September 24th, 2019 @qualcomm_tech Future of 5G Workshop San Diego, CA

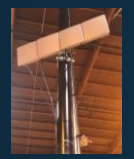
Qualcomm

Future of 5G Demo Stations

Demonstrating the future of 5G today

Sub-7 GHz testbed

mmWave testbed



Industrial IoT and spectrum testbed

Automotive testbed

E2E system: antenna range

5G Industrial IoT

Outdoor mmWave

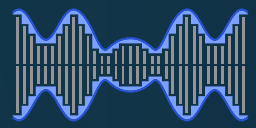
Synchronized NR-U

Indoor mmWave

Wide-area augmented reality

5G NR C-V2X

System RF front-end



5G standardization

3GPP
A GLOBAL INITIATIVE

2019

Early end-to end prototyping, drive evolution, drive and reflect standards, accelerate commercialization

End-to-end 5G System Leadership

We build our own end-to-end 5G prototype systems

Early technology proof-of-concept to drive future 5G NR evolution

5G Core Network (CN)

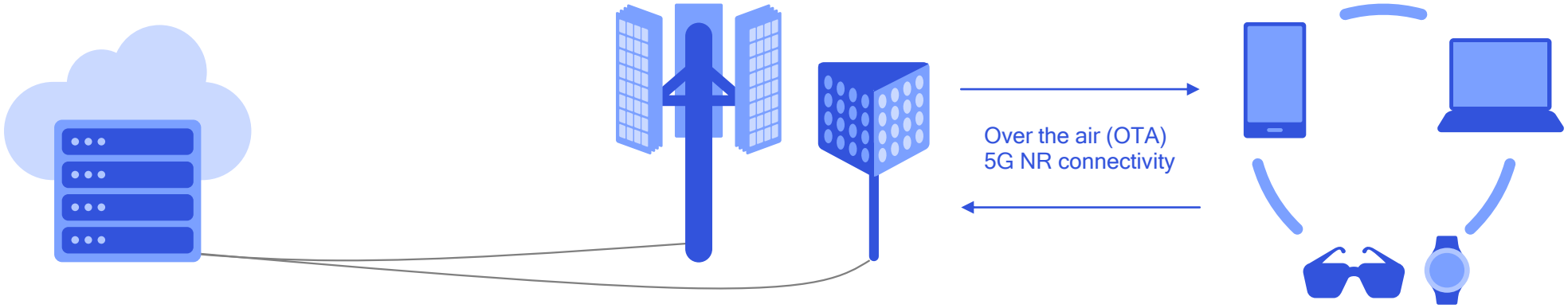
Supports key features such as network slicing, mobile edge compute, standalone mode and more

Base Stations (gNodeB)

Full stack gNodeB implementation includes advanced baseband, MIMO processing, radio and antenna design

5G NR Devices (UE)

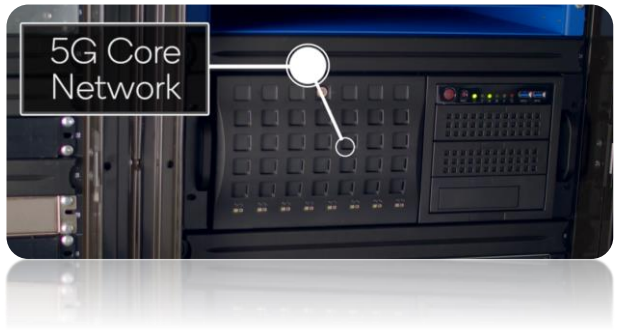
We start with FPGA based functional prototypes then optimize our design to fit device formfactors, e.g., smartphones



Early end-to-end system prototyping – Massive MIMO

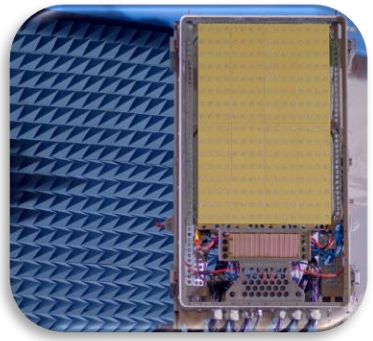
5G Core Network (CN)

Standalone (SA) mode operations and extensible to future capabilities



Base Stations (gNodeB)

3.5 GHz band with 256-element massive MIMO antenna and 64 RF paths



5G NR Devices (UE)

Now utilizing test devices powered by Qualcomm® Snapdragon™ X50/X55 modems

Qualcomm Snapdragon is a product of Qualcomm Technologies, Inc. and/or its subsidiaries.
Qualcomm Reference Design is a program of Qualcomm Technologies, Inc. and/or its subsidiaries.

MWC 2017
Demonstrated first 3GPP-based 5G NR connection based on FPGA

MWC 2018
Validated our Rel-15 UE design with ecosystem IoDTs started in 2H 2017

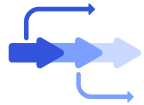
MWC 2019
Showcased Rel-15 e2e 5G NR SA network including multi-user MIMO

2H 2019+
Expanding to Rel-16+ designs and new use cases (e.g., wide-area XR)

Further evolving our 5G NR massive MIMO test network

Enhance 5G NR foundational areas

More capacity
Additional gNodeBs, UL-SDM, …



Lower latency
Self-contained slot structure, …

Improved mobility
0 ms mobility interruption, …

Better reliability
CQI for low PER, per-channel precoding, …

Expand capabilities to support new devices/services

Connected PCs
New formfactor and antenna design

Low/mid-tier IoT
Lower bandwidth devices with NR-Light

Extended reality
Wide-area XR utilizing ultra-low latency

Positioning
Single- and multi-cell, cm-accuracy

Continued upgrades to validate/showcase Rel-16+ designs and new use cases

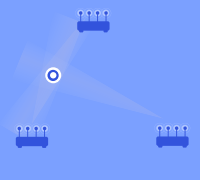
Prototyping new 5G NR capabilities – Positioning

A rich evolution roadmap to meet 5G NR positioning requirements[1]

Release 16

Meeting initial accuracy requirements of 3m (indoor) to 10m (outdoors) for 80% of time

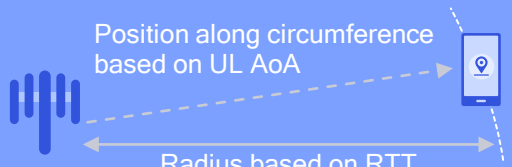
Roundtrip time (RTT)



Angel of arrival / departure (AoA/AoD)

Time difference of arrival (TDOA)

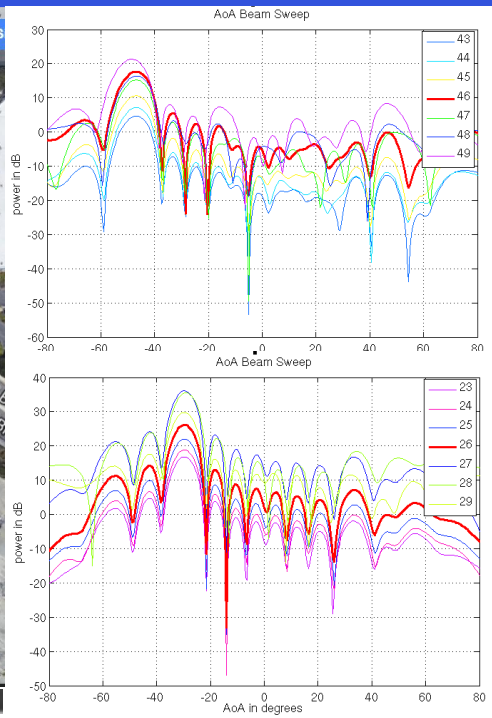
Single cell positioning



Evolving in Release 17 and beyond

Enhancing capability and performance for a wide range of use cases

- Higher accuracy
- Lower latency
- More capacity
- New evaluation scenarios (e.g., IIoT)



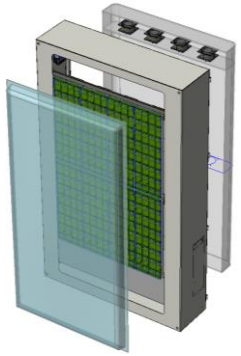
Our advanced 5G NR positioning prototype on the end-to-end massive MIMO test network

