6G Víziótól a technológiai szabványokig

2026 április 8.

Bertenyi Balázs

Agenda

The Vision

Governing conditions

6G standards timeline and machinery
Spectrum governance

Technology divers

Radio performance
Diverse device types
Architecture
AI
Sustainability and Energy Efficiency
Security

Migration to 6G

MultiRadio Spectrum Sharing (MRSS)
Spectrum aggregation

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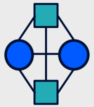
From Connectivity → Intelligence

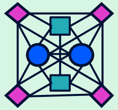
Humans   Machines/IoTs   AI agents/tokens

Today's networks



- Excel at connecting people and devices reliably and efficiently, optimizing speed, coverage and capacity
- They are still predominantly data transport systems

Tomorrow's networks



- Evolve from connecting data to understanding and processing intelligence
- They will provide perception, coordination, and governed autonomy.

2G & 3G

Built mainly for human communications

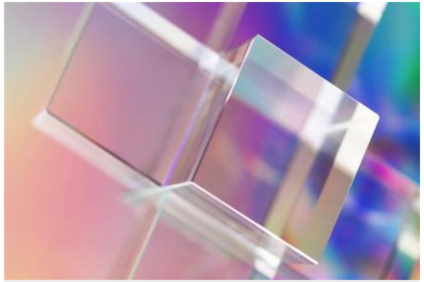
4G & 5G

Expanded to support machine and IoT connectivity

6G

Extend further to connect AI agents and intelligence

Key considerations for architecting 6G



Performant

Driving performance, network efficiency, innovation, and unlocking a new spectrum to fuel economic growth

Intelligent

Leveraging AI for network design, optimization, and operation, while ensuring seamless connectivity for devices and applications

Sustainable

Supporting a low-carbon, circular future, and fostering greater equity for people and the planet

Secure & cyber-resilient

Focusing on innovative security measures and pioneering quantum-safe technologies

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Expected benefits

Performant

- Uplink capacity boost by **10x**
- Downlink capacity boost by **6x**
- Uplink coverage and cell edge data rate boost by **2-4x**
- Scalable device design and new value creation opportunities
- Simple upgrade on top of 5G Standalone

AI-native 6G

Intelligent

Sustainable

- Network energy saving by **40%**
- Device energy saving by **50%**

Secure & cyber resilient

- Quantum safe
- From AI risk to built-in ally
- Strengthened radio security

Capacity scenario: 5G with 100MHz@mid-band, 6G with 100MHz@mid-band + 200MHz@upper mid-band + UL booster; Energy saving scenario: Low load / Low activity

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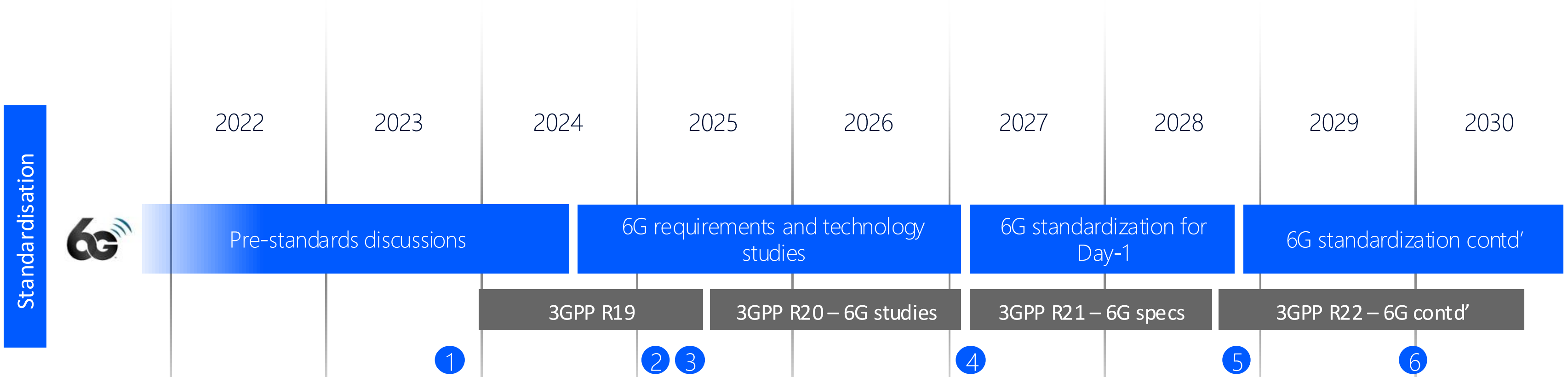
6G will come with 3GPP Rel-21

