6G
Vision Whitepaper

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Definitions, acronyms and abbreviations

Definitions

Sub-GHz	Frequency bands below 1GHz
Sub-THz	The research community is currently in discussion regarding the exact definition of this term. For the purposes of this document it refers to frequency ranges between 100GHz and 300GHz

Acronyms and abbreviations

3GPP	Third generation partnership project
Adv.	Advanced
AF	Amplify and forward
AI	Artificial intelligence
API	Application programming interface
APP/App	Application
AR	Augmented Reality
CP-OFDM	Cyclic prefix OFDM
C-RAN	Centralized RAN
DF	Decode and forward
DFT-s-OFDM	Direct Fourier transform spread OFDM
ECC	Electronic communications committee (Europe)
eMBB	Enhanced mobile broadband
FCC	Federal communications commission (USA)
FDD	Frequency division duplex
FR	Frequency Range
GEO	Geosynchronous equatorial orbit
IoT	Internet of things
KPI	Key performance indicator
LEO	Low Earth orbit
LOS	Line-of-sight
LTE	Long-term evolution
MAC	Medium access control (protocol)
MDT	Minimizing drive tests
MIMO	Multiple input multiple output
ML	Machine learning
mMTC	Massive MTC
mmW	Millimeter wave
MTC	Machine-type communications
NR	New radio
NTN	Non-terrestrial network
OFDM	Orthogonal frequency division multiplexing
OPEX	Operational expenditures
ORAN	Open RAN

PA	Power amplifier
PAPR	Peak-to-average-power ratio
PDCP	Packet data convergence protocol
Ph1, Ph2	Phase 1, Phase 2
PHY	Physical layer
QoE	Quality of experience
QoS	Quality of service
RAN	Radio access network
Rel-18	3GPP Release 18
Rel-19	3GPP Release 19
Rel-20	3GPP Release 20
Rel-21	3GPP Release 21
Rel-22	3GPP Release 22
Req	Requirement
RF	Radio frequency
RIC	RAN intelligent controller
RLC	Radio link control (protocol)
RRH	Remote Radio Head
Rx	Receiver
SESSy	Sustainable environmental sensing systems
SON	Self-optimizing network
TDD	Time division duplex
TN	Terrestrial network
Tx	Transmitter
UHD	Ultra-high definition
URLLC	Ultra-reliable and low-latency communications
V2X	Vehicle-to-everything
WRC	World radiocommunications conference (Year)
XR	Extended reality

1 Introduction

With 5G availability fast expanding worldwide and a "mid-generation" evolution cycle anticipated in 3GPP Release-18, now is the right time to lay down the foundations for the next generation, global 6G standard. MediaTek has played a leading role in the design, standardization and ongoing evolution of 5G. It has led the way in bringing to the market mature 5G devices that can operate in new groundbreaking 5G systems (i.e. both Radio and Core). As the world's leading smartphone chip supplier[1] and an undisputed 5G commercial product leader, MediaTek is in a prime position to define and drive the vision and realization of next generation mobile technologies for 6G.

5G was engineered and has evolved around three core sets of use cases: enhanced mobile broadband (eMBB), ultra-reliable & low-latency communications (URLLC) and massive machine-type communications (mMTC). It has been purpose-built not only to embrace the mobile broadband revolution unleashed by 4G in the consumer space, but also to enable new growth opportunities beyond this market. Capitalizing on the foundations laid by 4G evolution into the cellular IoT market, 5G took a further, more significant leap to address the stringent requirements of industrial IoT. 5G has been conceived to bring the transformative power of mobile communications into every sector of our society; for the first time ever, a single communication system was designed not only to cater for a very diverse range of consumer and professional use cases in licensed and unlicensed spectrum, across sub-6 GHz and mmW bands, but also to provide connectivity beyond the traditional reach of terrestrial networks through airborne and satellite infrastructure that altogether integrates seamlessly. However, this ambitious design has translated into significant complexity for both networks and devices, leading to higher deployment costs and power consumption. As a result, the 5G rollout has been incremental, focusing mostly on eMBB consumer applications, in sub-6 GHz. Achieving ubiquitous mmW coverage has been a challenge, especially from network economic perspectives. Further, while it is encouraging to see the rise of open RAN architecture coming together for 5G deployments to bring more flexibility and intelligence, the fundamental network design is still based on traditional mobile networks and layering. Significant enhancement will be expected to drive the architecture into the age of artificial intelligence and machine learning.

While industry continues to evolve current 5G technology to address the aforementioned challenges, 6G technology is on the horizon to not only address these issues but also to bring fundamental transformation to mobile networks. Our 6G vision is of *one global standardized technology* to significantly outclass 5G and its evolution from the outset. 6G will deliver *extreme performance* using native adaptive radio and networking technologies that can support consumer and professional markets with diverse data consumption models, in a fully *secure and sustainable* manner. The 6G architecture will bring much better network economics and energy efficiency through a heterogeneous architecture that natively blurs the boundary between dedicated network infrastructure and devices. With 6G targeting to enable ubiquitous mmW coverage and going further to exploit even higher spectrum (~THz), there comes an inherent need for *compact network densification* to build coverage, and with this, a vital need to contain

[1] Counterpoint Handset Model-Level Chipset Tracker: Q1 2020 - Q2 2021

deployment costs. In such context, we foresee that 6G devices will not only be communication *end-points*; 6G devices will be able to act as *active network nodes* in a data path and, ultimately, form standalone networks. Our 6G vision is of an adaptive, integrated and super-heterogeneous wireless communication system, delivering pervasive mobile connectivity in a truly ubiquitous manner: for anything and everything between short-range to satellite communications. The 6G systems will be highly scalable, addressing any deployment scenario in the leanest possible way. The revolutionary advances in artificial intelligence and machine learning will play a central role in making this 6G vision a reality; setting up, operating and managing such a system will require novel tools that can automatically and dynamically tailor its overall configuration and operation to the requirements at hand, without human intervention, while iteratively learning to improve its performance.

This white paper details our 6G vision along the following themes: timeline, key drivers and enablers.

2 Timeline – 2030 and beyond

6G standardization and roll-out will follow the timeline of ITU-R IMT2030 and beyond for commercialization, starting in 2030 with pre-commercialization likely taking place ca. a year earlier.

While ITU-R is planning IMT2030+ trends and vision to be available respectively in mid-2022 and mid-2023, MediaTek anticipates the initial standardization effort in 3GPP to start around 2023/2024 with normative work from the turn of 2026/2027.

The above is illustrated in Figure 1 below, also depicting the anticipated 3GPP releases (Rel-19~Rel-22).

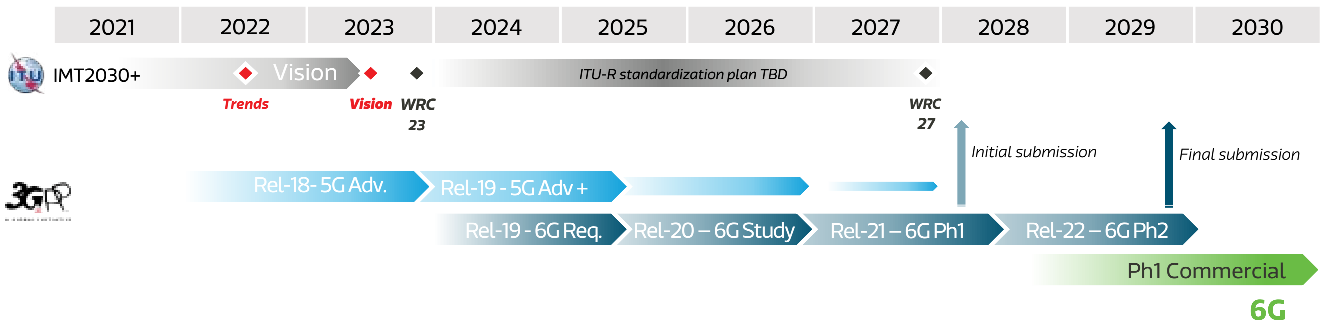

Figure 1. 6G Timeline

3 Trends and Practical Technology Principles

3.1 Trend overview

A few core trends drive our vision for the definition of a new generation:

- **New killer applications will drive the need for more performance**, such as extreme holographic and tactile communications, digital twins, advanced telepresence, etc. applied to both consumer and non-consumer applications such as industrial, tele-medical, etc.
- **10x-100x data rate increase with guaranteed low latency**, primarily driven by advances in 5G applications and new applications such as those stated above.
- **Additional spectrum availability in 7-24GHz and sub-THz frequencies**, in the order of 50GHz total addressable bandwidth. This new spectrum opens up a significant opportunity for service delivery of extreme applications, but also creates significant challenges to overcome poor propagation at higher frequencies.
- **Strong focus on network densification** for two major reasons: as a means to increase low band capacity, and as a means to overcome poor propagation in new frequency ranges. Known challenges related to indoor base station deployment costs and other practicalities will need to be solved differently than in 5G.
- **Ubiquitous global connectivity**, including remote areas currently not covered by cellular networks.
- **Incremental improvement of 5G use cases and applications** added for the first time after the initial 5G release. These will benefit from a design without any legacy constraints from earlier 5G releases, while minimizing system overheads where 6G share resources with 5G.

Figure 2 depicts the observed 6G trends relative to previous cellular generations.