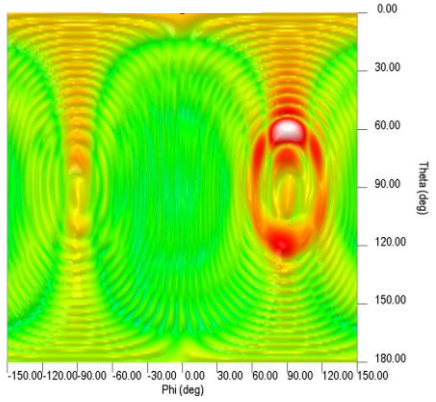
1 5G positioning requirements defined in TS 22.261

We design, prototype, and test 5G NR antenna systems

Antenna Design

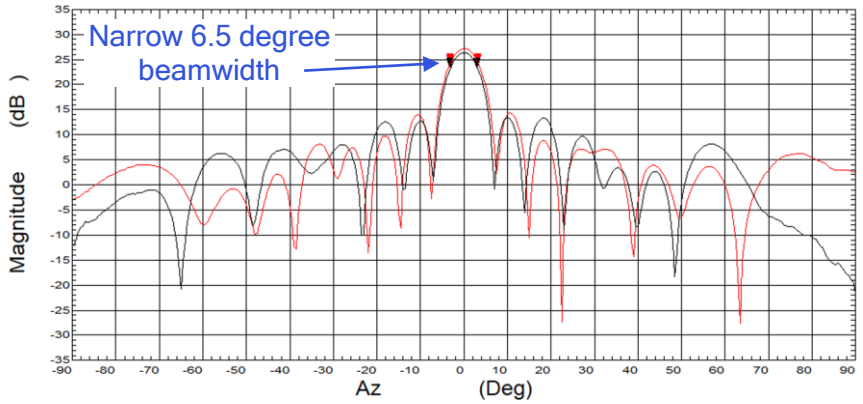
Electronically steerable beamforming array based on computer model simulations





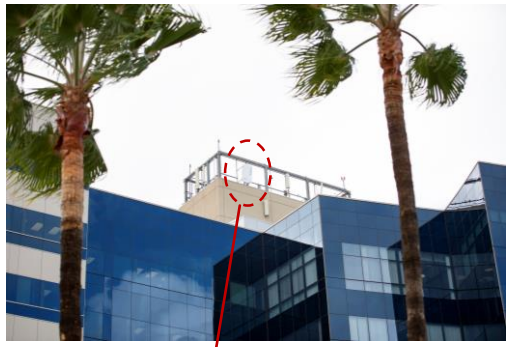
Lab Prototype

Prototype gNodeB and UE antennas: built, calibrated and tested on our radiated test range



Live OTA Network

Rooftop gNodeBs communicate with live 5G UEs to demonstrate realistic OTA end-to-end system performance

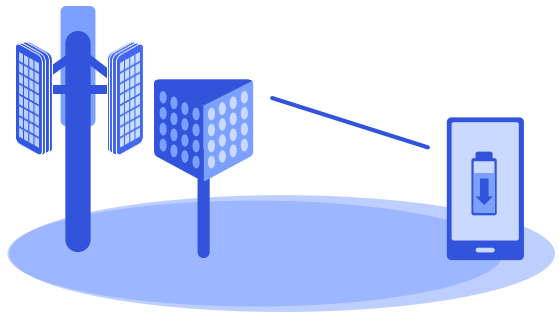


Innovative radio antenna designs enable improved data and location services

Wide-area Augmented Reality over 5G

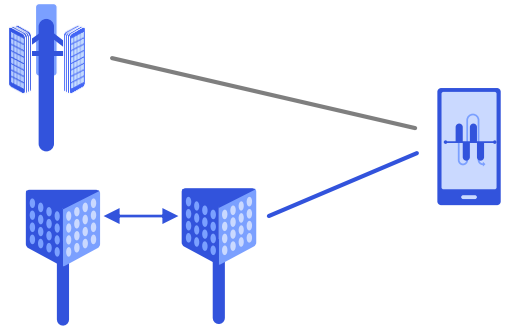
Continue enhancing 5G mobile broadband experiences

Foundational enhancements
Building on the Rel-15 baseline



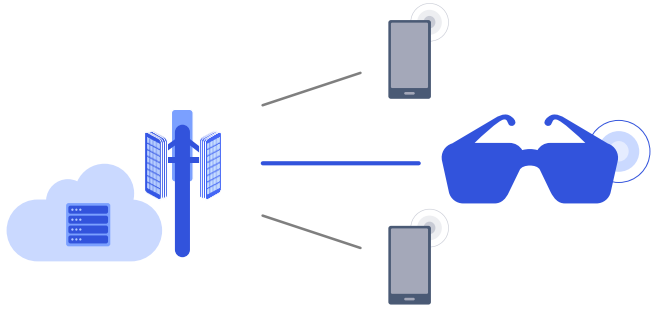
Improving coverage, capacity, latency, power, mobility, reliability, …

New spectrum & deployments
Beyond traditional bands/networks



Supporting unlicensed, shared, higher band spectrum, and IAB, D2D, …

New devices & services
Beyond fixed access/smartphones

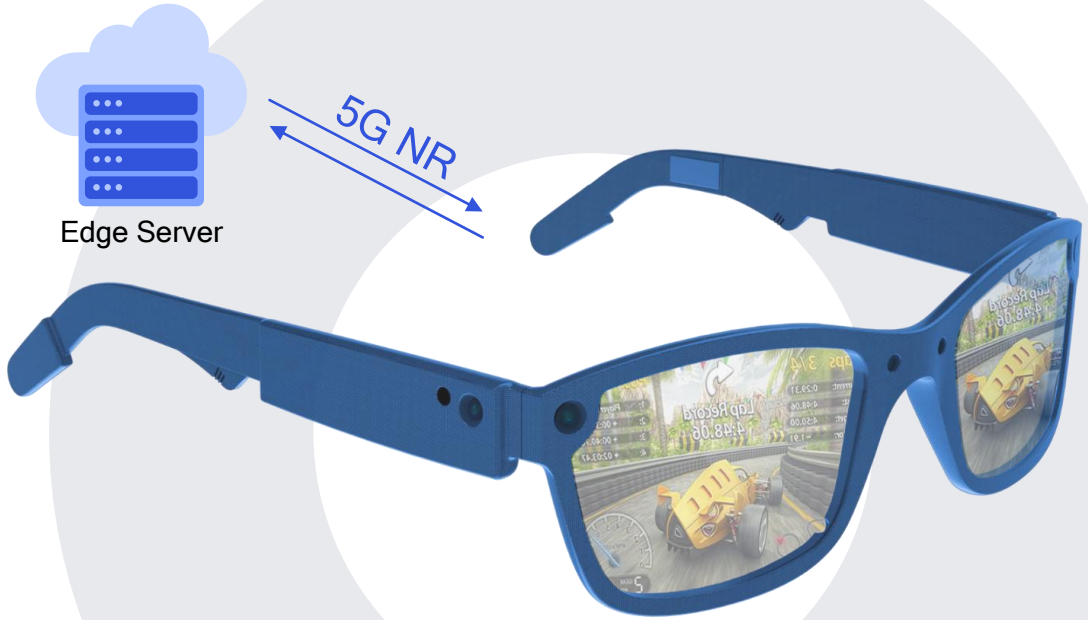


Optimizing for e.g., wide-area XR, more diverse IoT use cases, …

Augmented Reality (AR) is the next mobile platform

Optimizing 5G NR for wide-area XR experiences

Building on 5G NR Rel-16 designs – URLLC, TSN and positioning



Potential areas of enhancements

- More simultaneous users
- More seamless mobility
- Reduced latency
- Increased coverage
- Optimized power consumption
- Higher reliability

Edge processing framework

Defining a standardized system architecture / interface (e.g., APIs) for XR split processing over 5G NR

