speed Hybrid Transceiver	N/A (Typically covered under hardware hub platforms or generic processors).	#3 Optical Transceiver Chipset	
		#113 140GHz Fully Integrated Transmitter/Receiver Module		#104 LEO Satellite Components & GNSS RF Front End ASIC	
		#118 Polymer Based Low Cost mmWave Transceiver			

Table 4: Platforms

Architectural Layer (Rows) / Domains (Columns)	6G User Equipment (UE) & Edge Devices	Radio Access Network (RAN)	Network Core	Transport / Backhaul / Quantum	Applications & Vertical Use Cases
Platforms *(Development testbeds, labs, integrated controller platforms, software stacks)*	*N/A (UE platform testing sits predominantly within applications or RAN platforms).*	**RAN Platforms & RICs:**	**Core Software Stacks:**	**Optical/Quantum Network Testbeds:**	**Distributed Edge Platform Frameworks:**
		#9 6G Radio evaluation platform	#73 India 5G Stack (Made in India 5G SA Core)	#23 Lab-scale Quantum Fiber Network Platform	#13 Dynamic computational offloading
		#18 Reconfigurable RF-ML Platform		#75 Integrated Free Space & Underwater Optical Quantum System	#62 Zero-touch Federated Learning for Edge
		#20 AI-powered Open-PHY for 6G RAN		#101 Advanced Optical Communication Test Bed	#100 BB84 Protocol Simulation Toolbox
		#43 SMART-RIC6G (Drift Handling Enabler)		#102 THz Test bed with OAM and Multiplexing	
		#64 Open RAN FR-1 and FR-2 integration		#115 Quantum Communication Network Security	
		#110 Disaggregated 5G RAN Solution (RIC & SMO modules)			

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Table 5: Systems

Architectural Layer (Rows) / Domains (Columns)	6G User Equipment (UE) & Edge Devices	Radio Access Network (RAN)	Network Core	Transport / Backhaul / Quantum	Applications & Vertical Use Cases
Systems *(End-to-end hardware assemblies, complete base stations, integrated networks, full hub units)*	**Terminal Hardware:**	**Integrated Radio & RIS Arrays:**	**Network Infrastructure Systems:**	**Backhaul / Non-Terrestrial Networks:**	**Sensing & Local Network Systems:**
	#105 Gigabit Speed Customer Premise Equipment (CPE) Radio	#2 Building Blocks for 6G THz Front Ends	#7 Core Network System for 6G & Beyond	#6 Project Patang – Tethered drone backhaul carpet	#40 AI for Integrated Sensing and Secured Edge Networks
		#14 THz Comm: Prototype Development	#109 Hardware-based Encrypted Communication System Hub (100 Gbps)	#17 NTN and RIS enabled Ubiquitous Connectivity	#41 RIS Assisted Integrated Sensing and Communication
		#42 Test-Bed for RIS-Enable Joint Sensing & Comm Systems	#111 NavIC based IST traceable Primary Reference Time Clock	#35 Multihop Hybrid THz FSO Assisted Backhaul Links	#53 IRS Enabled Comm, Sensing & Localization
		#49 TARANG: Design of THz Wireless Comm		#36 Ubiquitous Connectivity Cell-free Communication	#124 Wi-SUN Based Smart Utility Systems for Rural IoT
		#89 Controller Unit of IRS for 6G		#72 Drone-aided FSO VLC based 6G for HAP/LAP	
		#128 RIS Based Hardware System Demonstration		Smart & Green Terrestrial & Non-Terrestrial Network Integration	
		#132 Rel-17 NB-IoT-NTN eNodeB		#95 Rural Connectivity via IRS & Resource Allocation	
				#119 Cell Free 6G Access Points	
				#123 Pilot for GSAT Capacity in Ku-Band with VSAT Backhaul	
				#130 Optical wireless village user backhaul connectivity	

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Table 6: Applications

Architectural Layer (Rows) / Domains (Columns)	6G User Equipment (UE) & Edge Devices	Radio Access Network (RAN)	Network Core	Transport / Backhaul / Quantum	Applications & Vertical Use Cases
Applications *(End-use software, vertical integrations, safety nets, medical or industrial specific solutions)*	**Wearables & Personal Monitoring:**	*N/A (RAN acts as the utility wrapper, applications sit higher on the stack).*	*N/A (Core systems enable applications but do not represent the vertical end-use case itself).*	*N/A (Transport networks deliver data rather than handling user application code directly).*	**Autonomous Mobility & V2X:**
	#4 Wearable IoT Pre-disease & Epidemic Surveillance				#39 Vehicular Autonomy Critical Data Transmission
	#28 Sub-THz Sensor for Real-time Skin Hydration				#63 6G Accelerated Smart Transportation with C-V2X
	#87 AI-Enhanced Remote Monitoring Wearable Biosensors				#77 Smart/Secure System for Sustainable Autonomous Vehicles
					Smart Verticals & Safety Systems:
					#19 Health & Agriculture 6G Ubiquitous Connectivity Lab
					#26 ARISE ML: AR optimization for IoT
					#29 LandSense: Landslide Detection and Prevention Use-case
					High Precision Positioning AGI/ML
					#80 6G Lightweight Mutual Authentication Protocol for UAVs
					#96 Speech Signal Human Intent Recognition for Telerobotics
					#97 Threat Detection and Mitigation in 6G Technologies
					#107 Digital Mining Infrastructure Using Private 5G
					#117 Face Recognition Using Drones
					#125 5G NB-IoT-based Smart Water Monitoring
					#129 Device-to-device communication in Immersive Applications

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Proposed 2026 series of R&D Project List

Table 1: Proposed R&D in Key 6G Technologies

Architectural Layer (Rows) / Domains (Columns)	6G User Equipment (UE) & Edge Devices	Radio Access Network (RAN)	Network Core	Transport / Backhaul / Quantum	Applications & Vertical Use Cases
Key Technology Blocks *(Algorithms, Waveforms, Channel Models, Security Protocols, AI/ML Models, Materials)*	AI-Native Radio for 6G Semantic Communications	AI-driven Semantic Communications	AI-ML for Energy-Aware Networks	Optical Fiber Technology for Quantum 6G	Railway Mobile Comm Upper Layers
	ARISE ML for AR IoT Optimization	AI/ML Beam Management & Initial Access	Secure Decentralized Deep Learning	Room Temp Quantum Sources for Key Distribution	Calamity Data Transmission for Vehicular Autonomy
	EMI Mitigation in CMOS Circuits	Semantic Learning End-to-End Architecture	ML Anomaly & Fraud Detection	Fiber Design for Wired THz Comm	V2V Multipath Profiling & Fingerprinting
	Lightweight Quantum-Safe Protocols for IoT	AI for ISAC & Secured Edge Networks	Federated Learning for Edge Networks	Quantum Comm for Optical Network Security	Molecular Comm for NanoBio Drug Delivery
		THz Waveform & Signal Processing	Digital Twin LLMs for Semantic Comm		Terrestrial & NTN Integration Framework
		Wideband Spectrum Sensing & Sharing	FL-Auth Secured Authentication Protocol		AGI/ML High Precision Positioning
		mmWave Joint Radar & Comm Waveform	DL Threat Detection & Mitigation		PUF/Blockchain Auth Protocol for UAVs
		DL Joint Channel Estimation & Feedback	Code-Based PQC Algorithms		Meta Learning Underwater Acoustic Comm
		Semantics on Cooperative Comm	5GSec Core Threat Detection		Human Intent Recognition for Telerobotics
		Open RAN FR-1 & FR-2 Integration QoS			
		Quantum Algorithms for Wireless Systems			
		AI/ML Waveform for 6G Air Interface			
		On-the-Air RIS-Assisted Semantic Comm			
		Deep Learning CSI Prediction			
		cGAN Resource Allocation for Semantic Comm			
		IRS-Aided Channel Estimation for ISAC			
		THz Channel Modelling & AI Transceivers			
		DL RF Signal Identification			
		6Sense Spectrum Sharing & Multi-link			
		Low-dielectric Ceramics for mmWave			
		Waveform Engineering for Short Packets			
		HAPS Channel Modeling			

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Table 2: Subsystems

Architectural Layer (Rows) / Domains (Columns)	6G User Equipment (UE) & Edge Devices	Radio Access Network (RAN)	Network Core	Transport / Backhaul / Quantum	Applications & Vertical Use Cases
Subsystems (Antennas, Analog RF Front-Ends, Optical Switches, Passives, IRS Modules)	GapWave Sub-THz Skin Hydration Sensor	6G THz Front-End Building Blocks	*None mapped in this document subset*	Photonic D-band Signal Generation & Transport Subsystem	Vehicular Wideband Directive Antennas
	210-255 GHz Analog Front End	F-Band GaN Power Amplifier			
	Nano and Dot Antennas for THz	RIS Array for Joint Localization & Comm			
	IRS Subsystem for IoT Devices	RIS-enabled Hybrid RF/VLC Subsystem			
		High-Purity OAM Antennas			
		Active Fluid Cell Metasurfaces			
		RIS Subsystem for ISAC			
		THz Topological Photonic Passives			
		Photonic Wideband Spectrum Sensing Unit			
		Advanced Antenna System Architecture			
		Sub-THz IRS Subsystem for Localization			
		Fluid Cell Antenna Subsystems			
		3D Printed Fluid Antennas			
		High-Speed Hybrid Transceiver Subsystem			
		RIS Subsystems for ISAC			
		Timed Antenna Array for Beam Steering			
		Fluid Antennas for Wireless			
		Graphene THz Beamforming Antenna			
		Controller Unit for IRS			
		Smart MIMO Antenna Subsystem			
		D-Band THz Antenna Subsystem			
		ML Reconfigurable THz Antenna			
		Multiport Tunable Antenna Switch			
		Base Station Antenna Architecture			
		OAM Antenna Subsystem			

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Table 3: Proposed R&D on Chipsets

Architectural Layer (Rows) / Domains (Columns)	6G User Equipment (UE) & Edge Devices	Radio Access Network (RAN)	Network Core	Transport / Backhaul / Quantum	Applications & Vertical Use Cases
Chipsets *(Integrated Circuits, ASICs, Dedicated Silicon Modules, Transceiver Chips)*	Chip-based CV-QRNG	Optical Transceiver Chipset	*None mapped in this document subset*	On-Chip Photonic THz Carrier Generator	*None mapped in this document subset*
		mmWave PA Chips IP Core		Silicon Photonic N×N Switch Chip	
		140GHz Integrated TX/RX Chipset Module		LEO Satellite Components & GNSS RF Front-End ASIC	
		Wideband Spectrum Sensing On-Chip Hardware			
		Polymer mmWave Transceiver Chip			