	3G	4G	5G	6G
Broadband Data Rate Device MIMO	1 – 10Mbps 1Tx / 1Rx	10Mbps – 1Gbps 1Tx / 2+Rx	100Mbps – 10Gbps 2Tx / 4+Rx	1Gbps – 1Tbps 4Tx / 8+Rx
Spectrum	FDD + new TDD (e.g. 2.3GHz) ~100MHz more	+more TDD (2.5GHz) +unlicensed (5GHz) ~600+ MHz more	+3.5-7GHz +mmW ~3+ GHz more	+7-24GHz +Sub-THz ~50+GHz more
Network densification[1]	Nominal	+	+ device	++ device
Killer App	Mobile web (e-mail, browsing)	Mobile video Social media (+LPWA IoT)	UHD video Cloud Gaming, XR Other Verticals	N-D holographic comm. AI-efficient system

Note 1: As spectrum goes higher, the boundary between "infrastructure" and "device" challenges blurs

Figure 2. Observed 6G trends relative to previous cellular generations

3.2 S.O.C. – The Practical Technology Principles

The successful delivery of 6G trends described in the previous section will rely upon the combination of three fundamental design principles: Simplexity, Optimization and Convergence, as outlined in Table 1 and further described in the subsections below.

Table 1. S.O.C. design principles: Simplexity, Optimization, Convergence

Simplexity	Optimization	Convergence
Sustainable improvement under simplexity principle	*System optimization driven by practical user experiences*	*Cross-domain convergence for high cost efficiency and performance*
• Enable the necessary complexity for higher performance • Simplify traditional designs to enable higher performance • No compromise of energy efficiency	• Focus on key future dimensions and applications of importance to end user experience • Optimize radio interface, spectrum usage and network architecture	• Wireless access: integrated access with front and backhaul across licensed, unlicensed and shared spectrum • "Device-ification" of network nodes; Hybrid Nodes • Terrestrial and Non-terrestrial (e.g. satellite) access • Communication and computing • Communication and sensing

3.2.1 Simplexity – The 6G experience enabler

Simplexity is the combination of increased complexity and simplicity.

- Complexity increase is a necessity to deliver a system performance leap e.g. in data rates, necessary for new 6G applications.
- Simplicity is necessary to achieve 6G goals with significantly lower complexity per bit delivered to keep the overall design constraints within realistic bounds. While complexity reduction should remain the responsibility of the designer, 6G standards will need to be carefully delineated to ensure that devices and base stations are not unduly constrained. Unnecessary constraints may otherwise preclude achieving best possible power/cost efficiency to meet sustainability goals. Careful standard delineation is necessary for all disciplines (e.g. RF, digital, analogue, cloud) and all protocol layers. Some illustrative examples are described in Table 2.

Table 2. Illustrative examples for the Simplexity principle

Necessary complexity for high-performance radio interface and technologies	Native lean design for simplicity and high performance

• Data capability expansion with wider component bandwidth (≥1GHz)
• Operation at new frequencies
  • High-mid bands: 7-24GHz
  • High bands: Sub-THz
• Higher-order MIMO: network and device
  • Network: High-density antenna
  • Device: 8x8 and beyond
	• Radio interface overhead reduction: control, signaling, reference signals and headers
	  • Spectrum efficiency
	• Lean protocol design: fewer protocol layers and overhead, simplified procedures
	  • Enable extreme QoS (latency, data rate)
	• High power efficiency
	  • Low energy cost per bit

3.2.2 Optimization

6G will inevitably be optimized, however, the process of optimization must be led by practical user experiences, whether the user is providing or consuming 6G. This will articulate around three optimization pillars, namely:

- An architecture optimized to support any practical deployment and topology scenario, central to which is a *heterogeneous radio access architecture*;
- A system optimized to operate and orchestrate itself from access to core, with no human intervention, thanks to revolutionary advances in *artificial intelligence and machine learning*;
- A system optimized to deliver the best end-to-end application performance with highest desired efficiency, through *application-specific cross-layer design*.

Some illustrative examples are listed in Table 3.

Table 3. Illustrative examples for the Optimization principle

Heterogeneous radio access architecture	AI-integrated system and Machine Learning	Application-specific cross-layer design

• Centralized, distributed, peer to peer
• Seamless extreme QoS user experience
  • Super-massive MIMO
  • Distributed MIMO – no cell edge
• Cooperative device and network mesh
  • Native *sidelink* and mesh: address mmW / Sub-THz shadowing
	• AI-assisted radio access
	• AI-enhanced network operation
	• Machine-learning for iteratively increased performance
	• Across network and devices
		• Optimal support for AI applications
		  • Efficient data passing and model update pipeline
		• Optimal support for fully-immersive and ultra-low-latency applications
		• Energy-aware QoS delivery

3.2.3 Convergence

Cross-domain convergence will open up additional dimensions of opportunity to widen the 6G experience space and to enable additional performance, coverage and cost efficiency. A broad range of opportunities are anticipated: within wireless access (unified access for front/backhaul, licensed/unlicensed convergence), integrating terrestrial and non-terrestrial (e.g. satellite) accesses, communication and computing, communication and sensing, and fundamentally, convergence between devices and network nodes. Additional details can be found in Table 4.

Table 4. Illustrative examples for the Convergence principle

Wireless access	Terrestrial and non-terrestrial	Communication and computing

• True "all-wireless" mobile networks
  • Integrate access, front- and backhaul
• Convergence of licensed, unlicensed and shared spectrum
  • Thin protocol for low overhead
  • Flexible RF and fast access
• Communication and sensing
  • Shared or separate radio resource for communication and sensing
• "Device-ification" of network nodes
  • Compact network densification with Hybrid Nodes
	• Integration of terrestrial and non-terrestrial networks, accesses and services from the outset
	• Same device for TN and NTN
	• Spectrum re-use across TN and NTN
		• Unified network system architecture
		  • Enable resource sharing across mobile and edge compute
		• Integrated security across cloud, network and device
		• Address overlap between 3GPP and IETF for advanced immersive applications

4 Wireless Access Convergence

Our 6G vision is one of a truly universal system based on a common technology design platform that supports virtually any deployment scenario, using terrestrial, airborne or satellite radio access, to offer connectivity whenever and wherever needed. We envision a system that can tap into an unprecedented set of spectrum assets (from Sub-GHz to Sub-THz) and associated regimes in a smart and flexible manner (see §11) to provide the most efficient wireless access for any given communication need. Such a vision poses a great engineering challenge especially at the radio interface. With respect to the notion of technology fragmentation resulting from different radio interfaces (*e.g. Uu vs. Sidelink*), spectrum ownerships, spectrum regimes and deployment scenarios, we oppose such fragmentation and propose instead the notion of a *unified radio access technology through wireless access convergence*. Not only will such convergence enable high economies of scale, it will also deliver a compellingly affordable and reliable alternative to e.g. point-to-point, wired or fibered communication links, thus facilitating deployments.

Building coverage and capacity at high frequencies (~mmW and above) will require a higher level of densification of radio nodes to overcome far more significant shadowing effects specific to these frequency bands, and hence their unsuitability for Non Line-of-Sight operation. Radio node densification is economically viable only provided the radio nodes providing coverage are themselves economically viable, that is: easy to install, maintain and replace and with little or no real-estate costs to deploy. In other words, this is made possible if these radio nodes not only feature very high synergies with devices but can also be actual devices; these radio nodes result from the convergence between devices and network nodes. We call such radio nodes '*Hybrid Nodes*' as illustrated in Figure 3. A Hybrid Node can communicate with any other Hybrid Node, device or base station. Hybrid Nodes can also adapt their relaying capability, e.g., in the possibility of configuring them to make trade-offs between latency and throughput. A heterogeneous network architecture containing both analog (e.g. AF[2] repeater) and digital (e.g. DF[3] relay) Hybrid Nodes allows intelligent routing of traffic through the system as a function of service requirements. 6G Hybrid Nodes will transform the way radio coverage is built and networks are planned and operated in the 6G era. They will play a key role in efficiently harnessing high frequency short-range spectrum assets.

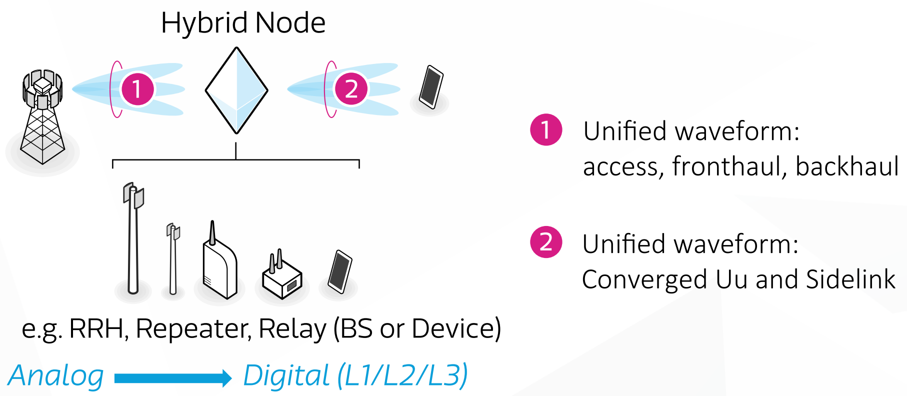

Figure 3. Hybrid Node

[2] AF: Amplify and forward
[3] DF: Decode and forward

At the core of wireless access convergence and a primary enabler of Hybrid Nodes is also the need for a *unified waveform* principle that in accordance with the above must be designed from the outset:

1) to fulfill access, fronthaul and backhaul communication links requirements (at least in terms of throughput, communication range and reliability), and
2) to enable *Uu* network to end-device radio communication, and *Sidelink* end-device to end-device direct radio communications under a single converged design.