Traffic awareness

Optimizing XR traffic scheduling in the network to improve user experience and network efficiency

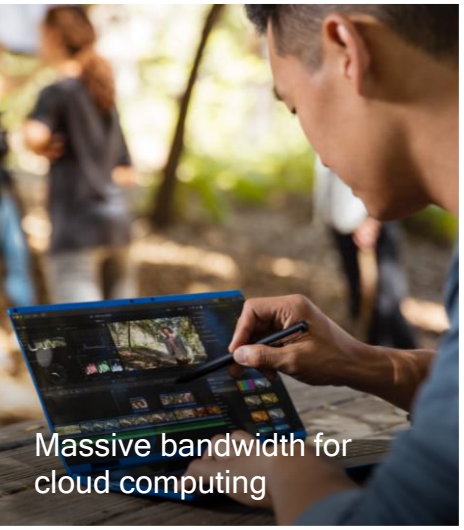
System enhancements

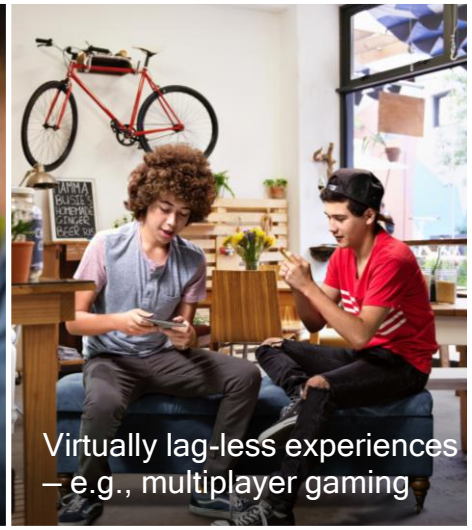
Additional improvements tailoring to the XR use case and device limitations (e.g., formfactor, power)

Outdoor 5G NR mobile mmWave OTA Network


Rich media and entertainment for outdoor – augmenting lower bands


More indoor capacity as outdoor mmWave offloads outdoor lower bands


Massive bandwidth for cloud computing


Virtually lag-less experiences – e.g., multiplayer gaming


Dense indoor & outdoor connectivity for venues


New indoor opportunities – e.g., connected enterprises


Fiber-like broadband to the home – fixed mmWave


Beyond smartphones – e.g., smart manufacturing

5G

5G NR mmWave will support new and enhanced mobile experiences

- Fiber-like data speeds
- Low latency for real-time interactivity
- Massive capacity for unlimited data plans
- Lower cost per bit

We overcome the “impossible” mobile mmWave challenge

Limited coverage and too costly

Limited to just a few hundred feet, thus requiring many small cells

Significant coverage with co-siting

Analog beamforming w/ narrow beam to overcome path loss. Achieving significant coverage when reusing existing sites.

Works only line-of-sight (LOS)

Blockage from hand, body, walls, foliage, rain severely limits signal propagation

Operating in LOS and Non- LOS

Pioneered advanced beamforming, beam tracking leveraging path diversity and reflections.

Only viable for fixed use

Only commercially proven for wireless backhauls and satellites

Supporting robust mobility

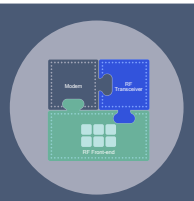
Robustness with adaptive beam steering and switching to overcome blockage from hand, head, body, foliage.

Immature RFIC technology

Power hungry due to wider bandwidth with thermal challenges in small formfactor

Commercialized smartphone

Launched modem, RF, and antenna products to meet formfactor, thermal constraints and regulatory compliance.



5G NR enhancements for mmWave

Ongoing Release 16 Projects

Integrated access and backhaul (IAB)

Enabling flexible deployment of small cells reusing spectrum and equipment for access and backhaul

Enhanced beam management

Improving latency, robustness and performance with full beam refinement and multi-antenna-panel beam support

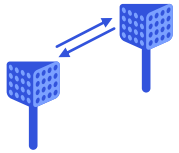
Power saving features

Maximizing device sleep duration to improve power consumption as well as allowing faster link feedback

Dual connectivity optimization

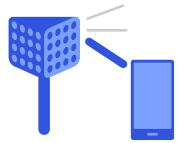
Reducing device initial access latency and improving coverage when connected to multiple nodes

Release 17 Project Candidates



Improved IAB for distributed deployment

Introducing full duplex operations and mobile relays for improved capability, coverage, and QoS

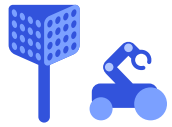


Further optimized beam management

Reducing overhead and enhancing performance (e.g., demodulation, beam selection)

Expanded spectrum support

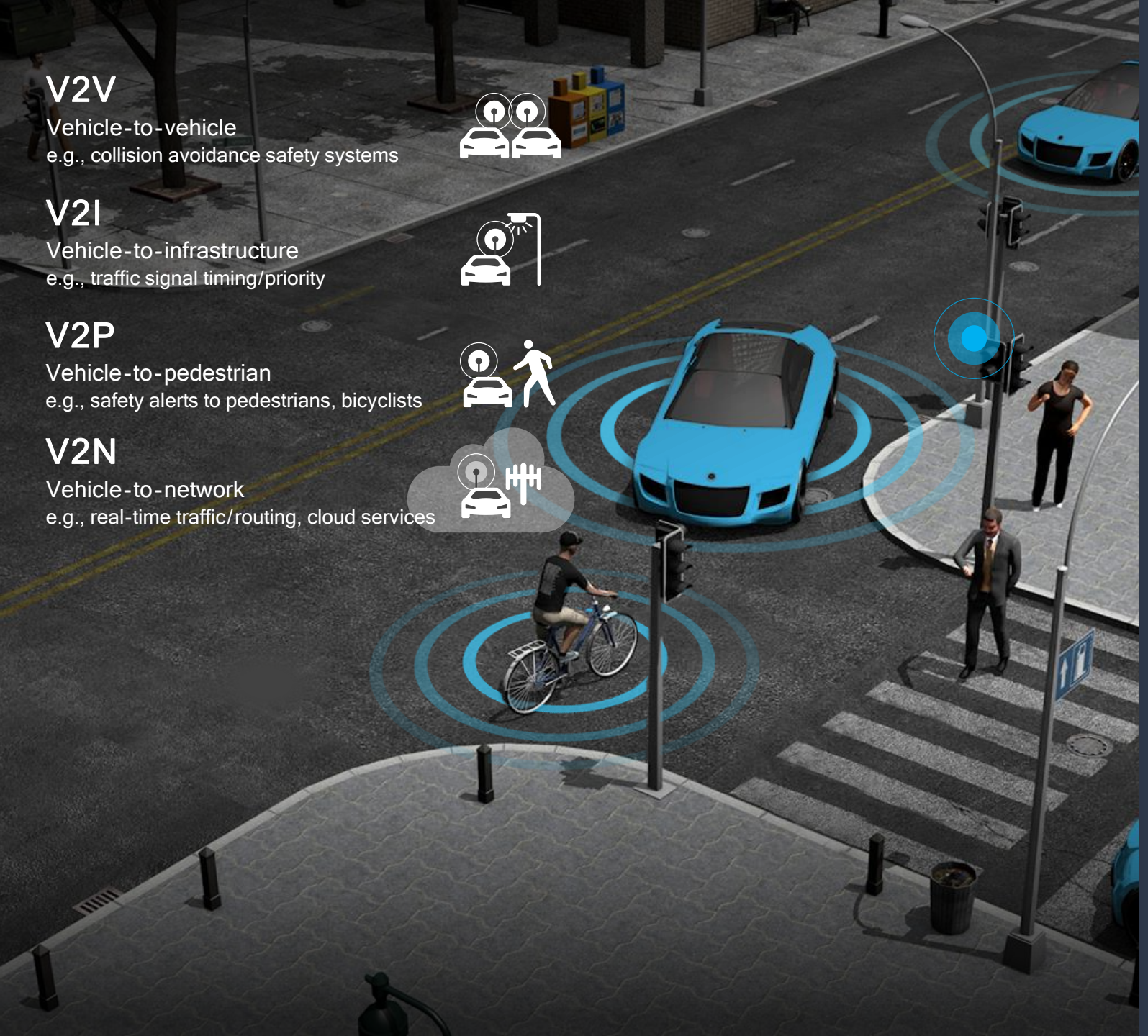
Supporting frequency range from 52.6 GHz up to 114.25 GHz as well as unlicensed spectrum



