Qualcomm @QCOMResearch San Diego, CA November 2022

Why and what you need to know about 6G in 2022

5G Advanced is establishing our early vision and the technical foundation for 6G in 2030 and beyond

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Agenda

There is a rich roadmap of 5G technologies coming with the 5G Advanced evolution

6G will be the future wireless innovation platform for 2030 and beyond

6G will be more than a new radio, expanding AI, sensing in the connected intelligent edge

We are leading cutting-edge wireless research across six technology vectors on the path to 6G

Transportation

Manufacturing

Industrial

Retail

Energy

Driving digital transformation across industries

5G will enable $13.1 Trillion in global sales activities in 2035

Agriculture

Public safety

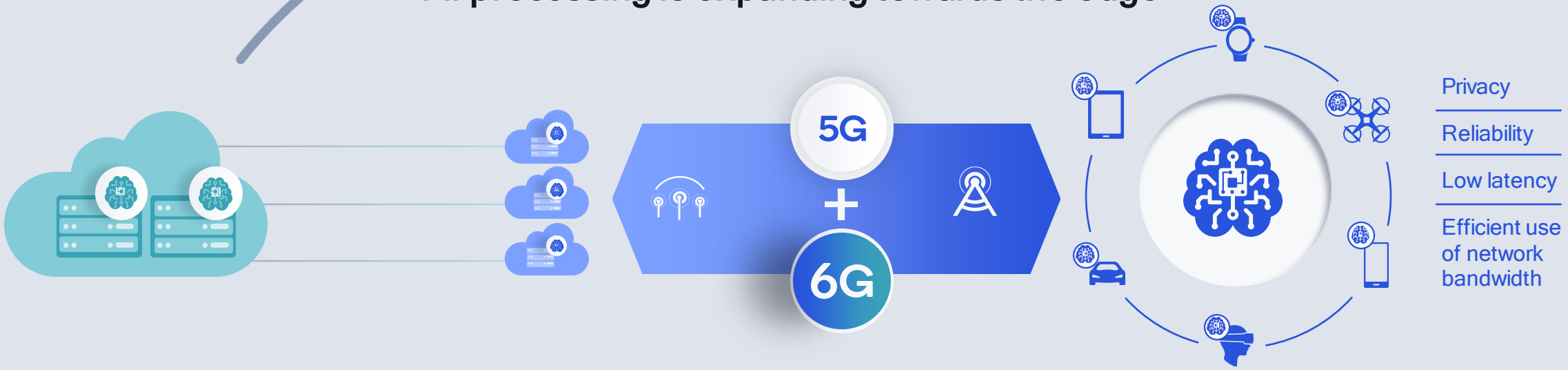
Smart cities

Healthcare

Entertainment

Source: The 5G Economy, an independent study from IHS Markit, commissioned by Qualcomm Technologies, Inc., November 2020

To scale efficiently, AI processing is expanding towards the edge



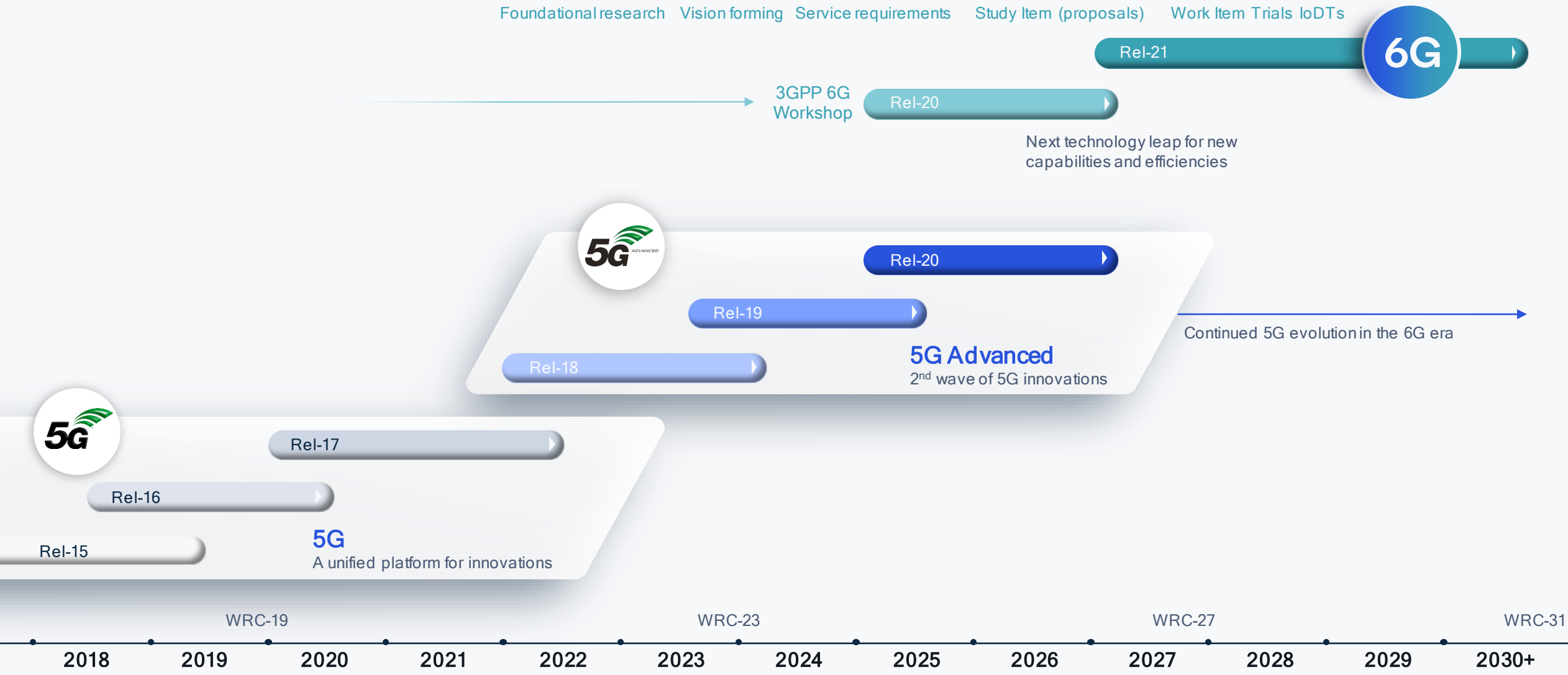
Qualcomm is leading the realization of the connected intelligent edge

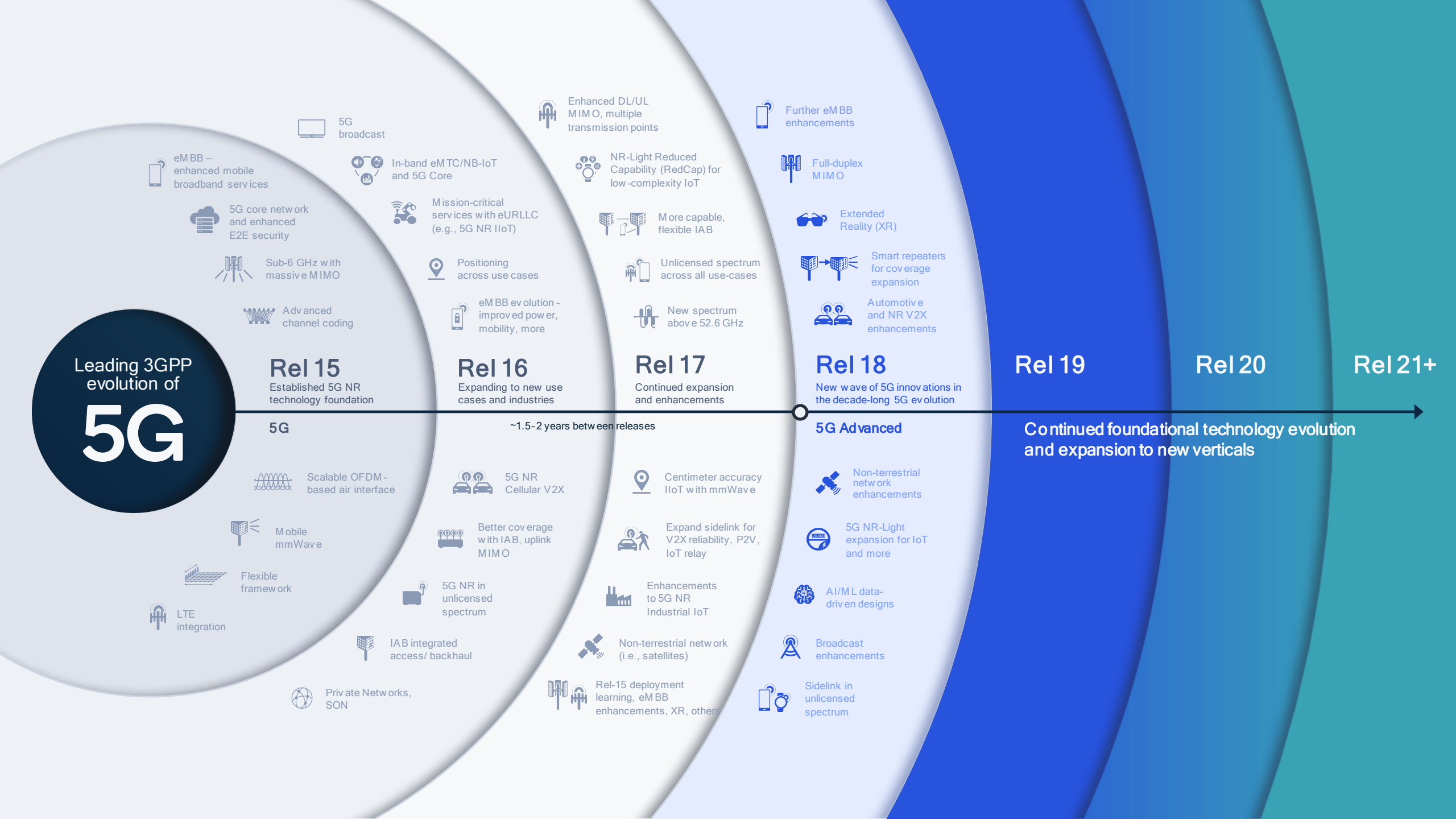
Convergence of:

- Wireless connectivity
- Efficient computing
- Distributed AI

Unleashing massive amount of data to fuel our digital future

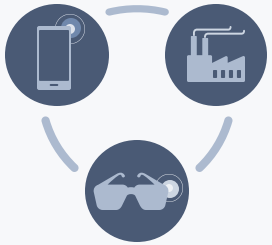
5G Advanced on the path to 6G




Leading 3GPP evolution of 5G
eMBB – enhanced mobile broadband services
5G core network and enhanced E2E security
Sub-6 GHz with massive MIMO
Advanced channel coding
Scalable OFDM-based air interface
Mobile mmWave
Flexible framework
LTE integration
Rel 15
Established 5G NR technology foundation
5G
5G broadcast
In-band eMTC/NB-IoT and 5G Core
Mission-critical services with eURLLC (e.g., 5G NR IIoT)
Positioning across use cases
eMBB evolution - improved power, mobility, more
5G NR Cellular V2X
Better coverage with IAB, uplink MIMO
5G NR in unlicensed spectrum
IAB integrated access/ backhaul
Private Networks, SON
Rel 16
Expanding to new use cases and industries
Enhanced DL/UL MIMO, multiple transmission points
NR-Light Reduced Capability (RedCap) for low-complexity IoT
More capable, flexible IAB
Unlicensed spectrum across all use-cases
New spectrum above 52.6 GHz
Centimeter accuracy IIoT with mmWave
Expand sidelink for V2X reliability, P2V, IoT relay
Enhancements to 5G NR Industrial IoT
Non-terrestrial network (i.e., satellites)
Rel-15 deployment learning, eMBB enhancements, XR, others
Rel 17
Continued expansion and enhancements
~1.5-2 years between releases
Further eMBB enhancements
Full-duplex MIMO
Extended Reality (XR)
Smart repeaters for coverage expansion
Automotive and NR V2X enhancements
Non-terrestrial network enhancements
5G NR-Light expansion for IoT and more
AI/ML data-driven designs
Broadcast enhancements
Sidelink in unlicensed spectrum
Rel 18
New wave of 5G innovations in the decade-long 5G evolution
5G Advanced
Rel 19
Rel 20
Rel 21+
Continued foundational technology evolution and expansion to new verticals

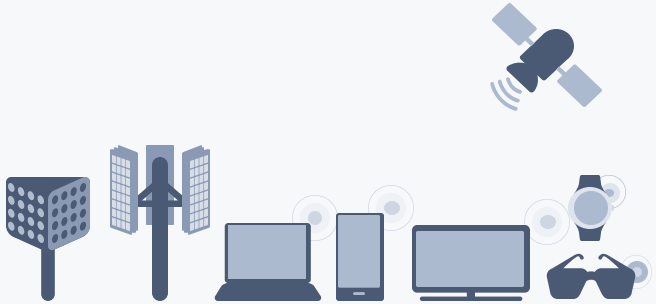
Driving a balanced 5G Advanced evolution across key technology areas

Mobile broadband evolution and further vertical expansion



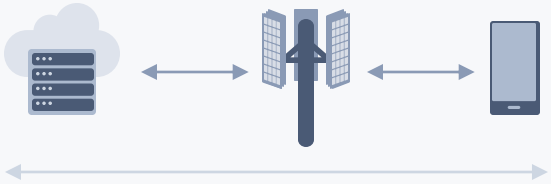
Deliver enhanced mobile broadband experiences and extend 5G's reach into new use cases

Immediate commercial needs and longer-term 5G vision



Drive new value in commercialization efforts and fully realize 5G's potential with future deployments

New and enhanced devices and network evolution



Focus on the end-to-end technology evolution of the 5G system to bring new levels of performance

Release 18 starts the 5G Advanced evolution and it prepares for new and enhanced features coming in subsequent releases

5G ADVANCED

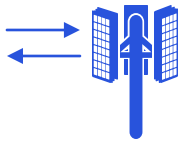
Release 18

3GPP Release 18

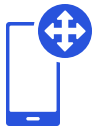
sets off the 5G Advanced Evolution

[Learn more about 3GPP Release 18]

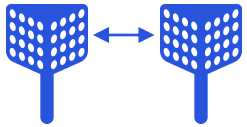
Strengthen the end-to-end 5G system foundation



Advanced DL/UL MIMO



Enhanced mobility



Mobile IAB, smart repeater

Evolved duplexing

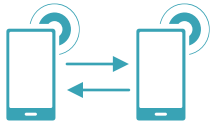
AI/ML data-driven designs

Green networks

Proliferate 5G to virtually all devices and use cases

Boundless extended reality

NR-Light (RedCap) evolution



Expanded sidelink

Expanded positioning

Drones & expanded satellites comm.

Multicast & other enhancements

CONTINUED TECHNOLOGY EVOLUTION

Key market trends and technology drivers

leading the way to 6G

Core technology advancements

Environmental and societal sustainability

Enhanced and new experiences

CONTINUED TECHNOLOGY EVOLUTION

6G

Key market trends and technology drivers leading the way to 6G

Core technology advancements

- Advanced RF
- Compute topology
- Machine learning and AI
- Silicon / material
- Extreme disaggregation
- Multimedia / display
- Perception / human interface
- Power management
- Others...

Key market trends and technology drivers leading the way to 6G

Environmental and societal sustainability

Wireless ecosystem reach to fuel sustained global economic growth

System design to consciously minimize environmental impact

More accessible networks, devices, services to promote digital equality

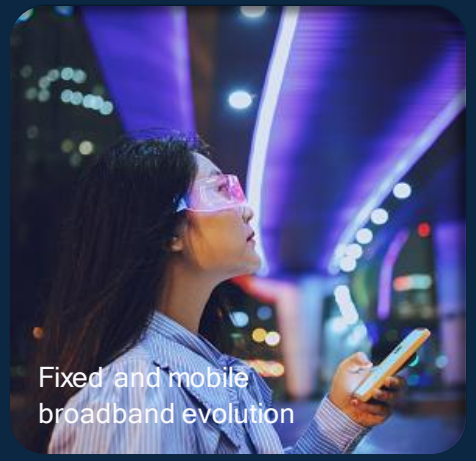
CONTINUED TECHNOLOGY EVOLUTION

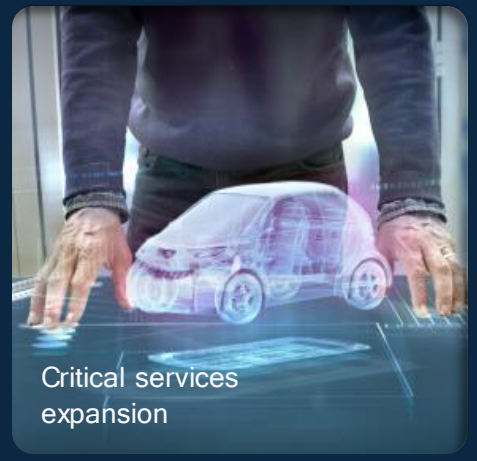
6G

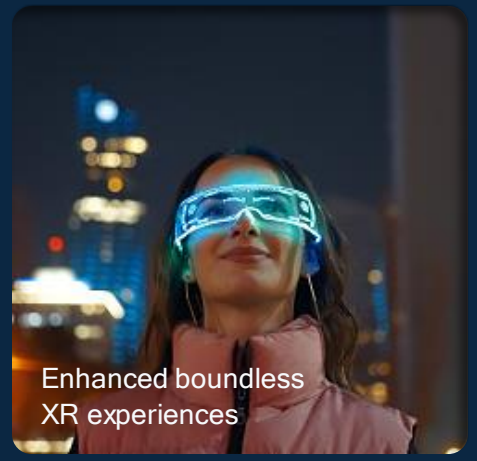
Key market trends and technology drivers leading the way to 6G

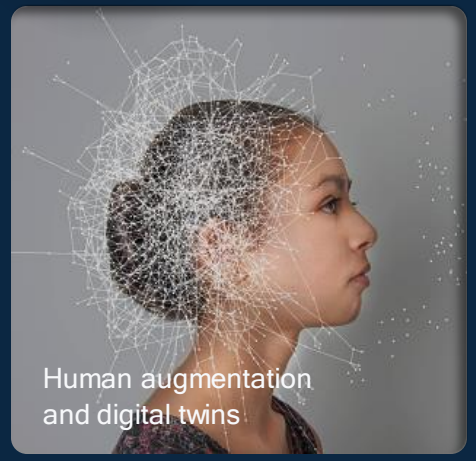
Enhanced and new experiences

- Fixed and mobile broadband to further evolve bringing next-generation experiences
- Digital twins to more accurately model the physical world continuing to derive new values
- Metaverse to further augment the physical world creating next-level immersivity