Table 4: Proposed R&D on Platforms

Architectural Layer (Rows) / Domains (Columns)	6G User Equipment (UE) & Edge Devices	Radio Access Network (RAN)	Network Core	Transport / Backhaul / Quantum	Applications & Vertical Use Cases
Platforms (Development Testbeds, RIC Controllers, Software Stacks, Lab Platforms)	*None mapped in this document subset*	6G Radio Evaluation Platform	DARPAN Indigenous Digital Twin Platform	Lab-Scale Quantum Fiber Network Platform	Computational Offloading Edge Platform
		Reconfigurable RF-ML Platform	Made in India 5G/6G SA Core Stack	BB84 Quantum Protocol Simulation Toolbox	6G Ubiquitous Connectivity Lab Platform
		AI-Powered Open-PHY Platform	Automated Service Management Platform	Advanced Optical Communication Testbed	
		SMART-RIC6G Controller Platform	Post-Quantum Secure Compute Platform	6G THz OAM Testbed Platform	
		Disaggregated RAN RIC & SMO Platform			

Table 5: Proposed R&D on Systems

Architectural Layer (Rows) / Domains (Columns)	6G User Equipment (UE) & Edge Devices	Radio Access Network (RAN)	Network Core	Transport / Backhaul / Quantum	Applications & Vertical Use Cases
Systems (Full Integrated Assemblies, Base Station Nodes, Gateway Units, Pilot Solutions)	Wearable IoT Pre-disease Surveillance Device	Tera Hertz Communication System Prototype	Core Network System	Project Patang Tethered Drone Backhaul System	LandSense Landslide Detection System
	Wearable Biosensor Monitoring System	Cell-Free Communication System Prototype	100 Gbps Encrypted Traffic Hub System	NTN & RIS Rural Connectivity System	C-V2X Highway Deployment System
	Gigabit Speed Customer Premise Equipment (CPE) Radio	RIS-Enabled Joint Sensing/Comm Testbed System	NavIC IST Traceable PRTC System	Multihop THz FSO Backhaul Link System	Sustainable Autonomous Vehicle System
	Immersive Device-to-Device Comm System	TARANG THz Wireless Comm System		Drone FSO/VLC System for HAP/LAP	Digital Mining Infrastructure System
		Rural IRS Connectivity System		Free Space & Underwater Optical Quantum System	Drone Face Recognition System
		Cell Free 6G Access Point Systems		XGS-PON OLT and ONU Prototype System	Wi-SUN Smart Utility IoT System
		RIS Hardware System Demonstration		Ku-Band GSAT VSAT Backhaul Pilot System	NB-IoT Smart Water Monitoring System
		Rel-17 NB-IoT-NTN eNodeB System		Gram Panchayat Optical Wireless Link System	Phygital Services Pilot System

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Chapter 10: Identification of priority areas for 6G R&D in India

One of the goals of this technology whitepaper is to identify key priority areas for 6G R&D in India. The previous chapters cover the 6G Standardization, timelines, key technologies that might become part of 6G, the 6G use cases along with a detailed analysis and list of the technology matrix for the UE, RAN, Core and Transport domains. This chapter uses this background material to identify areas of R&D which requires focus and funding by the academia, R&D institutions, industry and startups along with the support from the government.

The chapter is organised in three parts. The first part lists six priority technology pillars, along with the platforms, trials and testbeds needed to develop them. The second part attempts to shed light on the internals of the UE, Base Station, Core and Transport - with a block diagram, tabulation of subsystems and IP blocks for each network element. The third part groups these blocks into a set of candidate projects, each with a target, a phase and a priority.

The emphasis is on building design capability, intellectual property (IP) and products within the country. Where an item cannot be built in India in the near term, it is marked for licensing, partnership or import, so that the complete system can still be put together on schedule. These are the current assessment and are subject to change as per the progress made in R&D indigenization and things can be moved from “license” to “develop” if enough progress/capability is demonstrated.

Priority Technology Pillars of 6G

The table below groups the priority R&D areas into six technology pillars. These are AI-native communications, cell-free massive MIMO, integrated sensing and communication (ISAC), non-terrestrial networks (NTN), digital twin networks and sustainable networking. For each pillar, the table lists the technologies to be developed, the target for each technology and the deliverables expected.

Five of these pillars correspond to the cross-cutting technology threads identified in Chapter 5. Sustainable networking is added as a separate pillar since energy efficiency is a requirement in every domain. The other two threads of Chapter 5, namely new spectrum (FR3) and post-quantum security, are covered in the domain tables and the project list given later in this chapter.

SN	Technology Pillar	Technology	Target	Deliverables
1	**AI-Native Communications**	AI-PHY	Adaptive Waveform	• AI-enabled gNB stack • AI-assisted UE modem • AI-RAN platform • Network digital twin
		AI Beamforming	Distributed MIMO	
		AI Scheduling	Resource Optimization	
		AI Mobility	Handover optimization	
		Semantic Communications	Meaning-oriented transmission	
		Federated Learning	Distributed AI	
		Network Foundation Models	Autonomous networks	
2	**Cell-Free Massive MIMO**	Radio	Distributed radios	• Distributed Radio Unit • Cell-free controller • Cell-free RAN software
		PHY	Joint precoding	
		Synchronization	Sub-100ns sync	
		Fronthaul	Deterministic Ethernet	
		Scheduling	Multi-point AI scheduling	

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SN	Technology Pillar	Technology	Target	Deliverables
3	**Integrated Sensing and Communications**	Radar	Object detection	• ISAC gNB • ISAC UE • ISAC analytics platform
		Localization	cm-level positioning	
		Imaging	Environment mapping	
		Tracking	Drone detection	
4	**NTN and Non-Terrestrial Integration**	LEO NTN	Broadband	• NTN modem • NTN gNB • NTN gateway
		HAPS	Regional coverage	
		Direct-to-device	Global access	
		NTN Handover	Multi-orbit mobility	
5	**Digital Twin Networks**	RAN Twin	Virtual RAN	• Twin platform • Twin orchestrator • Predictive operations system
		UE Twin	Device modelling	
		Service Twin	Application twin	
		Network Twin	End-to-end simulation	
6	**Sustainable Networking**	AI Energy Saving	Reduce power	• Green network controller • Sustainability dashboard
		Sleep Modes	Dynamic operation	
		Green RAN	Carbon reduction	
		Renewable Integration	Energy-aware scheduling	

Platforms to be delivered

The technologies under each pillar have to be integrated and tested as working systems. The table below lists the platforms proposed for this purpose. Each platform is a combination of hardware and software on which the technologies of one or more pillars can be demonstrated. The 6G radio platform and the 6G core form the base, and the other platforms are built over them.

SN	Platform	Components	Potential Hardware	Remarks
1	**6G Radio Platform**	• Radio Unit (RU) • Distributed Unit (DU) • Central Unit (CU) • RAN Intelligent Controller (RIC) • AI Engine	• RFSOC • DPU Accelerators • FPGA cards • AI Accelerators	• FR3 and mid-band radios • Base for other platforms
2	**AI-RAN Platform**	• GPU Cluster • RAN Functions • AI Inference	• GPU servers • AI accelerators • DPU	• Beam Prediction • Traffic Prediction
3	**Cell-Free Platform**	• Distributed Radios • Joint Processing Cloud • AI Scheduler	• Distributed radio units • Fronthaul switches • Timing and synchronization hardware	• User-centric Networking • Multi-point transmission
4	**ISAC Platform**	• Communication Stack • Radar Processing • Sensor Function	• RFSoc and SDR platforms • Phased-array front ends	• Smart Cities • Industry • Mobility
5	**NTN Platform**	• LEO • Ground Station • 6G Core	• Satellite channel emulator • SDR platforms • Ground station RF equipment	• Rural broadband • Maritime • Aviation
6	**Digital Twin Platform**	• Network Twin • AI Models • Simulation Engine	• GPU servers • Storage	• Planning • Optimization • Autonomous Operations
7	**Edge AI Platform**	• GPU • NPU • DPU • Storage • Networking	• Edge servers • GPU and NPU cards • DPU	• AI agents • XR rendering • Robotics

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SN	Platform	Components	Potential Hardware	Remarks
8	**6G Core**	• 6G Core • 6G Data Plane • 6G Policy System	• COTS servers • DPU / SmartNIC • HSM	• Cloud-native • Service-based architecture
9	**6G Mgmt System**	• Network Digital Twin • Agentic and Cognitive AI • AI-native architecture		• Intent-based Management • Zero-Touch Automation

Trials Roadmap

Once the platforms are ready, they have to be tested and proven using a set of pilots and trials. The table below lists the proposed trials in five groups, namely AI-native network, cell-free massive MIMO, ISAC, NTN and Industry 5.0. Each group has listed about three trials as representative of the domain. In the cell-free massive MIMO group, for example, the trials move from an indoor factory to a campus network and then to a city deployment. For each trial, the table gives the objectives and the KPIs to be measured.

SN	Platform	Objectives	KPIs
A	**AI-Native Network**		
A1	**AI Scheduler**	• Capacity improvement • Energy reduction	• Throughput • Power savings
A2	**AI Mobility**	• Mobility/ Handover	• Handover success • Reduced drops
A3	**Autonomous RAN**	• Closed-loop automation • Self-configuration and self-healing	• Zero-touch operation • OPEX reduction
B	**Cell-Free Massive MIMO**		
B1	**Indoor Factory**	• 5-10 Radio Nodes • 50 UEs	• Cell-edge throughput • Reliability
B2	**Campus Network**	• 10-20 Radio Nodes • 200 UEs	• Uniform QoS • Mobility robustness
B3	**City Deployment**	• 100+ Radio Nodes	• Spectral efficiency • Energy efficiency
C	**ISAC**		
C1	**Traffic Monitoring**	• Vehicle sensing using base station signals	• Vehicle Detection • Traffic Accuracy
C2	**Drone Detection**	• Detection and tracking of low-altitude drones	• Range • Detection Rate
C3	**Factory Digital Twin**	• Real-time positioning of assets and machines	• Positioning • Tracking Latency
D	**NTN**		
D1	**Direct-to-Handset**	• Satellite service to standard handsets	• Voice • Messaging • Broadband
D2	**Maritime Connectivity**	• Coverage for coastal and deep-sea vessels	• Coverage Service availability
D3	**Aviation Connectivity**	• In-flight broadband	• Throughput Service continuity
E	**Industry 5.0**		
E1	**Connected Robots**	• Wireless control of mobile robots	Deterministic Latency Reliability
E2	**Autonomous Factory**	• Wireless production line	Production Efficiency Network resilience
E3	**Human-Robot Collaboration**	• Safe shared workspace using sensing and positioning	Safety Positioning Accuracy

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6G Testbeds required

Building lab-scale functional prototypes using off-the-shelf development platforms bridges the gap between theoretical 3GPP 6G study items (Release 20/21) and real-world physical layers.