New use cases beyond eMBB

Expanding mmWave support for sidelink, URLLC, and industrial IoT use cases

5G NR C-V2X



C-V2X

3GPP standard for V2X communication

Fundamentally different from normal WAN operation

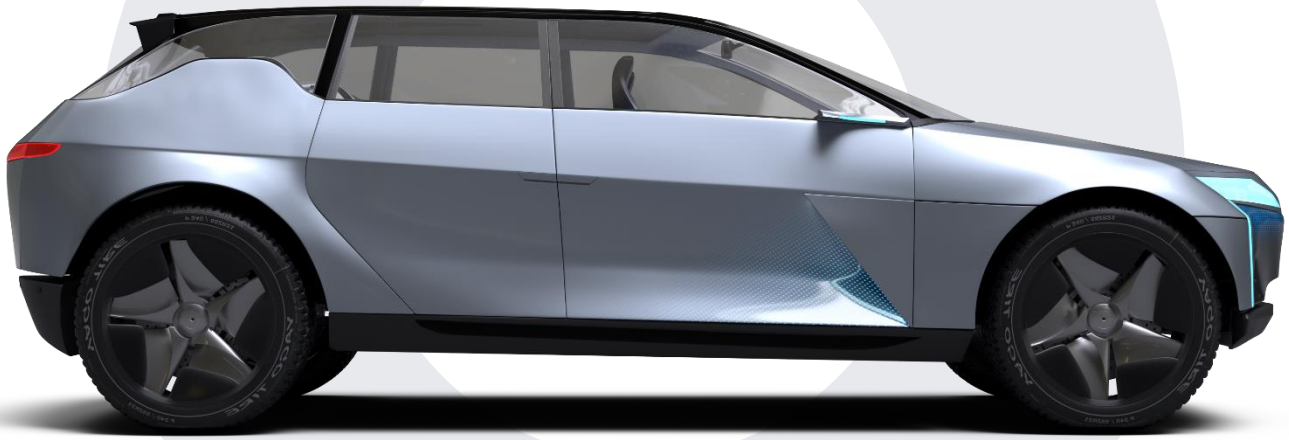
- Operate without any network coverage or SIM
- Direct D2D, i.e., sidelink or PC5
- Dedicated spectrum @ 5.9GHz
- Distributed operation

Rel-14 C-V2X
Automotive safety

Rel-16 5G NR C-V2X
Advanced applications

5G NR C-V2X

Brings new benefits



Increased situational awareness

Sensor sharing

Coordinated driving / intention sharing

Real-time infrastructure updates

Advanced safety

Real-time situation awareness and sharing of new kinds of sensor data take safety to the next level

Faster travel / energy efficiency

More coordinated driving for faster travel and lower energy usage

Accelerated network effect

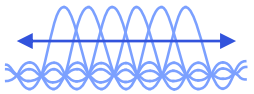
Sensor sharing and infrastructure deployment bring benefits, even during initial deployment rollouts

A design that addresses tomorrow's use case requirements

Building on existing frameworks

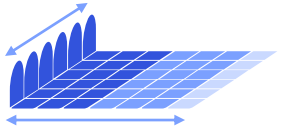
Adapting R15 5G NR flexible framework

Scalable OFDM-based air interface



Such as wideband carrier support (>20 MHz) and different sub-carrier spacing

Flexible slot-based framework



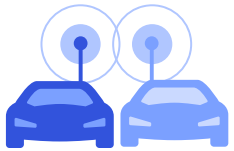
Such as adding sidelink and dynamic reference signal for various speed

Advanced channel coding

State of the art LDPC/ polar coding to deliver performance

Building on R14/15 C-V2X with backward compatibility

Such as frequency division multiplexing, guaranteed latency performance and prioritization support



5G NR C-V2X

Enabling a new paradigm of communication design

- Efficient sidelink link level design for optimized performance at all speeds
- Connectionless 'on-the-fly' distance-based groups
- Multicast with distance-based reliability and application relevancy

And increased performance

- Lower latency
- Higher reliability
- Higher throughput

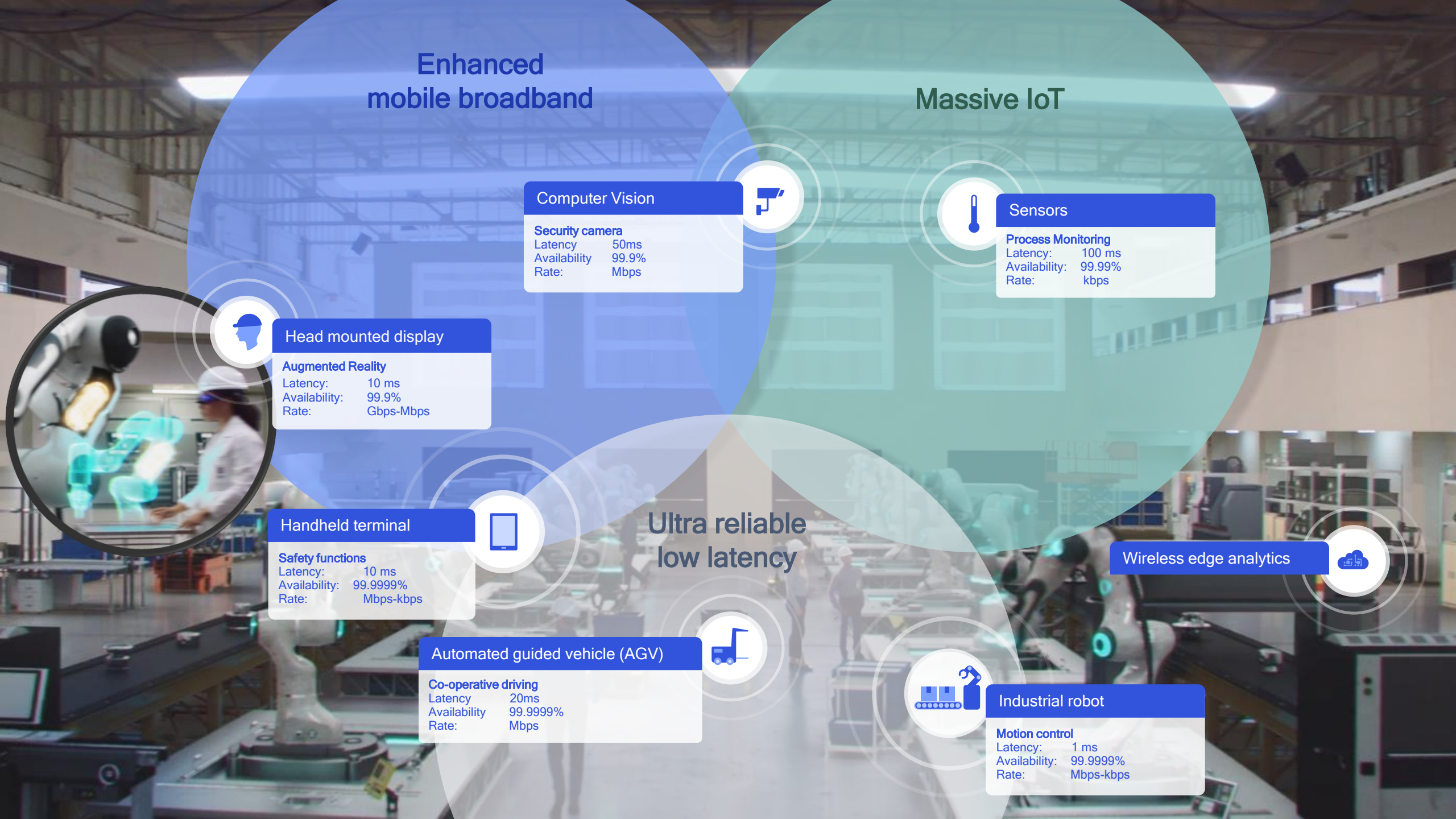
5G NR
Industrial IoT

>$5 Trillion[1]