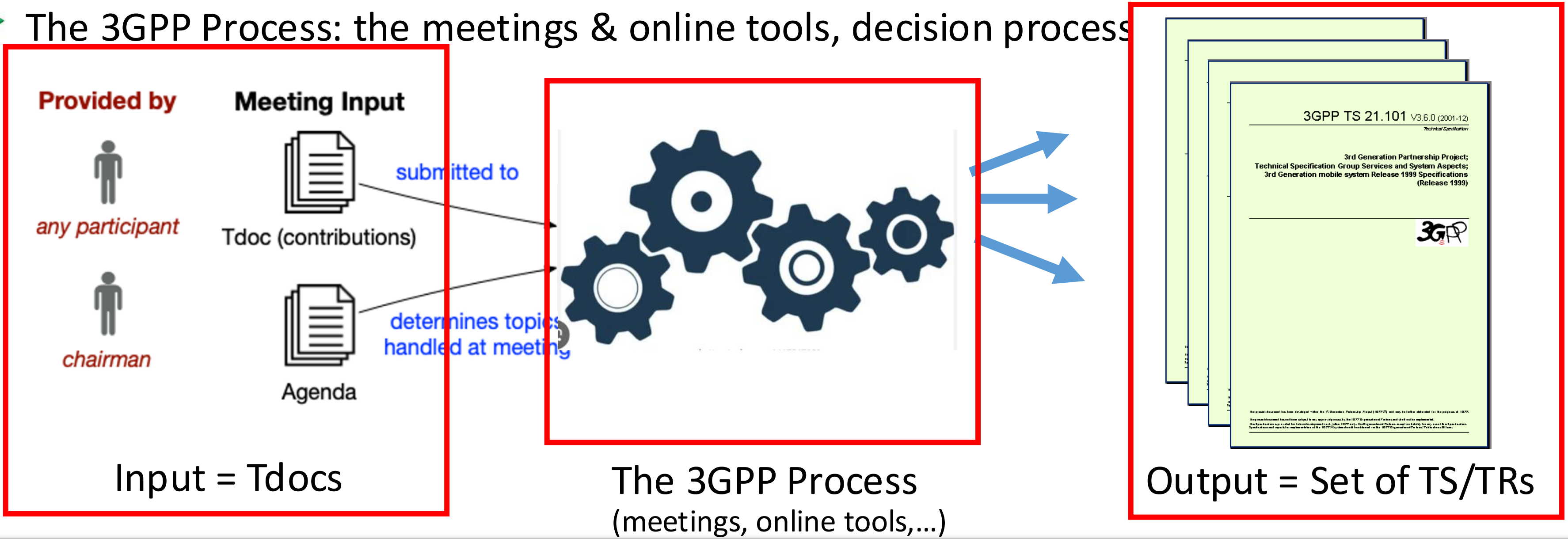
Commercialization from Q4 2029



1. 3GPP time plan set December 2023
2. 3GPP 6G workshop March 2025
3. 3GPP 6G Study start June 2025
4. 3GPP 6G normative Specification start March 2027
5. 3GPP 6G Specifications functional freeze December 2028
6. 6G Day One Deployments

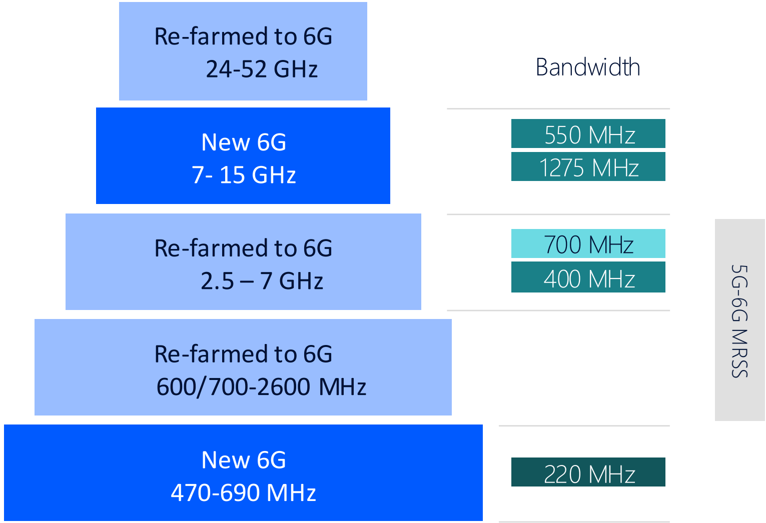
Nuts and bolts of 3GPP

- Inputs: The set of “contributions” or “tdocs”
- Outputs: The set of TS/TR, describing the system for a given Release
- The 3GPP Process: the meetings & online tools, decision process



WRC-27/31 expected to provide good spectrum grounds for 6G

Existing and new bands for 6G



14.800 GHz - 15.350 GHz 7.125 GHz - 8.400 GHz	Wide area capacity and data rate boost
6.425 GHz -7.125 GHz 4.4 GHz - 4.8 GHz	Expansion of existing 5G mid-bands
470 MHz - 690 MHz	Extended coverage at low bands

Note: frequency ranges and availability of bands may vary from one ITU Region to another

IMT: International Mobile Telecommunications

WRC-23 IMT identification | WRC-27 approved to study for IMT | WRC-31 subject for discussion