The table below lists seven testbeds that can be set up in academic and R&D laboratories using SDR platforms, RFSoC evaluation boards and open-source software stacks. For each testbed, the table gives the main components and the key R&D problems to be addressed. The results from these testbeds can also be used for contributions to 3GPP and ITU-R, as in the case of FR3 channel models.

SN	Platform	Components	Key R&D	Remarks
1	**ISAC**	• Host Server/Processing Unit with open-source SDR Stack • USRP or RFSOC evaluation Board • RF Front Ends using evaluation board • Sensing loopback (RF) •	• Shared Waveform DSP • Clutter Cancellation Filter: • Synchronization Mechanism:	• Signal Analyzer • Vector Signal Generator
2	**AI-Native Air Interface (Neural Receiver)**	• AI Training/Inference Server • Hardware Interface Server (RFSOC) • Software Stack		Replace standard 3GPP channel estimation, equalization, and de-mapping blocks in the physical layer with an end-to-end deep neural network trained to handle non-linear hardware distortions and complex multipath fading environments
3	**FR3 Channel Sounder & E-MIMO**	• SDR/vector Sounder, • 7–24 GHz front ends, • Positioning rig;	Key R&D: Channel models for 3GPP/ITU-R	
4	**Cell-free / D-MIMO Sync**	• multi-node RRH/USRP cluster, • PTP/White-Rabbit sync, • CU/DU server	• sub-100 ns over-the-air sync, • Joint Precoding	
5	**NTN Emulation**	• channel emulator with Doppler/delay profiles, Rel-19 NTN stack, regenerative-payload SDR;	• GNSS-resilient timing, • TN–NTN handover	
6	**RIS Control**	• 1-bit metasurface panel, controller MCU, • Channel-Feedback Quantizer;	• RIS control interface (open in 3GPP), • Near-Field modelling.	
7	**6G Core & PQC**	• Cloud-native SBA stack (free5GC/Open5GS evolution), • NWDAF, • PQC HSM;	• Compute-aware SMF, • quantum-safe AKA.	

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Proposed List of Key Components and Master Project List for creating indigenous 6G Ecosystem

Based on the analysis in the previous chapters, this section provides a list of key projects for creating components/subsystems/IP for building an indigenous 6G Ecosystem.

The components are taken up domain-wise in the sections that follow, for the 6G User Equipment (6G UE), 6G Base Station, 6G Core and 6G Transport. They cover chipsets, hardware subsystems and software stacks. The common enablers and the list of candidate projects are given at the end of the chapter.

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6G User Equipment (UE)

While there are many aspects still being debated about 6G, there will definitely be a 6G User Equipment (6G UE). It could be a module, smartphone, embedded system which is static or mobile. This section tries to unravel the internals of a potential 6G UE.

The figure below shows the main blocks of a 6G UE. The key modules are - Application SoC, the 6G modem SoC, the Security Subsystem, the RF transceiver IC, the RF front end and the power management unit.

The tables after the figure list the UE subsystems, the baseband IP blocks of the modem, the RF and analog IP blocks and the RF front-end components. Against each item, the tables give the proposed route for building it and the phase in which it is to be taken up. The subsystem table also gives the present status in India.

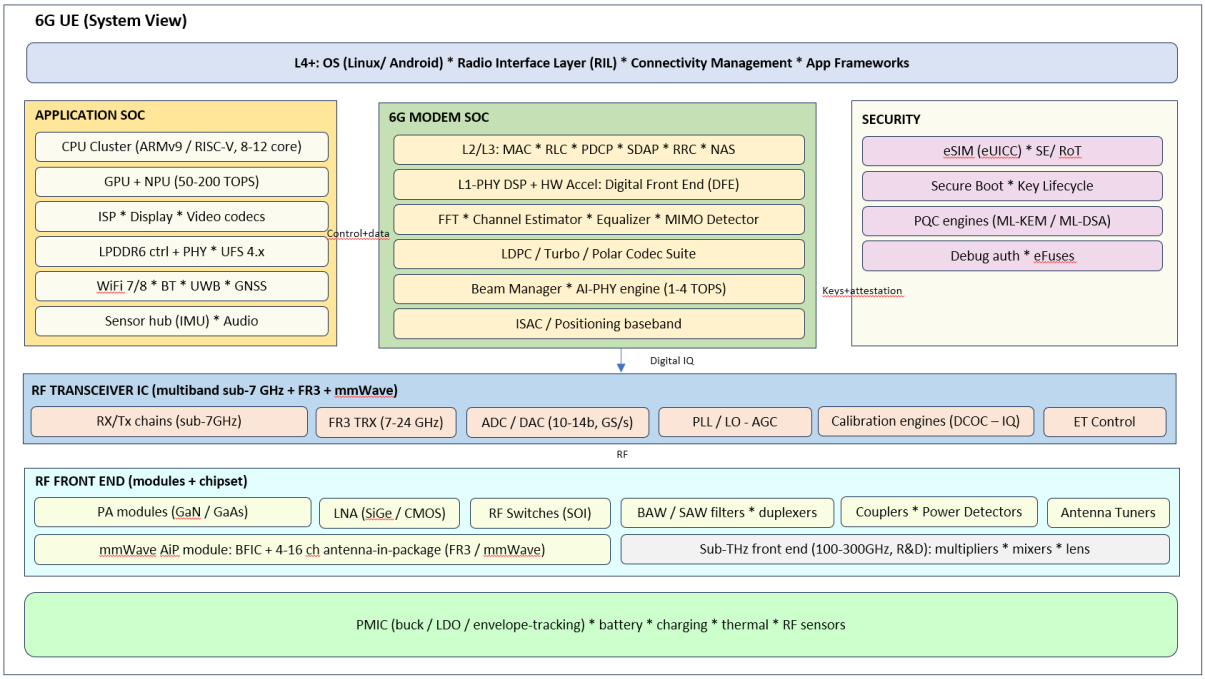

Figure 10.1: 6G UE System View - Block Diagram

The codes used in these columns are explained in the legend below. The phases P1, P2 and P3 broadly correspond to Phase 1, Phases 2 and 3, and Phase 4 of the roadmap in Chapter 6. The same codes are used in the tables for the base station, Core and transport.

Legend

Build codes	**D**: Design/Develop in India	**L**: License IP	**P**: Partner/JV	**B** = Buy (import)
Status codes	**S**: Strong Existing Base	**E**: Emerging Capability	**G**: Gap	
Phases	**PH1**: 2025–27 (Research, IP, Testbeds)	**PH2**: 2027–29 (Silicon, Trials)	**PH3**: 2029–31 (Commercialization)	**PH4**: 2030 onwards

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6G UE: Top Level Subsystems

ID	Subsystem	Contents / Function	Status	Build	Phase
UE-S1	**Application SoC**	CPU/GPU/NPU/ISP/LPDDR6/UFS; Hosts apps + Modem control	G	L+P	PH3
UE-S2	**6G Modem SoC**	Full L1–L3 protocol processing, AI-PHY, ISAC, Positioning	E	D	PH1–PH2
UE-S3	**RF Transceiver IC**	Analog/RF conversion, Multiband direct-conversion + FR3	G	D	PH2
UE-S4	**RFFE components**	PA, LNA, Switches, BAW/SAW filters, Duplexers, Tuners	G (BAW), E (PA)	D+P	PH2–PH3
UE-S5	**mmWave AiP module**	Phased-array RFIC + Antennas in Package (AiP) (FR3/mmWave)	G	D	PH2
UE-S6	**sub-THz front end**	100–300 GHz access (Research: multipliers, mixers, lens)	R&D	D	PH1
UE-S7	**PMIC / power**	Buck/LDO, envelope tracking, charge mgmt	E	D	PH2
UE-S8	**Security subsystem**	eSIM/eUICC, SE, RoT, PQC, secure boot	E	D	PH1
UE-S9	**Sensors & positioning**	GNSS BB, UWB, IMU fusion, hybrid positioning	E	D	PH2
UE-S10	**ISAC / sensing**	Radar/sensing mode, WiFi sensing, fusion engine	R&D	D	PH1–PH2
UE-S11	**Protocol software**	L2/L3/NAS stack, RIL, conformance SW	E	D	PH1–PH2

6G UE: Modem Baseband IP-Level Table

ID	IP block	Function	Indicative target spec	Build	Phase
UE-BB-01	**Modem control CPU**	Runs L2/L3/NAS, real-time control	4–8× Cortex-R/M or RISC-V, multi-core, RTOS	D	PH1
UE-BB-02	**Digital front end (DFE)**	DDC/DUC, resampling, NCO, AGC, IQ/DC correction	Up to 400–800 MHz per CC, 1–4× resample	D	PH1
UE-BB-03	**Sync / cell-search engine**	PSS/SSS correlators, PRACH detector, CFO/TO estimation	Multi-beam parallel, AI-assisted search	D	PH1
UE-BB-04	**FFT/IFFT engine**	Scalable OFDM transforms	256–65k points, 8+ CCs	D	PH1
UE-BB-05	**Channel estimator**	LS/MMSE/NN estimation, multi-port	8–32 antenna ports, DMRS-driven	D	PH1
UE-BB-06	**Equalizer / MIMO detector**	MMSE, MMSE-SIC, sphere/NN detection	16–32 layers DL	D	PH1–PH2
UE-BB-07	**Channel codec suite**	LDPC enc/dec (+6G codes TBD), Turbo (legacy), Polar	5–20 Gbps decoder @ 0.5–1 GHz	D	PH1
UE-BB-08	**HARQ / rate matching**	Process mgmt, buffers, retx control	16–32 processes, ~32–64 MB HARQ buf	D	PH1
UE-BB-09	**Modulator/precoder**	QAM mapping (incl. 4k/8k-QAM), layer mapping, precoding	Per 3GPP Rel-21	D	PH2
UE-BB-10	**Reference-signal engines**	DMRS/SRS/CSI-RS/PT-RS gen & processing	Per band/numerology	D	PH1
UE-BB-11	**Beam manager**	Sweep, refine, TCI state machine, AI beam prediction	Millisecond-class switching	D	PH1
UE-BB-12	**Measurement engine**	RSRP/RSRQ/SINR, L3 reporting	Multi-cell, low power	D	PH1
UE-BB-13	**PHY-AI engine**	Neural receiver, CSI compression, near-L1 inference	1–4 TOPS INT8/FP16	D	PH1