Global economic output in 2035 enabled by 5G in the following five categories

Manufacturing	Transport	Construction	Utilities	Mining
$3,364B	$659B	$742B	$273B	$249B

1. “The 5G economy: How 5G technology will contribute to the global economy” by IHS Economics / IHS Technology


Enhanced mobile broadband
Massive IoT
Ultra reliable low latency
Computer Vision
Security camera
Latency 50ms
Availability 99.9%
Rate: Mbps
Sensors
Process Monitoring
Latency: 100 ms
Availability: 99.99%
Rate: kbps
Head mounted display
Augmented Reality
Latency: 10 ms
Availability: 99.9%
Rate: Gbps-Mbps
Handheld terminal
Safety functions
Latency: 10 ms
Availability: 99.9999%
Rate: Mbps-kbps
Wireless edge analytics
Automated guided vehicle (AGV)
Co-operative driving
Latency 20ms
Availability 99.9999%
Rate: Mbps
Industrial robot
Motion control
Latency: 1 ms
Availability: 99.9999%
Rate: Mbps-kbps

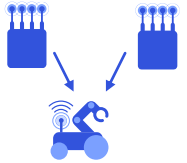
Dedicated and reliable networks optimized for local services

Scalable wireless connectivity on a future proof platform

Capabilities for new use cases e.g. wireless Industrial Ethernet

Private 5G network

Licensed, shared and unlicensed Spectrum



Ultra Reliable Low Latency Communication (URLLC)

Time Sensitive Networking (TSN)

Positioning

Designing 5G to meet industrial IoT requirements

Private 5G network

- Unique network ID
- Integrated and independent architectures
- Seamless fallback to public networks

Spectrum

With NR-U, 5G NR will support:

- Licensed spectrum
- Shared spectrum
- Unlicensed spectrum

URLLC

- Ultra-reliability
- Low latency
- CoMP multi-TRP
- Service multiplexing
- Enhanced mobility

TSN

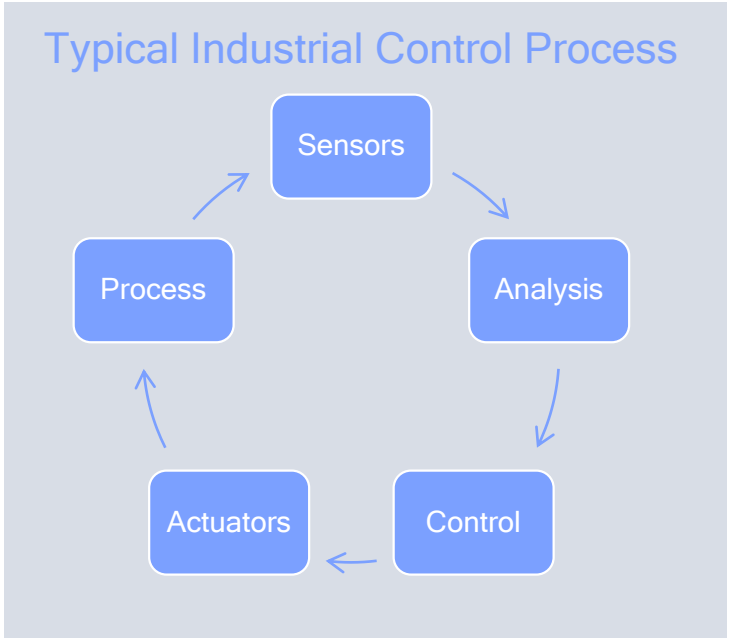
- Ethernet over 5G
- Deterministic networking
- Device time synch.

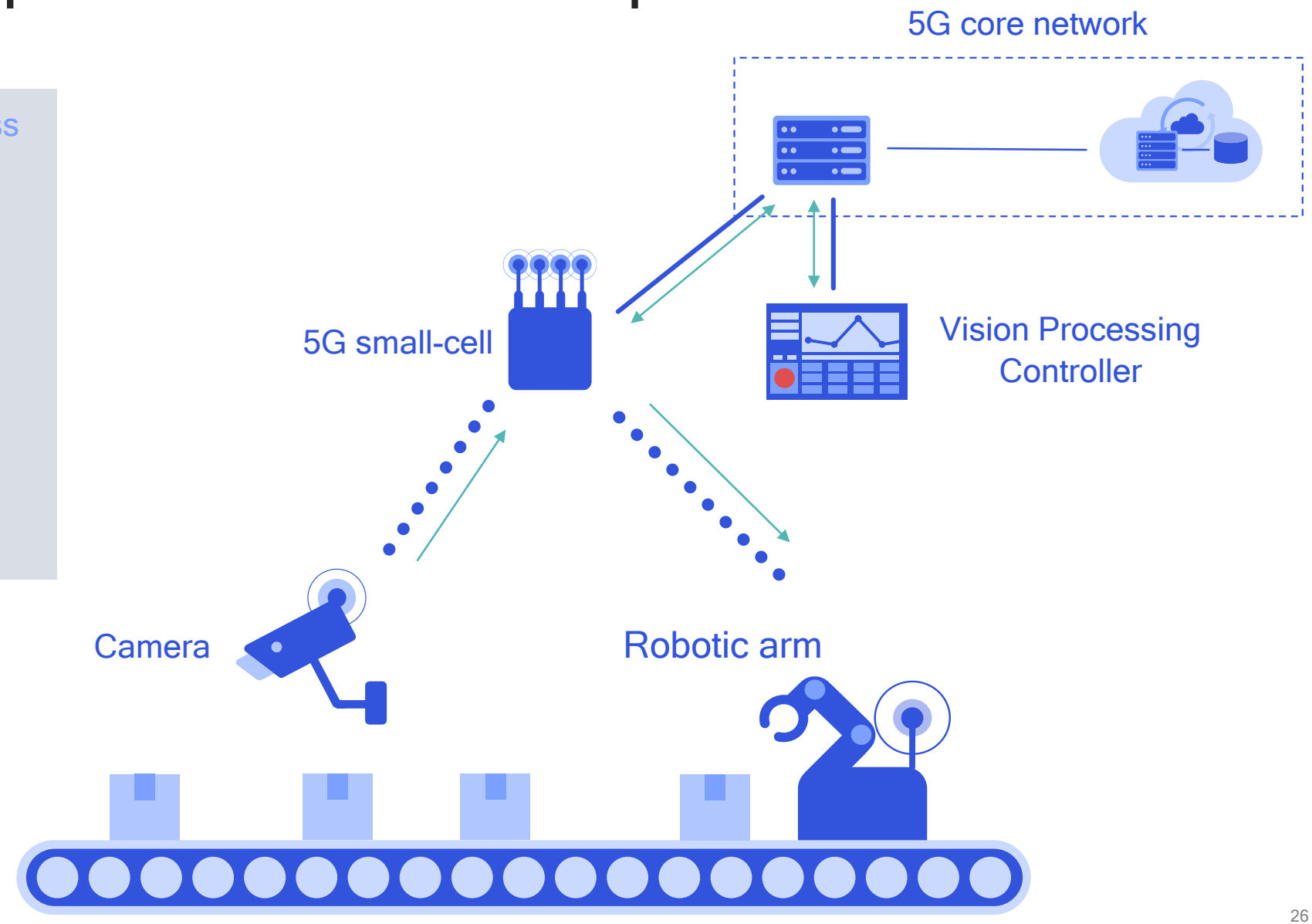
Positioning

- Network & device based
- Industrial IoT requirements

5G NR supports many industrial IoT use cases today; 3GPP Rel-16 brings additional capabilities

