APEX STANDARDS

Lessons from 4G and 5G – Reflections on the 6G Workshop in Incheon

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Reflecting on the past illuminates the path to the future. In the spirit of ancient philosophy, understanding our history—its achievements, missteps, and hard won lessons—empowers us to chart a clearer, more practical strategy. The evolution from 5G to 6G embodies this approach: by learning from the ambitious yet often unwieldy visions of early 5G work, the industry is now shifting toward a network architecture that is simpler, more efficient, and more cost effective.

Historical Reflections and Lessons Learned

A decade ago, the "RAN Workshop on 5G" held in Phoenix, Arizona, United States, on September 17–18, 2015, gathered 550 delegates and received 90 contributions, primarily focused on Radio Access Network (RAN) technologies. Dino Flore, who was Chairman of RAN at that time, captured the era's mission succinctly, highlighting the formidable challenges posed by rapidly evolving mobile communications. The exponential growth of mobile broadband and proliferation of diverse connected devices demanded innovative radio technologies. Discussions emphasized ambitious technical innovations, such as millimeter wave (mmWave) frequencies, massive MIMO systems, and novel multiple access techniques to address emerging needs. Concurrently, the role of ongoing LTE evolution as a foundation for 5G was widely anticipated, promising a robust core network and smooth interworking capabilities.

During those days, the industry sought flexibility through numerous technical options, including redundant fallback methods for voice and diverse IoT connectivity schemes. Yet this flexibility quickly revealed itself as a double-edged sword, substantially increasing complexity and driving up capital expenditure (CapEx) and operational expenditure (OpEx). Recognizing these consequences, industry consensus gradually shifted towards reducing the Total Cost of Ownership (TCO) and improving Return on Investment (ROI).

From 5G Complexity to 6G Simplicity

Fast forward to March 10–11, 2025, when the 6G Workshop convened in Incheon, Korea. Unlike the RAN-centric Phoenix event, Incheon integrated RAN, Service & System Aspects (SA), and Core Network and Terminals (CT), drawing 748 in-person and 948 online participants with 230 contributions. Discussions covered strategic, financial, and operational dimensions called by operators—such as from Deutsche Telekom—for measurable gains in spectrum efficiency, energy efficiency, security, privacy, and user-centric services.

The contrast was clear. While Phoenix had fewer TDocs, it featured diverse thinking and broad excitement, with companies eager to explore any added value or new applications 5G could bring; Incheon saw more contributions but a more converged mindset. Participants focused on narrowing the scope of 6G, introducing more constraints around architecture and use cases—shifting toward clarity and control.

Lessons from 5G deployments inform this thinking. The transition from 4G to 5G yielded modest commercial gains, as real-world demand for very high data rates or very low latency was limited. Using 5G Non-Standalone (NSA) architecture allowed quick deployment and short-term benefits by leveraging existing 4G structures. However, the shift to 5G Standalone (SA) led to unexpected complexity and costs that became long-term challenges. These lessons highlight the need for well-thought-out yet simpler designs in 6G.

In RAN, early 5G efforts ambitiously explored high frequencies, including the millimeter wave and even terahertz (THz) ranges, attracted by their potential for extremely high data rates. However, these explorations quickly faced substantial propagation losses, challenging hardware limitations, complex beamforming requirements, and cost barriers. Although the 5G Workshop initially sparked considerable interest in mmWave technologies and advanced network automation, it was recognized that these approaches were going to be commercially impractical for a while. By the time of the 6G Workshop, the industry had formed a new, pragmatic consensus, focusing specifically on frequency bands above 6–7 GHz. This strategic shift aimed to deliver meaningful performance enhancements through technologies like ▸