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ID	IP block	Function	Indicative target spec	Build	Phase
UE-BB-14	**MAC HW engine**	Timing advance, SR/BSR, PHR, DRX control	µs-class latency	D	PH1
UE-BB-15	**L2 offload**	RLC AM/UM, PDCP cipher+integrity (AES/SNOW-3G/ZUC, 256b), SDAP, ROHC	Line-rate	D	PH1
UE-BB-16	**Crypto + PQC engine**	3GPP algo set + ML-KEM/ML-DSA (FIPS 203/204), TRNG	Hybrid PQC capable	D	PH1
UE-BB-17	**ISAC / positioning BB**	UWB radar, sensing waveform proc., fusion	cm–dm positioning, sensing ranges	D	PH1–PH2
UE-BB-18	**Co-existence controller**	Wi-Fi/BT/UWB/GNSS co-scheduling, dBm/spectral mgmt	Shared RF path arbitration	D	PH2
UE-BB-19	**NoC / DMA / bus fabric**	AXI/NoC, QoS, low-power domain mgmt	Multi-Tbps on-chip	L	PH1
UE-BB-20	**Boot & debug security**	Secure boot, eFuses, debug authentication	PSA/SESIP certifiable	D	PH1

6G UE: RF / Analog IP-Level Table

ID	IP block	Function	Indicative target spec	Build	Ph
UE-RF-01	**RX analog chain (per ch)**	LNA ctrl, IQ mixers, VGA, anti-alias LPF	BW 5–100+ MHz, NF <3 dB (sub-6)	D	PH2
UE-RF-02	**TX analog chain (per ch)**	IQ up-mixer, driver, LO-leak cal	EVM < −35 dB target	D	PH2
UE-RF-03	**ADC / DAC**	High-dynamic-range converters	10–14 b, 0.1–4 GS/s (SAR/pipeline/ΔΣ)	D	PH1–PH2
UE-RF-04	**PLL / synthesizer**	Fractional-N, multi-band VCO, autocal	<200 fs jitter, fast lock	D	PH2
UE-RF-05	**Calibration engines**	DCOC, IQ mismatch, LOFT, power detect	Automated RF cal firmware	D	PH2
UE-RF-06	**Transceiver control IP**	SPI/I2C, RF-cal firmware, power-state control	—	D	PH2
UE-RF-07	**FR3/mmWave RFIC**	4–8 TRX channels, phase shifters, PA+LNA on-die	7–47 GHz, SiGe/CMOS, AiP-ready	D	PH2
UE-RF-08	**BFIC (analog beamform)**	Per-element phase+gain for subarrays	5–6 b phase, 16–32 ch	D	PH2
UE-RF-09	**ET modulator + PA ctrl**	Envelope-tracking supply modulation	>20 MHz signal BW	D	PH2
UE-RF-10	**sub-THz MMIC set**	×3/×6 multipliers, subharmonic mixers, LNAs	100–300 GHz, SiGe/GaN (research)	D	PH1

6G UE: RF Front-End Component Table (modules/chipsets)

ID	Component	Notes	Build	Ph
UE-FE-01	**PA modules**	GaN-on-Si / GaAs for n77/n78-class + FR3; 0.5–2 W class	D+P	PH2–PH3
UE-FE-02	**LNAs**	SiGe/CMOS, band-switchable	D	PH2
UE-FE-03	**RF switches**	SOI, SPDT–SP16T, high linearity	D	PH2
UE-FE-04	**BAW/SMR filters**	Mid/high-band, piezo (POI/LN) materials — critical gap	D+P	PH2–PH3
UE-FE-05	**SAW/TC-SAW filters**	Low bands	D	PH2
UE-FE-06	**Duplexer/multiplexer**	Multi-band integration	D+P	PH3
UE-FE-07	**Couplers + power detectors**	For DPD/PA control	D	PH2

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ID	Component	Notes	Build	Ph
UE-FE-08	**Antenna tuners**	Aperture/impedance tuning (varactor/BST)	D	PH2
UE-FE-09	**mmWave AiP module**	RFIC + 2×2/4×4 antenna in package	D	PH2
UE-FE-10	**Antenna arrays**	Sub-6 MIMO, FR3, mmWave, UWB/ISAC apertures	D	PH2

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6G Base Station

The figure below shows the main blocks of a 6G base station. It consists of the radio unit (RU), the distributed unit (DU) and the central unit (CU), along with the RIC, synchronisation and power blocks. The tables that follow list the top-level subsystems, the IP blocks of the RU, the Layer 1 accelerator IP blocks of the DU, and the compute and management components of the CU. A separate table covers the elements that are still at the research stage, such as RIS, NTN payload, sub-THz radio and ISAC.

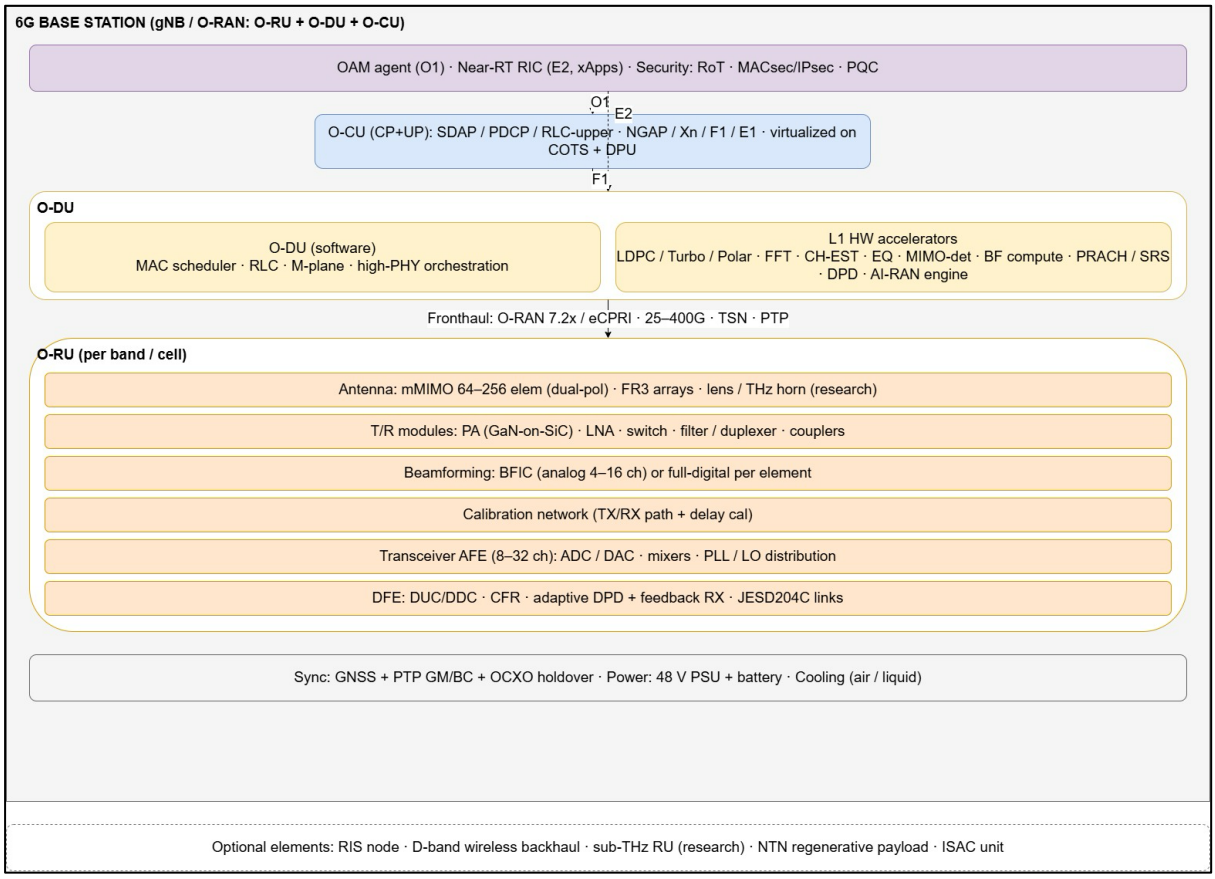

Figure 10.2: 6G Base Station - Block Diagram

6G Base Station: Top Level Subsystem

ID	Subsystem	Contents / Function	Status	Build	Phase
BS-S1	**Antenna subsystem**	Passive low-band panels; FR3 mMIMO 64–256T; mmWave AiP; THz apertures	E	D	PH2
BS-S2	**O-RU (RF/DFE)**	Transceiver AFE, PA/LNA, filters, DFE, calibration	E	D	PH1–PH2
BS-S3	**Beamforming subsystem**	Analog BFIC / hybrid / full-digital	E	D	PH2
BS-S4	**DU (L1)**	SW + hardware accelerators	E	D	PH1–PH2
BS-S5	**CU (L2-high)**	Virtualized CP/UP, SDAP/PDCP, interfaces	E	D	PH1
BS-S6	**RIC / intelligence**	Near-RT RIC + xApps, non-RT rApps, SMO integration	E	D	PH1
BS-S7	**Fronthaul/backhaul NICs**	25/50/100/200/400G eCPRI, timing, security offload	E	D	PH2
BS-S8	**Sync subsystem**	GNSS + PTP + SyncE + OCXO holdover	E	D	PH1
BS-S9	**Security subsystem**	RoT, secure boot, MACsec/IPsec, cert mgmt	E	D	PH1

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ID	Subsystem	Contents / Function	Status	Build	Phase
BS-S10	**Power & cooling**	48 V PSU, rectifier+battery, liquid for mMIMO/THz	S	B+D	PH3
BS-S11	**RIS node**	Metasurface + controller ASIC + mgmt/backhaul	R&D	D	PH1–PH2
BS-S12	**NTN payload**	Regenerative LEO: OBF, on-board L1/L2, ISL	R&D	D	PH1–PH3
BS-S13	**ISAC unit**	Sensing waveform gen, echo processing, fusion	R&D	D	PH1–PH2
BS-S14	**sub-THz radio**	Photonic+MMIC chain, high-speed DSP (research)	R&D	D	PH1