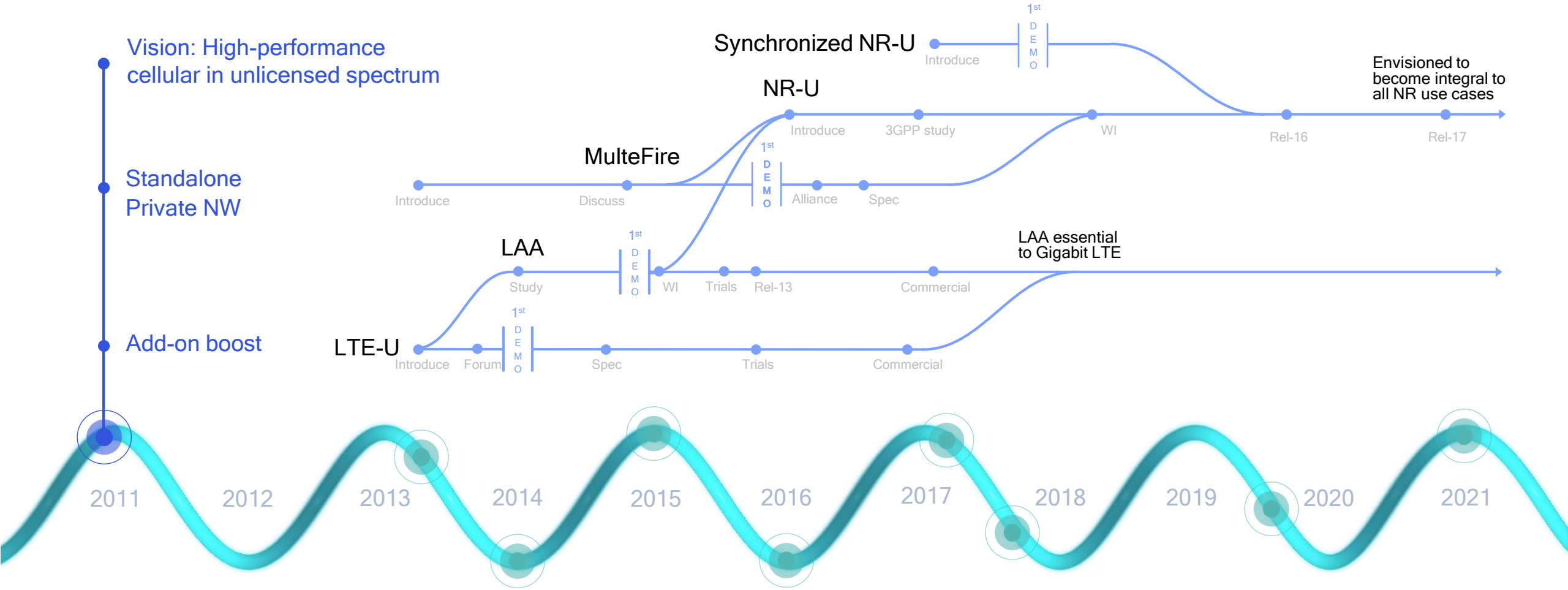
Industrial IoT Application Demo Setup





5G NR for Unlicensed/Shared Spectrum

Vision and persistence brought unlicensed spectrum to 5G



Continuous research, industry first over-the-air LAA, eLAA, MulteFire demos, interoperability with Wi-Fi

5G NR in unlicensed spectrum (NR-U) part of 3GPP R16

Asynchronized sharing

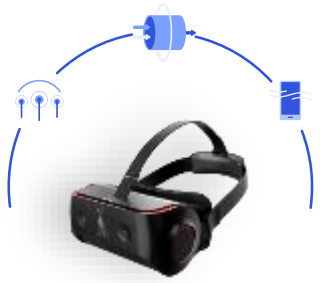
Evolutionary path: existing coexistence rules in unlicensed spectrum

5G

Synchronized sharing

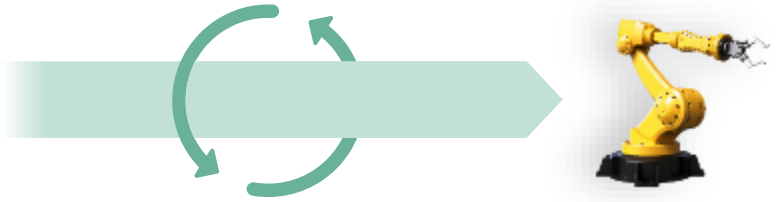
Revolutionary path: new rules for time synchronized sharing in unlicensed and shared spectrum

LAA NR-U



Stand-alone NR-U

Time synchronization



Provides great potential
to share spectrum more efficiently

- URLLC w/ CoMP
- Predictable sharing
- Spatial sharing

Synchronized sharing vital for many IIoT applications

5G

Synchronized sharing

Revolutionary path: new rules for time synchronized sharing in unlicensed and shared spectrum

Time synchronization

URLLC w/ CoMP

- 5G CoMP (Coordinated Multi-Point)
- Ultra-reliability from spatial diversity (enhanced URLLC)
- Significantly increased network capacity

Predictable sharing

- Prioritized resources for each deployment
- Predictable quality of service (QoS)
- Opportunistic sharing of unused resources

Spatial sharing

- CoMP with spatial division multiplexing
- Can enable adjacent deployments to simultaneous use of the same spectrum

	Single deployment	Co-located deployments
URLLC w/ CoMP	✓	✓
Predictable sharing		✓
Spatial sharing		✓

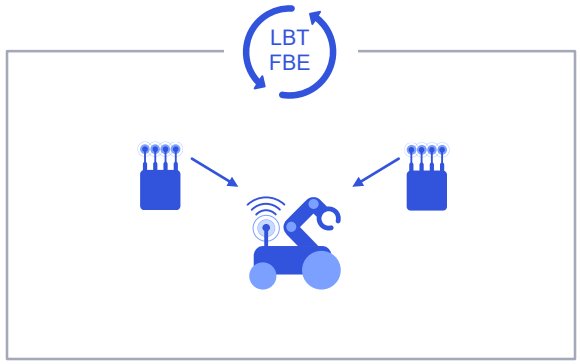
Synchronized sharing—opportunity to share more efficiently

Support URLLC and higher capacity by exploiting spatial domain with CoMP

Existing unlicensed spectrum

Example: 5 GHz global

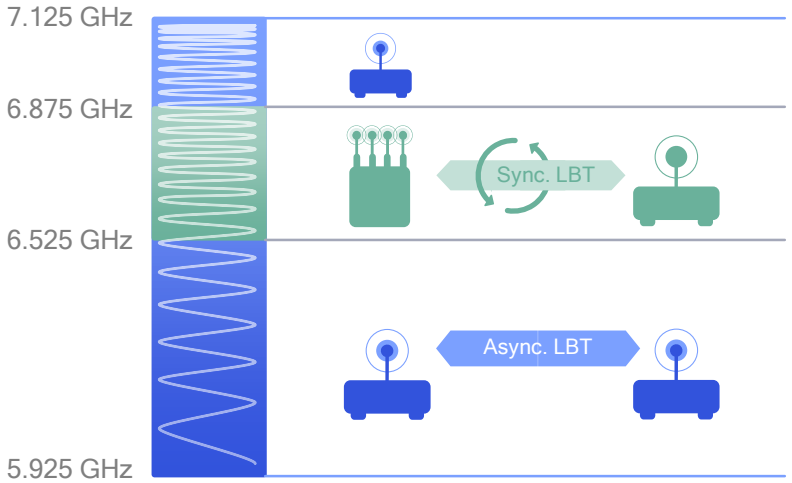
Feasible with today's regulation rules in controlled environments using LBT FBE[1]



Greenfield unlicensed spectrum

Example: 6 GHz USA

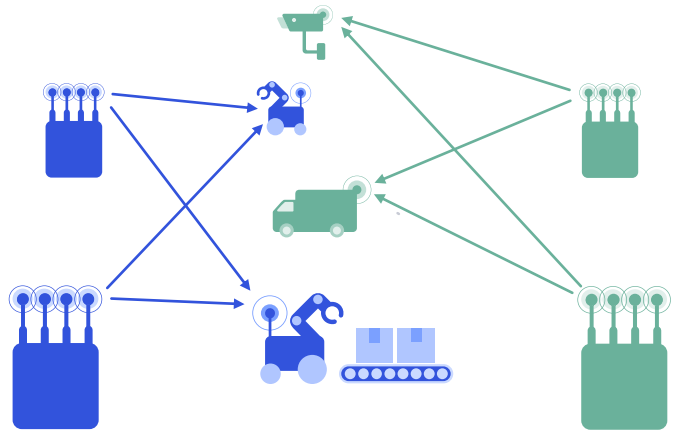
Concept: allocate a portion of the spectrum for time synchronized compatible operation