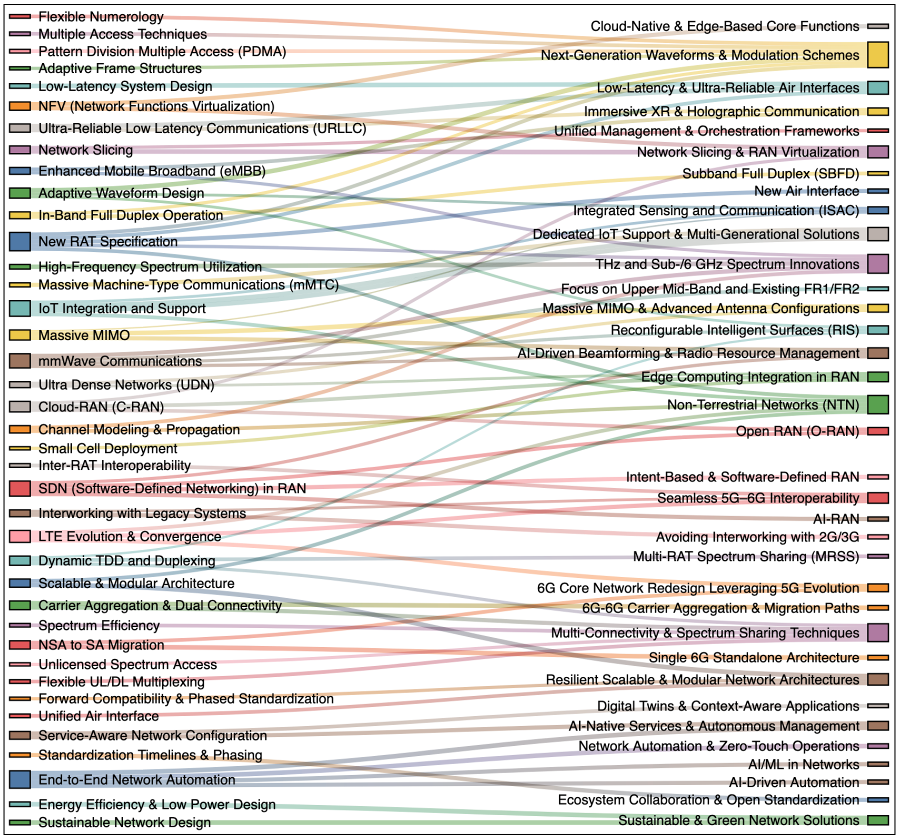

CHART depicts how terminology and concepts evolved from the diverse expectations of the 5G Workshop (left slabs) into the more refined themes of the 6G Workshop (right slabs), mapped through a ten-year backward TDoc citation analysis tracing topic progression. For example, Adaptive Waveform Design, Flexible Numerology, and Adaptive Frame Structures in 5G have converged into Next-Generation Waveforms & Modulation Schemes in 6G. URLLC has evolved into Low-Latency & Ultra-Reliable Air Interfaces; XR in 6G is built on 5G's URLLC and eMBB, reflecting the shift toward immersive communication. mmWave, once a hot topic in 5G, now inspires THz and Sub-6 GHz research for high data rates, AI-driven beamforming for optimization, and RIS for signal control and mmWave loss mitigation in 6G. 5G's ideas in End-to-End Network Automation has transitioned into AI-Native Services & Autonomous Management, and Zero-Touch Operations in 6G. NTN extends LTE Evolution & Convergence, which provided a foundation for satellite communications beyond coverage by integrating 5G's Channel Modeling & Propagation for satellite and aerial reliability, New RAT Specification for terrestrial integration, and Scalable & Modular Architecture for flexible deployment and spectrum use—key elements that predated NTN-specific standardization, with the first NTN Work Item introduced in RP-81 in September 2018. Meanwhile, transitioning from 5G's in-band full duplex to flexible duplex took years of 3GPP meetings to establish a viable niche, with sub-band full duplex (SBFD) now emerging as the most widely accepted approach in 6G. Sustainability has also evolved—5G's Energy Efficiency & Low Power Design and Sustainable Network topics have merged into the umbrella concept under Green Network Solutions in 6G. These keywords support TDoc reference searches, providing insights into historical trends and future directions, while guiding key studies and ensuring relevant aspects remain in view.