It is important of course that the definition of a unified waveform for both 1) and 2) above, takes into account the differing characteristics[4] from Sub-GHz to Sub-THz. While the unified waveform design will be natively scalable using different numerologies (e.g. cyclic prefix, sub-carrier spacing), different-yet-complementary unified waveforms may be needed to accommodate the full spectrum range from Sub-GHz to Sub-THz depending on these characteristics. For instance, while OFDM[5] waveforms, namely CP-OFDM[6] and DFT-s-OFDM[7] , are used in 4G LTE and 5G NR, they do suffer from large PAPR and high sensitivity to frequency offsets. These issues are especially relevant in Sub-THz. Other candidates such as single carrier waveform should therefore be investigated. It will of course also be necessary to investigate suitable modulation schemes to complement the above, taking into account aspects such as e.g. demodulation complexity in conditions of extreme data rates, and abrupt phase change between (consecutive) modulated symbols. Last, common protocol layers ought to be defined to further eliminate dependencies between service and transport (see §7).

Following the above principles, *wireless access convergence* will enable 6G to scale into different deployment and usage scenarios from its inception while reducing the implementation effort needed to do so.

[4] Channel characteristics (e.g. propagation loss, Doppler frequency shift), device characteristics (e.g. phase noise, PA power efficiency, PA non-linearity), system characteristics (e.g. signal bandwidth, beamforming)

[5] orthogonal frequency division multiplexing

[6] cyclic prefix orthogonal frequency division multiplexing

[7] direct Fourier transform spread orthogonal frequency division multiplexing

5 Distributed Network Architecture

Historically, cellular systems have been centralized, with the user device as a client at the edge of an operator-controlled network that offers services from the core. Increasingly, there are reasons to decentralize services and offer them from a variety of points in the network e.g. closer to the point of consumption to minimize latency or risk of congestion, within a private network only, or directly between devices without the involvement of network nodes (e.g. for V2X). These trends call for a flexible model of data consumption, in which the system offers an optimal data path from the point where the service is offered to the point where it is consumed. This may involve paths through various network nodes, using various access technologies, and/or directly between devices, as illustrated in Figure 4.

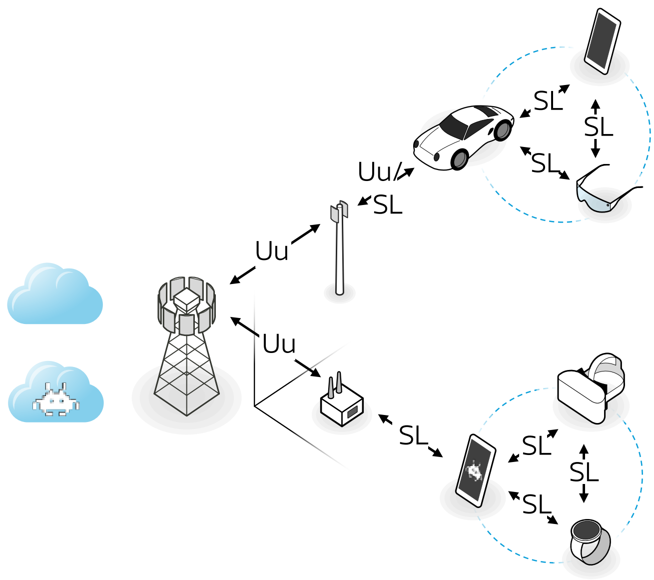

Figure 4. Flexible model of data consumption

From this flexible data consumption model originates our vision of the 6G architecture, which is tailored for applications: an *application-driven distributed architecture* supporting *flexible topology*. This vision will allow handling data generated by applications with optimal resource usage efficiency in terms of computing, storage, transport and energy, while at the same time fulfilling all associated QoS and security requirements.

While the 4G architecture was defined primarily for delivering mobile broadband data, the 5G architecture added means to enable better data management in the network, namely by allowing the isolation of resources as a function of data types and/or ownership (network slicing, private networks) and the localization of applications closer to end users through access/core convergence (edge computing)[8]. Building on 5G, the 6G architecture will offer native support of functionality to best serve applications. Central to this vision are:

[8] Note: with the exception of network slicing that is natively supported in 5G, other functionalities are add-ons.

a) The advent of AI/machine-learning especially for consumer applications (e.g. environment detection for AR applications, real-time voice translation) and the related need for computing resources;

b) The anticipated explosion of XR consumer applications and the need for localization of servers closer to the end-users (e.g. due to latency demands);

c) The related need for low-latency, high-rate data exchange between devices in close proximity such as a smartphone and AR glasses.

These three use cases epitomize key native functionalities of the 6G architecture:

- To enable *Compute* resources at the network edge and/or at the device, including potential compute sharing between device and network edge;
- To enable *Server* functionality divided between multiple nodes, which may be distributed in the network;
- To enable *Device-to-device* operations.

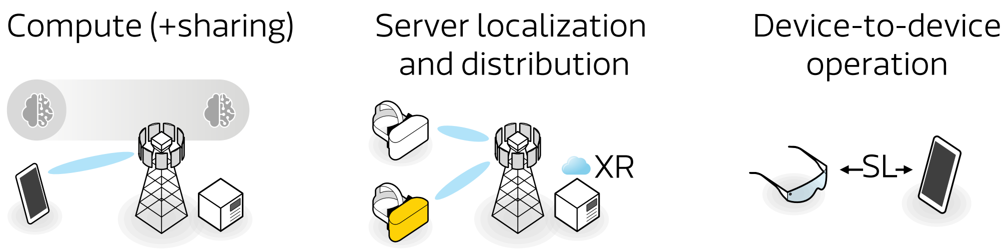

Figure 5. Key functionalities for application-driven architecture

Another defining characteristic of the 6G architecture originating from a flexible model of data consumption is *flexible topology*. The definitions of "network" and "topology" have diversified significantly since the advent of cellular communications. With 5G, a major leap has occurred in diversification of network types:

- In addition to public terrestrial networks controlled by a commercial operator, non-terrestrial networks and private networks have been introduced;
- Device-to-device communication is supported via sidelink communications, with steps towards supporting device-to-device ad-hoc networking being taken in the form of sidelink relaying;
- Access to a network through another network has also been defined, whether using cellular or non-cellular wireless technologies such as Wi-Fi or Bluetooth.

This diverse environment offers an opportunity for convergence in 6G, with support for all deployment models under a common architecture framework, including seamless interworking between these models.

Key to achieving flexible topology is the support of *Hybrid Nodes* (see §4) and *mesh networking* they enable. As explained in section 3, 6G Hybrid Nodes will transform the way radio coverage is built and networks are planned in the 6G era e.g. multi-hop transmissions will enable devices to connect to a network with high efficiency. Crucially, Hybrid Nodes will cooperate with one another in order to dynamically determine (and adjust)[9], with or without network involvement, the most efficient topology and associated data path(s) to provide coverage of any given service

[9] This includes the ability to swiftly and dynamically join or leave an existing topology, in a secure manner.

to end devices, taking into account parameters such as resource usage efficiency, QoS and security requirements, as well as any variable conditions (such as fading, load, battery level) possibly experienced by Hybrid Nodes and end devices. In addition, Hybrid Nodes will be able to isolate a sub-network topology from the parent network topology to which they belong, thus enabling the secure operation of sub-networks within a parent network.

6 MIMO evolution towards True Edge-less Experience

MIMO and multi-antenna technology has been a key technology component in increasing the spectrum efficiency of the system in both 4G and 5G, with beamforming techniques a key enabler in facilitating the expansion to operation into the 3GHz range, and beyond into the 24-71 GHz frequency range. For 6G we expect MIMO to evolve along that same path, but we also expect it to be the foundation of a more collaborative, seamless and heterogeneous approach to the 6G radio access network architecture design.

6.1 (Super-)Massive MIMO scaled to higher carrier frequency

MIMO and enhanced beamforming will be key to compensate for the challenges caused by signal characteristics in the sub-THz frequency range, enabled by a smaller antenna element size (see §11). The number of elements in a 2D MIMO antenna array of a given size is expected to increase by 25 times for antennas operating at 140 GHz versus 28 GHz. The narrower beams that this enables would maximize achievable spectrum efficiency and range to make the most of the anticipated larger bandwidth available, although limited primarily to Line Of Sight operation. In this respect, beam management design would require particular attention to ensure transmitted beams are able to keep track of the channel status at the receiver, in order to enable optimal link performance.

If RF complexity challenges can eventually be overcome (after they have been overcome for existing mmW systems) to justify enabling future hybrid beamforming to become more digital than analogue, this could offer the ability to more flexibly multiplex data traffic for different users, and drive further capacity, spectrum efficiency, and latency gains.

Another challenge would be to ensure acceptable power consumption in mobile devices that are battery limited, due to additional RF branches and MIMO processing operating in the mobile device to support more optimal beam-tracking.