6G Base Station: RU IP-Level Table

ID	IP block	Function	Indicative target spec	Build	Phase
BS-RU-01	**Multi-ch ADC/DAC IP**	Wideband converters for mMIMO/FR3	12–14 b, 0.5–4 GS/s	D	PH1–PH2
BS-RU-02	**JESD204B/C link IP**	AFE↔DFE serialization	Multi-lane, 16+ Gbps/lane	D	PH1
BS-RU-03	**DUC/DDC + NCO**	Digital up/down conversion	Per-channel, 32-b NCO	D	PH1
BS-RU-04	**CFR engine**	Crest-factor reduction pre-PA	< −65 dBc ACLR contribution	D	PH1
BS-RU-05	**DPD engine + feedback**	Adaptive digital predistortion	>10 dB ACPR improvement	D	PH1
BS-RU-06	**Calibration engine**	IQ/LO/delay cal for arrays, power detect	Periodic + online	D	PH1
BS-RU-07	**PLL / LO synthesis + distribution**	Low-jitter LO for arrays	<100 fs jitter	D	PH2
BS-RU-08	**Transceiver AFE IP**	Per-channel RX/TX: mixer, VGA, filters	8–32 ch per IC	D	PH2
BS-RU-09	**O-RAN fronthaul framer**	7.2x M/C/U-plane, eCPRI, RoE	O-RAN WG4 conformant	D	PH1
BS-RU-10	**RF control + O-RU OAM SW**	YANG models, telemetry, alarms	O-RAN M-plane	D	PH1
BS-RU-11	**mmWave BFIC**	4–16 ch T/R with phase+gain	FR3/mmWave, TDD	D	PH2
BS-RU-12	**PA modules (GaN-on-SiC)**	100–320 W class (mMIMO), FR3/ mmWave PAs	Doherty / ET-assisted	D+P	PH2–PH3

6G Base Station: DU L1 Accelerator IP-Level Table

ID	IP block	Function	Indicative target spec	Build	Phase
BS-L1-01	**LDPC encoder/decoder**	Data channel FEC (BG1/BG2 → 6G codes TBD)	100–800 Gbps/card, scalable	D	PH1
BS-L1-02	**Polar / Turbo / BCH**	Control & legacy channels	Gbps-class	D	PH1
BS-L1-03	**Rate match / HARQ mgr**	Puncturing, retx combining, buffers	100+ GB/s DDR bw	D	PH1
BS-L1-04	**FFT/IFFT bank**	OFDM processing	1k–32k scalable, per-cell BW 400 MHz–1 GHz+	D	PH1
BS-L1-05	**Channel estimator**	MMSE/NN, multi-user	64–256 ports	D	PH1
BS-L1-06	**Equalizer**	ZF/MMSE/SIC, MU-MIMO	16–64 layers	D	PH1
BS-L1-07	**MIMO detector**	Sphere/NN detection	Line-rate, AI-assist	D	PH1–PH2
BS-L1-08	**BF weight computation**	Beam weight calc + calibration	µs-class update	D	PH1
BS-L1-09	**Channel pipelines**	PDSCH/PUSCH/PDCCH/PUCCH end-to-end	~100 Gbps/cell DL target	D	PH2
BS-L1-10	**PRACH detector**	Multi-beam preamble detection	64+ preambles	D	PH1
BS-L1-11	**SRS processor**	Sounding, positioning, beam mgmt	TDD streaming	D	PH1

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ID	IP block	Function	Indicative target spec	Build	Phase
BS-L1-12	**Scheduler HW assist**	Grant generation, TDD mgmt	µs determinism	D	PH2
BS-L1-13	**L2 offload (MAC/RLC/PDCP/SDAP)**	Cipher (AES/SNOW/ZUC), integrity, F1 framer	100+ Gbps	D	PH2
BS-L1-14	**PTP/SyncE HW**	Timestamping, T-BC; TAE < ±1.3 µs (130 ns advanced)	G.8273.2 class C/D	D	PH1
BS-L1-15	**AI-RAN engine**	RIC xApps, beam/CSI/positioning models	10–100 TOPS	D	PH1
BS-L1-16	**Crypto offload**	MACsec/IPsec + PQC for O-DU/CU	Line-rate	D	PH2

6G Base Station: CU/ Compute & Management Table

ID	Component	Notes	Build	Phase
BS-CU-01	**Server SoC platform**	ARM Neoverse / x86 / RISC-V, 64–128 cores	L+D	PH1
BS-CU-02	**NIC/DPU**	TSO/RDMA/vDPA, P4-programmable	D+L	PH2
BS-CU-03	**PCIe Gen5/6 switch**	L1-card ↔ host fabric	L	PH2
BS-CU-04	**Hypervisor/K8s + O2**	Cloud-native DU/CU deployment	D	PH1
BS-CU-05	**Protocol SW (NGAP/Xn/F1/E1)**	3GPP conformance	D	PH1
BS-CU-06	**E2 agent + xApp SDK**	O-RAN WG3	D	PH1
BS-CU-07	**O1/VES/YANG M-plane**	O-RAN WG5/WG10	D	PH1
BS-CU-08	**Timing card**	GNSS + OCXO + PTP IP integration	D	PH1

6G Base Station: Special/Research Element Table (RIS, NTN, Sub-THz, ISAC)

ID	IP block	Function	Indicative target spec	Build	Phase
BS-X-01	**D-band MMIC set (backhaul)**	PA/LNA/multipliers/mixers, 110–175 GHz	10–100 Gbps, 1–3 km LOS	D	PH1–PH2
BS-X-02	**Photonic sub-THz chain**	Laser + MZM + UTC-PD IF transport to RU	>100 GHz IF	D	PH1
BS-X-03	**Lens/horn/quasi-optics**	High-gain THz apertures	40–60 dBi	D	PH1
BS-X-04	**RIS controller ASIC**	Thousands of varactor channels (DAC/ADC), phase config	1024–16384 elements	D	PH1
BS-X-05	**RIS sensing/calibration SW**	Beam alignment, environment sensing	ETSI RIS ISG aligned	D	PH1–PH2
BS-X-06	**NTN regenerative payload**	On-board L1/L2, OBF, IP routing in space	Ka + optical ISL	D	PH1–PH3
BS-X-07	**Optical ISL terminal**	Laser inter-satellite link	100–400 Gbps	D	PH2
BS-X-08	**ISAC processing chain**	Waveform gen, radar DSP, fusion with comm sched.	Joint design	D	PH1

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6G Core

The 6G core is largely software running on a cloud platform. The figure below shows its structure, with the control plane, the user plane, the new 6G functions and the AI and data plane placed over a common cloud infrastructure. The first table lists the compute, storage and networking infrastructure on which the core runs. The second table lists the network functions, including the new functions proposed for sensing, AI, trust and identity, and ambient IoT. The third table covers the AI, security and operations blocks that are common to all the network functions.

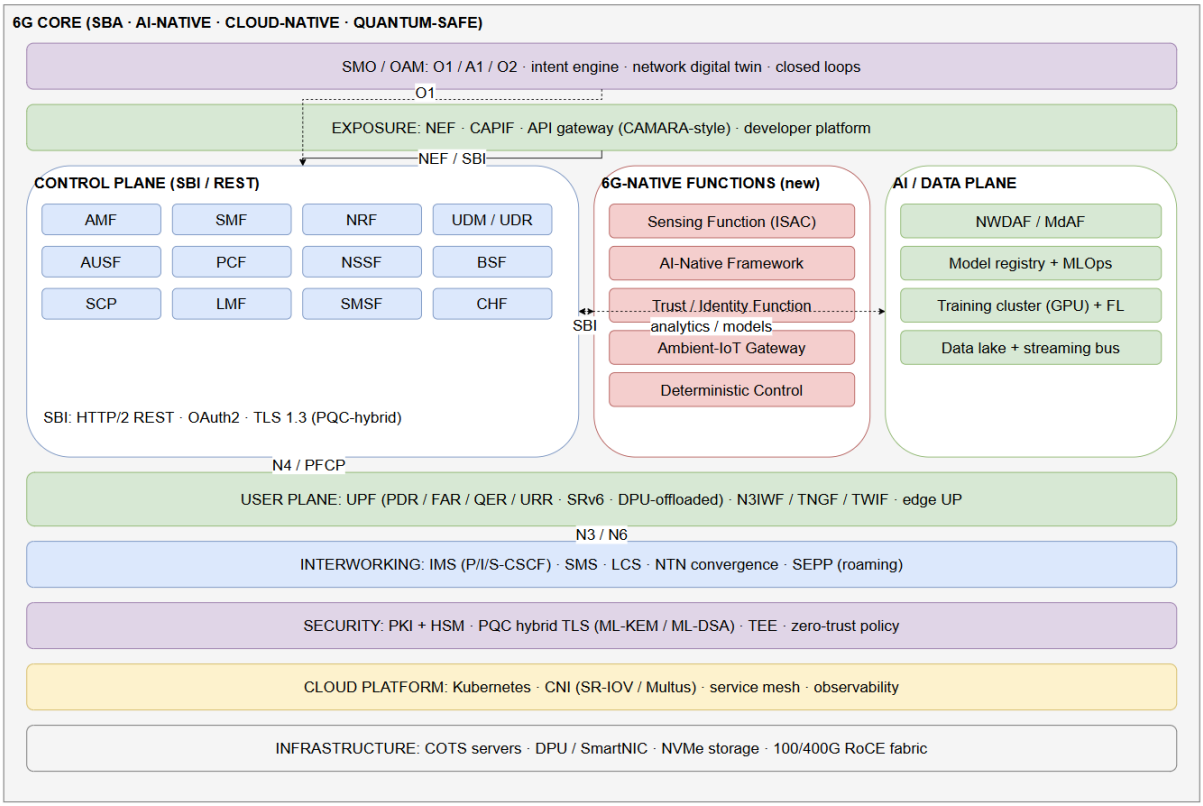

Figure10.3: 6G Core Block Diagram

6G Core: Infrastructure & Cloud Platform Table

ID	Subsystem	Function	Status	Build	Phase
CO-S1	Compute	COTS servers; 6G: DPU/SmartNIC (P4, crypto, RDMA)	S/G	L+D	PH1–PH2
CO-S2	Storage	Distributed NVMe, tiered, for UDR/UDSF/data lake	S	D	PH1
CO-S3	DC fabric	100/400G RoCEv2 leaf-spine	S	B+D	PH1
CO-S4	Cloud platform	K8s, CNI (SR-IOV/Multus), service mesh, GitOps	S	D	PH1
CO-S5	Observability	Metrics/log/trace, telemetry TSDB	S	D	PH1

6G Core: Network Function Inventory Table

ID	Network Function	Function	6G Evolution Notes	Build	Phase
CO-NF-01	AMF	Registration, mobility, NAS	NTN + Ambient-IoT scale (10^8/km²)	D	PH1
CO-NF-02	SMF	Session mgmt	Deterministic/slicing-aware	D	PH1