Dedicated shared spectrum

Example: 3.7 GHz Germany

With spatial sharing, adjacent deployments can simultaneous use the same spectrum

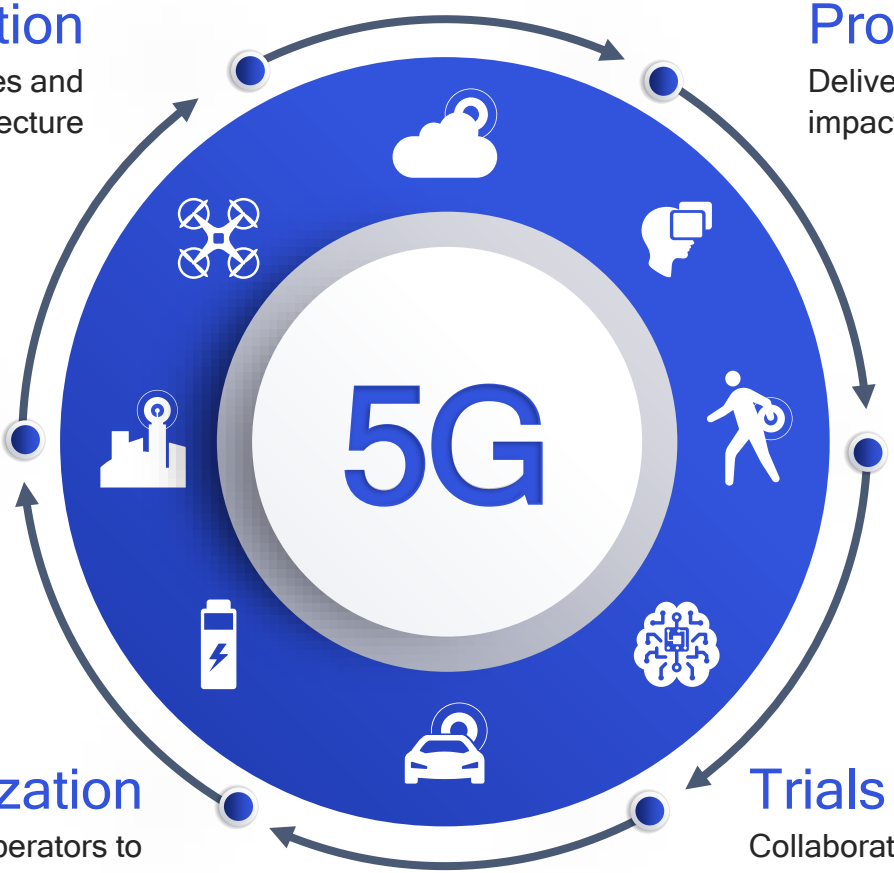


1. Listen before talk (LBT) with Frame Based Equipment (FBE)

5G Standards Leadership

The virtuous circle of cellular technology innovation

Early R&D and technology inventions essential to leading ecosystem forward



Invention

Invent new technologies and end-to-end system architecture

Proof-of-concept

Deliver end-to-end prototypes and impactful demonstrations

Vision

Identify a problem or need; establish requirements

Standardization

Lead ecosystem towards new projects & drive system design through technology standardization process

Commercialization

Engage with global network operators to deploy new features with standards-compliant infrastructure and devices

Trials

Collaborate on over-the-air field trials that track 3GPP standards development & drive ecosystem towards rapid commercialization

The telecom industry is based on technology standards

Technology standardization is key for an openly competitive ecosystem

Ensuring inter-vendor system interoperability

Vendors design and manufacture products adhering to standards, so products from one vendor can work seamlessly with ones from another – a cornerstone of global roaming

Spurring transparent and fair industry competition

Standards are available to anyone who wishes to access them; in many cases, they are free to download on the Internet (e.g., cellular standards at www.3gpp.org)

Standards are essential for commercializing new technologies

Inventions from early R&D need to be first standardized, e.g., 5G NR in 3GPP, before productization

3GPP drives global cellular standards – 2G, 3G, 4G and 5G

20
Years driving cellular tech evolution

14
Major releases

>1.2K
Tech specifications*

100,000's
Technical contributions

3rd Generation Partnership Project

600+
Member companies

~20
Technical groups

6-8
Working group meetings per year

2,000+
Man years in cumulative meeting time*

* Source: 3GPP Mobile Competence Centre (3GPP Support Team) Summary Report from RAN#79 (RP-180616)

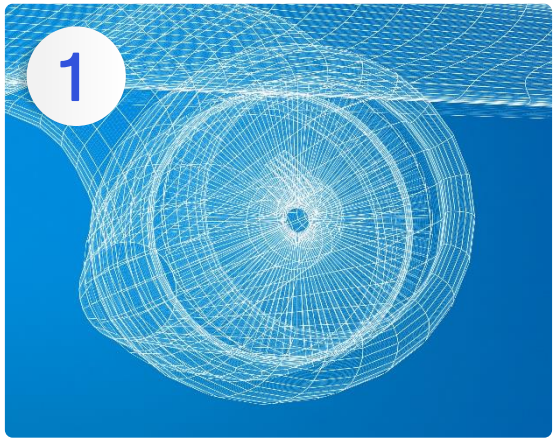
Member-driven organization
Relies on R&D and tech inventions from members, e.g., 'contributions'

Collaborative engineering effort
Consensus-based, tech-driven effort across 100s of entities

Distributed work-flow
Scale/complexity requires division of work into smaller, specialized pieces

3GPP is a collaborative, system-engineering effort

Analogous to other large scale engineering efforts e.g., building an airplane



Early R&D and project proposal to management

Break project into specialized areas, e.g., jet engine

Feasibility study and explore different technical solutions

Develop solution(s) based on agreed work plan

3GPP projects are similar to other complex system-engineering effort, e.g., designing an airplane. 3GPP develops technical specifications for different parts of the system (vs. jet engines, wings, …), is constrained by meeting time (vs. OPEX) and is a collaborative, consensus-based effort across 100s of different entities with diverse interests/incentives (vs. collaboration of teams & suppliers in a single company).

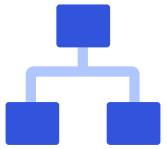
3GPP is a distributed, systems-engineering effort

Technical work occurs across 3 Plenaries + 16 specialized Working Groups

Radio Access Network (RAN)

Defines the radio communications between UEs and core network

- **RAN WG1** — Layer 1 (Physical Layer)
- **RAN WG2** — Layer 2 & 3 (Radio protocols / Access Stratum)
- **RAN WG3** — Access network interfaces + O&M
- **RAN WG4** — Performance requirements
- **RAN WG5** — UE conformance testing
- **RAN WG6** — Legacy RAN, e.g. GSM/EDGE, HSPA



Service / System Aspects (SA)

Responsible for overall architecture and service capabilities

- **SA WG1** — Service requirements
- **SA WG2** — System architecture
- **SA WG3** — Security
- **SA WG4** — Codecs, multimedia system
- **SA WG5** — Telecom management, charging
- **SA WG6** — Mission-critical services, middleware

