NOKIA

Transforming the 6G vision to action

6G

Architecting tomorrow

Contents

Executive summary

6G will support the vast and growing device ecosystem and harness and accelerate the power of AI along with many other emerging technologies—besides addressing the increasing need for network capacity. 6G will realize the next level of digital inclusion by offering greater accessibility, affordability and consumability. It will be sustainable and “Green” by design, trustworthy and highly secure. In this white paper, we outline Nokia’s views for the 6G era, how the key emerging technologies enable this vision, and what to focus on for 6G day one to ensure it paves the way for commercial success and establishes a firm foundation for the future.

Introduction

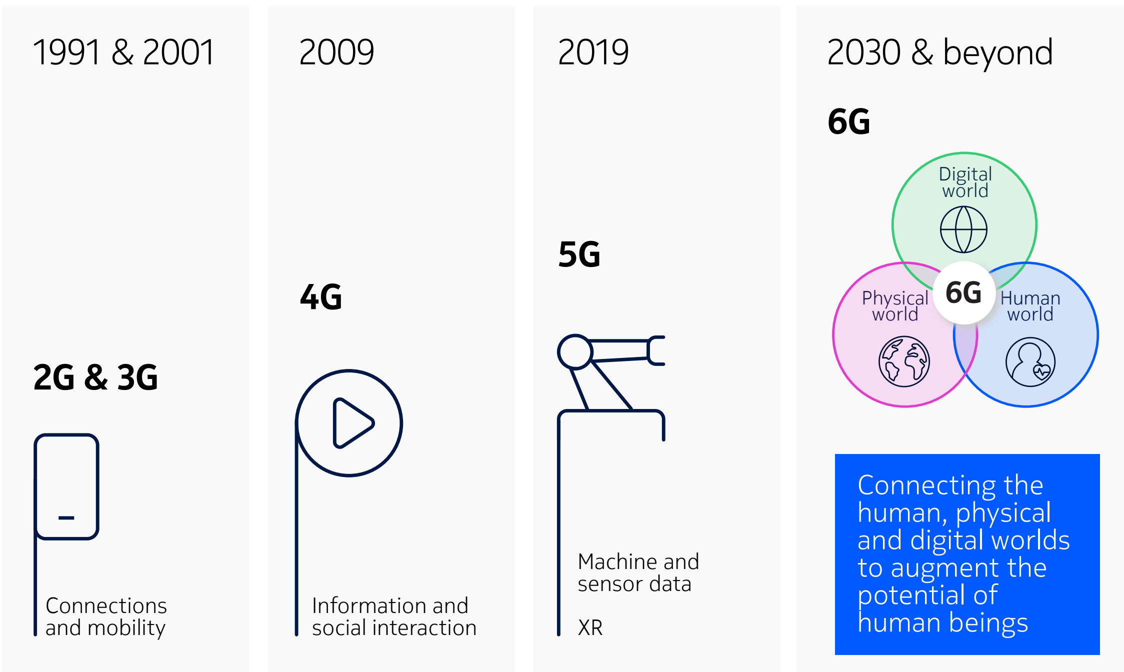
At Nokia, we believe the relationship between cellular technology, society and industry is evolving to the point that, by the mid-2030s, the next-generation mobile broadband network will need to do much more than simply provide increased bandwidth. Many of the use cases not yet realized for 5G in fields as diverse as industry, transportation and personal health, although at present slow to be adopted, will be putting new and different demands on the network and the data carried across it by the end of this decade. Furthermore, end-user devices will evolve beyond the smartphone to create new experiences with new communications requirements. The network will have to meet these new demands while using much less energy and including more individuals and communities within its digital reach. This will be critical for achieving a secure, adaptable, and sustainable future.

To counter the “more-of-the-same, bandwidth argument”, we must address how 6G will create true value to society, verticals, as well as new ways for monetization in the cellular industry. This requires a clear perspective on where 6G should focus on day one to ensure that it addresses immediate needs to ensure a healthy ecosystem from the beginning while simultaneously creating a robust platform for the subsequent 10+ years. In this paper, we outline how to realize the 6G vision, what to focus on to arrive at a robust and extensible day one 6G baseline, and which key technology enablers are needed.

The 6G vision

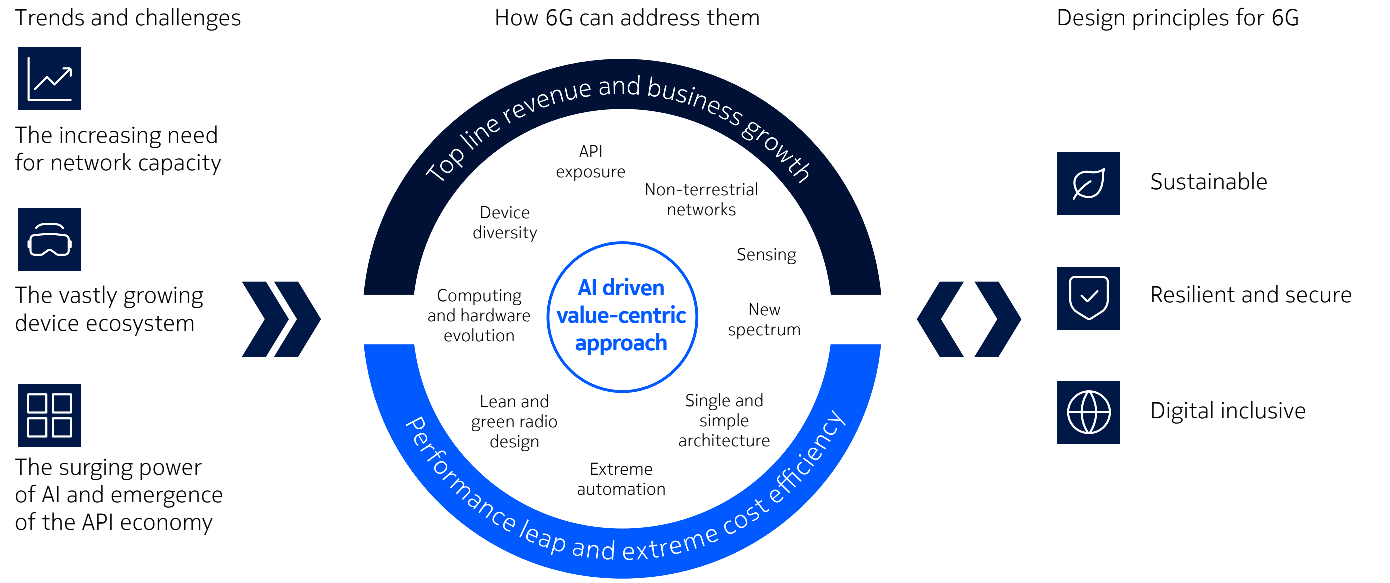
Over the past 30 years, cellular communications have brought unprecedented benefits to humankind. 2G and 3G unleashed the potential of mobility and connectivity. 4G gave us greater access to information and social engagement. 5G enables the enterprise and extended reality (XR) experiences. In 6G, we believe the fusion of physical, digital and human worlds will allow us to interact with the digital and physical space more intuitively, transforming the way we live and work.

Figure 1. The evolution to 6G



The full realization of this vision will come in stages. For 6G day one, the priority will be to meet growing user expectations and demand and to ensure cost-effective migration. It will focus on infrastructure reuse and extensibility to properly address the increasing data traffic, accommodate greater diversity of devices, and support the surging power of AI and the emergence of the API economy. In addition to the traditional key performance indicators (KPIs) such as throughput and latency, key value drivers for the 6G era will include sustainability, trustworthiness and digital inclusion.