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ID	Network Function	Function	6G Evolution Notes	Build	Phase
CO-NF-03	UPF	User plane (PDR/FAR/QER/URR)	SRv6, DPU offload, edge-flexible, 6G UP extensions	D	PH1
CO-NF-04	NRF	NF discovery/registration	AI-assisted NF orchestration	D	PH1
CO-NF-05	UDM/UDR	Subscription data	Quantum-safe credential mgmt	D	PH1
CO-NF-06	AUSF	Authentication	Massive-device auth (Ambient IoT), PQC	D	PH1
CO-NF-07	PCF	Policy	Intent-driven, AI-generated policy	D	PH1
CO-NF-08	NSSF / BSF / SCP	Slicing, binding, indirect comm	Standard evolution	D	PH1
CO-NF-09	NEF + CAPIF	Exposure	Developer/CAMARA-class APIs, ISAC exposure	D	PH1–PH2
CO-NF-10	NWDAF / MdAF	Analytics	Model registry, training, MLOps, FL	D	PH1
CO-NF-11	CHF/OCF	Charging/converged	Real-time, AI-fraud	D	PH2
CO-NF-12	LMF	Positioning	Hybrid GNSS/UWB/ISAC fusion	D	PH2
CO-NF-13	N3IWF/TNGF/TWIF	Non-3GPP access	Wi-Fi 8 convergence	D	PH2
CO-NF-14	SEPP	Roaming security	PQC-hybrid TLS	D	PH2
CO-NF-15	IMS (P/I/S-CSCF)	Voice/multimedia	AI-enhanced codecs, 6G voice	D	PH2
CO-NF-16	Sensing Function (new)	ISAC service mgmt & data	3GPP Rel-20/21 candidate	D	PH1–PH2
CO-NF-17	AI-Native Framework (new)	Model lifecycle, AI service exposure	Native SBA AI APIs	D	PH1
CO-NF-18	Trust/Identity Function (new)	Zero-trust, decentralized identity	Post-quantum PKI integration	D	PH2
CO-NF-19	Ambient-IoT gateway (new)	Energy-harvesting device mgmt	No-battery security profile	D	PH2
CO-NF-20	Data layer (UDSF/lake)	Unstructured + analytics store	Unified data fabric	D	PH1

6G Core: AI/ Security/ OAM Cross-Plane Table

ID	Block	Function	Build	Phase
CO-X-01	Data lake + streaming bus	Network + sensing data pipelines	D	PH1
CO-X-02	Training cluster (GPU) + MLOps	Model train/validate/deploy	D	PH1
CO-X-03	Digital twin engine	Network model + simulation (what-if)	D	PH1–PH2
CO-X-04	Intent engine + closed loops	Natural-language intents → policies	D	PH2
CO-X-05	PKI/RA + HSM	Certificates, key custody	D	PH1
CO-X-06	PQC library + migration kit	ML-KEM/ML-DSA, hybrid SBA/SEPP TLS	D	PH1
CO-X-07	TEE / confidential computing	NF isolation (CCA/SEV-class)	D+L	PH2
CO-X-08	Zero-trust policy engine	Identity-based access everywhere	D	PH2
CO-X-09	SCAS / fraud mgmt	Spam, SIM-swap, bypass detection	D	PH2
CO-X-10	QKD pilot integration	Quantum-safe key transport (select routes)	D	PH2–PH3

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6G Transport (Fronthaul, Midhaul, Backhaul, Optical)

The transport network connects the radio sites to the data centres that host the DU, CU and Core functions. The figure below shows the data/control path from the radio site through the cell-site router, the aggregation network and the optical core to the data centre, along with the timing and management layers (which are present across all network elements). The tables that follow list the transport subsystems, the IP blocks for routing and switching silicon, optical transport and wireless backhaul in the E-band and D-band.

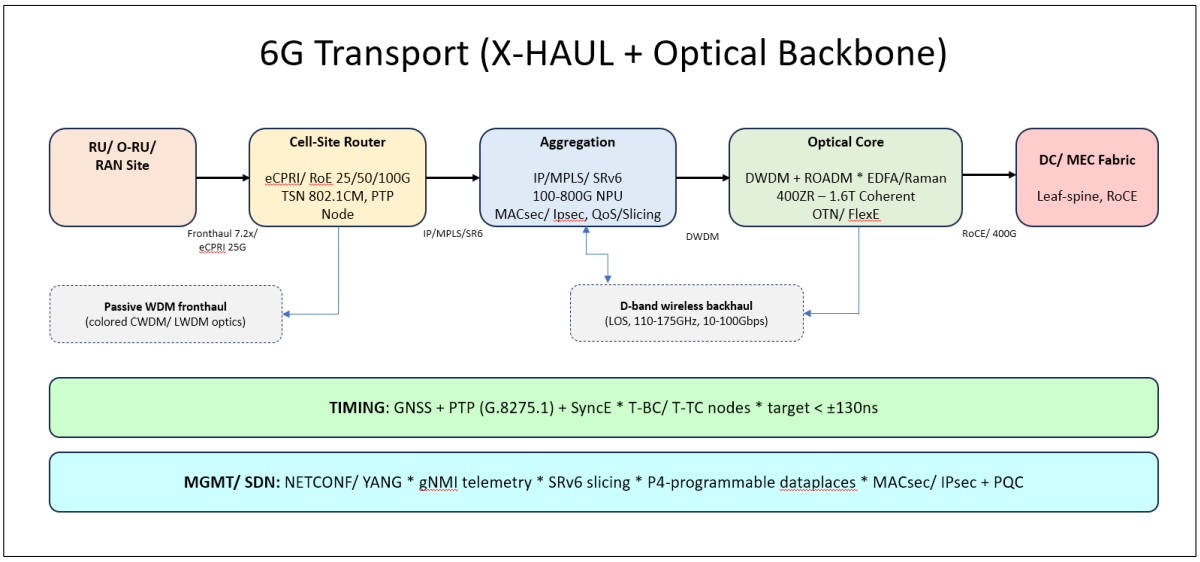

Figure 10.4: 6G Transport Network Block Diagram

6G Transport: Segment/Subsystem Table

ID	Subsystem	Contents / Function	Status	Build	Phase
TR-S1	Fronthaul network	eCPRI/RoE switches, CSR, TSN, timing, passive WDM	E	D	PH1–PH2
TR-S2	Aggregation/backhaul routers	IP/MPLS/SRv6, 400–800G, slicing	E	D	PH2
TR-S3	Optical transport	DWDM/ROADM/OLS, 400ZR–1.6T coherent	G	D+P	PH2
TR-S4	Wireless backhaul	E-band today → D-band 6G-era radios	E	D	PH1–PH2
TR-S5	DCI/MEC fabric	Leaf-spine, RoCE, micro-DC	S	B+D	PH2
TR-S6	Timing distribution	PTP GM/BC/TC, SyncE, GNSS+holdover	E	D	PH1
TR-S7	Security	MACsec/IPsec line-rate, PQC migration	E	D	PH1–PH2
TR-S8	SDN/OAM	Controller, YANG models, telemetry, slicing	S	D	PH1

6G Transport: Routing/ Switching Silicon IP-Level Table

ID	IP block	Function	Indicative target spec	Build	Phase
TR-RT-01	SerDes	112G → 224G → 448G PAM4	224G PAM4 design start P1	D	PH1–PH2
TR-RT-02	PCS / FEC (link)	RS(544,514)/KP4, staircase oFEC	Line-rate	D	PH1
TR-RT-03	MAC	50/100/200/400/800G Ethernet	Multi-instance	D	PH1
TR-RT-04	FlexE shim	OIF FlexE 2.0 grouping/calendar	n×100G calendar	D	PH1
TR-RT-05	NPU pipeline	L2/L3 lookup, LPM, ACL, tunnel encap	TCAM/EM, P4-programmable	D	PH1–PH2
TR-RT-06	Traffic manager	Buffers, scheduling, QoS/shaping	Deep buffer class	D	PH2

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ID	IP block	Function	Indicative target spec	Build	Phase
TR-RT-07	SRv6/MPLS engines	SID processing, EVPN, VPN encap	HW SID lookup	D	PH1
TR-RT-08	MACsec/IPsec engines	Line-rate crypto incl. PQC-ready	400G+ per port	D	PH1–PH2
TR-RT-09	PTP/SyncE IP	T-BC/T-TC, HW timestamping	G.8273.2 class C/D	D	PH1
TR-RT-10	RoCE/RDMA + INT	RDMA offload, in-band telemetry	DCI-ready	D	PH2
TR-RT-11	Routing SW stack	BGP/ISIS/OSPF/SRv6, gNMI/NETCONF		D	PH1

6G Transport: Optical IP-Level Table

ID	IP block	Function	Indicative target spec	Build	Phase
TR-OP-01	Coherent DSP	ADC/DAC, adaptive EQ, chromatic+PMD comp, NLC (DBP), carrier recovery	8–9 b, 100–200 GS/s; 800G→1.6T λ	D	PH1–PH3
TR-OP-02	FEC (optical)	SD-FEC/oFEC/HD-FEC, concatenated	25–30% OH	D	PH1
TR-OP-03	Probabilistic shaping	Constellation shaping engine	DSP-integrated	D	PH2
TR-OP-04	OTN mapper	G.709/OTUCn, ODUflex, client mapping	400G/800G	D	PH1
TR-OP-05	Silicon photonics: modulators	MZM/ring modulators	>50 GBaud	D	PH1
TR-OP-06	Ge-on-Si photodetectors	RX detection, monolithic integration	>50 GBaud	D	PH1
TR-OP-07	TIA / driver ICs	Analog front-end for SiPh	>50 GBaud	D	PH1–PH2
TR-OP-08	Laser control + laser sources	DFB/EML/CW; external dependency	InP — partner/fab	P	PH2
TR-OP-09	WSS / ROADM control	Wavelength selective switch logic + calibration	20–96 ch	D	PH2
TR-OP-10	Amplifier control	EDFA/Raman gain flattening, telemetry	DWDM C+L, multi-band	D	PH2
TR-OP-11	400ZR/ZR+ / 800G module ctrl	Pluggable DSP mgmt, CMIS	QSFP-DD/OSFP	D	PH2
TR-OP-12	Passive WDM fronthaul optics	Coloured CWDM/LWDM for RU chains	Cost-optimized	D	PH1

6G Transport: Wireless Backhaul (E/D-band) IP-Level Table

ID	IP block	Function	Indicative target spec	Build	Phase
TR-WB-01	D-band BB modem DSP	High-order QAM (up to 256/512), adaptive coding	10–100 Gbps	D	PH1–PH2
TR-WB-02	XPIC / MIMO	Dual-pol frequency reuse	2× capacity	D	PH2
TR-WB-03	mmWave/D-band front end	Multipliers, mixers, GaN PA, LNA, PLL chains	110–175 GHz	D	PH1–PH2
TR-WB-04	OMT + high-gain antennas	Orthomode transducer, 40–60 dBi antennas	Waveguide/reflectors	D	PH2
TR-WB-05	Link adaptation SW	ACM, E-band+D-band aggregation, mesh	Always-on LOS mgmt	D	PH2
TR-WB-06	Timing over wireless BH	PTP transparent support	<1 µs over chain	D	PH1

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Cross-Cutting Enablers

Some requirements are common to all the four domains and cannot be met through any single product project. These include EDA tools, foundry access, packaging and assembly, test and measurement instruments, standards and IPR, spectrum policy, talent and testbeds. The table below lists these enablers along with their present status. These are listed to highlight the importance of the domains in the 6G R&D ecosystem and this document does not address any of the items listed below in detail. There will be other whitepapers which will elaborate the topics.