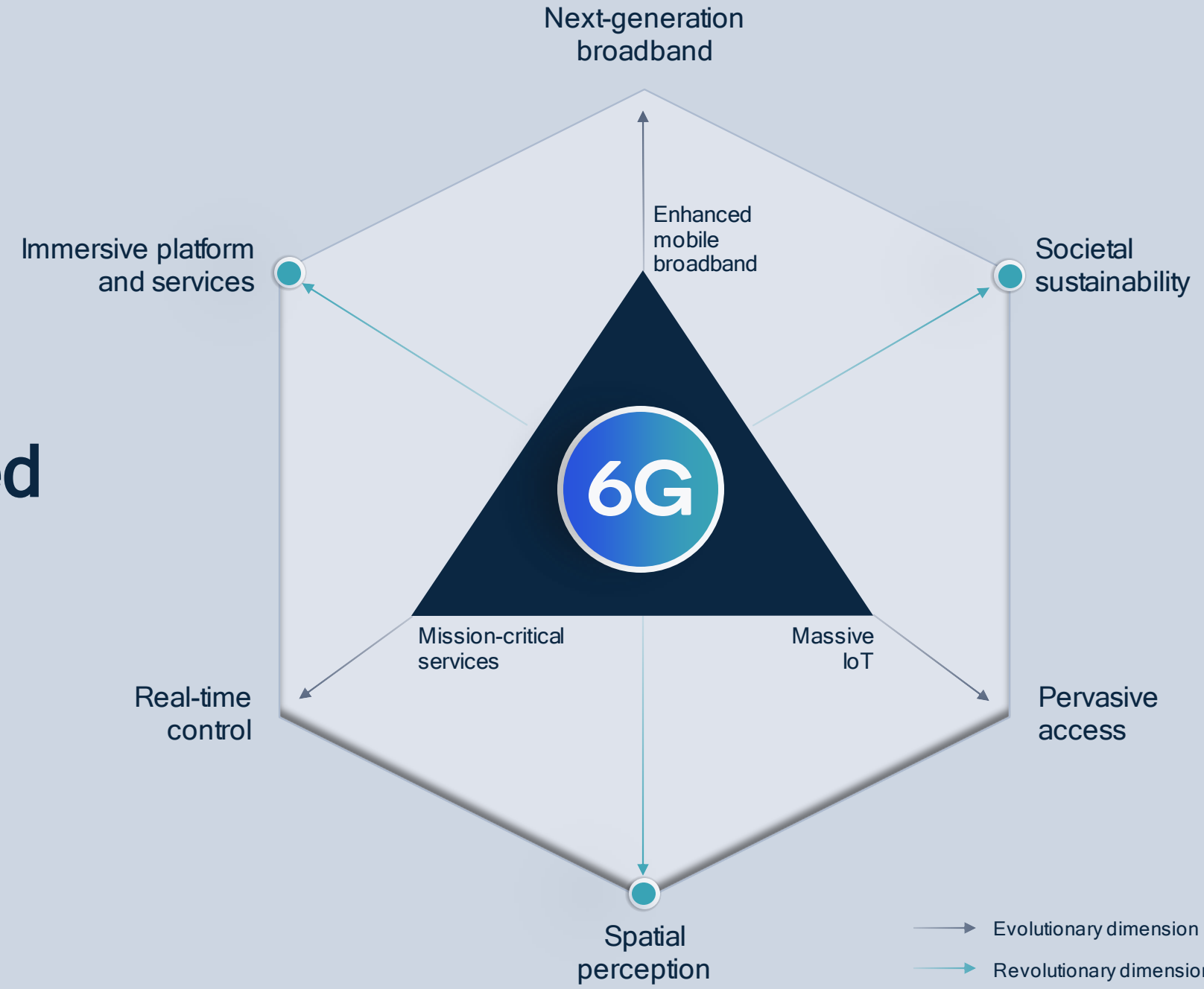


6G

Propelling next-level experiences and innovative use cases in the new era of the connected intelligent edge for 2030 and beyond

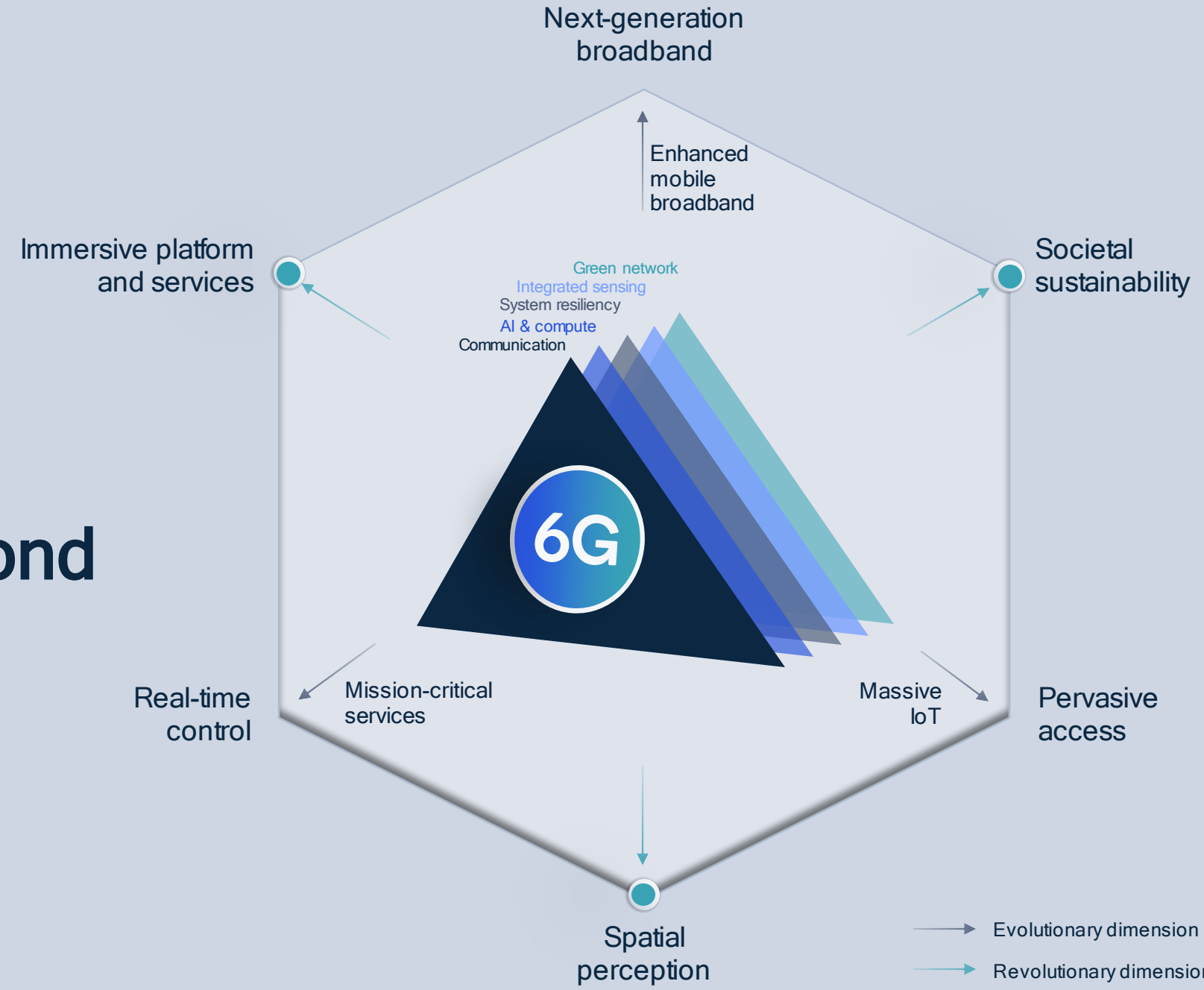
A smarter wireless platform to

support enhanced services and new use cases

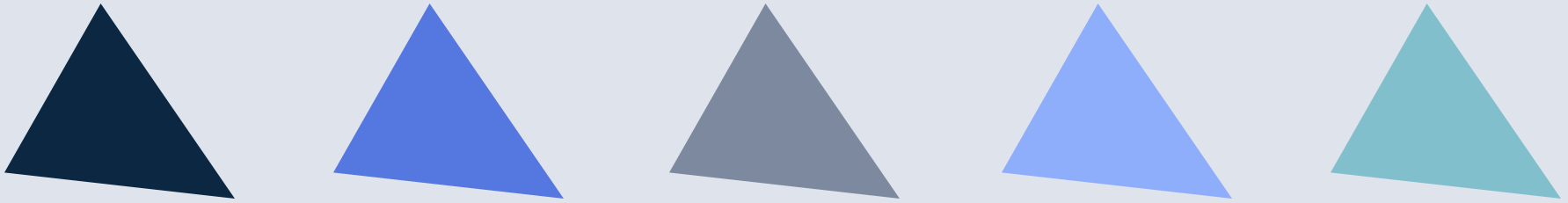


A smarter wireless platform with

new capabilities that expand beyond communication



System design targets for expanded 6G capabilities



Key Performance Indicators	Communication	AI & compute	System resiliency	Integrated sensing	Green network
	Capacity	Inference accuracy	Confidentiality	Range	Network energy efficiency
	Data rate	Model transfer latency	Integrity	Confidence level	Network carbon intensity
	Mobility	AI service roundtrip time	Availability	Sensing accuracy	Carbon neutrality
	Coverage	Compute capacity	Mean time to detect / resolve / contain	Resolution	ECO rating
	Connection density	Scalability / adaptability	...	Latency	Battery requirement
	...	...		...	...