Figure 2. High-level summary of value-centric approach



Humankind is increasingly aware and committed to conserving the planet, which drives the green agenda for the future. Key goals of sustainability, including energy efficiency and circular economy, are built into the 6G design process. Every aspect of 6G design, implementation and operation will be scrutinized to maximize sustainability. In addition, many new technologies and services enabled by 6G, such as large-scale environmental sensing, advanced analytics and power saving, will contribute to a greener planet. AI/ML will be essential to achieve the 6G vision in all of its dimensions.

In a world where all aspects of life are moving into the digital space, security and privacy is of paramount importance. Native state-of-the-art security and privacy is not an add-on feature of 6G; it is a fundamental must-have — especially as cellular technology continues to expand beyond the consumer space into industrial and critical infrastructure roles. With the proliferation of billions of devices and sensors the attack surface grows larger every day. And the introduction of quantum computing raises the threat of malicious attacks to new levels. At the same time, open interfaces and architectural disaggregation, the mingling of open-source and multivendor software, and multi-stakeholder supply chains introduce threat vectors from new dimensions. We need a comprehensive set of security and resilience technology enablers for the 6G era and new principles of cyber-resilience.

Digital inclusion entails making connectivity accessible, affordable, secure, and focused on real commercial needs, optimized for rapid deployment. The delivery of cost-effective 6G solutions combining terrestrial and non-terrestrial access networks will enable ubiquitous coverage and help make global connectivity a reality. 6G aims to enhance performance where it makes a tangible difference while being affordable for all key stakeholders.

In addition to being centered around the values sustainability, trustworthiness, and digital inclusion, the 6G design should follow a data-driven approach to harness the transformational nature of AI for 6G. It needs to address both top line revenue and business growth and extreme cost-efficiency. For instance, there are emerging services expected in the next decade including XR, sensing, smart factories and cities, robots/cobots/sobots, and digital twins. It is impossible to foresee at what speed these visionary services will materialize. Future networks will need to adapt to and enable the performance that these different services will require.

This point touches on device capabilities, the evolution of which impacts the kind of services that we consume and how we consume them. Already today we see many different types of devices. New emerging services like XR are expected to grow the variety of device types even further. 5G is inherently designed as one-size-fits all for enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low-latency communications (URLLC) in mind. Thus, supporting these different devices has triggered a number of rather complex tailor-made solutions to enable different device form-factors, sizes and cost and complexity optimizations. 6G will need to natively support the ever-growing variety of devices using a modular design to avoid technology fragmentation and a highly complex system.

With 6G we see the potential need for several hundreds of MHz of new spectrum for each operator in the 6-15 GHz range. This may just about address the needs over a new decade — assuming a leap in radio technology performance — but only if coupled with sustainable and affordable macro deployments. As a critical deployment baseline, operators need to be able to deploy 6G for new higher band spectrum utilizing the existing macro site grid and achieve comparable coverage to 5G mid-band. This will only be possible with more extreme MIMO configurations that expand capacity beyond what 5G is capable of.

In the continuous quest for automation, simplification and utilization of network and data assets, both 5G and 6G can be further enhanced through APIs allowing network programmability and exposure of network and data and service capabilities. This will not only drive increased automation but potentially enable a third-party application developer community to build value around the information extracted from the network, for bottom-line performance leaps and extreme cost efficiency.

For the benefits of 6G to become widely and rapidly available, it is important to have a simple architecture and a single step migration towards 6G. To this end we believe that a standalone 6G system with a migration scheme built around highly efficient and dynamic sharing of spectrum across 5G and 6G is the best middle ground between re-using existing network assets and driving 6G uptake. To get there, the cellular industry baseline, which currently uses predominantly LTE-based 5G non-standalone (NSA), must accelerate 5G standalone (SA) deployments. This upgrade will be needed anyway as NSA deployments will reach their capacity limit and end of life for EPC over the coming years.

In essence, 6G is the sweet spot where technology push and commercial pull of the 2030s meet. Let's dive into how exactly 6G will meet this sweet spot through a variety of enablers and technology elements.

6G day one focus

Given the 6G vision, we now describe our view of what should be supported in the first release of 6G – we call this 6G day one. A robust and extensible day one 6G baseline is of paramount importance for the initial success of 6G, as well as for its forthcoming releases to continue offering value.

Affordable and super-efficient 6G rollout

The 6G day one rollout must leverage earlier 5G investments, making it affordable with one single 6G architecture and reusing cloud-native 5G core network functions where possible with critical extensions. Initial roll-out and deployment of 6G must be highly efficient. AI will play an important role in increasing efficiency.

6G day one will be ready for rollout on existing macro-cell sites, including support for both traditional distributed RAN deployments as well as supporting cloud RAN cases. Multi-RAT Spectrum Sharing (MRSS) will ensure seamless transition between 5G and 6G for the existing bands without compromising network performance [3]. 6G Carrier Aggregation is then used to combine coverage and capacity. Dual connectivity may be needed to achieve the same combination for non-collocated 6G sites.

Next-generation mobile broadband (MBB) services

6G day one should support the next generation (NextGen) of affordable enhanced mobile broadband with much better performance than 5G. This is important as NextGen MBB is estimated to be the dominant traffic in 2030 when 6G is launched. Improved NextGen-MBB performance comes from the systems, architecture, and radio technology enablers as outlined in the previous section. The International Telecommunication Union has recently published its framework for the initial requirements for IMT-2030 [17], where higher overall spectral efficiency, user-experienced data rates of 500 Mbps, and more will define NextGen-MBB requirements.

Enhanced fixed wireless access

Excellent support for fixed wireless access (FWA) is also a priority for 6G day one. FWA has been one of the fastest-growing use cases for 5G, and the traffic volume from FWA is expected to account for up to one-third of the network traffic volume of 6G. FWA builds on NextGen-MBB and has several characteristics that can be explored for both leaner operation and higher performance. FWA customer premises equipment (CPE) has a larger form factor than a smartphone and is connected to a power outlet. A CPE is stationary, and the location of the CPE can be optimized for the network layout.

The new mid-band from 6-15 GHz is ideal for high-capacity FWA as carrier bandwidth (BW) is up to 400 MHz. More antenna ports can be implemented on both the network and the CPE to increase capacity and compensate for higher path loss than at lower frequency bands. By using situational awareness sensing at the CPE, the uplink transmit power can be increased without health issue violation. The fixed location of a CPE omits mobility requirements and the numerous link adaptation and repetition features in 5G can be made leaner, thus reducing the signaling overhead and latency. The target of FWA in 6G is to achieve data rates and latency performance competitive to fiber-based broadband solutions and benefit from the much simpler and more flexible service installation. Figure 3 shows the relative cell edge and mean user throughput at 7 GHz and 13 GHz compared to 3.5 GHz carrier frequency. At 7 GHz the FWA CPE throughput is significantly increased both at the cell edge and mean by a factor of 2.3-3.6 and 4.4-5.1, depending on inter-site distance (ISD). At 13 GHz the FWA performance is still superior to 3.5 GHz, except for the cell edge throughput at an ISD of 500 m; here a minor throughput loss to 0.81 is observed.

Figure 3. Simulated cell edge and mean user throughput @ 7GHz and 13GHz compared to 3.5GHz.