ID	Block	Function	Status	Phase
CC-1	**EDA + design ecosystem**	All silicon flows depend on Synopsys/Cadence/Siemens; DLI-funded IP commons mitigate	G	PH1
CC-2	**Foundry access**	28 nm at Dholera (NSM), SCL legacy nodes; <7 nm via partners; GaN-on-SiC, InP for lasers	G	PH1–PH2
CC-3	**OSAT/ATMP + AiP assembly**	Micron/CG Semi/Tata OSAT; RF module assembly for AiP	E	PH2
CC-4	**T&M instruments**	FR3/sub-THz signal generation, channel emulators, OTA CATR chambers, conformance labs (TEC/MTCTE/GCF)	G	PH1–PH2
CC-5	**Standards & IPR**	3GPP TSG seats (TSDSI/companies), IMT-2030 evaluations, SEP/patent strategy	E	PH1
CC-6	**Spectrum policy**	WRC-27 mid-band studies (4.4 – 4.8GHz, 7.125–8.4 GHz, 14.8 – 15.35 GHz), trial licenses, mmWave/sub-THz research bands	Policy	PH1–PH2
CC-7	**Talent pipeline**	VLSI + RF + AI-native networking curricula; industry PhDs	E	PH1
CC-8	**Testbeds**	Bharat 6G Testbed extension: FR3 radio, sub-THz link, ISAC, RIS, NTN emulator	E	PH1

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6G Ecosystem: Converting Blocks into Implementation Projects

The subsystems and IP blocks listed in the earlier sections are large in number, and many of them depend on multiple other subsystems/blocks. They are therefore grouped into implementable projects below. Each project delivers a product, a silicon-proven IP, a software release or a facility that can be used by other projects. Every project is given a target technology readiness level (TRL), a phase and a priority. This project list is a proposal for enabling a larger discussion across the ecosystem.

Proposed Project Portfolio for 6G Indigenous R&D Ecosystem Development

The table below gives the candidate projects. The project ID shows the domain to which the project belongs. BS stands for base station, UE for user equipment, CO for core, TR for transport, EN for enablers and OV for items common to more than one domain. The priority of each project is marked as P0 (High), P1 (Medium), P2 (Low). The TRL target is the level to be reached by the end of the phase shown. In line with Chapter 6, targets up to TRL 4 fall in Phase-1 (PH1), targets from TRL 5 to TRL 8 fall in Phase-2 (PH2), and commercial readiness falls in Phase-3 (PH3).

Project ID	Project	Output/ TRL Target	Phase	Priority (P0: Highest)
PRJ-OV-01	Telecom-grade Linux Distribution – Indian variant	TRL7	PH1	P1
PRJ-OV-02	RISC-V based SoC for UE / Baseband / CU	TRL7	PH1	P1
	6G UE Projects			
PRJ-UE-01	UE modem SoC: L1 IP pack → 7/6 nm tapeout	IP TRL 5→6	PH1 - PH2	P0
PRJ-UE-02	AI-PHY engine + Neural-receiver model zoo	TRL 5	PH1	P1
PRJ-UE-03	FR3/mmWave AiP RFIC + module	TRL 5	PH2	P1
PRJ-UE-04	RFFE SiP line: BAW+PA module (materials JV)	TRL 5–6	PH2 - PH3	P1
PRJ-UE-05	sub-THz UE link feasibility testbed	TRL 3	PH1	P2
PRJ-UE-06	UE L2/L3/NAS + Radio Interface Layer (RIL) software stack	Conformance-ready SW	PH1	P0
PRJ-UE-07	PQC crypto engine + eSIM lifecycle for UE	TRL 6	PH1	P1
PRJ-UE-08	Indigenous OS and market-place for UE/Smartphone	TRL7	PH1	P1
	6G Base Station Projects			
PRJ-BS-01	FR3 mMIMO O-RU (64T64R: AFE+DFE+BFIC+PA+antenna)	Product TRL 7	PH1 - PH2	P0
PRJ-BS-02	L1 accelerator PCIe card (LDPC/FFT/CH-EST/MIMO/BF)	Silicon-proven IP TRL 6	PH1 - PH2	P0
PRJ-BS-03	RAN DU/CU SW + RIC xApps (O1/E2/A1)	Interop-certified	PH1	P0
PRJ-BS-04	D-band wireless backhaul radio (110–175 GHz, 10–100 Gbps)	TRL 6	PH1 - PH2	P1
PRJ-BS-05	RIS node: metasurface + controller ASIC + mgmt	TRL 5–6	PH1 - PH2	P1
PRJ-BS-06	Photonic-aided sub-THz RU research pilot (100–300 GHz)	TRL 3–4	PH1	P2
PRJ-BS-07	NTN regenerative payload BB + optical ISL (with ISRO)	TRL 4–6	PH1 - PH3	P2
PRJ-BS-08	RU multi-ch ADC/DAC + transceiver AFE silicon	TRL 5	PH1 - PH2	P1
PRJ-BS-09	DPD/CFR IP + GaN PA module line	TRL 6	PH1 - PH2	P1
PRJ-BS-10	Indigenous 6GR Physical Layer implementation (FPGA-based)	TRL 7	PH1	P1

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Project ID	Project	Output/ TRL Target	Phase	Priority (P0: Highest)
PRJ-BS-11	Indigenous 6GR L2/L3+ Protocol Stack	TRL 7	PH1	P1
PRJ-BS-12	Open IP for all Physical/Layer-1 on FPGA	TRL3	PH1	P1
	6G Core Projects			
PRJ-CO-01	6G SBA Core NF suite (cloud-native, hardened, ODA-aligned)	Field SW TRL 8	PH1	P0
PRJ-CO-02	UPF datapath on DPU (P4, SRv6, 100–400 Gbps/site)	TRL 6	PH1 - PH2	P1
PRJ-CO-03	NWDAF/AI framework + model zoo (RAN analytics, ISAC)	TRL 6	PH1	P1
PRJ-CO-04	Sensing Function + ISAC service exposure	TRL 5	PH1 - PH2	P1
PRJ-CO-05	Ambient-IoT Core support (massive auth, no-battery security)	TRL 5	PH2	P1
PRJ-CO-06	PQC migration kit (hybrid TLS, SEPP, HSM)	TRL 7	PH1	P1
PRJ-CO-07	Digital Twin + Intent-based SMO for 6G	TRL 6	PH2	P2
PRJ-CO-08	6G voice/IMS evolution (AI codecs)	TRL 6	PH2	P2
PRJ-CO-09	Indigenous 6G Core Protocol Stack	TRL 7	PH1	P1
	6G Transport Projects			
PRJ-TR-01	224G SerDes + NPU routing silicon feasibility and silicon delivery	IP TRL 5	PH1 - PH2	P1
PRJ-TR-02	Coherent DSP feasibility and build 800G prototype	TRL 4→6	PH1 - PH3	P1
PRJ-TR-03	SiPh components (MZM/GePD/TIA/driver) + 400ZR module	TRL 5	PH1 - PH2	P1
PRJ-TR-04	Fronthaul CSR: eCPRI switch + TSN + PTP TC	Product TRL 7	PH1	P0
PRJ-TR-05	6G timing chain: PTP GM/BC <±130 ns + GNSS holdover	TRL 7	PH1	P1
PRJ-TR-06	Indigenous ROADM/WSS + amplifiers	TRL 5	PH2	P2
PRJ-TR-07	E-band to D-band ODU + antennas (indigenous)	TRL 6	PH1 - PH2	P1
PRJ-TR-08	Line-rate MACsec/IPsec/PQC transport engines	TRL 6	PH1 - PH2	P2
PRJ-TR-09	SDN controller + open YANG models (ODTN-style)	SW release	PH1	P2
	6G Enabler Projects			
PRJ-EN-01	Bharat 6G Testbed extension (FR3 + sub-THz + ISAC + RIS)	Facility	PH1	P0
PRJ-EN-02	T&M indigenization: Channel Emulator, FR3 VSG/VSA, OTA chamber	Facility	PH1 - PH2	P1
PRJ-EN-03	6G Conformance/Certification lab (TEC/MTCTE/GCF alignment)	Facility	PH2	P1
PRJ-EN-04	3GPP/ITU engagement + SEP/IPR program	Program	PH1	P0
PRJ-EN-05	Talent program: VLSI/RF/AI-networking (NRF/TTDF)	Program	PH1	P1

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Chapter 11: Further Areas to be studied

- Optical technology required for 6G Network
- NTN/HAPS
- AI Platforms, Tools and Infrastructure required for AI-Native RAN, AI-Native 6G
- EDA/Simulation Tools requirement for creating IP
- Testing & Measurement equipment/tools requirement for 6G R&D
- Pilots and Trials – Detailed Study
- 6G Testbeds – Detailed Study
- CPE not discussed at all. Have to study and update CPE implications across the document considering the interest in 5G FWA.

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Annexure A: Survey of B5G and 6G Programs around the World

The global 6G race is entering the **pre-standardization and prototype development phase (2025–2028)**. While commercial deployment is expected around **2030**, every major technology power has already established long-term national programs. Although the objectives are similar—AI-native networks, integrated sensing, sustainability, and digital sovereignty—the implementation strategies differ considerably.

Region	Flagship Program	Approx. Timeline
European Union	SNS JU / Hexa-X / Hexa-X-II	2021–2030
China	IMT-2030 (6G) Promotion Group	2019–2030
United States	Next G Alliance	2020–2030
Japan	Beyond 5G Promotion Strategy	2020–2030
South Korea	K-Network 2030 / K-6G	2021–2030
United Kingdom	UK Future Telecoms / 6G Research Programmes	2022–2030

A.1) European Union

Program

The EU's 6G strategy is centered on the **Smart Networks and Services Joint Undertaking (SNS JU)**, supported by Horizon Europe. The flagship technical programs are:

- Hexa-X (Phase I)
- Hexa-X-II (Flagship)
- SNS Stream B and Stream C projects
- 6G Flagship (Finland)
- TrialsNet
- 6G-SANDBOX
- DESIRE6G
- 6G-BRICKS

Hexa-X-II serves as the principal architectural flagship for European 6G.