Global momentum for spectrum for 6G

US
Study 7.125-7.4 GHz, 2.69-2.9 GHz, and 4.4-4.94 GHz for 6G

Europe
EU RSPG opinion Nov 2025 - at least 665 MHz for IMT in 6425-7250 MHz

Ukraine
700 MHz of Upper 6 GHz for IMT from 2028

China
U6 for IMT added in the Chinese table of frequency allocations in Jul 2023

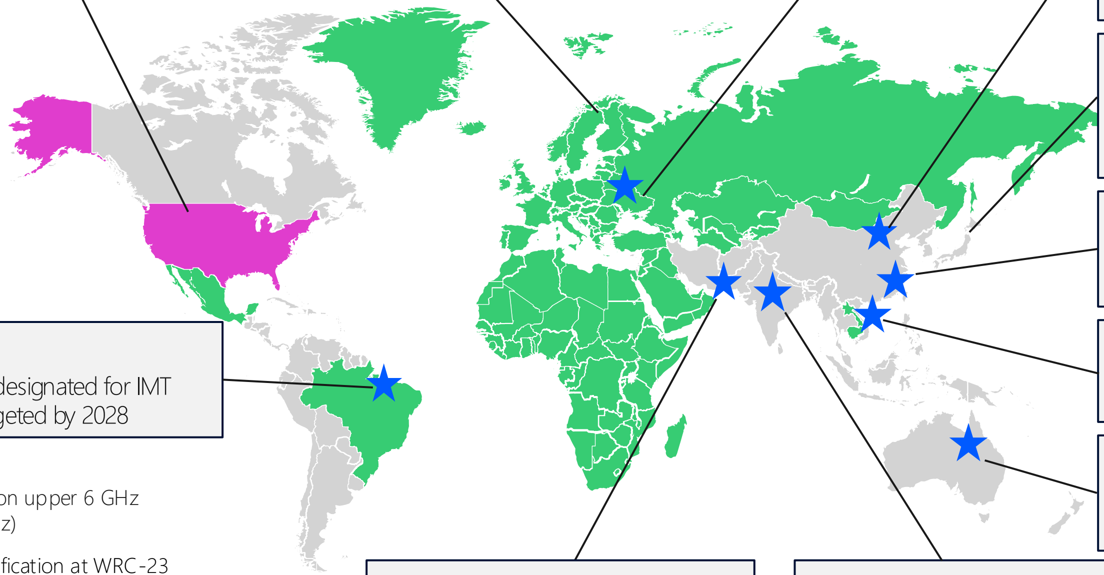
Japan
XGMF recommendation to consider 6-8 GHz range for IMT in Dec 2025

Hong Kong
6 GHz auction Nov 2024
100 MHz * 3 operators

Vietnam
700 MHz of U6 reserved for IMT in Oct 2025

Australia
Plan published Dec 2024
6585-7100 MHz for IMT

Brazil
6425-7125 designated for IMT
Auction targeted by 2028



UAE
6425-7125 MHz licensed Nov 2024

India
6425-7125 MHz designated Dec2025

★ National decisions on upper 6 GHz (U6; 6425-7125 MHz)

■ Upper 6 GHz identification at WRC-23 (International mobile radio spectrum allocation)

■ Spectrum provision and studies to support 6G

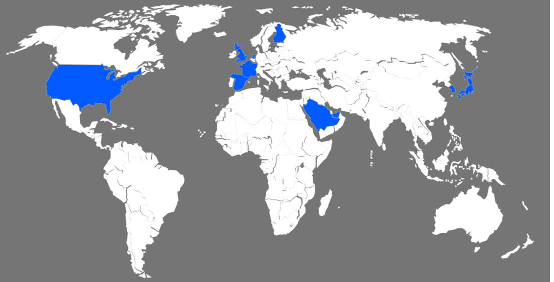
Realizing the vision of 6G in upper mid-bands

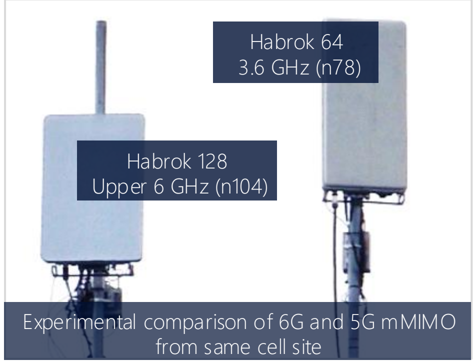
20+ trials and PoC completed during 2025

3GPP ITU WRC

Public references

Telia Company · du · T Mobile · SoftBank · BT · stc · Telefónica · orange · A1





Experimental comparison of 6G and 5G mMIMO from same cell site

- Nokia is building industry consensus on 6G spectrum with government bodies and telecom providers.
- Initial pilots indicate the 6-8 GHz frequencies are good prospects for utilizing existing site grids for capacity and coverage.

Key learnings:

6G can be deployed at upper 6 GHz and 7 GHz radios with 5G site grid in urban and dense urban areas by means of :

- Double the spectrum (3.5 GHz ⟶ 7 GHz)
- Double # of TRX (64 ⟶ 128)
- Add at least 4x more antenna elements (198 ⟶ 768)

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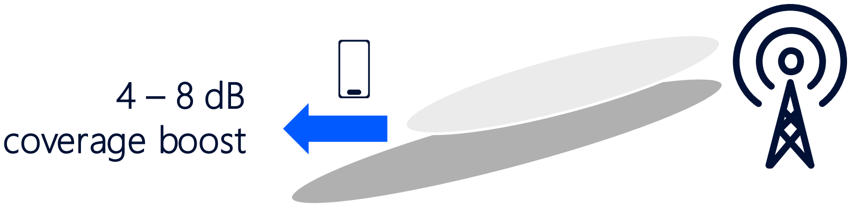
Uplink coverage and cell edge data rate boost

Solution	Gain
Higher power up to 26/29 dBm	Up to 3.0 dB
Spectrum shaping	Up to 2.0 dB
Dynamic UE RF requirements	Up to 1.5 dB
Wideband 200-400 MHz	Up to 1.5 dB
Redefine P_{CMAX_H}	Up to 1.0 dB
UL scheduling range introduction	Up to 1.0 dB
Multi-slot transmission	Up to 0.5 dB
Total combined coverage gain	4 – 8 dB



- Enhancing uplink coverage: filtering, power optimization, and multi-slot solutions.
- Evaluated in 5G-Advanced. Implemented in 6G.