DL throughput relative to 3.5 GHz*	Cell Edge throughput				Mean user throughput			
	500m ISD		350m ISD		500m ISD		350m ISD	
	UE	CPE	UE	CPE	UE	CPE	UE	CPE
7 GHz** vs 3.5 GHz	1.2x	2.3x	2.5x	3.6x	3.2x	4.4x	3.8x	5.1x
13 GHz va 3.5 GHz	0.35x	0.81x	1.2x	2.0x	2.0x	3.2x	3.0x	4.2x
* 85 dBm/100 MHz DL EIRP; UE 8RX OMNI and CPE 16RX DIR antennas; BS 256 AE, 64 TRX ** 82 dBm/100 MHz DL EIRP; UE 4RX OMNI and CPE 4RX DIR antennas; BS: 1024 AE; 256 TRX					80% indoor; full buffer; 10UEs/cell; DSUDD (no data on 'S') 50/50 High/Low Pen.Loss model; WB ZF - GoB Type 1			

NextGen XR

The evolution of the family of XR services and the corresponding mobile communication solutions started in 5G-Advanced are expected to take another leap in performance for 6G day one. It will provide even better support for high-data-rate real-time applications with bound latency constraints everywhere when needed. It will build on the foundation of enablers introduced in 5G-Advanced (being led by Nokia) as outlined in [1], and work in concert with the Nokia-developed and award-winning Low Latency, Low Loss, Scalable throughput (L4S) scheme, which boosts variable rate service over the internet [16]. This underlines Nokia's compelling XR value proposition of real-time XR multimedia [12], which provides truly immersive, real-time experiences that can redefine how people work together and enables new revenue sources for operators. It leverages ground-breaking 360° video and spatial 3D audio to, for instance, improve industrial productivity, enhance employee safety and wellbeing, and initiate a more sustainable working world.

One of the new building blocks to achieve this is the introduction of a new resource type for "adaptive QoS" that defines QoS flow with a soft upper bound and target values. It enables the RAN to autonomously upgrade and downgrade QoS metrics within the given range to work in collaboration with the application to achieve a higher quality of experience (QoE) [19]. The NextGen XR will essentially offer further fusion of the physical and digital worlds and open numerous new services, including futuristic use cases not on our radar today.

IoT use cases

In addition to NextGen MBB, FWA, and XR, 6G day one should naturally also support baseline services like public safety, messaging services, and voice. Also, hooks for low-power wide area (LPWA) and reduced capability (RedCap) devices will be important. As will be explained in greater details in the next Chapter, a modular 6G RAN protocol design will be key to facilitate such IoT use cases.

Satellite-enabled 6G

We also foresee that non-terrestrial network (NTN) support will be part of the 6G day one design. This includes NTN connectivity for 6G LPWA/RedCap devices as well as smartphones. This ensures that 6G service continuity will not be limited to regions with cellular coverage from terrestrial network (TN) base stations. This shall come with loose integration between TN and NTN, as well as TN spectrum reuse for NTN under control of the terrestrial operator. NTN support for 6G will help boost accessibility to affordable digital access and make global connectivity a reality. This is an important step to achieve true digital inclusiveness. Having NTN as an integral part of the 6G design from day one will, furthermore, open new use cases and business opportunities.

Fundamental positioning and sensing capabilities

Beyond the above-mentioned communication services, basic positioning should also be an integral part of 6G day one. New innovations such as sensing are also expected to be part of the first 6G standards release. Combining these with functionalities such as NextGen MBB, XR and RedCap will expand applicability and opportunities for value creation. This will enable new “sensing as a service” applications by using the radio signals to detect and/or track objects such as UAVs, intruders, and hazardous objects on roads and railways. Sensing will also improve situational awareness for NextGen-XR applications and for many more use cases such as traffic monitoring. Eventually, sensing will become a source of almost infinite data, which must be used in a responsible way, contributing to the fusion of the physical and digital worlds.

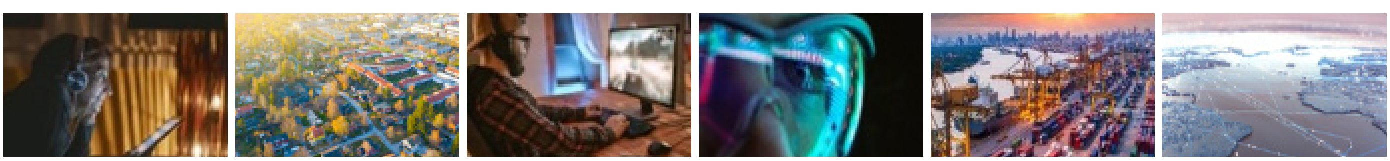
The importance of a mature device ecosystem

Finally, a successful launch of 6G depends on an extensive device ecosystem that expands much beyond today’s traditional use of smartphones and simple IoT sensors to offer new use cases and open additional revenue streams. There needs to be support for emerging XR applications (e.g., cloud gaming, augmented reality, virtual reality), IoT applications and wearables, to mention only a few examples.

The device ecosystem is expected to span both private consumers and professional users in a variety of industries; one example is the use of NextGen XR to boost industrial productivity and efficiency. Devices will naturally need to be available on time, cost effective, and power efficient. We also foresee a leap in the use of AI for many device types.

Device types such as smartphones should support a majority of the high-value features standardized for 5G-Advanced, which are not fully materialized in the field today, with several new innovations, in addition. Examples of these unrealized 5G-Advanced features include full support of energy efficient small data transmissions, a set of harmonized UE power saving features, full support for coverage enhancements, XR enhancements, and UE assistance for network energy saving features.

Figure 4. Examples of primary services supported for 6G day one



NextGen mobile broadband | Fixed wireless access (FWA) | Immersive/cloud gaming | Extended reality (XR) | IoT/LPWA native support | Integrated global connectivity

As we recently reported in a blog post [13], 3GPP just held a key workshop that will further define and refine the use cases for 6G networks. Goals discussed in the workshop such as sustainability, building on 5G’s success and global collaboration should continue to be in focus.

Technology enablers and spectrum for 6G

In the following we present an overview of the technology enablers that are essential for achieving the 6G day one ambitions, while making sure it is easily extendable to develop also beyond day one.

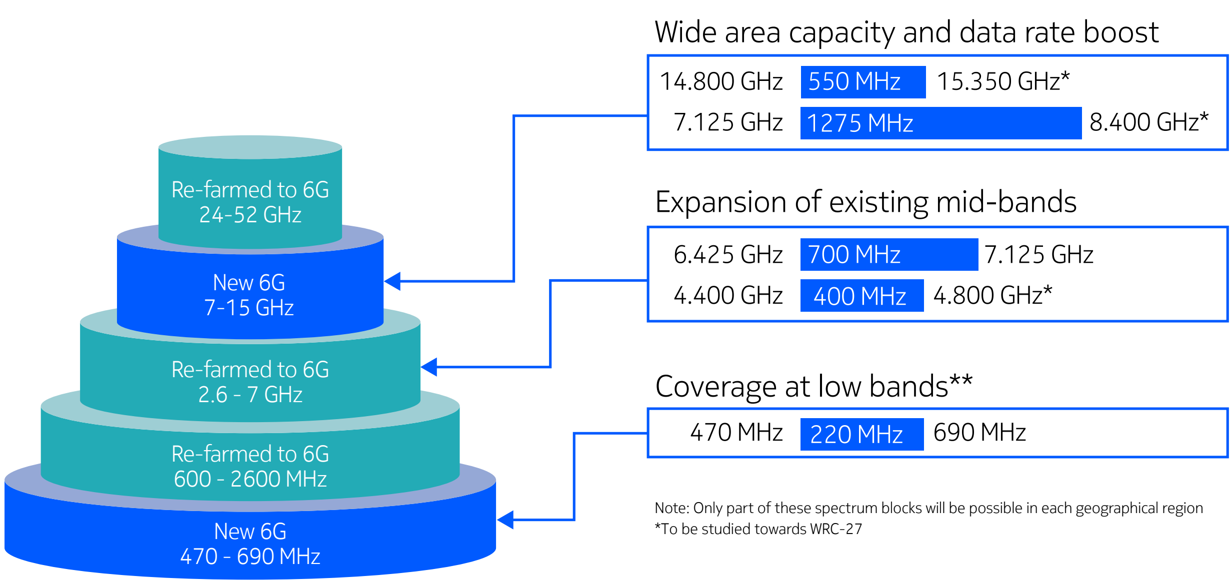
Spectrum for the 6G era

The "ground" for building the "6G house" is spectrum. As an industry, we are designing 6G solutions that take full advantage of new frequency bands in an affordable manner. Our vision is that 6G will be ready for deployment using frequency ranges from 410 MHz to 6.425 GHz, as well as new unexplored ranges such as 6.425–7.125 GHz (aka the upper 6 GHz) as well as 7–15 GHz. This is aligned with the ITU World Radiocommunication Conference 2023 (WRC-23) [18], which agreed to study and address the allocation of new licensed spectrum for cellular mobile communications at 7.125–8.4 GHz and 14.8–15.35 GHz. These new bands will provide substantial and much-needed additional capacity with 6G.