6G will be designed to meet enhanced traditional communication requirements as well as KPIs for new capabilities

Designing 6G to meet a

diverse set of system requirements

Further enhancing foundational wireless performance vectors (e.g., capacity, data rate, latency)

Introducing new dimensions (e.g., user experience, positioning capability, ease of onboarding)

Key longer-term research vectors

enabling the path towards 6G

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enabling the path towards 6G

AI-native E2E communications

Data-driven communication and network design, with joint training, model sharing and distributed inference across networks and devices

Scalable network architecture

Disaggregation and virtualization at the connected intelligent edge, use of advanced topologies to address growing demand

Expanding into new spectrum bands

Expanding to THz, wide-area expansion to higher bands, new spectrum sharing paradigm, dynamic coordination with environmental awareness

Air interface innovations

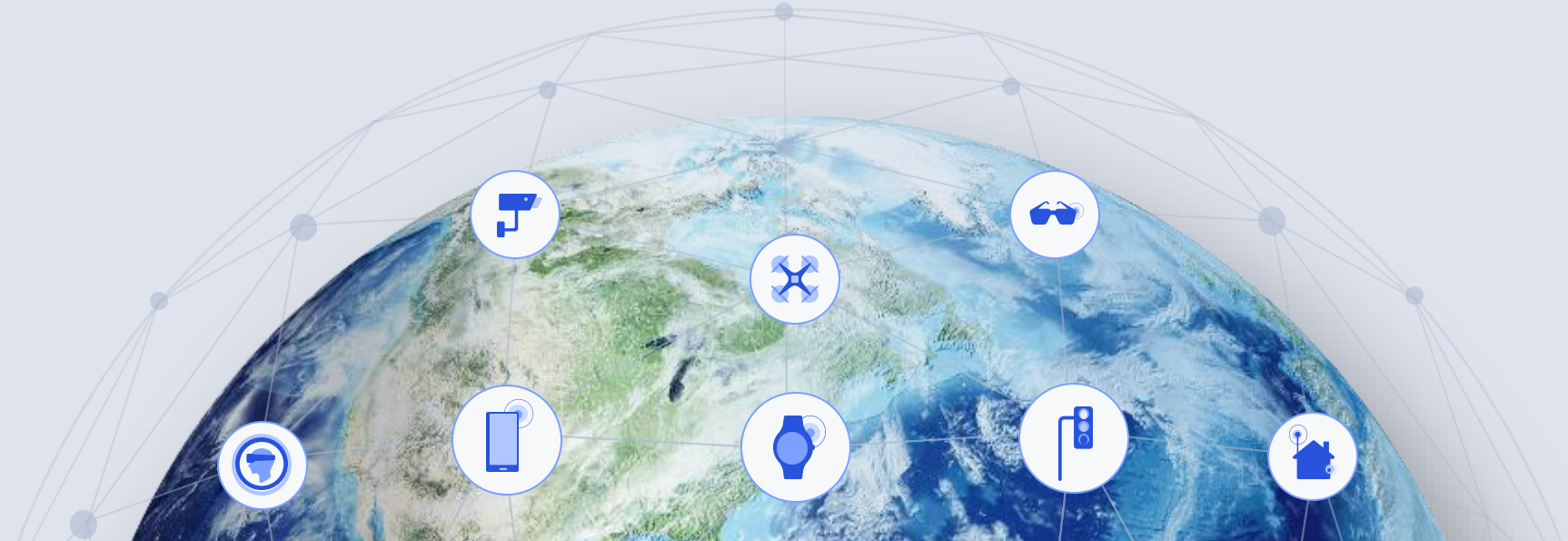
Evolution of duplexing schemes, Giga-MIMO, mmWave evolution, reconfigurable intelligent surfaces, non-terrestrial communications, waveform/coding for MHz to THz, system energy efficiency

Merging of worlds

Physical, digital, virtual, immersive interactions taking human augmentation to next level via ubiquitous, low-power joint communication and sensing

Communications resiliency

Multifaceted trust and configurable security, post quantum security, robust networks tolerant to failures and attacks



Advancement in AI is making

Wireless better

Elevated level of performance

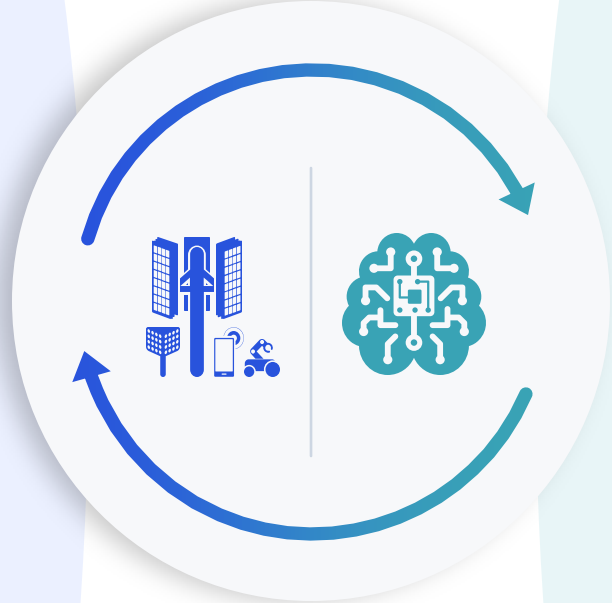
More efficient resource utilization

Energy reduction for longer battery life

Personalized security and privacy

Continuous enhancements over time

New and enhanced system capabilities



Proliferation of cellular is making

AI better

Responsive user experiences and services

Lifelong learning

Flexibility for distributed functionality across devices

On-device intelligence assisted by cloud

Scale intelligence through distributed learning

Massive data aggregation for improved AI models

5G and AI are working together to accelerate innovations

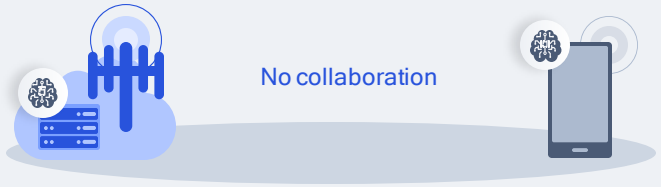
Evolving towards native wireless AI/ML

Multiple wireless AI/ML training and inference scenarios

6G

Overlay AI/ML

Independently at the device or network



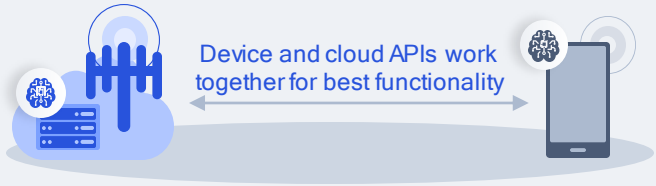
ML operates independently at the device and network as an optimization of existing functions

Proprietary ML procedures including model development and management

Proprietary and standardized data collection used as input to training

Cross-node AI/ML

Coordinated between device and network



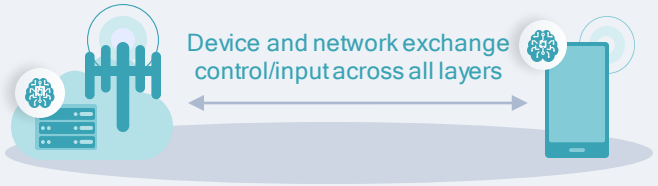
ML operates in a coordinated manner between the device and network

Proprietary and standardized ML procedures including model development and management

Further data collection used as input to training as well as monitoring

Native AI/ML

At all device and network layers



ML operates autonomously between the device and network across all protocols and layers

Integrated ML procedures across to train performance and adapt to different environments

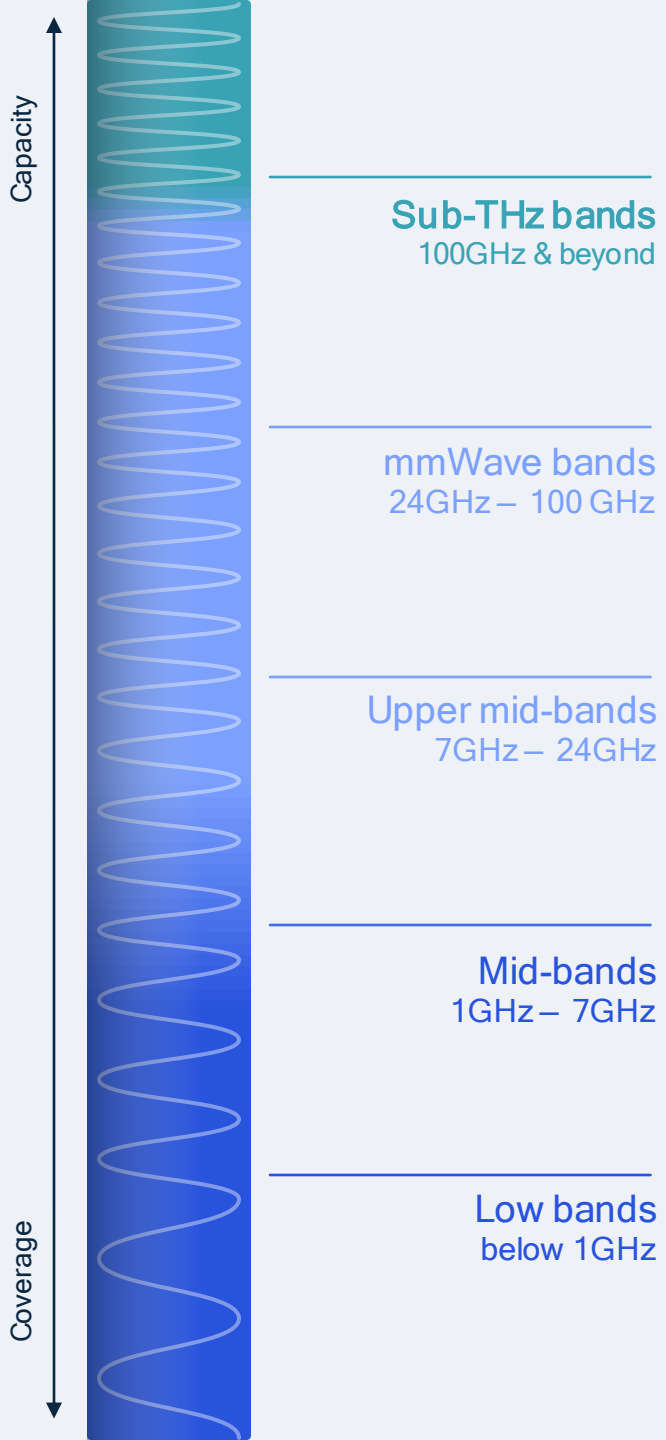
Data fusion for integrated dynamic ML lifecycle management