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Category	Conbributors
Companies that contributed TDoc to both the 5G and 6G Workshops	AT&T, CATT, China Mobile, China Telecom, China Unicom, CAICT/CATR **(CN)**, Deutsche Telekom, Ericsson, ETRI **(KR)**, Fraunhofer HHI/IIS **(DE)**, Fujitsu, Huawei, III (TW), Intel, InterDigital, ITRI (TW), KDDI, KPN, KT, Lenovo, LGE, MediaTek, NEC, Nokia, NTT Docomo, Oppo, Orange, Panasonic, Qualcomm, Rakuten, Samsung, Sharp, SK Telecom, SoftBank, T-Mobile/Sprint, Telefónica, Vodafone, ZTE
Exclusive to 5G Workshop	Alcatel-Lucent, Anite, ASTRI, ASUS, BlackBerry, Broadcom, Coolpad, Dish, General Motors, Hitachi, Mitsubishi, Motorola, National Instruments, NGMN, Potevio, Sequans, Small Cell Forum, Sumitomo, TAICS (TW), TCL, TeliaSonera, TSDSI
Exclusive to 6G Workshop	5G MAG, Aalyria, BBC, BMW, Bosch, Bouygues, BT, Cap Gemini, China Broadcast Network **(CBN CN)**, CEWiT **(IN)**, Cisco, Cohere, COAI, China Satellite Network **(CSCN CN)**, DeepSig, DSIT **(UK)**, Echostar, ESA **(EU)**, Eurecom **(FR)**, Eutelsat, EUTC, FAI, FBI-OTD **(US)**, FiberCop, FirstNet **(US)**, Futurewei, Google, GSOA, Hanbat Univ **(KR)**, Hispasat, IISc Bangalore **(IN)**, IIT Kanpur/Hyderabad/Madras **(IN)**, Intelsat, Iridium, iDirect, IRT Saint Exupery, ISSDU, JSAT, JHU/APL **(US)**, Juniper, KAIST **(KR)**, Keysight, Kookmin Univ **(KR)**, Kyocera, Leonardo, LG Uplus, Lockheed Martin, Meta, MITRE **(US)**, National Spectrum Consortium, NICT **(JP)**, Novamint, Nvidia, Omnispace, one6G, Pengcheng Lab **(CN)**, Philips, Purple Mountain Lab **(PML CN)**, Rohde-Schwarz, Sateliot, Semtech, SES, Siemens, JSAT, SNT Luxembourg, Spreadtrum, Telus, Telstra, Tejas, Thales, Tiami, Toyota, TNO, TTP, UNISOC, VIAVI, Vivo, Volkswagen, Xiaomi

TABLE categorizes contributors into three groups: those submitting TDocs to both the 5G and 6G Workshops, demonstrating consistent 3GPP commitment across generations; those contributing only to 5G, indicating a fading presence; and those contributing exclusively to 6G, representing new entrants. Each group is sorted alphabetically by company name. This classification highlights the shifting industrial focus from 5G to 6G; for example, the "Exclusive to 6G Workshop" group now predominantly features satellite/NTN companies, followed by IoT, automotive, and academic institutions. For entities such as government agencies, universities, national research institutes, or major federal contractors (directly state-owned or government-funded), the associated **(country/region code)** is provided. CAICT, previously known as CATR in 5G, is treated as one entity; T-Mobile, which merged with Sprint in 2020, is also considered a single entity. This table reflects only direct TDoc contributions to the 5G/6G Workshops; related contributions (e.g., delegate attendance, background discussions, TSG/WG contributions and email reflectors) are not included. Further research is recommended to capture a complete picture of the transformation from 5G to 6G.

massive MIMO and advanced beamforming while carefully managing implementation complexities and costs, thus aligning realistically with TCO goals. Similarly, lessons from LTE-derived features—particularly redundant fallback mechanisms and overly complex IoT schemes—prompted selective integration of only financially and technically sound elements.

Technological Convergence & Strategic Shifts

The industry began transitioning towards cloud-native core networks, further extended into AI-native and energy-native architectures. Recognizing the operational advantages of artificial intelligence, operators implicitly acknowledged AI as the foundation for simplified, maintainable network architectures. AI has evolved from a speculative concept in the 5G era into a crucial centerpiece of modern network management. At the 6G Workshop, experts demonstrated how AI now automates key tasks such as dynamic resource allocation, proactive fault detection, anomaly prediction, network optimization, and real-time reconfiguration, thereby reducing manual intervention, minimizing downtime, and lowering operational expenses. At the same time, energy efficiency emerged as a challenge, as the computational demands of AI-driven solutions required careful balancing to prevent unsustainable energy consumption. The integration of computing with communication, known as Compute-as-a-Service, revealed substantial business potential. By processing data at the network edge, operators can effectively reduce latency, offload intensive processing tasks from centralized cores, and open new revenue streams from innovative applications such as real-time analytics, immersive augmented reality, and other advanced edge services.

Another strategic shift is the integration of terrestrial networks (TN) and non-terrestrial networks (NTN), enabling seamless TN-NTN connectivity. While early 5G proposals focused primarily on terrestrial connectivity and densification through small cells, the 6G vision now embraces the integration of satellite systems and high-altitude platforms to extend coverage to remote and underserved areas. A notable milestone in this journey occurred during the same meeting week after the 6G Workshop, when IRIS[2] landed in the TSG#107 Plenary. The joint contribution from the European Space Agency (ESA) and a dozen more companies, led by Dr. Stefano Cioni and funded by the European Commission, ESA, and SpaceRise, presented the first fully-fledged 5G NR NTN multi-orbit satellite communications system for broadband services in the Ku- and Ka-bands, demonstrating interoperability with terrestrial networks and a future-proof evolution of the entire system. Consequently, this expanded coverage not only creates new revenue opportunities by tapping into previously unserved markets but also leverages economies of scale to lower the cost per user.