In preparation for this, the current 3GPP radio channel model is currently being validated and potentially refined as part of Release 19, as reported in [1]. The new spectrum bands for 6G mark a unique opportunity, as there are no legacy constraints in those bands from existing cellular deployments, hence 6G should be designed to utilize those from day one. In [2], we recently provided an analysis comparing the overall system performance and cell edge coverage at 3.5, 7 and 13 GHz bands from existing urban macro cell sites, which confirms that the new mid-bands are promising for 6G on existing macro sites.

To ensure a seamless transition between 5G and 6G for the existing bands without compromising network performance, Nokia recommends Multi-RAT Spectrum Sharing (MRSS) and 6G Carrier Aggregation (CA). The use of MRSS sets a seamless migration path to 6G while maximizing the potential of existing infrastructure. More details on Nokia's MRSS solution can be found in [3]. An overview of the considered spectrum for 6G is summarized in Figure 5.

Figure 5. Overview of spectrum for 6G deployments



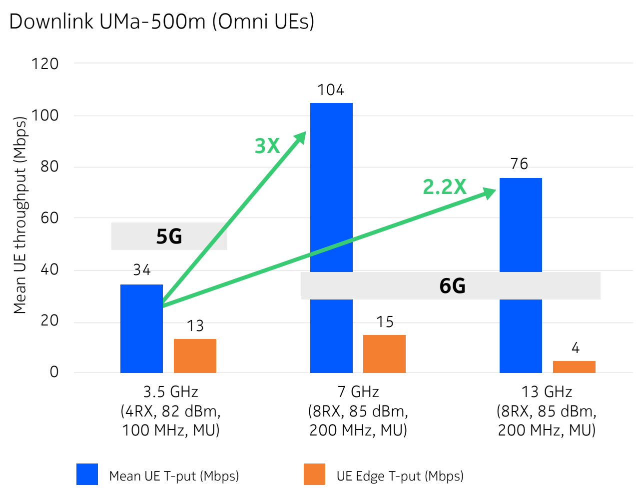
Modernized PHY layer with extreme MIMO

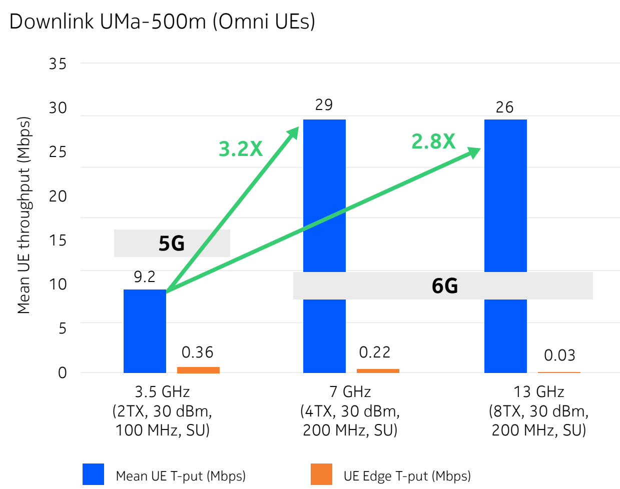
In our vision, a lean and high performance 6G radio will provide significant system benefits in terms of performance for new frequency bands and the existing FR1 TDD and FDD bands. 6G radio should aim at a lean design that provides overall high performance without over optimization for less typical operational scenarios and use cases. 5G NR provides a good basis for 6G numerology especially for the existing frequency ranges like FR1 and FR2. For new frequency ranges from 7–15 GHz, the 6G numerology can be derived from the 5G NR numerology with some extensions like enabling wider channel bandwidth up to 400 MHz for substantial capacity enhancements.

The 5G NR waveforms CP-OFDM for downlink and uplink and DFT-s-OFDM for uplink are well suited for 6G, enabling high performing and highly efficient MRSS between 5G and 6G on the existing FR1 band, much like mid-band when using 5G NR-compliant numerology in 6G. Energy efficiency (EE) will be an important metric in the PHY design and procedural choices. New 6G procedures and functionalities will then take 6G radio performance to the new heightened level. This approach combines the existing and well working physical layer fundamentals from 5G with new high performance and energy efficient 6G procedures and functionalities. This will allow 6G radio networks to benefit from the 5G radio network installed base and accelerate the development of the new 6G radio technology for practical use.

On top of these new features, 6G radio on day one will also build on 5G-Advanced features. These will be practical, lean solutions without a large number of options. They will include UE uplink coverage enhancements, scalable MIMO with unified feedback and signaling, and full XR readiness branches. They won't have the burden of legacy devices and existing deployments, which limit achievable performance gains. We see that the unified transmission configuration indicator (TCI) framework for DL and UL MIMO and beam management will unleash all MIMO and beam management gains from the start of 6G. Traditional step-by-step approaches where dedicated feedback and signaling are designed for different signals or channels, DL and UL, different MIMO and beam management solutions make practical deployments and implementation complex. Such approaches typically fragment the market as different vendors and operators select different solutions for their deployments. 6G MIMO will enable deploying 6G radio on new frequencies from 7–15 GHz using the existing macro site grid. Large antenna array sizes, up to 256 TRX at gNB and higher-order Multi-user MIMO at 7-15 GHz will significantly increase spectral efficiency while maintaining the same macro coverage as at 3.5 GHz as shown in Figure 6.

Figure 6. 6G Extreme MIMO throughput gains: 2x – 3x mean UE throughput increase with 256 TRX compared to 5G mMIMO with 64 TRX





Downlink configurations (MU-MIMO)
5G at 3.5 GHz: 4RX Max EIRP = 82 dBm, 100 MHz
6G at 7 GHZ: 8RX, Max EIRP = 85 dBm, 200 MHz
6G at 13 GHz: 8RX, Max EIRP = 85 dBm, 200 MHz

gNB configurations
5G at 3.5 GHz: 256AE (16,8,2) > 64 TRX (4,8,2)
6G at 7 GHz: 1024AE (16,32,2) > 256 TRX (4,32,2)
6G at 13 GHz: 1024AE (16,32,2) > 256 TRX (4,32,2)

Uplink configurations (SU-MIMO)
5G at 3.5 GHz: 2TX, Peak EIRP = 30 dBm, 100 MHz
6G at 7 GHz: 4TX, Peak EIRP = 30 dBm, 200 MHz
6G at 13 GHz: 8TX, Peak EIRP = 30 dBm, 200MHz
(average EIRP = 23 dBm in all cases above)

Full buffer traffic (10 UEs/call in average)
TDD split: 0.6 on DL, 0.2 on UL
UEs: 80% indoor, 20% outdoors
(38.090 - 50/50 high loss/low loss penetration model)

6G radio will also provide significant uplink coverage improvements. The practical transmit power of devices, especially the maximum achievable UE transmit power, plays a significant role in achieving good uplink coverage. Device transmit powers can be improved in a number of ways such as utilizing FDSS with spectrum extension together with UL DFT-s-OFDM waveform and QPSK modulation. One could also define UE Power class 2 with 26 dBm transmit power as the baseline in 6G instead of the current 23 dBm PC3. Dynamic waveform switching between UL CP-OFDM and DFT-s-OFDM enables efficient balancing between capacity optimized and coverage optimized uplink operations.