5G

5G ADVANCED

6G system targets all spectrum types and bands

Critical for the success of next-generation wireless systems



Licensed spectrum

Exclusive use of spectrum that remains the industry's top priority

Unlicensed spectrum

Shared use of more available spectrum

Shared spectrum

Evolving spectrum sharing that allow fair and more efficient sharing

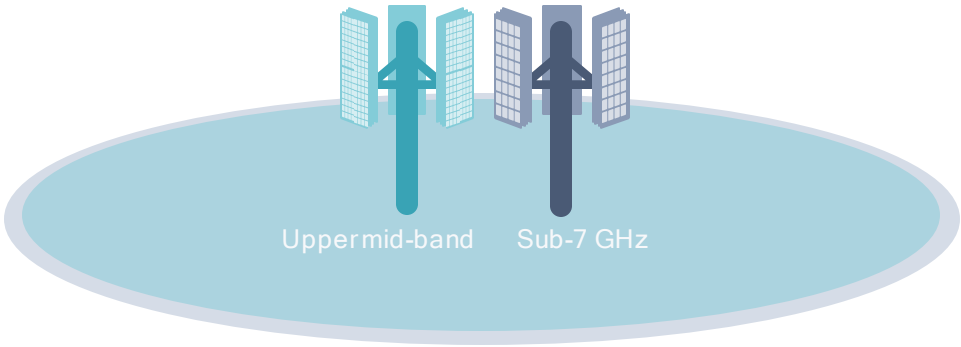
New upper mid-band brings order of magnitude more wide-area capacity

Larger contiguous bandwidths can bring efficiencies, fuel growing data demand, and enable new applications

Delivering new capacity for wide-area broadband (e.g., smartphones, smart cities, automotive, verticals)

Fueling scalable boundless XR user support in wide area through wider bandwidth availability

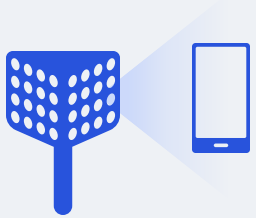
Supporting high-resolution RF sensing for new use cases (e.g., environmental monitoring, activity detection)



Opportunity to co-site with existing sub-7 GHz deployments for comparable coverage in higher band

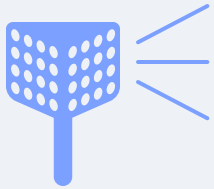
Upper Mid-Band
7 to 24 GHz

Best of wide-area coverage of sub-7 GHz and wide-band capacity of mmWave



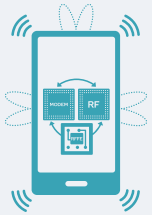
Coverage

Innovations to overcome significant path loss in mmWave bands



Beam management

Innovations to beam pairing, tracking and recovery

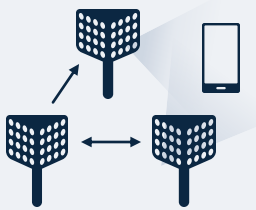


Device size / power

Innovations to optimize mmWave design for smartphone form factor

Robustness

Innovations to overcome blockage from hand, body, walls, foliage, etc.



Topology enhancement

Innovations to efficiently scale and densify the network

CONTINUED EXPANSION AND ENHANCEMENT OF

mobile mmWave technologies

Building on the solid foundation of 5G NR

Making sub-Terahertz spectrum viable for communications and beyond

Building on our mmWave experience to address key system challenges challenges at higher band spectrum

Use case feasibility

Evaluating diverse use case, form factor requirements and how sub-THz can deliver an effective solution

System design

Building early prototypes to overcome implementation challenges (i.e., device formfactor, power consumption, etc.)

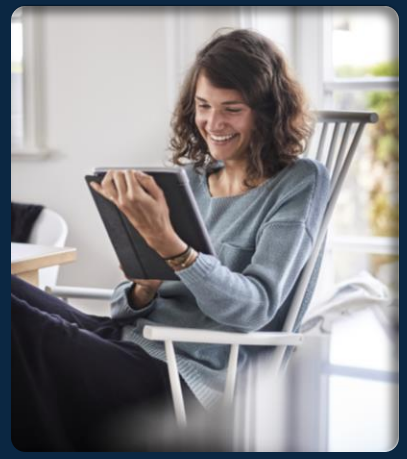
Propagation loss

Advancing intelligent beamforming to overcome indoor path loss, penetration loss, foliage loss, and others

Sub-THz can unlock new and enhanced use cases

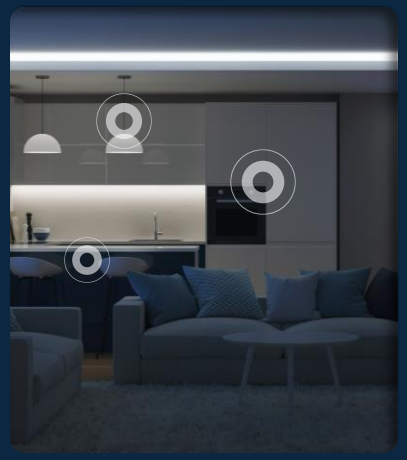
Wireless fronthaul

Wireless data center



Wireless fiber to the home

Ultra-precise positioning



RF sensing

Unlocking new spectrum that may require non-exclusive licensing and sharing with primary users

Designing for efficient and coordinated spectrum sensing / sharing that improves overall system performance

Leveraging O-RAN architecture to allow operators to cost-efficiently offer service differentiations (e.g., through RU sharing)

Utilizing adaptive AI/ML to address high-mobility scenario and public / private networks coexistence in the same band

Evolution to licensed spectrum sharing for improved efficiency, flexibility, and user experience

Building on 4G/5G spectrum innovations to optimize 6G experiences

6G XR requirements fueled by digital twins and spatial compute

Digital twins digitize the complex physical world in the metaverse

Spatial compute enables immersive interaction with 3D digital content

100x network capacity

0.1-10 Gbps per user

Use multiple frequency bands

(sub-THz, mmW, sub 7GHz, 7-24GHz, unlicensed, shared spectrum)

6G protocols can natively support distributed compute

Dynamically distributing workloads

Delivering low power and low latencies

Incorporating e2e QoS and session handling

- 6DoF/SLAM
- Hand Tracking
- Facial Expression
- Eye Tracking
- 3D Graphics Rendering
- Scene Understanding
- Objected Rec and Tracking
- Camera Processing

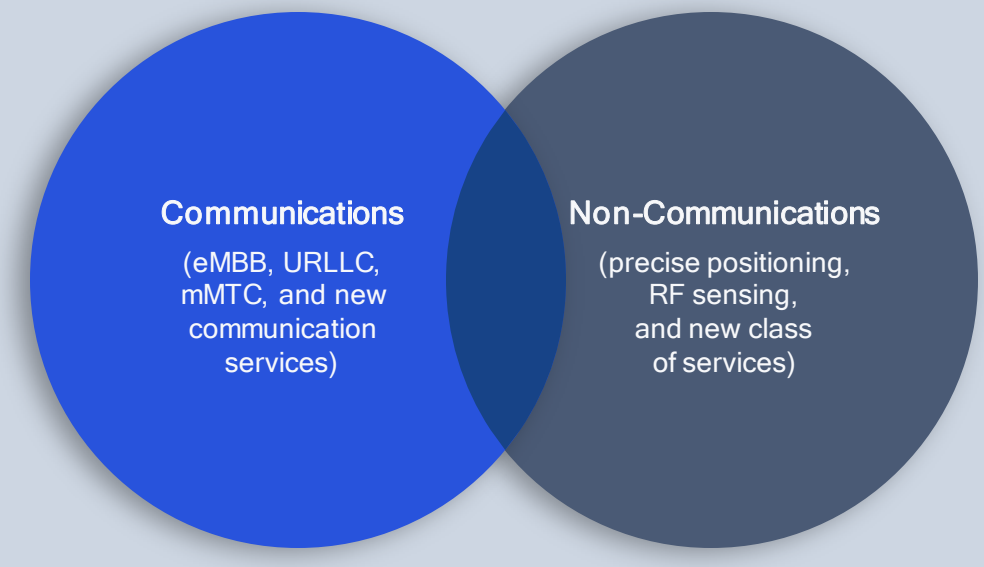
INTEGRATED TECHNOLOGY PLATFORM THAT CAN

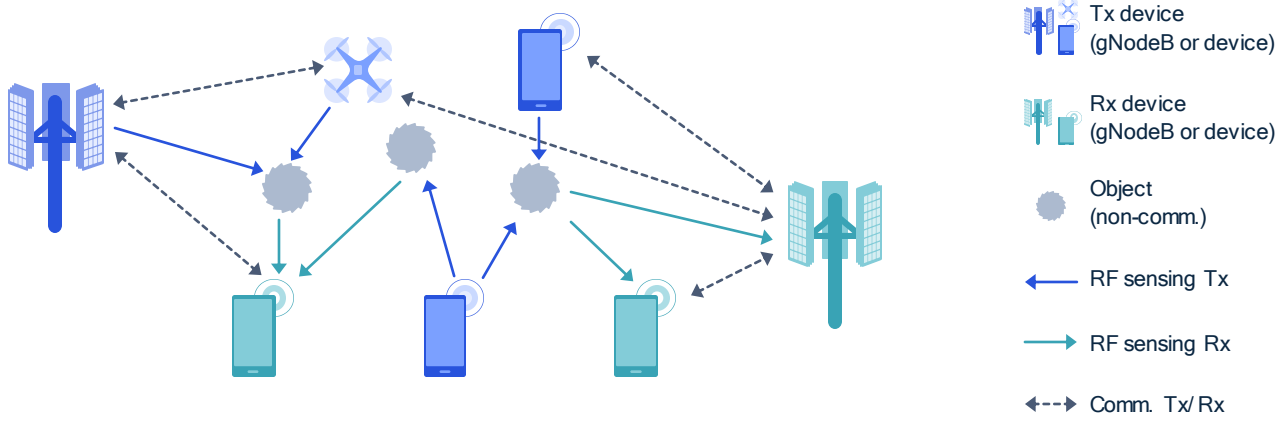
Enable joint communications, positioning, RF sensing, and more