6.2 Distributed and heterogeneous MIMO architecture

6.2.1 A "Cell-free" design approach

A distributed MIMO deployment, where Tx-Rx signal pairs are not just bound to one node/site but distributed across multiple sites and nodes, has the ability to improve spectral efficiency and user experience across an area. Consider the following components:

- Coherent Joint Transmission: Where the system has the ability to allow different radio sites to contribute actively to a single user's communication link without those signals interfering with each other, thus boosting the available user throughputs across a whole area, rather than being limited by the traditional "cell edge".
- Interference mitigation between users: Planning multi-user operation across radio sites to minimize and mitigate interference between users across this multi-site area.

Based on the above aspects, and supported further by the increased beamforming gain from higher bands and the increased sensitivity to directionality of the signal, this will drive the 6G radio access network architecture towards increased centralization of MIMO processing/scheduling functions. It permits different beams from different radio nodes to dynamically contribute to the signal as the device moves through an area, or as conditions around the user change, thus a seamless “Cell-Free” design approach is recommended.

We would like to stress here that the effect of centralizing RAN functions (C-RAN) puts very stringent requirements on the transport network architecture behind the radio site (in terms of synchronization, differential latency and front/mid-haul transmission bandwidth). Limitations on the transport network’s “last mile” to radio sites have been a major obstacle for the practical adoption of Centralized RAN in both 4G and 5G deployments. However, with 6G, we believe that the need for a more dynamic environment in dense urban and indoor distributed networking scenarios will drive the need for network site simplification where, for those specific deployment scenarios, the above challenges are less of an issue due to the short distances between sites leading to an opportunity for localized hubs. In suburban and rural deployment environments, we believe that those practical challenges will remain for some time, and alternative approaches (see §4, §5 and §9) are more suitable for enabling improved area spectral efficiency and user experience in those environments.

6.2.2 Incorporation of devices as Hybrid Nodes

In earlier sections we refer to mesh networking and the opportunity for devices to operate as Hybrid Nodes to reduce the costs of radio site densification, while also extending coverage. In the context of MIMO operation, we would expect such hybrid nodes to be utilized by any distributed MIMO network deployment to maximal effect to maximize coverage extension and user experience ubiquity within a geographical area. An example of this topology is shown in Figure 6 below.

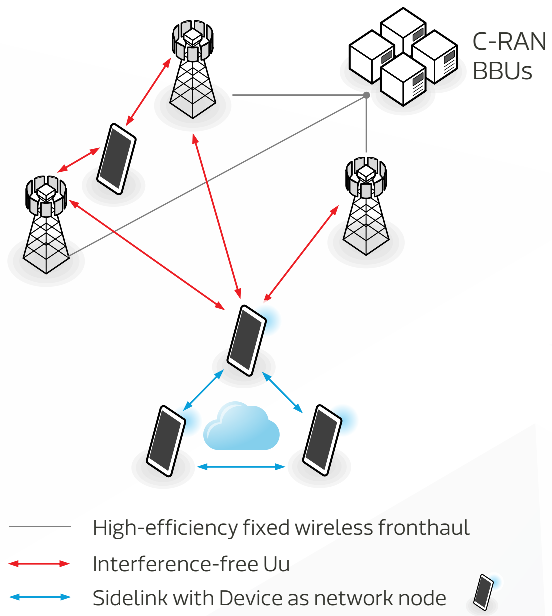

Figure 6. Example of 6G Heterogeneous MIMO topology (with Centralized RAN)

6.3 Main KPIs

The KPIs in Table 5 below will be essential for MIMO design in 6G networks.

Table 5. KPIs essential to MIMO design in 6G

KPI	Why is it important?
MIMO Power efficiency	As MIMO antenna arrays become more complex in devices and networks as part of the extension to sub-THz range, power efficiency becomes more challenging to maintain. In lieu of any expected battery breakthrough technologies, device power efficiency will still be important for 6G, and increasingly network energy consumption will also need to improve, see §8.
High-performance mobility	In FR2, and even more so in Sub-THz, the ability to perform accurate beam tracking and to ensure that those beams can be optimally paired between the optimal node(s)/antenna(s) will be key to optimal user experience.
Area spectral efficiency & capacity	The aim of moving to a “cell-free” approach is that the traditional cell-edge is no longer a performance limit. The ability to maximize throughput performance for all users ubiquitously across an area is a key driver for distributed and heterogeneous MIMO.

7 Towards Extreme and Predictable QoS – Lean User Plane Protocol Stack

7.1 Enabling extreme throughput for real-time immersive services

6G is envisaged to deliver real-time immersive applications for future applications such as holographic and tactile user experiences, with content typically rendered in an edge server and delivered to the user devices though a high-performance wireless link.

New 6G applications require a different and challenging combination of

- Guaranteed high data rates in excess of 1Gbps
- Guaranteed low latency in the range 0.5-5ms
- Limited tolerance to data loss without impacting end user experience

Legacy protocol stack design is focused on lossless data delivery, and this approach is unsuitable for highly-interactive immersive applications: there is fundamentally no practical difference between a lost packet and a late packet in audio and video streams for example, as late packets will be discarded anyway by the codec deadline at the receiving end.

7.2 New approach: congestion management/recovery instead of in-order delivery

The higher protocol layers in 5G and previous cellular generations (RLC or PDCP) have been specified with a focus on lossless in-order delivery to overcome a residual MAC PDU loss on the order of 1%. Lossless and in-order delivery is particularly important to prevent the application TCP/IP stack from triggering congestion control. Unfortunately TCP congestion control was not conceived for wireless environments, and subsequently it triggers a drastic data rate reduction as soon as small packet data loss is detected. Lossless delivery comes at a great cost because RLC PDU retransmissions have large associated round-trip delays. Worse than this, a redundant retransmission layer within TCP can cause yet another round of retransmission delays. Figure 7 depicts the retransmission delays across the 5G communication stack.

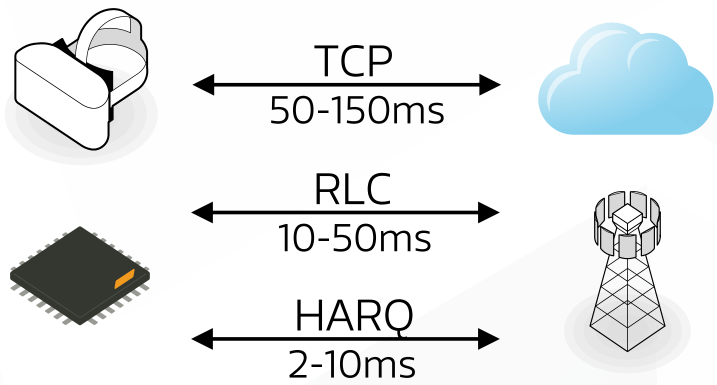

Figure 7. Retransmission delays across the 5G communication stack

A different approach is required to tackle the new user experience disruptors for highly-interactive immersive applications as summarized in Table 6 below. It is important to note that all these disruptors are of time-varying nature, and they cannot be overcome by traditional approaches based on retransmissions and lossless in-order delivery.

Table 6. Disruption factors for extreme 6G user experiences.

Major disruptor	Primary Cause
Packet Jitter	User mobility and data multiplexing (on-air and in core network).
Packet loss	Cell-edge transmission and reception is less robust.
Data rate fluctuations	Cell traffic temporarily exceeding cell capacity. Traffic at source codecs needs to be quickly and reliably adjusted according to available per-user data rate.

7.3 Cross-layer API for Dynamic Radio/Application Mutual Awareness

Dynamic *mutual* awareness between Radio/Transport and Application layers is a promising and necessary step forward to overcome the experience disruptors described in the previous section. The critical mutual awareness factors are listed hereafter in Table 7 while Figure 8 illustrates our vision of a cross-layer API concept.

Table 7. Critical mutual awareness factors between radio layers and applications

Mutual awareness aspect	Impact
Radio/Transport layer awareness of application traffic requirement	Radio layers are notified by application layers of any changes in traffic pattern characteristic in terms of e.g. block size, periodicity
Radio/Transport layer awareness of acceptable QoS	Radio layers are notified by application layers of any changes in acceptable QoS (e.g. acceptable packet loss rate, jitter or delay budget)
Application awareness of Radio Access QoS	Application layers are notified of environment changes in the radio layers causing a degradation or an improvement in the QoS that can be guaranteed by the network to a specific device and a specific application
Dynamic QoS adjustment at the application level	Application layers react to a change in radio conditions and select the best possible strategy (e.g. different codec quality, recovery strategy, etc.) that maximizes user QoE with available QoS
Dynamic split rendering partitioning	Dynamic determination of the device vs. edge rendering partitioning as a function of device/edge processing capability and radio conditions. This can jointly optimize user experience and network resource utilization

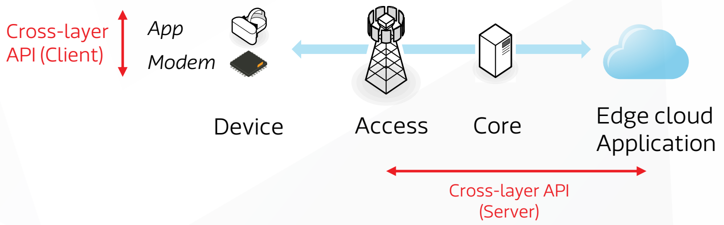

Figure 8. Cross-layer API concept

7.4 Lean User Plane protocol stack

The user plane protocol stack for 6G communications needs to be carefully redesigned to ensure that the user experience disruptors described in Table 6 are tackled. Lower layers in the communications stack need to be able to predict performance that can be guaranteed, and pass this information onto applications to take into account.