Integrated Sensing and Communication (ISAC) remains highly motivating for the scientific community. While early discussions in 2015 introduced inception ideas—such as dual-purpose radio links, IoT integration use cases for sensing, and potential waveform optimizations for sensing traffic efficiency—the 6G vision has matured considerably. It now prioritizes practical, scalable applications that deliver real business value. By merging data transmission with environmental sensing—capturing detailed information on distances, object movements, and ambient conditions—the network offers enhanced capabilities without incurring substantial extra costs, thereby further contributing to TCO reduction.

Unified Standardization & Reducing TCO

A recurring theme throughout this evolution is the imperative to reduce complexity. In the early 5G era, the proliferation of technical options—often introduced as redundant measures to cover all possible scenarios—created networks that were challenging to standardize and manage. Industry voices in Phoenix acknowledged that while multiple options could provide flexibility, they increased costs and delayed deployments. By 2025, consensus firmly shifted toward unified standards that define a single method per network function, thereby simplifying equipment design, reducing certification time, and enhancing interoperability. The emphasis on a unified, stable technological roadmap embodies the core spirit and value of standardization. A single standard family minimizes risks associated with fragmented technology choices, optimizes resource allocation, simplifies equipment design, reduces certification time, and mitigates vendor lock-in—collectively decreasing CapEx and OpEx. This approach provides clear guidance to the industry, reduces business risks associated with selecting incorrect technology paths, and allows for efficient allocation of R&D resources, ultimately fostering sustained innovation and deployment. Such strategic consolidation not only streamlines network management but also contributes to the TCO goals.

Security, resilience, and Quality of Service (QoS) remain essential, yet networks now prioritize superior Quality of Experience (QoE)—especially for advanced Extended Reality and Media (XRM) services and beyond—recognizing that user perception ultimately defines service value. While baseline security and reliability sufficed in the 5G era, the increasing sophistication and prevalence of cyber threats now demand advanced measures such as robust encryption, rigorous threat monitoring, and comprehensive incident response frameworks. Investments in resilient network designs—including redundant systems, proactive fault management, and intelligent self-healing capabilities—are essential to prevent costly outages and disruptions. These enhanced defenses not only safeguard network reliability but also protect revenue streams, ensure compliance with stringent privacy regulations, and sustain user trust, thereby underpinning the industry's vision for trustworthy and secure 6G services.

Historical experiences from disruptive business strategies offer valuable lessons and remind us that during standardization, market adoption can be accelerated through intense competition and a willingness to learn from every step of the innovation cycle. During the early period of 5G commercialization, intense global competition emerged among leading operators—including Japan's NTT DoCoMo, China Mobile, and Korean Telecom (KT)—to achieve the world's first commercial 5G deployment. The process of standardization, fueled by this fierce competition, demonstrated that rapid market adoption is possible when strategic risks are taken and lessons are learned along the way.

KT notably proposed an early drop of the initial 5G release using Non-Standalone (NSA) architecture—a proposal subsequently accepted by 3GPP. This strategic decision enabled KT to launch 5G services as early as April 2019, way ahead of global counterparts. While KT's early initiative propelled rapid commercialization, its gradual evolution from NSA to Standalone (SA) later revealed unanticipated complexity and deployment challenges, offering valuable lessons in hindsight ▸

that point to the need for a more streamlined, integrated approach in the upcoming 6G era.

Further back in history, during the early LTE era, commercialization began slowly due to challenges such as spectrum fragmentation, limited LTE-capable devices, and significant infrastructure investments. In December 2009, TeliaSonera launched the first commercial LTE network in Stockholm and Oslo, though rollouts remained slow into 2010. Widespread consumer demand did not materialize until mid-2010, when Apple partnered with AT&T in the United States to introduce a flat-rate unlimited data package. The 3G GSM network struggled to manage the resulting traffic explosion, giving operators strong reasons to invest in upgrading network infrastructure with new LTE Base Stations (BS). As higher data rates were unlocked, rapid rollouts of LTE-compatible User Equipments (UE) followed, which in turn spurred the development of new apps, services, and use cases—a cycle of innovation that reshaped the mobile communications landscape. Apple's business focus on enhancing consumer value influenced both commercial deployments and 3GPP standardization, while the rise of capable smartphones, sparked by the iPhone, further drove data demand. In contrast, 5G adoption has proactively anticipated market potential, even as consumer demand has yet to fully catch up. These reflections were echoed during 6G Workshop discussions, where increased awareness of TCO now informs various aspects of RAN innovation.