For making 6G truly available everywhere to realize full digital inclusion, the radio design for 6G should also support non-terrestrial networks (NTN) for eMBB and IoT services.

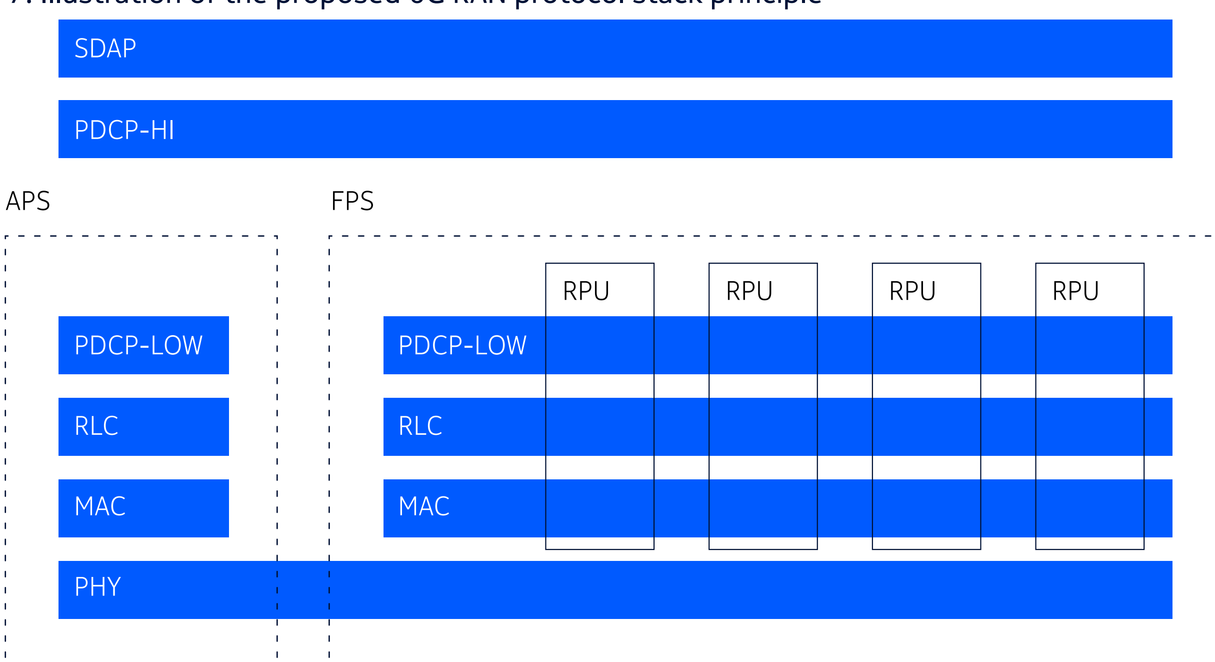
Modular radio protocol design

While earlier generations adopted a “one size fits all” radio protocol stack approach to serve all supported use cases, we are proposing a paradigm shift in how radio protocols are designed for 6G by relying on a more modular dual stack approach. This will enable native support of a variety of device types optimized for different use cases, form factors, hardware and processing power requirements, bit rates and cost constraints, etc. A modernized modular protocol stack approach would allow the 6G specifications to natively support, for instance, smartphones, XR devices, mid-tier IoT and FWA devices from day one rather than introducing dedicated enhancements or capability reductions later, which would make specifications significantly more complex and create technology fragmentation.

In our modular stack radio protocol approach, the first stack hosts control plane functions and optimizations for low bitrate services, denoted as the Anchor Protocol Stack (APS). The second stack is optimized for parallel processing with the notion of radio processing units (RPUs), leaving aside some optimizations that an implementation can only afford for low bitrate services. We refer to this stack as the Fast Protocol Stack (FPS). The RPUs can be decoupled from the physical layer to minimize dependencies between OSI model layers 1 and 2 (denoted as L1 and L2) and facilitate parallel processing in both layers. With those principles in place, 6G radio protocols could be less complex and less power consuming than earlier generations without sacrificing flexibility or performance. To allow parallel processing within the radio protocols of the FPS, each RPU needs to host sublayers of L2. As an example, this will be beneficial to efficiently serve future XR multi-flow services with less overhead.

A high-level block diagram of the proposed 6G RAN user-plane protocol stack is pictured in Figure 7, where several building blocks from the 5G protocol are kept in 6G. These include the Service Data Application Protocol (SDAP), the Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC) and Medium Access Control (MAC) functionalities, as well as a modern physical (PHY) layer with an improved baseline performance and superior energy efficiency. More information on Nokia’s vision for the 6G Radio protocol stack design is available in [4].

Figure 7. Illustration of the proposed 6G RAN protocol stack principle



Sustainability and energy efficiency

One of the challenges in the telecom industry is improving sustainability and resource efficiency, particularly energy efficiency (EE), even while traffic demands keep growing. That is the reason 6G is being created to be sustainable and energy efficient by design. EE will be tackled on the device, base station and core network. The goal is to achieve superior EE, while still efficiently serving the offered traffic. Different solutions will be available depending on traffic conditions.

For device EE, 6G will build on the 5G/5G-Advanced toolbox [5], taking the most promising features from that generation forward and making them fully available from day one. Similarly, radio (base station) EE will inherit many of the high-performing mechanisms developed for 5G-Advanced [6], making them fully available from 6G day one, for a much-elevated EE performance baseline compared to what is seen in the field today.

Naturally, additional EE innovations for the radio will also come with 6G, as EE goals are incorporated into the design of the PHY-layer and MIMO of 6G. To mention a few examples, more flexible transmission of systems information, control channels and MIMO layer adaptations are expected. The EE will be significantly lower for 6G at all offered traffic levels (ranging from quiet to busy periods). Core network EE features such as QoS adaptation based on cell load and exposure to energy-related information including the carbon intensity of the supplied electricity will also be pursued. EE will be boosted with AI-enabled methods, e.g., accurate prediction of traffic conditions in the network will enable the network to accurately adapt to serve the traffic with minimum energy use. Figure 8 summarizes the main functionalities for a sustainable and EE 6G design from a standards perspective.

Figure 8. Summary of sustainable and energy efficient 6G design from standards perspective

Sustainable C-plane design	**Sustainable U-plane design**	**Sustainable system design**	**Sustainable devices**
Leaner 6G carrier for always-available network rather than always-on 5G for extended cell sleep opportunity • SSB/SIB1 transmission based on the devices need/request • Non-uniform provisioning of SSB/SIB1/PRACH/paging in time and space based on cell load	Dynamic adaptations of number of TX antenna, TX power and cell discontinuous transmission (DTX) based on cell load	Core network features such as QoS adaptation based on cell load and network energy state to facilitate RAN energy saving, exposure of energy-related information including carbon intensity of the electricity used by the network	DRX, low power RRC states, efficient scaling of used bandwidth in single- and multi-carrier scenarios, uplink MIMO energy saving techniques, leaner UE measurements and reporting, efficient support for small data and background data

Powered by state-of-the-art AI

*Leveraging 5G-Advanced energy saving techniques for both network and devices

Privacy and security

The increased need for private and quantum-safe communications in the quantum computing era raises the question of where best to locate security features in 6G, as discussed in the Nokia white paper [6]. Research on improving security in the 6G era has, in fact, started already in 5G-Advanced Release 19. The goal is to publish 256-bit confidentiality and integrity algorithms for the air interface. In addition, an authenticated encryption with additional data (AEAD) mode will be introduced [1]. It is anticipated that governments will require quantum safety security standards for communication networks in the next two to three years. For example, the NSA recommends network switching subsystem (NSS) operators to transition to post-quantum cryptography by 2025.