Unfortunately, these mutual awareness principles described in the previous section are necessary but not sufficient. When coupling high data rates and low latency requirements together whilst ensuring security and privacy of 6G communications, the processing capabilities, memory and energy footprint of the 6G communication stack can significantly increase. It is therefore important to carefully design the protocol stack to cater to demanding 6G use-cases while not increasing the associated cost and energy consumption of data transfer.

While improvements in semiconductor technology will alleviate some of this pressure, communication and storage demands of proposed new immersive services are expected to far outstrip the pace of technology evolution and integration. Legacy functionality in the 5G protocol stack has been introduced for justifiable reasons, and will still be required for backwards compatibility with legacy services. At the same time, a new operational mode is necessary where the user plane protocol stack is as 'lean' as possible, keeping per-packet interventions within the data plane to a minimum, therefore reducing its contribution to total delay for any new, demanding services. In this new operational mode, functionality should only be introduced where necessary to maintain a good end-user experience. This will ensure that the 6G communication stack can serve evolving services within available processing and storage limits, while in an energy-efficient manner. Performance criteria for a lean operation mode are described in Table 8.

Table 8. Performance criteria for Lean Protocol Stack

Performance criteria	Justification
Avoid lossless operation	Delays associated with higher layer data recovery are not acceptable for real-time services. Required reliability will need to be guaranteed by lower layers.
Avoid in-order delivery	Reordering delays are not acceptable for real-time services. Delays and storage associated to head-of-line blocking must be avoided at all costs, with obsolete content dropped as soon as possible.
Prioritise a-priori grant information	To reduce uplink processing delays for real-time services, UL grant information that does not need to change at the same rate as scheduling intervals should be known ahead of time before the grant occasion.
Reduce header overhead	It is essential to avoid scale up of control information at the same rate as data, keeping processing overheads in check for high throughput services.
Tight PHY and MAC coordination	Tight coordination between MAC and PHY is needed such that only information that needs to be recovered should be stored in HARQ buffers, reducing the memory footprint of both the base station and the device.

8 System Energy Footprint and Power Efficiency

In previous cellular generations semiconductor technology evolution has delivered substantial performance increases coupled with significant power consumption reductions. In the past, these semiconductor power efficiency improvements have compensated for complexity increases in devices and base stations. While this power efficiency improvement trend is expected to continue, the anticipated rate of improvement over time is unlikely to be sufficient to compensate for 6G use case requirements for delivering extreme user experience (10x-100x data rate, latency reductions, higher MIMO order, low-efficiency Sub-THz RF, etc.).

After Release 15 some signs of exhaustion of this trend already appeared for NR: It became apparent that acceptable device power consumption could not be achieved without additional modifications to 3GPP specifications. As a result of this some remedial effort was undertaken by 3GPP in subsequent releases.

8.1 Extremely power-efficient devices

Handheld device design is fundamentally constrained by battery capacity and thermal dissipation capability. Thermal constraints in a typical fan-less 6-inch smartphone limit the total average device power consumption below the 3-5W region in order to respect device surface temperature safety levels. While battery technology is likely to improve its energy density over the next decade, the thermal power limit is unlikely to increase noticeably in the same period. Further to this, more compact device form factors are anticipated to become more prevalent in 6G e.g. for advanced telepresence, holographic communications, internet of senses, etc. These new formats may experience even more stringent limitations than smartphones not only because of their form factor (limited volume and battery capacity e.g. glasses) but also due to their being worn and not held/carried (i.e, even tighter heat dissipation requirement because of long-term skin contact). Some exemplary research directions are listed in Table 9.

Device peak power consumption and cost are generally dominated by the Rx downlink portion, and both are approximately proportional to peak Rx data rate. All else being the same, a 10x-100x increase in peak data rate results in an approximate 10x-100x increase in device peak power consumption leading to unacceptable levels. In order to keep device average power consumption within acceptable limits, power consumption must reduce significantly during inactivity periods and whenever device data rates are well below the peak device capability. This can only be achieved if required device housekeeping tasks (e.g. control channel monitoring, beam management, neighbor cell measurements, idle paging cycle, etc.) do not constrain the device to remain awake unnecessarily.

Table 9. Device-power saving directions

Solution	Description
System specification for power-efficient devices	Power-efficient device operation specified from day 1 as a fundamental KPI across all protocol layers, applicable to all relevant device housekeeping procedures.

Solution	Description
Big-Little modem architecture	6G specifications must enable Big-Little device implementations, allowing for a lightweight and power-efficient subsystem to take charge of low-activity states. See Figure 9.
Net-zero idle mode: low-power wake-up, energy harvesting	The combination of energy harvesting and optimised ultra-low-power devices can enable a new device type not requiring any battery power during low-activity operation.

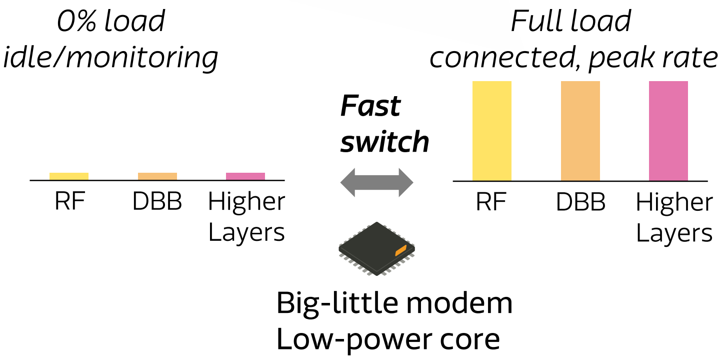

Figure 9. Big-Little device modem concept

8.2 Network power saving

5G network energy footprint is already a cause for concern not only because of its environmental impact, but also due to the network operator OPEX impact. At the radio level, two major, independent drivers will cause large energy consumption increases unless targeted action is undertaken: expected additional complexity per base station, and anticipated base station densification. In addition to this, distributed cloudification may also cause further increases in power consumption.

There is limited scope for compromise on this topic, and it is our view that in some cases ultimate network performance or flexibility may need to be sacrificed in order to address the power consumption challenges. A number of illustrative research directions are captured in Table 10.

Table 10. Potential research directions to overcome network energy footprint

Research direction	Description
System specification for power-efficient network	Power-efficient network operation specified from day 1 as a fundamental KPI across all protocol layers.
Hybrid network with Hybrid Nodes (see §4)	The convergence of network- and device-based relay anchors can achieve ambitious 6G performance targets with a significantly lower energy footprint.
Networks to inherit established device power saving techniques	Network design should be able to achieve more ambitious power reductions during inactivity periods and lower activity states. There may be some scope to transpose and adapt some of these established device power saving techniques to base stations.

Research direction	Description
Dynamic on/off & device-assisted network wake-up	Network nodes need to be shut down or left in lower capability states whenever possible while minimizing impact to connected devices. However, this cannot be easily achieved without significant side effects on the network operation. Better mutual awareness between network and devices may provide better criteria for joint optimal behaviour.

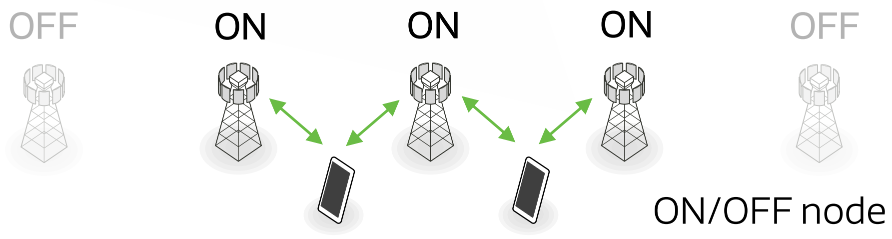

Figure 10. Dynamic network node on/off with device-assisted wake-up

8.3 Energy efficiency for extreme performance – a fundamental KPI

Table 11 summarizes a number of specific challenges related to device and network power consumption. Power-efficient device and network operation cannot be an after-thought as has been the case in previous cellular generations. Strong power-aware research will be required across all technical disciplines (RF circuit design, digital technology, waveform design, advanced MIMO, physical layer procedures, etc.) treating power consumption as a fundamental KPI from day one. This will likely require a change in research culture and in the standardization culture which have traditionally been performance-oriented. A number of existing system trade-offs will also need to be evaluated to carefully balance difficult trade-offs such as device vs. network power, power vs. performance, power vs. latency, etc.

Table 11. Specific challenges related to power consumption.

Challenge	Description
Power scaling vs. traffic load	Device and network power must reduce substantially whenever the data load reduces.
Network densification without increasing energy footprint	Additional densification is required to deliver additional capacity/Hz and to overcome higher propagation loss for higher bands (mmW, Sub-THz), but overall network power consumption must not increase.
Energy-aware end-to-end service delivery	There is a direct link between additional performance and additional power consumption. This must be a primary consideration in the definition of the technology solutions for adoption in the 6G standard.
Cooperation between network and device	Better mutual awareness between device and base station can help realize additional power saving gains at one or both ends.
Exploit device/network OFF time to save power in network/device	Active alignment of network and device inactivity periods to maximize joint energy saving.