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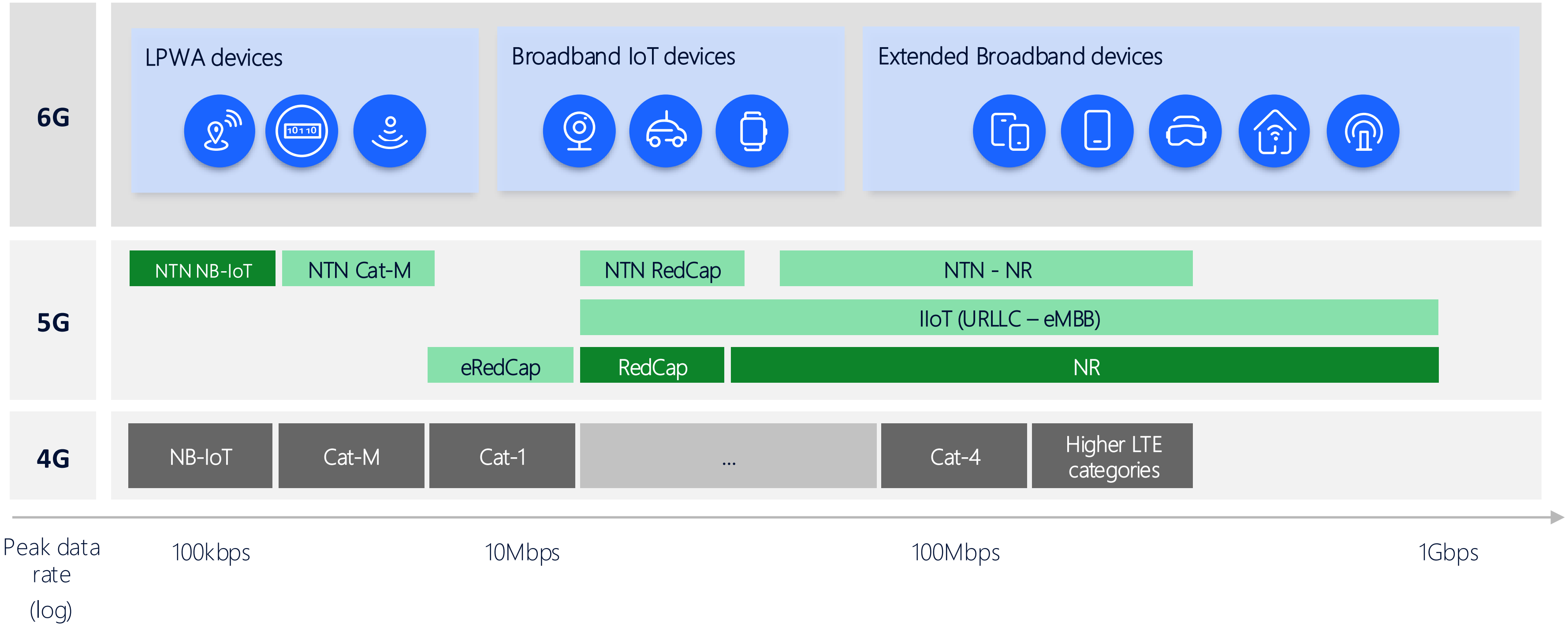
Native support of different 6G device types

Terrestrial and non-terrestrial connectivity for all devices



With a modular radio protocol design for optimized experience

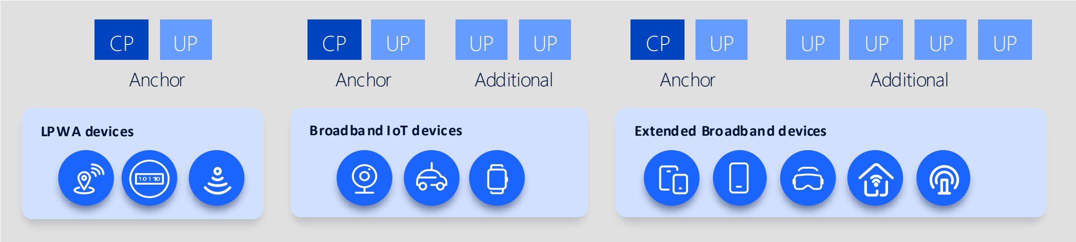
Modular radio protocol architecture for 6G

Radio protocols define how devices communicate efficiently across the network.

To support diverse device types optimized for different purposes, a modular design is critical.

Modular design components

- Anchor user plane (UP) + Control plane (CP): Supports lowest-capability devices and anchors existing services with known operation.
- Flexible UP modules: Enable additional processing and scalable implementation for higher-capability devices, such as immersive communications.



2G-5G:

A one-size-fits-all design to serve all possible use cases

(Challenges faced: growing complexity, less efficient)

6G:

A modular design to support diverse use cases and devices

(Simple, scalable, reliable - ensuring a high-quality customer experience)