Utilizing existing waveform and other fundamental physical layer designs in existing spectrum (sub-7, mmWave) and new higher-band spectrum (e.g., upper mid-band, THz)

Integrating environmental detection capabilities (e.g., positioning, RF sensing) to enhance quality of service and support emerging applications

Providing cooperative sensing capability across networks (e.g., TRP[1]) and devices, utilizing overall network processing with diverse topology





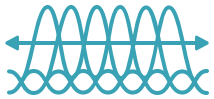
1. Transmission and Reception Point

6G technology platform will require a new air interface design

An innovation opportunity to achieve higher capacity, system throughput and efficiency

Channel Coding

Advanced channel coding targeting high-throughput, low-power, cost efficient implementation, approaching the theoretical bound on different block length and SNR regimes



Waveform

New waveforms and advanced signal processing to deliver higher spectral and power efficiency across a variety of spectrum bands within 6G unified air interface (UAI)

Modulation

Enhanced modulation schemes to achieve more efficient use of spectrum and resources, while enabling higher data rates and adapting to different MIMO transmission schemes

Multiple Access

Continued evolution of scheduled multiple access in conjunction with advanced MIMO, duplexing technologies to support extremely high cell capacity. Development of contention based random access to facilitate scaling up massive large number of devices in cellular system

Foundational PHY designs are crucial for enabling 6G new features:

Advanced RF and baseband joint design
Supporting wider bandwidth, faster Tx/Rx switching, higher PA efficiency, massive spectrum aggregation across new bands and existing bands

Efficient modem system implementation
Modem-RF implementation friendly PHY to facilitate data rate envelope scaling while maintaining superior power efficiency

Advanced air interface features
Coevolution of waveform and multiple access with next-gen MIMO, flexible/full duplex

Extreme energy-efficient devices
Diverse devices and use cases, ranging from extreme data rate to passive IoT

Seamless multi-RAT connectivity and spectrum sharing
Flexibility and efficient multi-RAT (5G/6G) spectrum access and resource sharing over multiple users and multi-RAT connectivity on the same device

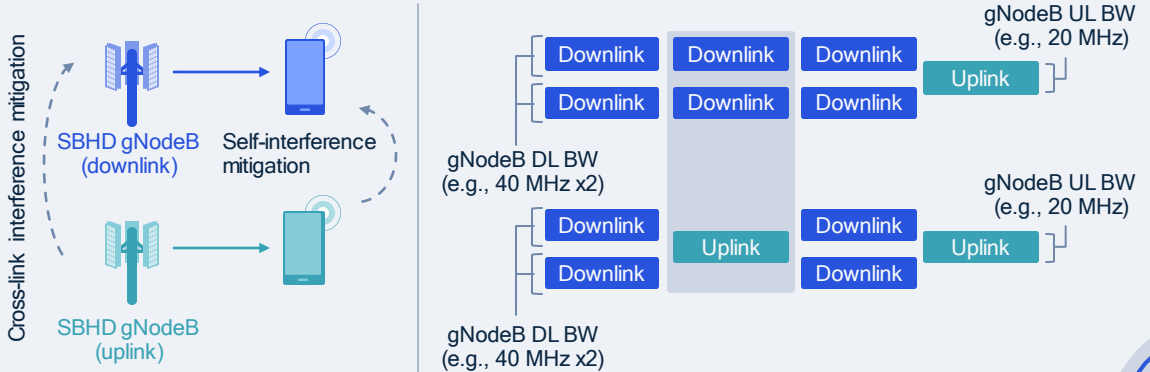
Enabling immersive experience
Enabling high capacity XR to facilitate immersive metaverse experiences using 6G air interface and new network topology technologies

Driving towards a full duplex wireless system

Lower latency, better coverage, expanded capacity, flexible spectrum deployment and service multiplexing

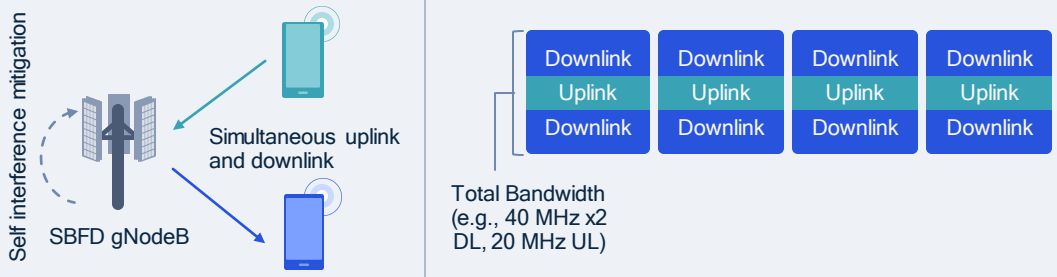
Subband half duplex (SBHD)

Frequency aligned to avoid inter-site interference; Time separation to avoid self-interference; Implemented in SD test network (MWC'21)



Subband full duplex (SBFD)

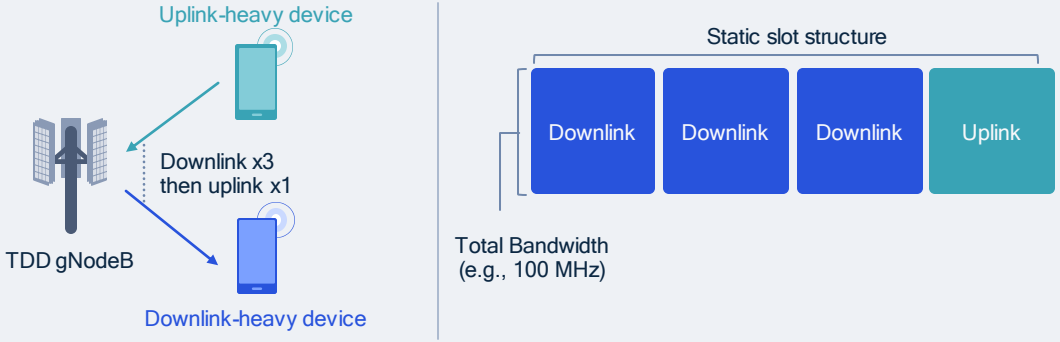
Frequency aligned to avoid inter-site interference; Frequency separation + interference cancellation to avoid self-interference; Implemented in SD test network (MWC'22)



Duplexing evolution

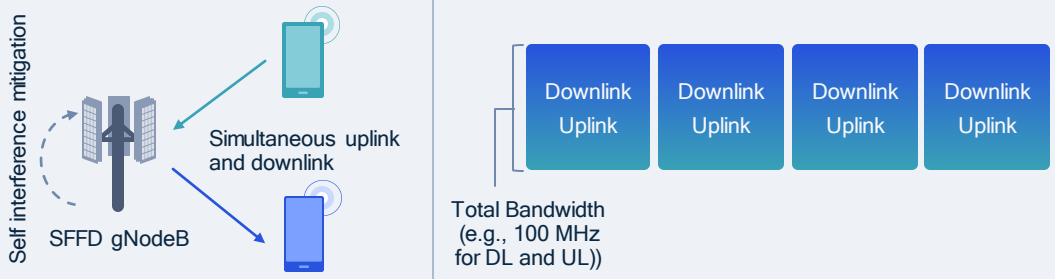
Static TDD

Time aligned to avoid inter-site interference; Time separation to avoid self-interference; Existing 5G systems (i.e., Rel-15) adopt static TDD (and FDD) duplexing



Single frequency full duplex (SFFD)

Interference cancellation to avoid self-interference; Targeting future simulations, prototyping, and standardization in 6G and beyond

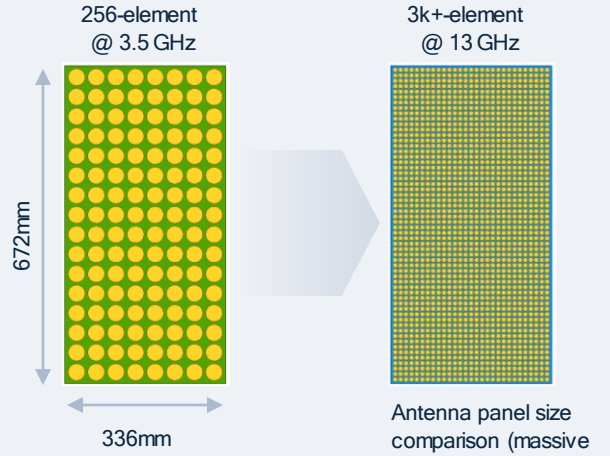


Giga-MIMO expands network coverage to upper mid-band

Giga MIMO with wide bandwidth and large number of antenna elements (i.e., >2k)

More antenna elements with same aperture, 3-4x wavelength reduction vs. sub-7 GHz

Building on 5G sub-7 GHz and mmWave technologies and approaches



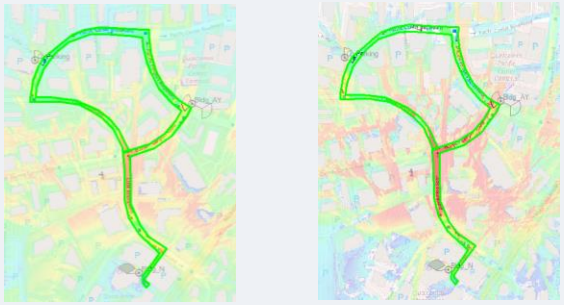
Antenna panel size comparison (massive MIMO vs. Giga MIMO)