9 Terrestrial and Non-Terrestrial Convergence

Non-Terrestrial Network (NTN) support is a promising development to complement existing terrestrial network (TN) deployments and fill existing coverage gaps with eMBB-like data rates. NTN systems can deliver wide coverage in sparsely populated areas at a much lower cost than cellular operator networks. However, a necessary condition is that NTN access poses no additional burden to end users: Re-using existing mainstream mass-market devices, such as smartphones, and existing cellular subscriptions is a key requirement.

Table 12. Challenges and research directions for Terrestrial and Satellite convergence

<table>
<tr><th></th><th>Increased system capacity</th><th>High-end mass market devices</th><th>NTN service experience no different than TN</th></tr>
<tr><td>Native NTN/TN integration</td><td rowspan="2">TN/NTN switching and TN/NTN spectrum re-use</td><td>Align TN/NTN air interface and network</td><td rowspan="2">Seamless user experience, single subscription</td></tr>
<tr><td>Integrated TN/NTN device</td><td>Consumer-grade handheld TN/NTN devices</td></tr>
<tr><td>Spectrum re-use across TN/NTN in low bands (e.g. L/S)</td><td>Operator re-uses TN spectrum for NTN use when no TN coverage</td><td>No additional device RF front end components in handheld devices (PA/duplexers/filters)</td><td>Similar spectrum availability as in TN</td></tr>
<tr><td>Satellite segment cost reduction</td><td>Large number of LEO satellites deliver higher capacity</td><td></td><td>Large number of lower cost LEO satellites enable lower subscription cost</td></tr>
</table>

9.1 Native TN/NTN integration

5G NR technology was specified starting in 3GPP Rel-15 and was later expanded to support NTN during Rel-17. 6G presents an opportunity to jointly define NTN/TN from its inception; that is to define a highly-integrated network architecture and radio interface technology that are unconstrained from backwards compatibility with earlier standard releases.

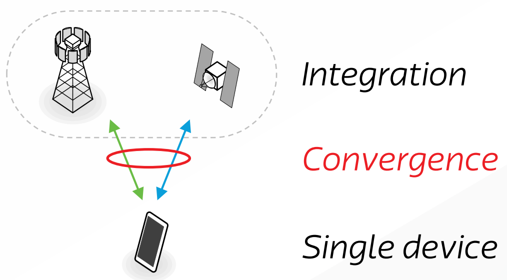

Figure 11. Native TN/NTN integration and convergence

In order to evolve from a niche service into a mass-market one, the following end-user objectives need to be achieved:

- **Truly ubiquitous service experience** for all relevant applications: broadband, IoT, SESSy[10], where NTN backfills existing TN coverage gaps.
- **Seamless TN/NTN mobility** for the end user and application, originating from a single subscription, similar to existing international roaming agreements.
- **Affordable NTN subscriptions** with acceptable broadband performance and/or indoor penetration when outside terrestrial coverage.
- **Affordable TN/NTN devices** available through already established retail channels.

9.2 Spectrum re-use across TN/NTN

Historically satellite and terrestrial frequency bands have been allocated on an exclusive basis and used completely independently, which prevents optimal spectrum utilization. The most desirable frequency bands on NTN-capable handheld devices are FDD bands located in the 1.5-2.5GHz range in L/S bands, where currently only a small amount of spectrum is available for satellite applications.

There is a substantial opportunity for terrestrial operators to extend their cellular coverage footprint by delivering NTN-based eMBB cellular service in remote areas, currently out of coverage. This can be achieved by leveraging their own licensed spectrum assets that are currently sitting unused in these sparsely populated regions. Available NTN spectrum alone is presently insufficient to deliver an acceptable broadband experience to handheld devices, and these unused cellular terrestrial spectrum assets can be instrumental to deliver eMBB service in remote areas.

This specific arrangement also has additional positive implications to enable device economies of scale. Re-using TN frequency bands for NTN allows full re-use of TN-specific RF front end components (filters, duplexers, wideband amplifiers, antennas) and fully avoids the need for additional cost, volume and complexity for NTN-capable devices.

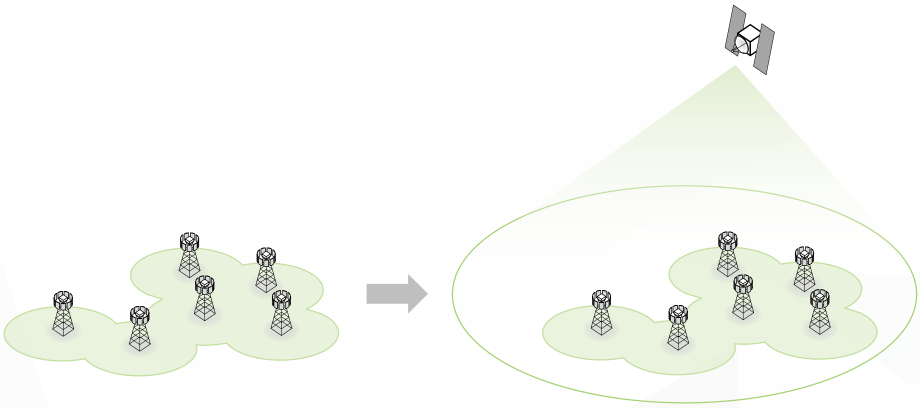

Figure 12. Spectrum re-use across TN/NTN

[10] SESSy: Sustainable Environmental Sensing Systems

9.3 Single, affordable TN/NTN device

Existing handheld satellite communication terminals are generally bulky, unattractive and costly when compared to terrestrial cellular devices. As discussed in the previous section, the combination of a common TN/NTN air interface and TN frequency band re-use can virtually suppress any device incremental complexity at any level (RF front end, RF transceiver, baseband, form factor, etc.).

NTN/TN technology alignment can then be combined with a single subscription covering both TN/NTN, and turn NTN into a mass-market mainstream feature of the existing vast, dynamic and highly innovative smartphone ecosystem. Crucially, 6G TN/NTN device capability can become one additional feature widely available by default to all consumers, with the same form factor and cost structure as before this feature is introduced. 6G TN/NTN capable devices can also be delivered through already well-established OEM manufacturing and existing retail channels.

Further to this, the combination of NTN technology with 6G device mesh/relay capability can be used to provide deeper indoor coverage in remote areas.

10 Native AI-integrated System – Communication and Computing Convergence

Artificial intelligence and machine learning are fast being introduced across all industry sectors, whether for professional or consumer use. AI/ML can perform complex tasks automatically (i.e. with minimal and ultimately no human intervention) while iteratively learning from its actions to systematically improve its performance over time. AI/ML is therefore not only a very promising tool in the 6G era, it will play a key role in the set up, optimization, management, orchestration and operation of 6G systems.

The target and ability of adding artificial intelligence to automatically and iteratively improve the performance of mobile networks without human intervention has been around for a long time. Within existing 4G and 5G systems for instance, SON (Self-Optimizing Networks) and MDT (Minimization of Drive Tests) functionality allow autonomous optimization of network and device operation with minimal human intervention. Machine Learning brings new opportunities for networks and devices to use large data sets to identify and learn by themselves how to optimize system performance, without a defined set of prescribed outcomes.

While AI/ML will be used to optimize the performance of 6G devices and 6G networks independently, it will also be used collaboratively between 6G networks and 6G devices to optimize the performance of the 6G system as a whole. AI/ML will enable performance optimization in real-time, near-real-time or non-real-time depending on the needs at hand, including for example:

- Real-time: physical layer operation, link adaption, scheduling, device power consumption.
- Near-real time: load balancing, QoS optimization, interference management.
- Non-real-time: network planning, network configuration.

ML could bring advantages to maximize network performance beyond what is possible today for essential high-level KPIs such as: area spectrum efficiency, service throughput/ latency/ reliability/ availability, device battery life, network/device energy consumption, connection setup latency/reliability, device location accuracy; and when breaking these down into the different functions impacting each KPI, the opportunities for ML to support those aims are endless, e.g. optimizing cell search, radio link adaptation for MIMO, mobility, interference mitigation, traffic routing among others.

Then when complementing this with data about the end-to-end application into the radio access domain, this can allow for further optimization of service provisioning.