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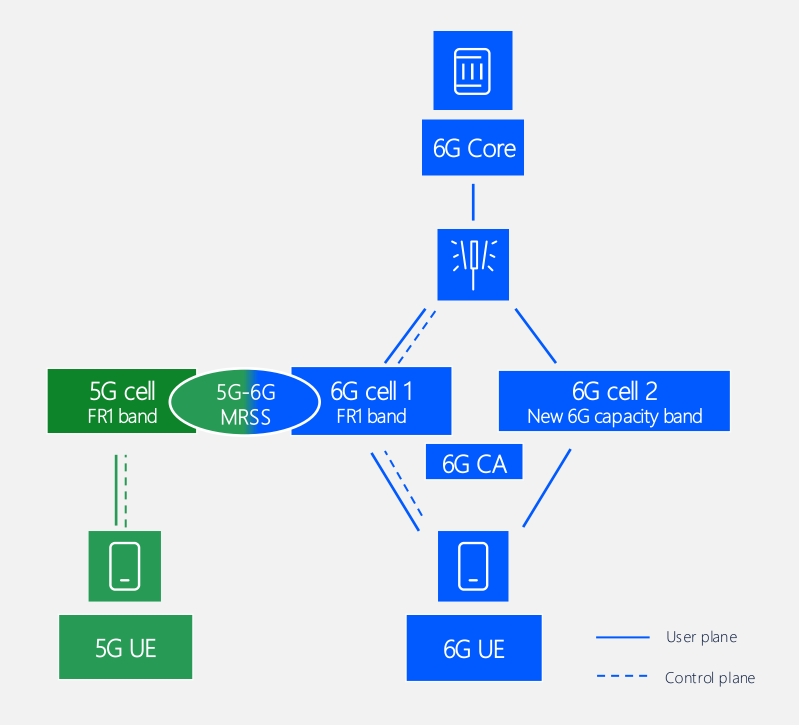
Single standalone architecture for smooth deployments

5G today	6G evolution
7 architectures defined in 3GPP and 2 implemented (NSA, SA)	Only **single architecture** option for simple evolution
5G core is a major upgrade on top of 4G core	6G **core is a smooth migration** from 5G core
4G + 5G dual connectivity (DC) and 4G RAN – 5G RAN interface	**No 5G – 6G dual connectivity** (just MRSS* control)
Two radios (LTE + 5G) active in devices simultaneously	**Only a single radio** active (6G) in a device at a time
Refarming mostly with static spectrum split	**Multi-Radio Spectrum Sharing (MRSS)** for truly dynamic refarming

** MRSS: Multi-RAT spectrum sharing*



Note: These are preliminary views for discussion – options need to be evolved as 6G concepts become more mature

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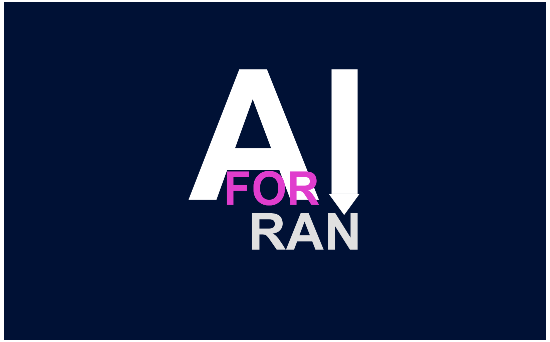
AI-RAN unlocks monetization and efficiency opportunities

Paving the path to AI-native 6G networks

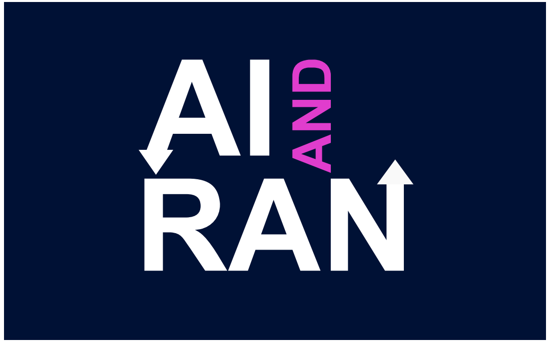
RAN augmenting
AI-app performance

Monetization



AI augmenting
RAN performance

RAN efficiency



Leveraging
synergies

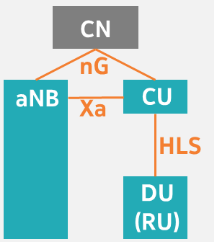
Future-proof

What is AI-RAN Architecture?

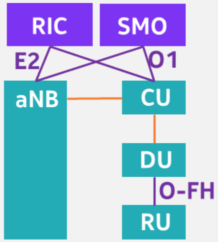
Standards Domain

Basic Design of Interfaces

3GPP



ORAN



Enable true multi-vendor interface design

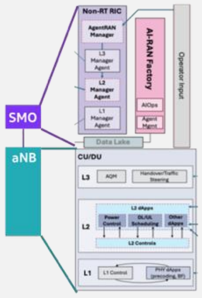
Protocols / Usage of Interfaces

- Service Awareness
- Data collection
- Information exchange (e.g., prediction)
- Exposure

Enable protocol enhancements to support AI for RAN and RAN for AI

Functional Split inside logical nodes

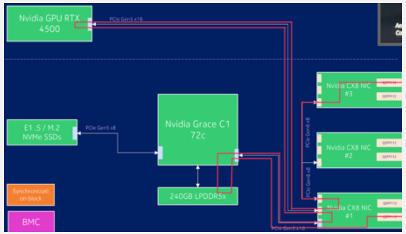
What is implemented in which node and how?



Well defined AI/ML framework and RAN functionalities

Hardware (and Software) Architecture

Hardware of the nodes



Integration of GPUs in RAN to provide better support for AI applications

AI-for-RAN use cases

Enhancing RAN performance with AI

Motivation and related use cases:

AI is a powerful tool for network management and user experience

Key use cases:

1) Mobility optimizations
2) Load balancing
3) Energy savings
4) Network slicing
5) Capacity and coverage optimizations

Other use cases like QoE were discussed as well.

AI/ML Framework:

- Natively support use cases where AI/ML can help improve performance and user experience. However, system should work without AI as well.
- AI/ML models and algorithms remains implementation specific. Data collection and signaling enhancements remains the main enabler of AI in RAN.
- AI services and any enablement of AI in RAN domain uses the existing interfaces to operate.
- Standards should not mandate mapping of the training and inference functionalities to the network element, or 6G NB. Same deployment scenarios (OAM vs Node B) as assumed in 5G are supported.
- Specific RAN Architecture for AI/ML should be avoided, and introduction of new interface/network element should be justified technically and commercially.