For supporting wide-area use cases in X-band (8– 12 GHz) and Ku-band (12– 18 GHz)

Global spectrum discussions underway

Experimental licenses e.g., 8.5-9 GHz, 12.75-13.25 GHz

Regional and ITU discussions ongoing for longer term refarming



256-element @ 3.5 GHz

2048-element @ 10 GHz

Network coverage testing near Qualcomm campus in San Diego, CA

Best of wide-band mmWave and wide-area sub-7 GHz

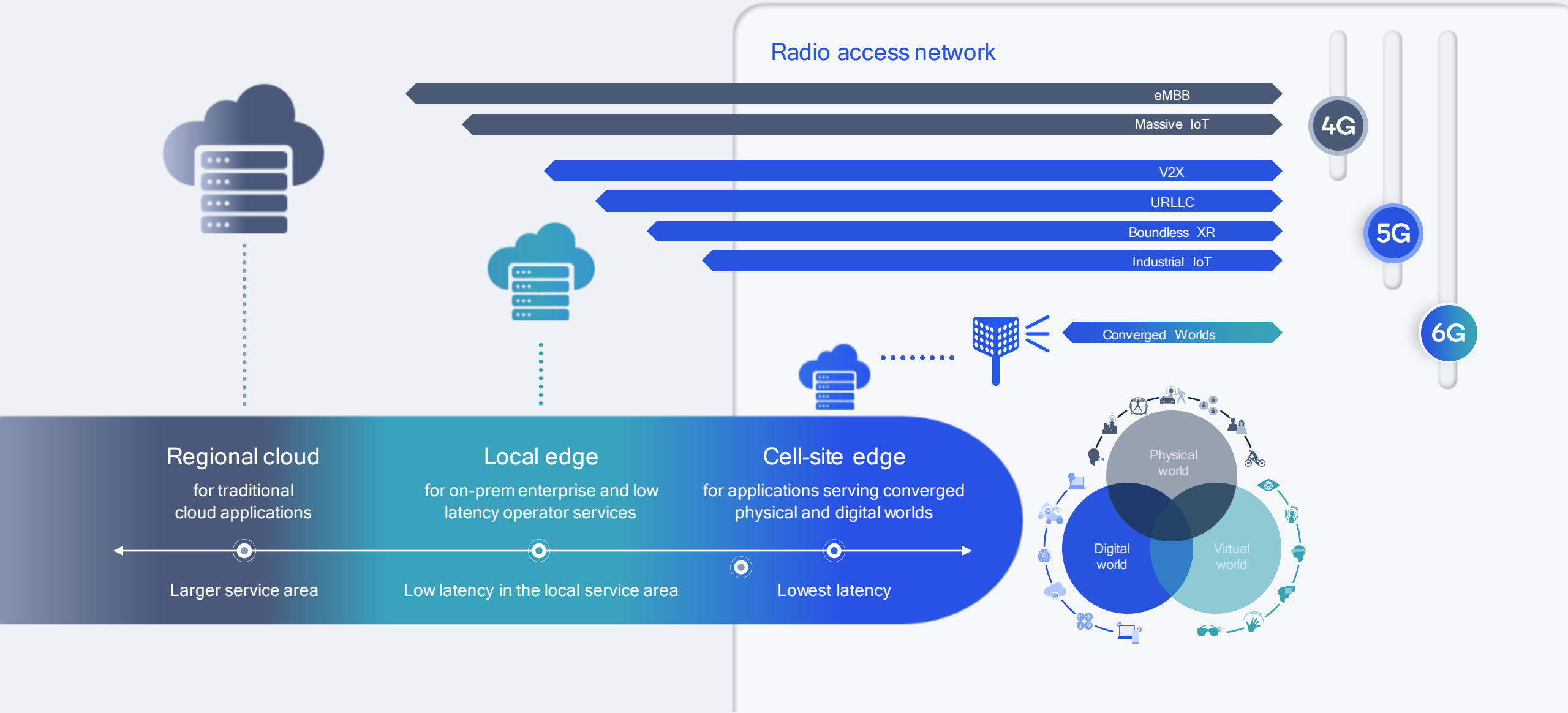
GHz bandwidth – 10x more capacity than existing massive MIMO systems

Comparable wide-area coverage to massive MIMO in sub-7 GHz

Higher positioning, radar, and RF sensing resolutions

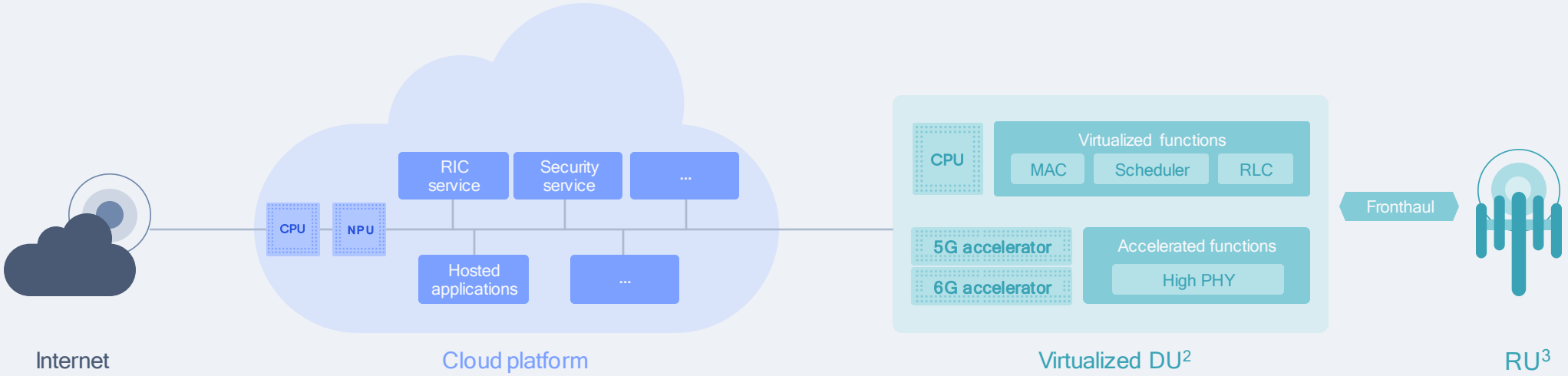
Note: Part of the spectrum may be studied or supported already in 5G NR Release 19+

Serving more diverse requirements with an evolving topology



Evolving network architecture towards 6G

Driven by disaggregation and cloudification of tiered services



Cloud-based core network

Core network hosted in public and/or private clouds

Flattening of architecture by moving 5G CU[1] functions to Core in 6G

Applications and Core on same platform crate opportunity for differentiated E2E performance

RAN Intelligent Controller (RIC)

Intelligent optimization via RIC applications from third-parties

Opportunity for network and device side intelligence framework synergy

Virtualized DU and open fronthaul

Virtualized DU with PHY processing in accelerators

Widespread adoption of standards-based fronthaul for interoperable RU

Rapid upgrade cycles on network create opportunity for more upgradable and modular device software

Upgrade for legacy bands

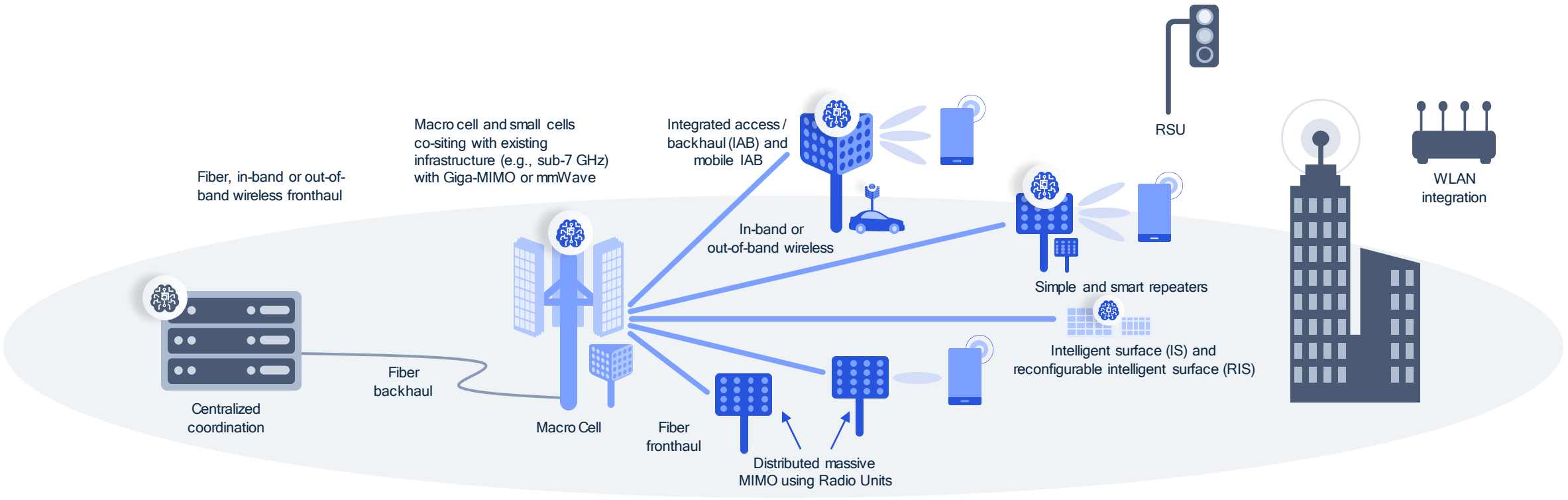
Leverage flexible 5G design to support efficient DSS with 6G