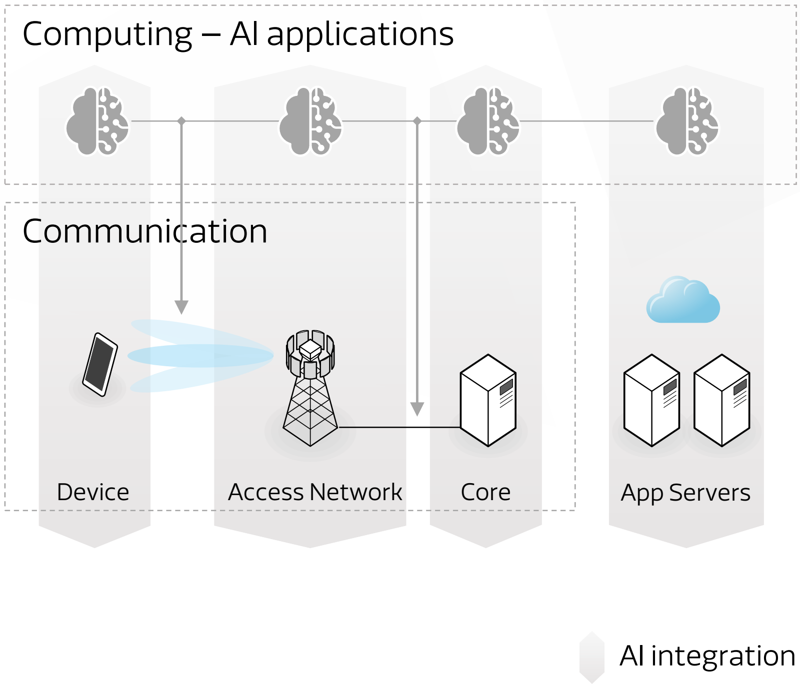

Figure 13. Opportunities for AI integration in 6G era

Such opportunity also brings a number of challenges including:

- How to perform optimal learning in a network where the "decision-making" is not centralized and where the data to support decision-making is not generated from a single node.
- How to ensure collaborative algorithms in a multi-vendor environment where nodes from different manufacturers inter-connect with each other.
- How to efficiently and securely manage and transfer data sets to the appropriate part of the system for making such decisions, without degrading relevant KPIs.
- How to validate the performance of ML techniques in networks and devices to ensure the best decision-making taking all KPIs into account.

The above challenges call for a collaborative standardization framework among all industry players to identify the key target areas for Machine Learning, to define the related framework(s) and architecture to facilitate the successful adoption of Machine Learning.

Preparatory discussions are taking place as part of 5G-Advanced in 3GPP. Also, within the O-RAN Alliance, there has been work to identify architecture and interfaces for data collection, and the O-RAN RAN Intelligent Controller (RIC) has been defined. However, 6G will be the first generation of mobile communication system where the ML form of AI is natively integrated from the outset, thus ensuring simplicity in the overall system design, whilst maximizing performance.

11 Spectrum – More Spectrum, Better Spectrum usage

The number of wirelessly connected devices serving different societal needs is continually increasing. This is a trend that shows no sign of abating and will consequently require ever-higher capacity, which in turn will require the availability of more spectrum to satisfy the traffic demands of those devices and applications. In this section we look at some of the potentially relevant new spectrum ranges for 6G, the continued need to create a smarter spectrum access, and how optimal spectrum sharing can create more new opportunities for the 6G platform.

11.1 Beyond 7 GHz (7-24 GHz)

3GPP currently specifies bands within FR1 for 5G NR up to the 7.125 GHz range with a gap before FR2 begins at 24.25 GHz. In the 7-24 GHz range, there are potentially large blocks of available spectrum[11]. The characteristics offered by this frequency range provide a "sweet spot" between the advantages of FR1 and FR2, and could enable the following advantages for 6G operation:

- Higher-order MIMO (8x8 or more) – due to the feasibility of a larger array of antenna elements integrated into a smaller physical dimensional area. This is a limiting factor for existing frequency bands in the FR1 range due to their longer wavelength.
- Improved propagation characteristics vs. bands operating in the FR2 range.

Therefore, the 7-24 GHz frequency range should be given strong consideration as a candidate frequency range for 6G operation.

11.2 Sub-THz

In the sub-THz frequency range there is the opportunity for large amounts of new spectrum for 6G communications. Table 13 below highlights the potential opportunities across different regions.

Table 13. Sub-THz spectrum opportunities

Frequency Range	Potential available spectrum and timeframe	Regions
100 – 200 GHz	130–134, 141–148.5, 151.5–164, 167–174.8 GHz with a total of 31.8 GHz identified for fixed and/or mobile.	USA (FCC), Europe (ECC)
≥ 200 GHz	23 GHz of bandwidth from 252–275 GHz designated for land mobile & fixed service on a co-primary basis.	Worldwide (WRC16)
275 – 450 GHz	175 GHz of bandwidth identified for fixed & mobile, of which 137 GHz is unrestrictive, 38 GHz is to be shared with earth exploration satellite service.	Worldwide (WRC19)
Various	A number of allocations totaling 21.2 GHz of bandwidth for experimental unlicensed usage.	USA (FCC)

[11] See 3GPP TR 38.820, "7 - 24 GHz frequency range (Release 16)" V16.1.1, 2021 - 03

However, wireless channels in this frequency range experience large propagation and reflection loss, sporadic availability of line-of-sight links due to blockage, and molecular absorption. These phenomena result in a link performance with shorter range and an intermittent on/off behavior. The small size of a Sub-THz antenna allows the transceiver to be equipped with a high number of antenna elements to achieve a narrow beam with high beamforming gain, which can help to overcome the attenuation loss and molecular absorption. Nevertheless, this also makes operation more sensitive to beam misalignment, resulting in an increasing challenge to perform beam tracking of mobile users.

In terms of use cases, these characteristics make sub-THz spectrum more suitable to the following applications:

- Fixed backhaul or nomadic devices, communicating with e.g. a hub or as part of a network mesh via LOS point-to-point/multipoint links with narrow stationary beams to maximize link range.
- Short range hubs providing high data rates/capacity to a potentially large number of users within localized LOS environments (e.g. indoor, large venues, etc.).

To maximize the opportunity of Sub-THz, an advanced radio access protocol design will be required that is able to overcome the challenges highlighted while meeting the needs of the target use cases, with a converged design (see §4) that can operate under different licensing regimes – licensed, unlicensed or a hybrid of the two approaches.

11.3 Smart spectrum access with flexible duplex

Existing 5G bands in the 0.4 – 3 GHz frequency range will still be important for the 6G ecosystem, due to their natural coverage benefits, especially for outdoor-to-indoor communication. The scarcity of spectrum assets make it important for 6G to maximize spectrum efficiency. Achieving this via higher orders of MIMO will be difficult in this range due to the physical antenna size constraints and the limitations they bring to networks and devices, so different approaches will need to be identified. The fact that such "always-on" network transmissions in 5G NR have been minimized should make re-farming from 5G NR to 6G radio access a *low-effort* process for operators, compared to re-farming from across previous generations (including 4G to 5G).

Better utilization of *existing* 5G high bands from 3GHz to 71GHz will also be important and we expect that "heterogeneous MIMO" (see section 6) will have a strong role to play here where devices collaborate as network nodes to maximize the overall spectrum resource efficiency in an area.

Whereas existing spectrum has largely been defined statically for "FDD" or "TDD" duplex operation, we expect that 6G will be revolutionary in driving an *unconstrained smart duplex access across all spectrum types*, via either full or partial duplex at the network and device, to maximize spectrum utilization. It may also allow separate blocks of spectrum to be combined (e.g. high + low frequency) in more innovative ways to realize a better performance vs. complexity trade-off.

11.4 Optimal spectrum sharing

The increased need for spectrum to fulfil the needs of both peak and average traffic capacity in an area (and associated application requirements) will lead to a requirement for an increased and more opportunistic access to spectrum to meet those needs at minimum cost to network providers.

In light of this, the 6G system needs to support optimal spectrum sharing, not just between operators and users of the same network, but also enabling optimal coexistence of different deployment topologies. One example is in ensuring that when end devices/Hybrid Nodes are used as part of a mesh network, then their transmission and reception is able to be coordinated with both the transmission and reception with other nodes of the same type, and with traditional network nodes, in order to avoid interference and maximize the experience for all users within the geographical area. The re-use of spectrum across Terrestrial and Non-Terrestrial nodes (see section 9.2) will bring new challenges to overcome in order to support an optimal re-use to enable fully seamless coverage.

Finally, enabling 6G to coexist with incumbent non-mobile technologies will also be key to ensure that industry verticals can adopt 6G and maximize reuse of any existing designated spectrum assets.

12 End-to-end Security Architecture – Across Cloud, Network and Device

With the 6G ecosystem poised to accelerate the digital transformation of our society (whether for people, businesses or governments), it must be natively robust against any accidental or malicious compromise and flexible enough to tackle new unknown threats. Only then can 6G be fully trusted by people, businesses and governments alike to deliver its promise.

As a condition of its success, trust in 6G will have to be conferred by end users and by the entities that operate and deliver 6G ("6G operators"). Trust is certainly about the ability of 6G to fulfill or exceed expectations in terms of user experience, but it is fundamentally about its ability to offer full *security* and *resilience*.

Trust in 6G will be built on:

- the assurance that the 6G system and equipment are fully *secure*, that is: By design, the 6G system fully protects all user data and identities it transfers or stores, at all times. By extension, the 6G equipment fully and verifiably complies with protecting all user data and identities.
- its high degree of in-built *resilience*, i.e. its ability to swiftly and automatically recover upon failure, and on its ability to selectively offer a higher degree of availability in scenarios where failure is not an option (e.g. some governmental deployments with necessary redundancy).

The 6G security encompasses not only the protection of user data and identities, but also the necessary means allowing any equipment (cloud, network and devices) intending to communicate with one another to authenticate each other and authorize such communication such as to protect not only against the unauthorized use of the system, but also against the malicious use thereof.