These examples illustrate how business innovations, though not solely driven by technological advancements, can inspire and even precede breakthroughs that reshape industry dynamics. Every step in standardization—whether imparting critical lessons or delivering immediate success—fuels an ongoing cycle of innovation. By embracing competition and learning from both successes and challenges, the industry can refine its approach, optimize resources, and accelerate market adoption, ensuring a forward-thinking foundation for future generations.

Forecasting an Intelligent 6G Future

The transition from 5G to 6G brings implications and influences corporate R&D, academia's research focus, governmental policymaking, and intellectual property (IPR) strategies, requiring thoughtful reflection and realignment across sectors.

Corporate R&D teams must revisit their investment strategies to match realistic market-driven innovations. Companies should focus on consumer-centric technologies that offer clear value, affordability, and ease of deployment. Practical examples include scalable XR solutions for education and training, reliable telemedicine systems for healthcare, accessible interactive media platforms, and innovations aligned with spectrum provisions anticipated by 6G. Important considerations include: How can companies meet user needs without excessive complexity? What approaches can enhance collaboration and speed up innovation without sacrificing sustainability?

Academia must prepare students for these new realities. Universities should adjust curricula to incorporate simplified network architectures, ethical AI development, and for example, emerging ISAC applications. Educational programs need to emphasize practical problem-solving skills, ensuring graduates understand market constraints alongside technical knowledge. Key questions include: How can academia align research with industry transformation? What educational models prepare students to meet real-world market and ethical challenges?

Government policymakers and regulatory authorities face the task of adapting frameworks to support simpler yet diverse network services. Regulators must create policies that ensure efficient spectrum management, security, and fair access, balancing consumer protection with incentives for innovation. Important questions for policymakers include: How can regulations remain flexible enough to support technology advances while safeguarding public interests? What proactive measures can regulators adopt to manage cybersecurity and privacy effectively?

In IPR and licensing, 6G's consumer-driven nature presents challenges. Patent strategies must focus on practical, market-driven technologies. Licensing models are evolving toward affordability and cross-industry collaboration, ensuring fair value sharing and long-term innovation. 3GPP mandatory and optional feature selection and prioritization will shape claim chart strategies, as well as, Standard Essential Patent (SEP) invention and declaration, subsequently influencing licensing, enforcement, and monetization. Revisiting cross-licensing agreements can mitigate litigation risks and facilitate mutual access to essential technologies. Key questions remain: How can licensing frameworks drive cross-sector innovation? What models ensure fair monetization and sustainable innovation in SEP ecosystems?

Extensive trials and real-world validation from 5G deployments will shape 6G standards, while broader discussions continue—especially on future services users have yet to articulate. Steve Jobs captured this essence, stating, "Innovation distinguishes between a leader and a follower," and, "One can't just ask customers what they want… By the time you get it built, they'll want something new." This highlights the dynamic interplay between technological advancement and market demand, raising fundamental questions:

- *Should technology push forward, expecting demand to emerge, as in the early years of 5G?*
- *Should innovation wait for clear consumer needs, prioritizing cost-effectiveness, as is now widely considered in the early days of 6G?*
- *Or is there a way to strike the right balance?*

Advancements in computing, sensing, and communication, shaped quietly yet profoundly by emerging user behaviors and novel possibilities, will organically drive technological progress. The industry, grounded in realism, simplicity, and thoughtful progression, sees 6G as a natural evolution—building incrementally on 4G LTE and 5G while introducing transformative capabilities that users will come to see as indispensable.

Sustained dialogue and collaboration across the ecosystem remain essential—not just to refine existing technology but to uncover hidden potential in everyday experiences.

6G commercialization is projected for 2029, based on history. The world awaits to see how refined standardization will redefine innovation priorities, cost structures, and market readiness. With this in mind, delegates in Incheon half-jokingly wondered how our choices today might be viewed at the 7G Workshop in 2035, also based on history.

As Zen teaches, 'See a mountain, and it is. Question it, and it fades. Understand, and it remains.'

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