Vision

- Human-centric 6G
- Sustainable networking
- AI-native network architecture
- Digital sovereignty
- Open ecosystem
- Trustworthy communications

Mission

Develop Europe's technological leadership before 3GPP Release 21 while ensuring European leadership in patents, standards, and semiconductor technologies.

Timeframe

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- 2021–2023: Hexa-X
- 2023–2025: Hexa-X-II
- 2025–2027: SNS Phase II
- 2027–2030: Large-scale trials and pre-commercial deployments

Budget

Representative investments include:

- SNS JU overall public-private investment: approximately **€900 million public funding**, matched by significant industry contributions.
- Hexa-X-II project cost: **€25.6 million**.

Key Highlights

- AI-native network architecture
- Integrated sensing and communications
- Digital twins
- Joint communication-computing
- Security by design
- Sustainability KPIs
- Open RAN evolution
- Non-terrestrial integration

Major Programs

- Hexa-X
- Hexa-X-II
- TrialsNet
- 6G-SANDBOX
- DESIRE6G
- 6G-BRICKS
- TERRAMETA
- 6G-XR

Current Status

The first flagship architecture work has been completed, with focus shifting toward validation platforms, large-scale experimentation, and contributions into early 3GPP 6G work.

Future Plans

- Large European testbeds
- AI-native RAN
- Joint sensing and communications
- NTN integration
- Early commercial demonstrations (2028–2029)

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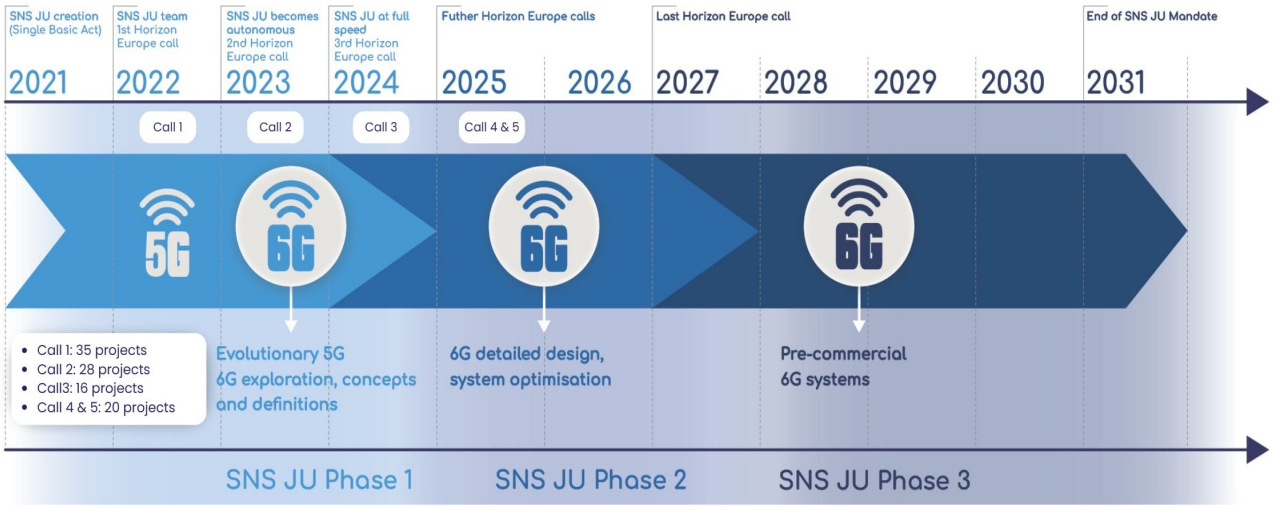

A.2) China

Program

China established the **IMT-2030 (6G) Promotion Group** in 2019 under the Ministry of Industry and Information Technology (MIIT), supported by:

- CAICT
- Major operators (China Mobile, China Telecom, China Unicom)
- Huawei
- ZTE
- Datang
- Universities and research institutes

Vision: Become the global leader in 6G standards, patents, equipment, and deployment.

Mission: Develop a complete domestic 6G ecosystem spanning chips, devices, networks, satellites, AI, and standards.

Timeframe

- 2019–2025: Fundamental research
- 2025–2027: Technology verification
- 2027–2029: Pilot deployments
- 2030: Commercial rollout

Budget

China does not publish a consolidated national budget. Public investment is distributed across:

- National Key R&D Programs
- MIIT initiatives
- Provincial funding
- Operator R&D
- State-backed industrial investment

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Independent analysts estimate total investment at **multiple billions of US dollars** through 2030.

Key Highlights

- Early 6G frequency trials
- Large patent portfolio
- AI-native air interface
- Integrated sensing
- Satellite-terrestrial integration
- Native AI
- RIS
- THz communications

Major Programs

- IMT-2030 (6G)
- National Key Laboratory projects
- China Mobile 6G Program
- Huawei 6G Research
- Purple Mountain Laboratory
- Peng Cheng Laboratory

Current Status

China is conducting technology verification and trial activities, including experimental spectrum authorizations for key 6G technologies and extensive standards contributions.

Future Plans

- Complete technology verification by 2028
- Lead ITU and 3GPP standardization
- Commercial deployment around 2030

A.3 – United States

Program

Unlike many countries, the U.S. does not operate a single centrally funded national 6G program. Instead, it coordinates through:

- Next G Alliance
- NSF
- DARPA
- DoD
- NTIA
- FCC research initiatives
- Industrial R&D

Vision: Secure leadership in next-generation wireless innovation while promoting open, interoperable, and secure networks.

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Mission: Strengthen semiconductor leadership, AI, cloud-native networking, and standards participation.

Timeframe: 2020–2030

Budget

Funding is distributed across multiple federal agencies and private-sector investments rather than a single dedicated program. Total investment reaches **multiple billions of dollars** when public and industry efforts are combined.

Key Highlights

- Open RAN
- AI-native networking
- Spectrum innovation
- Cloud-native RAN
- Edge AI
- Secure architectures

Major Programs

- Next G Alliance Roadmap
- NSF Future Networks
- DARPA wireless research
- O-RAN ecosystem programs
- Department of Defense experimentation

Current Status

Focus has shifted toward reference architectures, standards leadership, semiconductor innovation, and prototype development.

Future Plans

- Leadership in 3GPP Release 21
- AI-native RAN
- Open architectures
- Secure supply chains
- Digital twins

A.4) Japan

Program

Japan's national effort is the **Beyond 5G Promotion Strategy**, coordinated by the Ministry of Internal Affairs and Communications (MIC) and implemented largely through NICT.

Vision

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Maintain Japan's leadership in advanced communications and support Society 5.0 through Beyond 5G technologies.

Mission

Develop foundational technologies, strengthen industrial competitiveness, and accelerate international standardization.

Timeframe

2020–2030, with dedicated "Leading Activities" followed by "Activities Acceleration" phases.

Budget

Japan established a **Beyond 5G (6G) Fund** administered by NICT, with a scale of roughly **¥70 billion** for long-term R&D programs, complemented by additional government and industrial investments. The fund continues to support new competitive research calls.

Key Highlights

- Society 5.0 integration
- Optical-wireless convergence
- AI-native networking
- Satellite integration
- Semiconductor innovation

International collaboration

Major Programs

- Beyond 5G Fund
- Beyond 5G R&D Promotion Project
- Strategic commercialization programs
- International joint research (including UK collaborations)

Current Status

Japan continues to fund new research calls covering enabling technologies, commercialization, spectrum research, and international partnerships.

Future Plans

- Commercial demonstrations by 2028–2029
- Expanded international collaborations
- Leadership in optical networking and AI integration

A.5 – South Korea

Program

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South Korea's 6G strategy is led by the Ministry of Science and ICT through the **K-Network 2030** initiative, supported by ETRI, Samsung, LG Electronics, SK Telecom, KT, and LG Uplus.

Vision: Become the first country to commercialize advanced 6G technologies while strengthening domestic ICT manufacturing.

Mission: Develop indigenous 6G technologies, strengthen export competitiveness, and secure leadership in standards and patents.

Timeframe: 2021–2030

Budget: Government announcements indicate investments of approximately KRW 600–650 billion for core 6G R&D through the decade, supplemented by substantial private-sector investment.

Key Highlights

- AI-native networking
- Digital twins
- THz radio
- RIS
- Energy-efficient networking
- Semiconductor leadership
- Open RAN

Major Programs

- K-Network 2030
- ETRI 6G Research
- Samsung 6G Program
- National THz initiatives
- SK Telecom, ATHENA

Current Status

South Korea is advancing component technologies, prototype systems, and international standards participation.

Future Plans

- Large-scale field trials
- Semiconductor leadership
- AI-native infrastructure
- Commercial deployment around 2030

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A.6 – United Kingdom

Program

The UK's activities are coordinated through the **Future Telecoms Programme**, DSIT, UKRI, EPSRC, and university-led 6G research centers.

Vision: Build a secure, diverse, and innovative telecom ecosystem while developing sovereign capabilities in next-generation communications.

Mission: Support research excellence, strengthen telecom supply chains, and increase participation in international standards.

Timeframe: 2022–2030

Budget

Funding spans multiple initiatives, including the Future Telecoms Programme and UKRI research investments, amounting to **hundreds of millions of pounds** across telecom diversification, Open RAN, and 6G-related research.

Key Highlights

- Telecom diversification
- Open RAN
- AI-native networking
- Security
- Quantum networking research
- International collaboration

Major Programs

- Future Telecoms Programme
- UK Telecoms Innovation Network (UKTIN)
- 6G Research Centres
- University-led testbeds (JOINER: Joint Open Infrastructure for Networks Research)
- International partnerships with Japan and Europe

Current Status

The UK is emphasizing research infrastructure, security, Open RAN, and collaborative international projects.

Future Plans

- National 6G testbeds
- Stronger university-industry collaboration
- Leadership in secure telecom architectures
- Expanded participation in global standardization

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Contributions and Acknowledgments

This whitepaper was prepared by the **B6GA Technology Working Group**. The authors gratefully acknowledge all working group members for their technical leadership, analytical contributions, and dedication throughout the drafting process.

We also extend our sincere appreciation to the external reviewers and domain experts whose rigorous evaluation and strategic feedback significantly enhanced the quality, depth, and precision of this publication.

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