AI/ML in RAN is supported without disrupting the RAN architecture.

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AI-on-RAN use case – Service Awareness

Efficiently supporting mobile AI traffic

Motivation and related use cases:

- RAN needs to be able to quickly adapt to end users needs.
- RAN should play a stronger role in realizing the value of service differentiation to end users.
- RAN needs to know what end user wants in a dynamic manner: no time to rely on static allocations or so.
- There is also a need for a new KPI to measure how well applications are performing.

Clause 5.3.6 in TR 38.914

5.3.6 Service characteristics awareness in RAN

6G RAN shall be able to understand and be capable of adapting to traffic demands of applications while maintaining overall system efficiency in terms of radio resource utilization and energy consumption.

6G Radio and 6G RAN need to enable service characteristic differentiation for improving end-to-end user experience and enabling more dynamic and intelligent service and AI traffic handling in 6G RAN.

RAN should be able to support existing and new services (e.g., AI applications).

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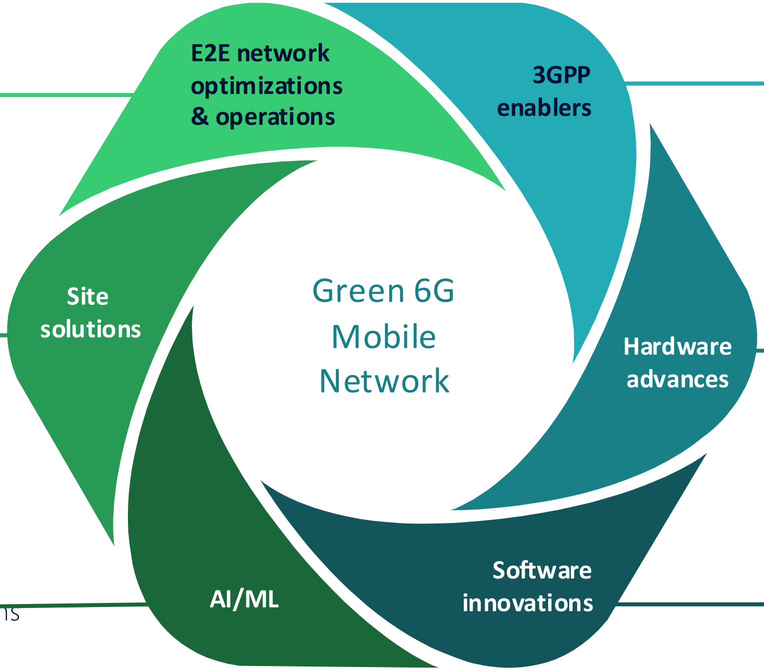
Key components for a green 6G network

An end-to-end view

Energy-and energy-supply-aware E2E optimizations, including densification and cloud solutions

Green site solutions (e.g., virtual power plant, liquid cooling)

Energy-saving algorithms selection and optimization leveraging predictions (traffic, radio KPIs, ..)

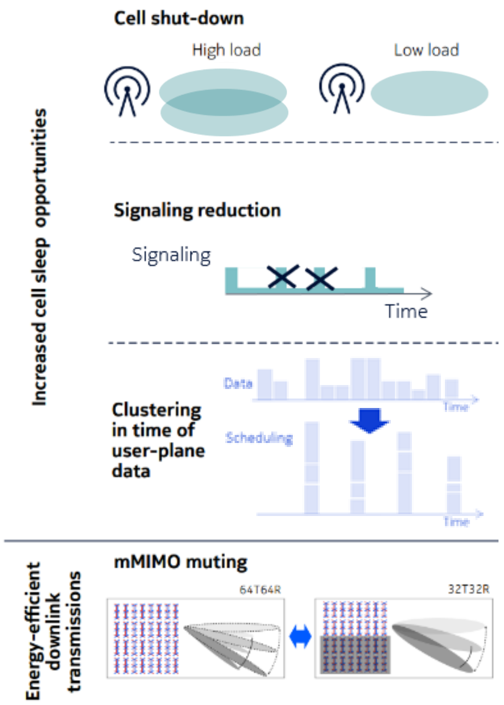


AI-native, energy-saving E2E design, from devices to RAN and entire system Supported by all devices on 6G day one

Power-optimized and highly scalable hardware (RF, digital/compute)

Energy-saving innovations that enable load-based allocation of hardware resources

RAN energy saving



3GPP Release 21 focus*	Key targets
Cell / beam shut-down schemes Enhanced elegant, more reliable, and faster shut-down of capacity cells and beams **Network Energy Saving design for Signaling Reduction** Leaner carrier for always-available network with on-demand or load-based provisioning of SSB, synchronization signals, system information, PRACH and paging occasions	Near-zero Watts at zero load
Network Energy Saving schemes for Data More flexible and effective cell discontinuous transmission and reception (cell DTX/DRX) Adaptive base station transmit antennas and transmit power control with UE assistance via SRS and CSI feedback	Maximize bits per Watt without compromising QoS/QoE

** Full device support required from 6G day one*

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Ensure a robust 6G security posture from the start