Potential reuse of legacy RU if 6G supports 5G symbol numerology

Easy upgrade of virtualized DU by adding 6G accelerator cards

1 Central unit; 2 Distributed unit; 3 Radio unit

6G will drive diverse deployment topologies and technologies



A scalable and distributed network architecture can meet diverse coverage, capacity, and other performance requirements

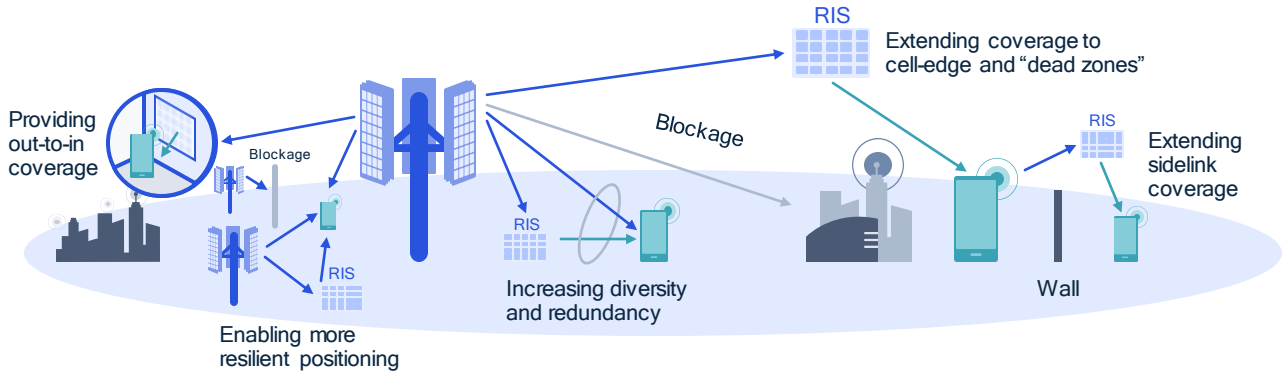
Passive MIMO for coverage extension and improved energy efficiency

Also known as RIS – Reconfigurable Intelligent Surfaces that can support various deployments and use cases

Providing dynamic control of reflective beam directions with PA[1]-less operations

Extending coverage for users in challenging locations (e.g., cell-edge, indoors, and with blockage)

Achieving better network energy efficiency



1 Power amplifier

Expanding the deployment toolbox to efficiently provide broader network coverage

Macro cells	Remote radio heads	RF repeaters	Integrated access/backhaul	Smart passive MIMO (IS & RIS)
Micro cells	Small cells	Smart repeaters	Passive MIMO	Other infrastructure options…

Further evolving cellular for non-terrestrial communication

That complements terrestrial communication

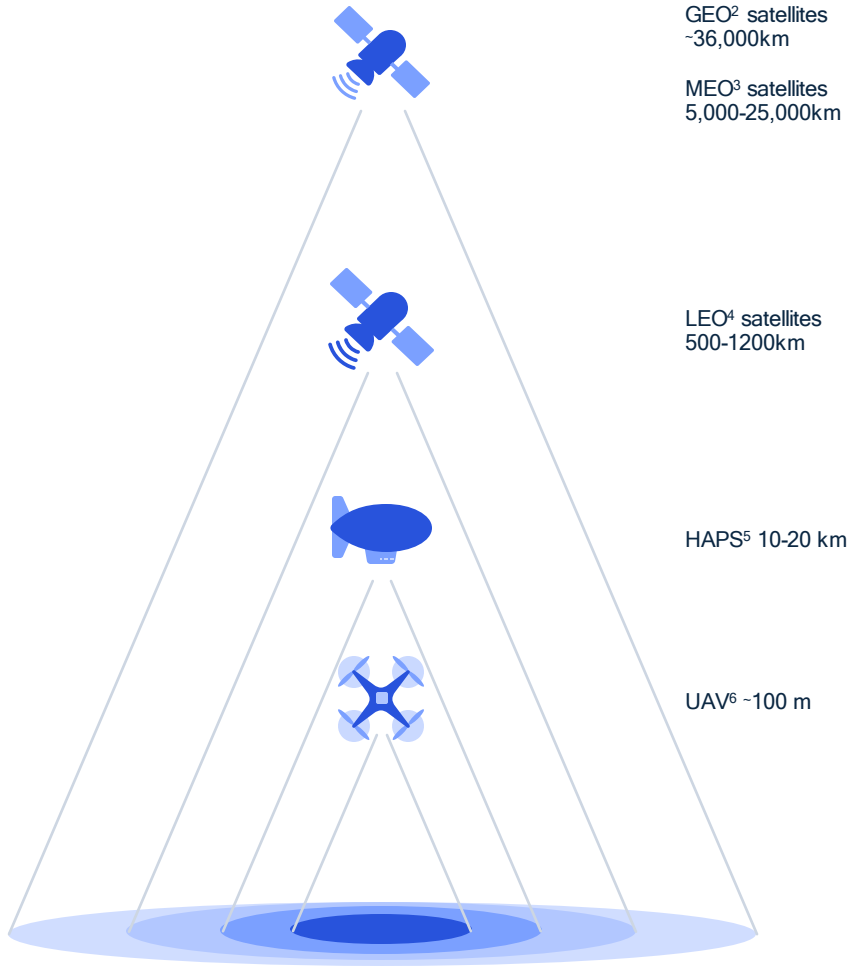
5G Rel-15
Study Item focused on deployment scenarios and channel models

5G Rel-16
Study Item focused on solutions for adapting 5G NR to support NTN

5G Rel-17
Work Item focused on supporting satellites and HAPS for eMBB and IoT[1] with enhancements to synchronization, scheduling, HARQ, mobility, and more

5G Rel-18+
Expected to further enhance communications for UAV, HAPS, and satellites

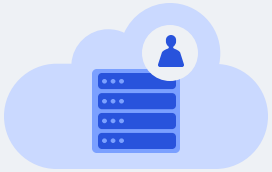
6G
Potential focus on delivering an integrated 3D heterogeneous network, where terrestrial infrastructure can be complemented by non-terrestrial ones



1 eMTC and NB-IoT; 2 Geostationary; 3 Medium Earth Orbit; 4 Low Earth Orbit;
5 Unmanned Aerial Vehicles; 6 High Altitude Platform Station;

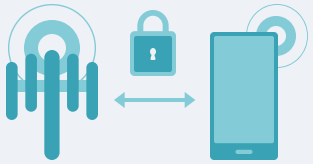
Our research focus in 6G security and privacy across all layers

Building on the proven, solid security foundation of 5G



Data security and privacy

- Data provenance (e.g., to defeat deep fake)
- AI/ML federated learning
- Secure multi-party computation
- Differential privacy
- Homomorphic encryption of secure off device data processing
- Zero knowledge proof for data/identity privacy



Secure communication

- PHY/MAC security
- Ultra secure communication
- Network hiding
- All encryption (including broadcast / scheduling info.)
- Jamming resilience
- Post quantum cryptography (resilient against quantum computers)
- Quantum security (key generation, key distribution)

Identity and device management

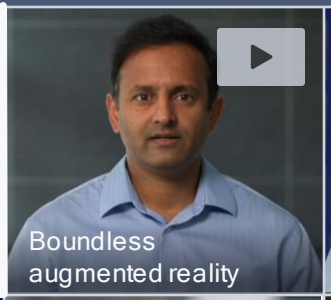
- Identity privacy
- Multifaceted trust
- User / device / subscription authentication
- Device onboarding and ownership structure/management
- Device / user attestation, multi-factor, continuous authentication
- Electronic ID ecosystem (e.g., secure, private, agile root of trust for identity, trusted D2D security bootstrapping

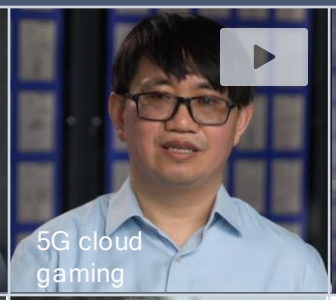
Platform security Blockchain Web 3.0 Confidential Computing

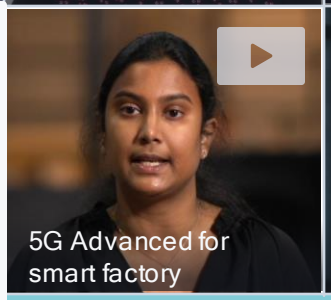
Qualcomm

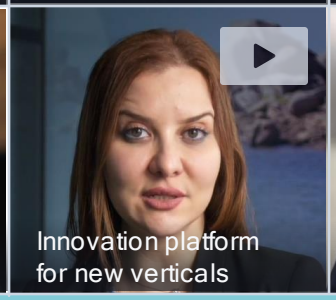
Driving the 5G evolution with our advanced R&D demonstrations

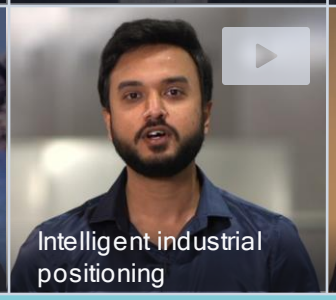
Watch all on YouTube











Foundational Air Interface Innovations

Expansion to New Applications

Driving the 5G Advanced technology evolution into 6G

Next technology leap for new capabilities and efficiencies

Foundational research, vision, requirements, etc.

6G

Rel-21 and beyond
New innovation platform

Historically 10 years between generations

Technology foundation for the next generation

A key enabler of the connected intelligent edge

5G

Rel-15
eMBB focus

Rel-16 and 17
expanding to new industries

5G ADVANCED

Rel-18, 19, 20 and beyond
Continued 5G evolution and proliferation

Strong 5G momentum sets stage for global expansion

Thank you

Qualcomm

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