Three main challenges face 6G in terms of security:

- New architecture models enabled by 6G, combining cloud, network, devices;
- The central role of AI/ML in 6G;
- The advances in computing.

The 6G ecosystem will combine a plurality of technologies involving cloud (and associated servers), network infrastructure, devices and interfaces between those. It will also feature decentralized network architecture model s with e.g. the widespread use of edge computing, and the advent of cellular mesh networks. This will generate potential new vulnerabilities where e.g. some functions are pushed towards the edge that were previously residing in secure areas of the core network. Devices will for instance play no longer only the role of a source or destination endpoint in the architecture, but also a more active role in offering connectivity to other devices in their vicinity and therefore will bear the responsibility to e.g. measure and log usage information that historically would have been in the core network. Distributed network components may also have their own requirements for handling of local data (e.g., network edge nodes deployed in a secure location may need to keep some data confined locally, rather than sharing it with other network nodes outside the edge). Therefore, individually and collectively, all components of the 6G system must natively deliver a basic yet high level of security and resilience no matter the architecture model, and importantly all the while ensuring no QoS degradation (e.g. in terms of latency).

AI/ML will play a central role in the operation of 6G systems, in particular to minimize or avoid human intervention. With it an unprecedented and sheer amount of data is anticipated to be generated, transmitted, stored and exploited in and by the 6G system. These data will include user-related data in part. Protecting the confidentiality, integrity and provenance of these data will be vital not only for 6G to be trusted, but importantly first for 6G to operate properly (e.g. any malicious data corruption could have detrimental effects on the operation of 6G). However it is not only the protection of the data that matters, but also the detection and identification of any potential corruption thereof such that these data can e.g. be discarded before they can affect the operation of 6G. While AI/ML must be inherently secure so it can be trusted and widely used for operating 6G systems, it will also be a critical tool in *making* these systems that are necessarily complex, secure. AI/ML will enable the fast detection of and response to security threats and vulnerabilities that may arise in 6G systems and, importantly, learn from such events to iteratively boost the security level of these systems.

Advances in computing, in particular quantum computing, pose a major threat to cryptography and with it the digitization of our society. Means that could protect against cryptanalytic attacks by quantum computers should be investigated for 6G, not only from a security standpoint, but also from a practical implementation standpoint, considering both asymmetric cryptography and symmetric cryptography algorithms.

Finally, a promising avenue i.e. physical layer security, complementary to more traditional cryptographic solutions, need to be investigated both in terms of security and in terms of implementation complexity for use in the 6G system. Physical layer security can offer effective and efficient means against vulnerabilities and threats on the radio medium that is naturally prone to attacks, whether in terms of eavesdropping or Denial-of-Service (e.g. jamming). For example, by exploiting the physical layer properties and randomness of the radio channels and/or of the radio equipment, physical layer authentication can be realized in a more efficient manner than at higher layer protocols. Physical layer security can also be a particularly powerful tool against e.g. eavesdropping attacks in communication systems using MIMO and/or relayed communications (such as using Hybrid Nodes, see §4) both of which being core components of the 6G System. MIMO beamforming techniques could be exploited to jam potential eavesdroppers; (trusted) Hybrid Nodes could also cooperate with one another to interfere with potential eavesdroppers.

13 Conclusions

6G, an IMT2030 and beyond technology, will be commercially available around 2030 as the result of a global standard that will be initiated by 3GPP from ca. 2024. This next generation wireless communication standard will be defined to expand the digital transformation of our society, whether for people, businesses or governments across various consumer and professional markets. Such an ambitious goal necessitates an overall system design that can cater to the extreme performance demands of these markets while also being adaptive to their various data consumption models and deployment scenarios in a fully secure and sustainable manner.

While intuitively highly complex, this exercise requires following from the outset, key practical technology principles so our vision can become reality i.e. Simplexity, Optimization and Convergence or “SOC”:

- Simplexity is the balance of necessary additional complexity alongside a focus on simplicity. This enables a leap in performance, while significantly reducing the processing requirements per bit delivered in order to keep cost and energy consumption within realistic bounds.
- Optimization must be guided by practical user experiences, whether the user is offering or consuming 6G. We expect optimization along three new key directions: *heterogeneous radio access architecture*, *artificial intelligence and machine learning*, and *application-specific cross-layer design*.
- Convergence between peer domains is an opportunity to tackle challenges on coverage, affordability and energy efficiency e.g. between *devices and network nodes*, between *spectrum regimes*, between *access/ front/ backhaul links*, between *device-to-device and base station to device access*, between *terrestrial and non-terrestrial access*, between *communication and computing*, etc.

The 6G system will feature a relative increase in complexity vs. 5G, in terms of e.g. traffic and device types, spectrum ranges and regimes, and networking topologies. Artificial Intelligence and Machine learning will allow the simplification of 6G deployment and operation, via integration into all aspects of network and device operation, iteratively learning to systematically improve 6G system performance whether in real-time (e.g. link adaptation, scheduling), near-real-time (e.g. load balancing, interference management) or non-real-time (e.g. network planning). This intends to support overall goals such as maximizing user experience, optimizing cost efficiency, and minimizing the energy consumed.

Energy efficiency will represent both a challenge and an opportunity for 6G to make a real difference. Societal sustainability goals will drive a reduction in overall network energy footprint whilst still requiring orders of magnitude increases in performance (and likely node densification). On the device side, thermal and energy storage challenges will need to be overcome to enable higher practical data rates and new device form factors for advanced, immersive applications. A substantial shift in research culture will be necessary to meet these needs – both in terms of wireless research disciplines and semiconductor technology – with energy efficiency as the fundamental KPI.

Spectrum will be another fundamental driver for the 6G system design. To cope with even more diverse demand in terms of service requirements and use cases, and the need for geographically ubiquitous and on-demand access to those services, the system will need to cater for both existing and new frequency ranges and enable optimal spectrum sharing. It will need to facilitate an improved utilization and ease of re-farming for existing spectrum assets used for 5G and legacy mobile systems (for both terrestrial and non-terrestrial deployments), as well as an extension into both the sub-THz range and the 7-24GHz range. Catering for different sharing regimes will allow 6G to facilitate both improved spectrum utilization for its system deployments, and legacy spectrum reuse by industry vertical markets. Different deployment scenarios will be required to allow the different frequency ranges to be used optimally.

MIMO will be an increasingly key technology for 6G, with an extended design needed to help to compensate for the challenges of sub-THz propagation characteristics, and with a substantial increase in antenna elements permitted by smaller antenna element size. We also expect that associated network densification due to mmW and sub-THz frequencies will drive demand for a distributed MIMO operation with a “cell-free” design approach to enable different radio nodes to seamlessly contribute to the user experience.

Convergence at the wireless access will be critical to support the target 6G architecture, by avoiding technology fragmentation to maximize technology economies of scale, and hence minimize network and device costs vs. performance. To this end, a unified radio waveform *principle* is recommended, that will be natively scalable via a simple set of waveforms and numerologies. In addition, convergence between devices and network nodes i.e. the “device ification” of network nodes, or development of “Hybrid Nodes”, will be necessary, as an economically viable means to extend terrestrial 6G coverage with spectrum assets located at higher frequencies (e.g. from C band to mmW and Sub-THz).

The 6G architecture should be fully adaptable to offer the best networking topology to serve any given data consumption model between communication endpoints, whether directly between devices in a local mesh, through traditional terrestrial network infrastructure, or relayed via airborne or satellite equipment. To this end, and from a radio architecture standpoint, Hybrid Nodes will play a major role and support the networking functionality necessary to cooperatively determine, with or without network involvement, the best corresponding radio networking topology. The 6G architecture will also be natively application-driven, and with configurability to support:

- optimal allocation, distribution and sharing of compute resource at and between the network edge and devices;
- localization and distribution of server functionality at and between multiple nodes;
- direct device-to-device operation.

The legacy user plane protocol stack has been traditionally configured to deliver lossless in-order data delivery, which is unsuitable for latency-constrained, highly-interactive immersive applications. A fresh approach is required to address the challenges posed by relevant user experience disruptors (jitter, packet loss and data rate fluctuations). A Lean User Plane protocol stack will rely upon stronger mutual awareness between applications and radio layers to achieve the required performance, while reducing the need for packet-level interventions causing unacceptable delay and traffic overheads, and also avoiding an otherwise significant memory footprint burden associated with data buffering.

Terrestrial and non-terrestrial access convergence is a necessary development to cost-effectively fill existing cellular coverage gaps in sparsely populated areas. Our vision is to leverage the scale and market footprint of existing device and network cellular terrestrial ecosystem to avoid any additional burden on users. Low-impact hardware modifications to consumer-grade devices are fundamental so that users can also access satellite service through single, affordable mainstream devices, cellular networks and subscriptions. Key ingredients towards this goal are native integration of terrestrial/non-terrestrial radio interface and network, and spectrum re-use between terrestrial and non-terrestrial access.

Finally, 6G will need to be intrinsically secure, resilient and thereby trusted in the presence of new threats. Physical layer security, complementary to traditional cryptographic measures, will not only improve the security of 6G systems over 5G systems, it will also tackle the latency issues of traditional security measures e.g. higher layer authentication, thus also fully enabling latency-sensitive applications. AI/ML will play an important role in allowing the fast detection and response to threats and vulnerabilities while learning from those to prevent new security gaps.