Threat vectors for 6G - fueled by emerging technologies

Quantum computing threatens current cryptography

Offensive use of **AI** crafts adversarial inputs

AI will amplify current cyberattacks

SW-defined radios can spoof signals and jam

We need to prepare today for tomorrow

- Post-quantum cryptography
- AI security
- Radio lower-layer protection
- Security for sensing
- AEAD support
- Authentication enhancement
- Security for new NAS
- Data security
- Security monitoring

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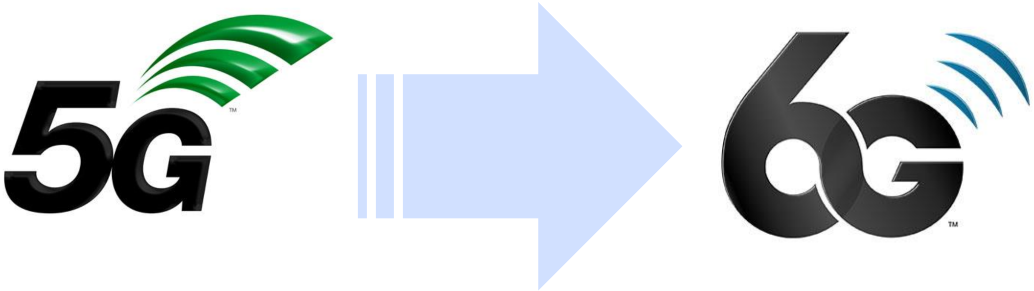
5G-to-6G Migration

Framing the Problem
& MRSS Overview
1

6G Spectrum Aggregation (CA vs DC)
2

Key Takeaways
3



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6G cannot afford a 4G-to-5G-style migration

NW-led MRSS is the only scalable path: No UE Heroics Required

The previous migration round to 5G:

- Relied on multiple migration paths and dual radios in devices
- Phased migration, extra complexity and long tail of legacy devices
- Suffered from LTE always-on overhead that sacrificed (spectrum) value and 5G customer experience

The reality we all still face:

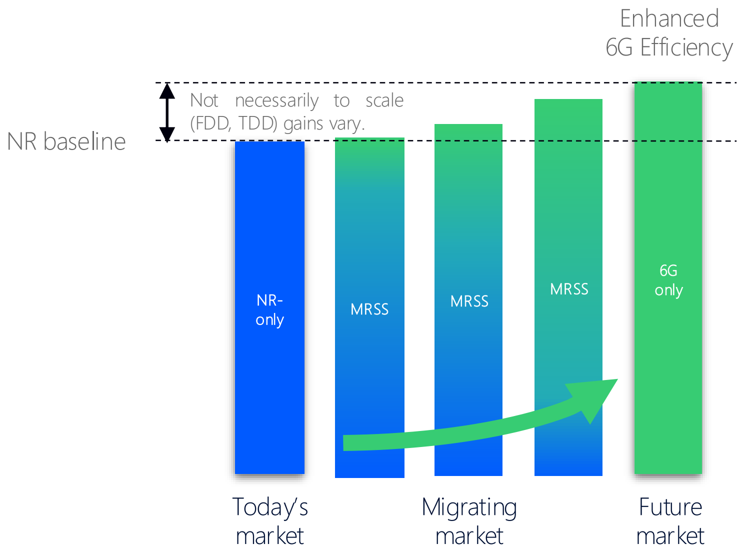
- Low-band spectrum remains the coverage anchor
- Revenue per MHz must be optimized continuously
- Static refarming leads to capacity cliffs and compromised user experience

Expectations for the next migration round to 6G:

- 3GPP agrees that 5G-6G MRSS is the streamlined migration pillar
- Existing spectrum will continue to carry 5G traffic for many years, well into the 6G era
- Migration solution should work for all 6G device types and we cannot mandate dual-radio UEs

Simplifying the Spectrum Migration to 6G

Industry baseline: Native spectrum sharing between NR and 6G (Day-1)