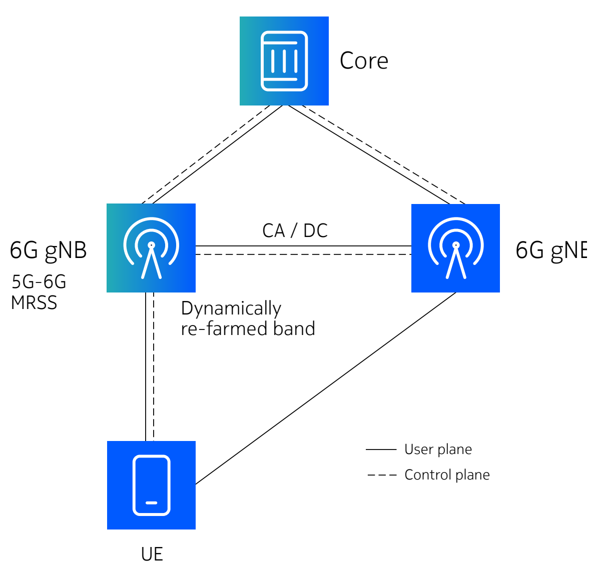
Nokia recently published a white paper on MAC-level security enhancement [8], with more to be published soon. Enhanced security measures are also required for the RAN and Core networks to address new attack surfaces resulting from distributed clouds, increased use of AI and related training data collection, as well as increased federation among network providers and exposure of network data. Moreover, as more and more sensitive user data is handled, for example during MDT data collection, privacy enhancing technologies (PET) need to be applied, such as homomorphic encryption, secure multi-party computation, k-anonymization, and differential privacy.

Architecture propositions

Moving from 5G to 6G, fundamental architecture principles and system design will remain unchanged. In the following, we highlight similarities and identify the needed changes. For 5G many architecture options had been specified, while only two options were eventually implemented and deployed; therefore, it is highly desirable to specify only a 6G standalone architecture, allowing for a lean and smooth migration from 5G standalone towards 6G standalone.

The functional split between different domains (UE, RAN, Core, OAM) should be maintained. To leverage alignment and harmonization across domains, we envision common and unified frameworks e.g., Life Cycle Management to natively support AI/ML, cloud-native functions as well as a uniform network exposure and programmability framework. Those areas are discussed further in subsequent sections.

Figure 9. 6G standalone architecture



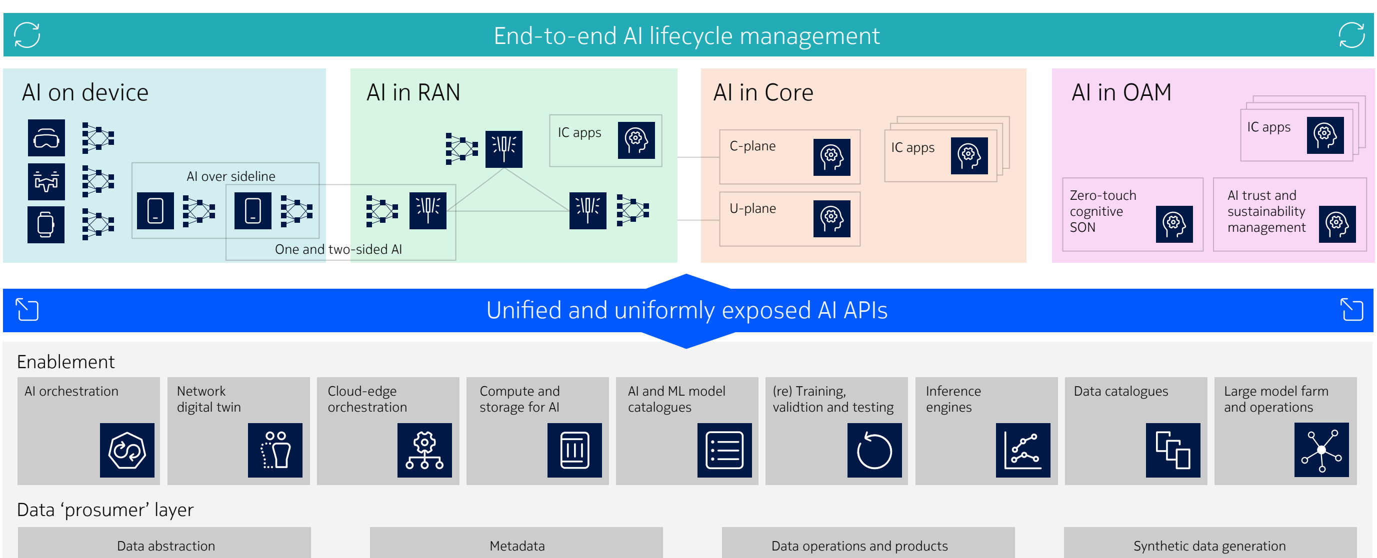
The 6G system architecture should continue to natively support both distributed RAN and cloud RAN architectures. We believe it is necessary to streamline the RAN architecture by focusing on standardizing only those interfaces that have proven commercially relevant. The 5G SBI framework is used as a baseline for 6G. This allows operators to re-use large parts of their investments in 5G while enabling architectural simplification and, when justified and needed, introduce new 6G network functions (NFs). Thus, we expect many 5G NFs can be shared or re-used with some necessary enhancements, leading to optimized procedures, increased security (e.g., strengthening and leveraging NAS security), and most important, new innovations. At the same time, the shared NF concept will make many of these benefits become available also to the 5G installed base.

6G should be able to take advantage of cloud platform services (identification, routing, resiliency, storage) as those become available and mature. Being able to flexibly deploy the 6G system in such heterogenous private or public cloud environments is one of our key design principles. Thereby, inherent capabilities of the cloud environment, including eased scalability, increased resilience, and efficient monitoring and troubleshooting can be leveraged.

Truly AI-native 6G

6G is envisioned to be fully AI native. AI will change the way we design, operate, and optimize networks and devices and bring unparallel performance and efficiency. Therefore, 6G will include AI/ML enablers at all layers of the network as illustrated in Figure 10 with AI for the air interface, RAN, core network, and for management. The journey towards AI-native 6G has already started in 5G-Advanced, with studies and standardization of multiple features [1]. The AI/ML framework shall address scalability, interoperablity, AI/ML Ops and life cycle management, in order to make it future-proof, and ready for additional use cases in 6G for day one and beyond [9]. AI is a fast-moving field, and 6G should provide an AI framework that allows for future innovations. Nokia also recently published a white paper on AI enablers for 6G L2 [10]. As we reported in a recent blog post, it is paramount to have a scalable and consistent testing framework designed for 6G AI solutions from day one [15].

Figure 10. High-level overview of AI native for 6G with AI at all layers of the system



AI will also help to achieve time savings across the entire deployment process of 6G, making the deployments much faster and more cost-effective. AI-driven automation enables automated inspections by analyzing data collected from field activities. AI will identify rare defects, anomalies, or deviations from desired quality standards, followed by quickly triggering proper actions [11].