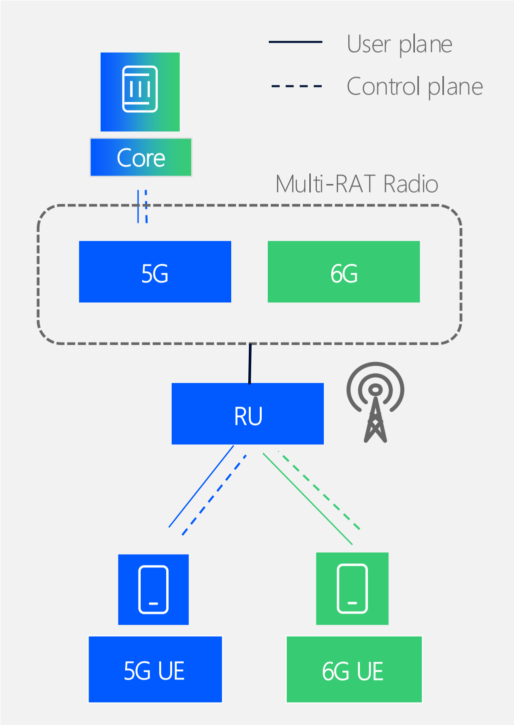
Minimal extra overhead due to MRSS

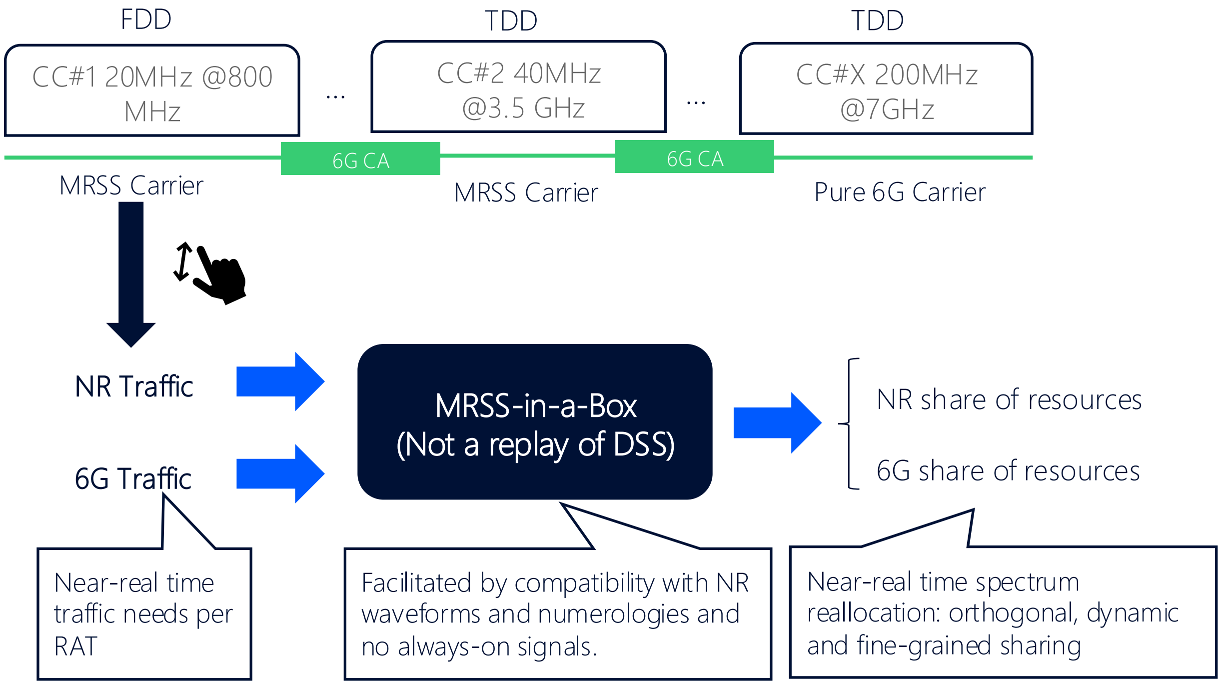
With increasing 6G traffic share, 6G performance gains result with increasing net capacity gain on an MRSS carrier

Multi-RAT Spectrum Sharing (MRSS) enables 6G deployment over existing 5G macro infrastructure (coverage) and spectrum (FR1 assets)

MRSS 101: How does it work?

(Over-) simplified black-box model of MRSS → capacity follows traffic





Summary of MRSS design

MRSS offers flexible capacity balancing between 5G and 6G.
Analysis did not account for any 6G gains, only overhead impact shown.

MRSS outperforms static refarming even with 5 MHz FDD

Less than 2-5% degradation for MRSS with 10 MHz FDD

With 20 MHz FDD and 100 MHz TDD, MRSS performance difference is almost invisible

Even in 5 MHz cells MRSS overhead has only a small performance impact.
In 20 MHz and wider BW cells the overhead impact all but vanishes.

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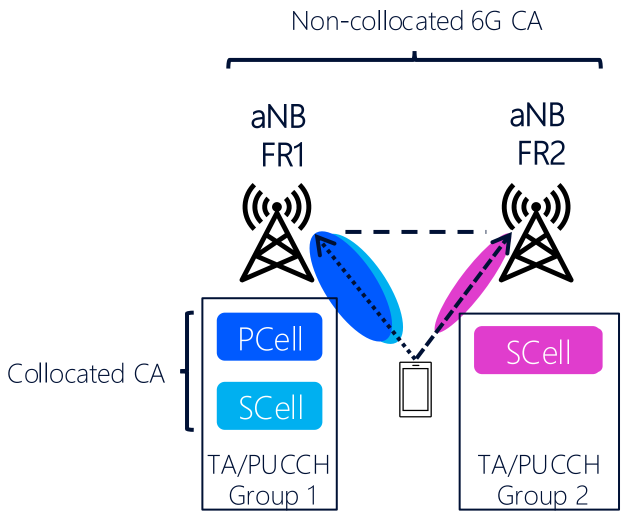
6G FR1 & FR2 non-collocated spectrum aggregation

Common PHY for DC and CA: Protocol behavior defines FR1-FR2 spectrum aggregation



Non-collocated FR1 & FR2 Carriers will have:

- Different propagation (delay)
- Potentially different numerology
- Possibly different beamforming techniques
- Non-collocated backhaul

MAC/RLC/PDCP/RRC

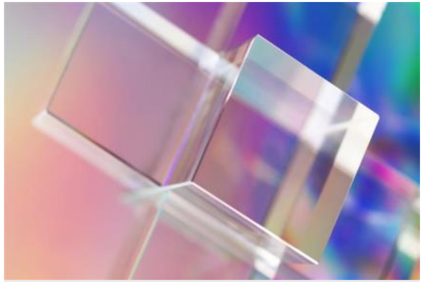
- L2 protocol stack coupling assumptions
- Scheduling, data split, reordering and flow control
- Tight x relaxed coupling determines spectrum aggregation

Dual PUCCH + TA groups:

- Help decouple timing and UL control between FR1/2 legs
- Reduces the amount of per slot coordination
- Allows loosely couped scheduling architectures to function

Summary

Key considerations for architecting 6G



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Leveraging AI for network design, optimization, and operation, while ensuring seamless connectivity for devices and applications

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