API-native platform design

API-native refers to a simplified and harmonized architecture for network programmability (network control) and network exposure that eases setup and management of fit-for-purpose networks. More important, additional monetization opportunities are provided by exposure APIs fostering innovation by enabling vertical applications to collect and leverage rich information available from the network. A value-adding network platform residing between the network and the developers and application users provides simplified vertical application-bound APIs to access the rich but more complex network APIs. It “translates” the developers’ and users’ needs (e.g., expressed as intents) aided by AI into the appropriate requests to the network APIs. These simplified APIs allow for intent-driven network programmability and resource optimization. In addition, an enhanced network automation level will enable a higher degree of autonomy and flexibility for service agility. Further, a network digital twin can be used to monitor the network, interact with it, verify configurations before they are deployed and run “what if” simulations without impacting the actual network. The native API capability will not only allow for additional monetization, but the associated automation and simplification for application developers will result in lower OPEX.

Summary of key 6G enablers

The key 6G technologies and their benefits are summarized in Table 1, illustrating how 6G will improve KPIs in multiple dimensions and offer value.

Table 1. Summary of key technologies and their benefits for 6G

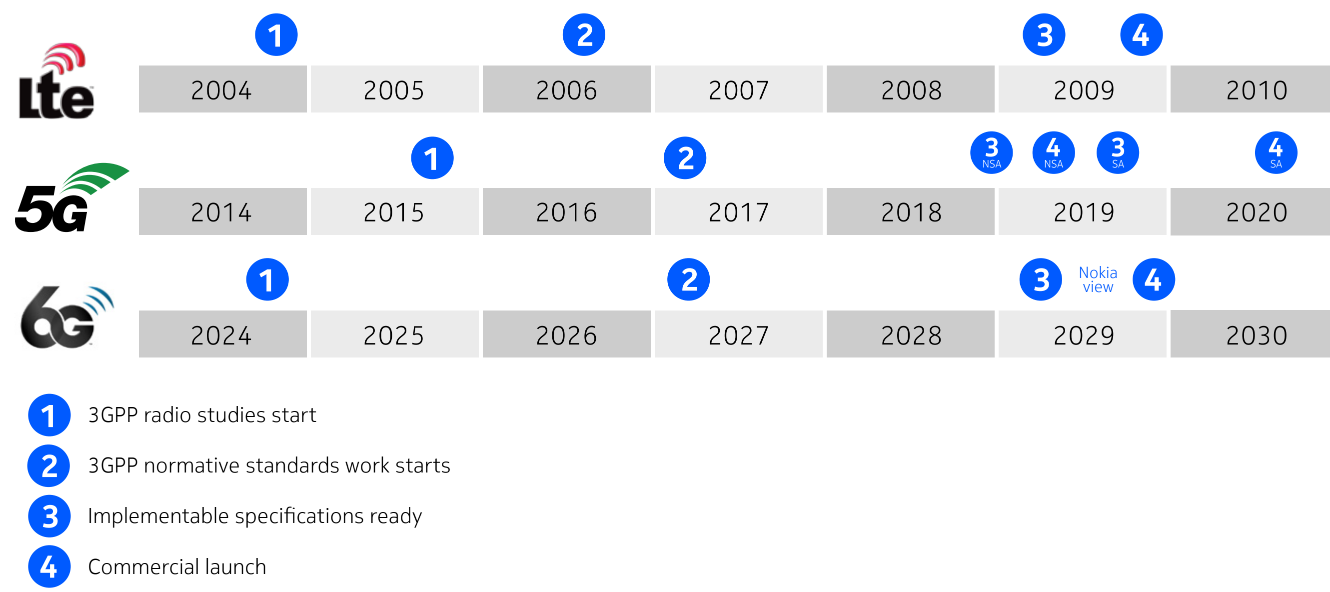
Item	Description	Benefits
Energy efficiency	Enhanced energy efficiency saving toolbox for devices and network, including embedded green-by-design principles at all layers of 6G	• Significant savings in operators OPEX and reduced carbon footprint • Superior end-user experiences from having devices with reduced charging needs
6G radio protocols	Modernized 6G radio protocol stack with APS, FPS, and RPUs for parallelization	• Faster processing with less overhead and more efficient parallelization. • Easier support for introduction of different device types
6G PHY & MIMO	Modernized PHY mechanisms, building on the 5G-Advanced base PHY numerology, but with many new procedures and innovations on top, including extreme MIMO with unified TCI framework	Much-elevated performance baseline: • Improved coverage • Higher spectral efficiency • Lower power consumption • Superior support for new mid-bands
AI/ML-native	Pervasive support for AI/ML at all layers of the system, including the network and terminals	• Making 6G deployments much faster and more cost-effective • Superior network automation and operational excellence • Improved air interface performance with a higher degree of robustness
6G NTN support	NTN connectivity for 6G LPWA/RedCap and smartphones. Integration between TN/NTN, as well as TN spectrum reuse for NTN under control of the terrestrial operator	• True digital inclusion for areas without traditional terrestrial communications access • Affordable digital access makes the vision of global connectivity a reality • Opens new use cases and business opportunities
Architecture	Simplify and streamline architecture: single 6G standalone architecture for day one. Focus on essential commercially viable open interfaces Detailed architecture and protocol design to be natively optimized for key 6G trends and technologies: AI, energy efficiency, a wide variety of devices, and rich network APIs. Functional split between UE, RAN, Core, OAM maintained as in 5G	• Optimal balance between re-using existing HW/SW assets and well-justified enhancements and extensions to achieve 6G objectives such as green by design, reduced costs and complexity, etc. • Single step migration path from 5G standalone to 6G standalone
Exposure and programmability	Common network exposure and programmability API framework	• New API monetization opportunities
Automation	Replacing manual operations with adaptive autonomy for deploying, managing, and optimizing the network resources and services, powered by AI/ML, incl. Generative AI	• Ensuring efficiently running network with high degree of autonomy • In short, operational excellence with significant OPEX savings
Privacy and security	Enhanced security and privacy, including automated identity management, cloud security, and more	• Quantum-resistant security • Holistic AI-native security and trusted framework • Next level privacy

6G standards and future evolution

6G standards driving day one deployments

Benchmarks based on learnings from history are always a good starting point for setting timelines. Although some of the circumstances impacting cellular industry dynamics have evolved over the last few decades, there are some good baseline inferences one can derive from a historical comparison. A brief outline of 4G, 5G and 6G (preliminary plans) standards timeline is shown in Figure 11.

Figure 11. Benchmarking of 4G-5G-6G radio standards timelines



From the benchmark above one can see that for the 3GPP standards machinery, it typically takes five years to produce an implementable stable version of radio specifications from the first 3GPP RAN workshop. This can potentially be accelerated to meet specific urgent commercial needs (like we have seen with 5G and NSA), but the jury is still out on whether such an acceleration brings benefits to the industry in the long run.

Another interesting comparison comes from the approach 3GPP took in terms of a number of technical options. Here we see that 3GPP has gone through a rollercoaster ride:

- 2G was monolithic with hardly any options specified; the focus was on making sure the system worked and interoperated without much extra industry effort
- 3G, because it was the first global cellular system adopted in all regions, involved several geopolitically motivated compromises with many of them never implemented; deployments suffered from a lack of compelling use cases as well as all the additional IoT activities that needed to be conducted to achieve interoperability
- 4G technical options were again more restrained, in large part helped by competition with WiMAX, which led to the adoption of a new waveform, OFDM, and a focus on enabling rapid commercialization, aided by the birth of the smartphone, that limited the number of technical options included in the specifications
- The expansion of cellular technology into a wide variety of adjacent verticals influenced the thinking

around 5G development and posed a diverse set of requirements, which resulted in a set of functions and a whole host of options across all the layers. Many of the those failed to materialize commercially as they first became fully available in later releases, and due to lack of market demands (e.g., from verticals for URLLC and drone support). Although not all options are implemented, they still cause unnecessary complexity in the specifications.

So, if we follow this pattern, 6G will surely revert back to a specification approach that favors simplicity over extensive flexibility. On a more scientific note, it would indeed be desirable for the cellular industry to focus on a coherent high-performance baseline that would be available in all devices and networks. See more information on the beginning of 6G standardization in our recent newsroom article [14].

Continuous growth and evolution

There have been few functional upgrades made to initial 5G network deployments, mostly due to a lack of new commercially proven use cases beyond mobile broadband. This will inevitably change as the commercial space diversifies, new device types emerge, and vertical industries insert cellular connectivity into their ecosystems. This "pull" from the commercial and vertical spaces may reach a tipping point towards the end of this decade giving a boost to 6G uptake and its evolution throughout the 2030s.

For 6G success, it is vital that value drivers are deployed in the network in a gradual fashion as business cases and opportunities for them mature. The superior performance and modular design of 6G will form a solid basis for continuous growth and development beyond day one. The modernized 6G radio protocol stack and PHY design makes it easy to introduce new types of devices based on future releases. Novel device types, many not on our radar today, will emerge during the 2030s with new form-factors and different sizes — including devices optimized for holographic use cases.

The 6G day one AI-native design, with a strong AI framework supporting all layers of the system, also forms a solid basis for the continuous addition of new AI solutions to 6G, both for devices and networks.

The flexible 6G day one design also paves the way to ultra-dense, low-power network configurations, as well as a vast number of specialized use cases for industries and public sectors such as sub-networks, learning networks, and unified networking experiences. As business needs emerge, these new use cases will in turn build support for 6G and open new revenue streams.

Nokia believes that the success of 6G, and its evolution, is fueled by collaborations across industries and academia. We invest significantly in multi-party research collaborations including the Nokia-led flagship projects HEXA-X-II and the 6G-ANNA (6G Access Network of Networks Automation). More information and news on cutting edge research and innovations and future evolutions of 6G are regularly published on the Nokia web site.

Summary

6G will address the increasing need for network capacity, support the vast and growing device ecosystem, and harness and accelerate the power of AI along with many other emerging technologies. It will provide new ways for monetization thanks to an API-native platform design. It will realize the next level of digital inclusion by offering greater accessibility, affordability and consumability. It will be green by design and highly secure.

In this white paper, we have outlined Nokia's vision for the 6G era, how the key emerging technologies enable this vision, and how to focus the content for 6G day one. Much-needed additional capacity will be provided by bringing the upper 6 GHz and 7-15 GHz bands into use. Support for NTN from day one ensures that 6G will be more digitally inclusive and enable more people to benefit from mobile services, especially in regions suffering from poor terrestrial coverage today. 6G day one will be ready for rollout on existing macro-cell sites, including support for both traditional distributed RAN deployments as well as supporting cloud RAN cases.

A 6G single standalone architecture will ensure lower operating costs for operators. Leveraging many of their 5G assets and investments while serving up new and compelling services are some of the additional advantages.

The 6G system will include state-of-the-art privacy and security mechanisms, offering quantum-safe communications. It will be highly resilient, so it is robust against a variety of potential threats. The envisioned native API capabilities with their associated automation and simplification for application developers will result in lower OPEX and create additional monetization opportunities.

We have shown how through lean design and native support of AI/ML, 6G on day one will achieve improved performance as a baseline along with superior and energy efficient 6G radio. Native support for AI/ML enables 6G system and device optimization, better system performance, and enhanced user experiences as well as leveraging automation and machine learning to reduce operational costs.

6G day one builds on 5G success in a more efficient, economical, scalable, and sustainable way by initially addressing NextGen MMB, FWA, immersive/cloud gaming, XR, broadband IoT and wearable use cases and services. Upon this established revenue base, it will expand in stages by providing more services and supporting more use cases by moving over time from connectedness to togetherness experiences, such as immersive holograms, and by moving from information to knowledge (e.g., through cognitive and complete context awareness, sensing, digital twins, etc).

To address 6G day one use cases and services, the focus should be on the following technology elements:

- Smooth migration from 5G to 6G with a single standalone architecture utilizing a cloud-native core built on 5GC as a baseline
- New radio protocol designed to natively support a variety of device types from low to very high bitrate services with low latency in processing and easy to implement
- Energy efficient networks and devices with long battery lifetimes
- Extreme MIMO on the existing macro grid
- Enhanced uplink coverage for all data rates
- Pervasive AI/ML support at all layers including proper life cycle management
- State-of-the-art security, privacy and resiliency
- Efficient automation powered by AI.

As the commercial device space diversifies, 6G addresses a driving need for an optimized, tailor-made network based on an AI-native platform. It will also meet the needs of the vertical opportunities that 5G has promised, which will materialize as relevant business dynamics mature.

As of May 2024, the cellular industry is experiencing a setback as network investments are slowing down. This momentary dynamic shouldn't define the narrative for 6G. It is not an "auto-pilot" refresh that the cellular industry drives "just because". There are monumental technology developments on the silicon side, in AI, and with networking technologies that will be essential to a more sustainable, inclusive and productive future. 6G is the means to bring all these advancements to the cellular industry in a smooth manner.

Glossary

5GC	5G core network
6GS	6G system
AEAD	Authenticated encryption with additional data
AI	Artificial intelligence
APS	Anchor protocol stack
BW	Bandwidth
CA	Carrier aggregation
CN	Core network
CP-OFDM	Cyclic prefix OFDM
CPE	Customer premises equipment
DC	Dual connectivity
DFT-s-OFDM	Discrete fourier transform spread OFDM
DL	Downlink
DRX	Discontinuous reception
DTX	Discontinuous transmission
EIRP	Effective isotropic radiated power
eMBB	Enhanced mobile broadband
FDSS	Frequency domain spectral shaping
FH	Fronthaul
FPS	Fast protocol stack
FWA	Fixed wireless access
gNB	Next Generation Node B
IC apps	Intelligent controller applications
LPWA	Low power wide area
MBB	Mobile broadband
MAC	Medium access control
MDT	Minimum drive test
(m)MIMO	Massive MIMO
ML	Machine learning
MRSS	Multi-RAT spectrum sharing
mMTC	Massive machine-type communications
MU	Multi-user
NextGen	Next-generation
NF	Network function
NSA	Non-standalone
NSS	Network switching subsystem
NTN	Non terrestrial Network
OFDM	Orthogonal frequency division multiplexing
OPEX	Operational expenses
OSI model	Open systems interconnection reference model
PET	Privacy enhancing technologies
PHY	Physical
PDCP-LOW	Packet Data Convergence Protocol lower layer
PRACH	Physical random access channel
QoE	Quality of experience
QoS	Quality of service
QPSK	Quadrature phase shift keying
RAN	Radio access network
RAT	Radio access technology
RedCap	Reduced capability
RLC	Radio link control
RPU	Radio protocol unit
RRC	Radio resource control
RU	Remote unit
SA	Standalone
SBA	Service-based architecture
SBI	Service-based interface
SMF	Session management function
SON	Self-organizing networks
SSB	Synchronization system block
SU	Single-user
TCI	Transmission configuration indicator
TN	Terrestrial network
TRX	Transmitter receiver
UE	User equipment
UL	Uplink
UMa	Urban macro
UP	User plane
UPF	User plane function
URLLC	Ultra-reliable low-latency communications
XR	Extended reality

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Nokia OYJ
Karakaari
702610 Espoo
Finland
Tel. +358 (0) 10 44 88 000
CID: 214027 (February)
nokia.com

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At Nokia, we create technology that helps the world act together.

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