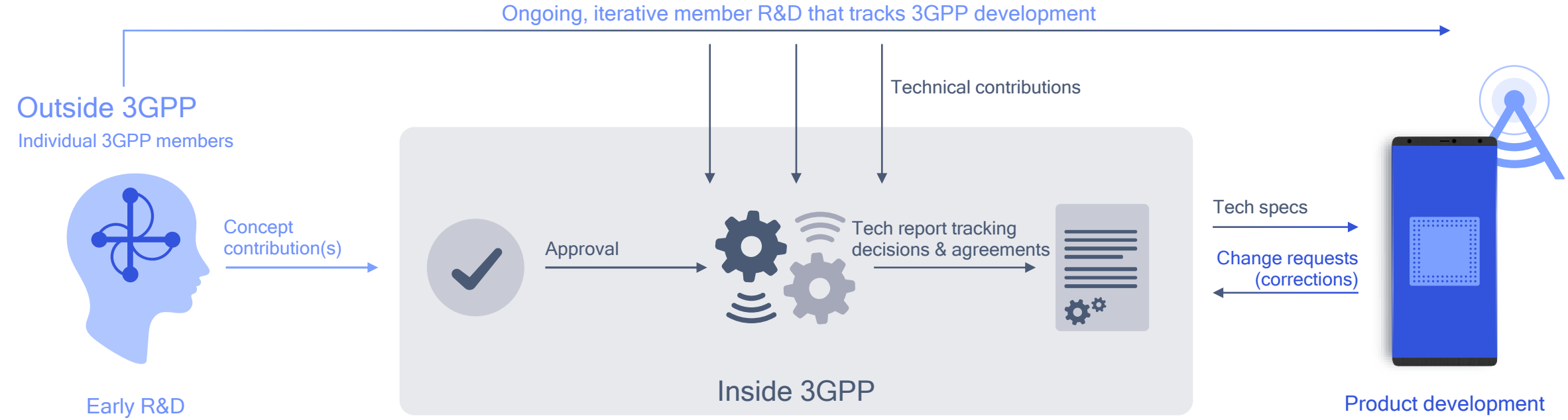
Core Network and Terminals (CT)

Responsible for core network; defines terminal interfaces and capabilities

- **CT WG1** — Protocols between device & core network (NAS)
- **CT WG3** — Policy, QoS and Interworking
- **CT WG4** — Core network protocols
- **CT WG6** — Smart card application

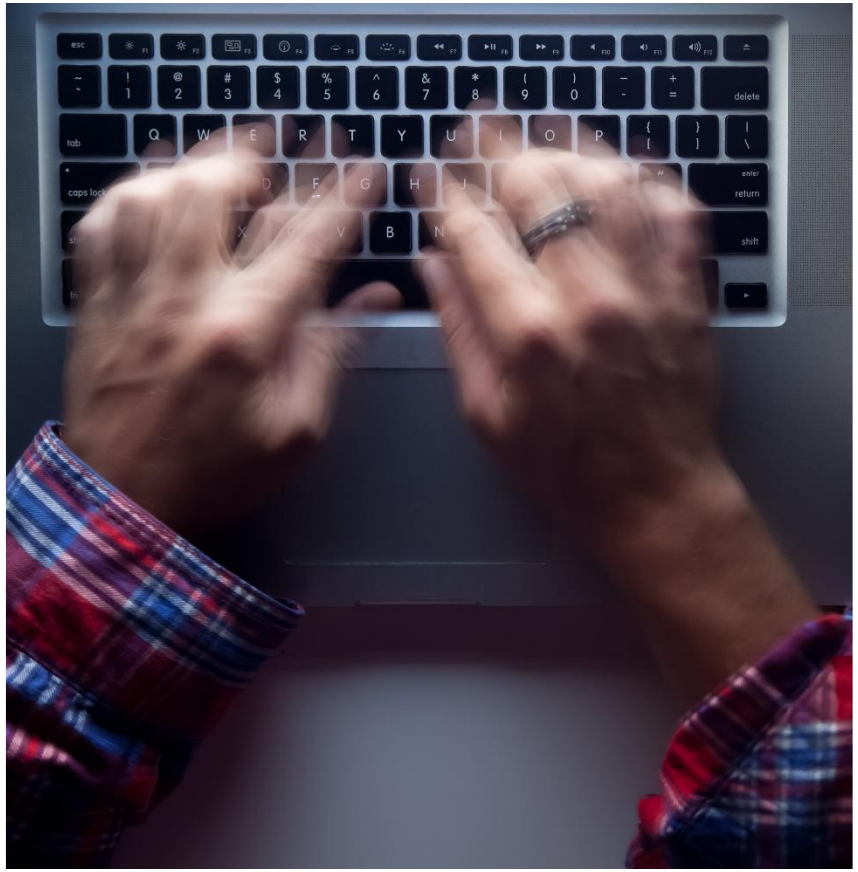
* 3 Technical Service Groups (TSGs) and 16 Working Groups (WGs)

A typical workflow in 3GPP



Some assert 3GPP leadership based on # of contributions

Analogous to asserting leadership in sports on the basis of time-of-possession



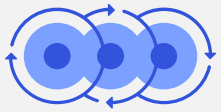
Analogous to assessing the impact of an author by counting the # pages written

Analogous to assessing the quality of an artist by counting the # paintings completed

Driving innovation into 3GPP requires competence + persistence

Early vision

Cutting-edge R&D



Ecosystem validation & support

New concept contribution(s)

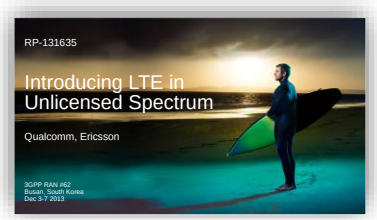
3GPP™ A GLOBAL INITIATIVE

Consensus Driven Work Model

For new concept to be carried forward & for a new project to start (so-called Study or Work Item phases) –
All members have to agree

Pioneering LAA in 3GPP: a vision plus a lot of hard work

Received heavy skepticisms but ultimately adopted & commercially successful



Concept introduction @ 3GPP RAN #62
RP-131635[1]

Vision & research
Basic research started >5 years earlier

RAN workshop with 20+ companies

Pioneered concept
Intense work to educate and overcome initial reluctance

Approved study item
RP-141664

Defined the fundamentals
LBE access & DRS-based RRM (R1-150477), adaptive frame structure & DL-UL configuration (R1-150977), Discovery procedure RRM, CQI (R1-150998), reservation signal design (R1-151406), multi-carrier LBT (R1-152784)

Study complete TR 36.889

Approved work item
RP-151045

Led new project in SA1/SA2/CT to address emerging regulatory requirements related to LAA (USOS[2])

Led new project in RAN4 to create multi-node coexistence testing framework to resolve related industry concerns[3]

Workshop with IEEE/WFA[4]

LAA feature included in Rel-13

Led the work to completion
Including resolving new issues as they emerged through creation of separate projects in other working groups (e.g., regulatory, charging, testing)

2013 2014 2015 2016

1. With Ericsson; 2. Unlicensed Spectrum Offloading System-enhancements: novel solution related to identification of traffic carried over unlicensed spectrum for charging & regulatory (e.g., SP-160117, SP-160835, SP-170740, CP-172028); 3. Coexistence tests, e.g., R4-156326 “Proposal for coexistence testing” & R4-1706224 “Way Forward on Multi-node tests”; 4. Qualcomm led engagements with IEEE and WFA through “liaisons” (formal correspondence between groups)

Initial focus:
eMBB – enhanced mobile broadband services

5G core network

LTE integration

Advanced channel coding

Sub-6 GHz with massive MIMO

Mobile mmWave

Scalable OFDM-based air interface

Flexible framework

Rel-15

Established 5G NR & 5G core technology foundation:
new spectrum, new capabilities, more flexible air interface

5G NR IIoT with eURLLC

5G NR Cellular V2X

5G NR in unlicensed spectrum

5G broadcast[1]

5G massive IoT[2]

Positioning across use cases

eMBB evolution[3]

IAB – integrated access/backhaul

Continuation of Rel-15 projects, others[4]

Rel-16

Expanding to new industries:
new capabilities, efficiencies, and use cases

Enhancements to 5G NR IIoT

Expand sidelink e.g., V2X reliability, P2V, IoT relay

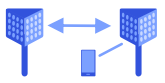
Unlicensed spectrum across all uses cases

New spectrum above 52.6 GHz

NR-Light e.g., wearables, industrial sensors

Centimeter accuracy e.g., IIoT with mmWave

Continued eMBB enhancements[5]



More capable, flexible IAB

Rel-15 deployment learning, XR, drones, others[6]

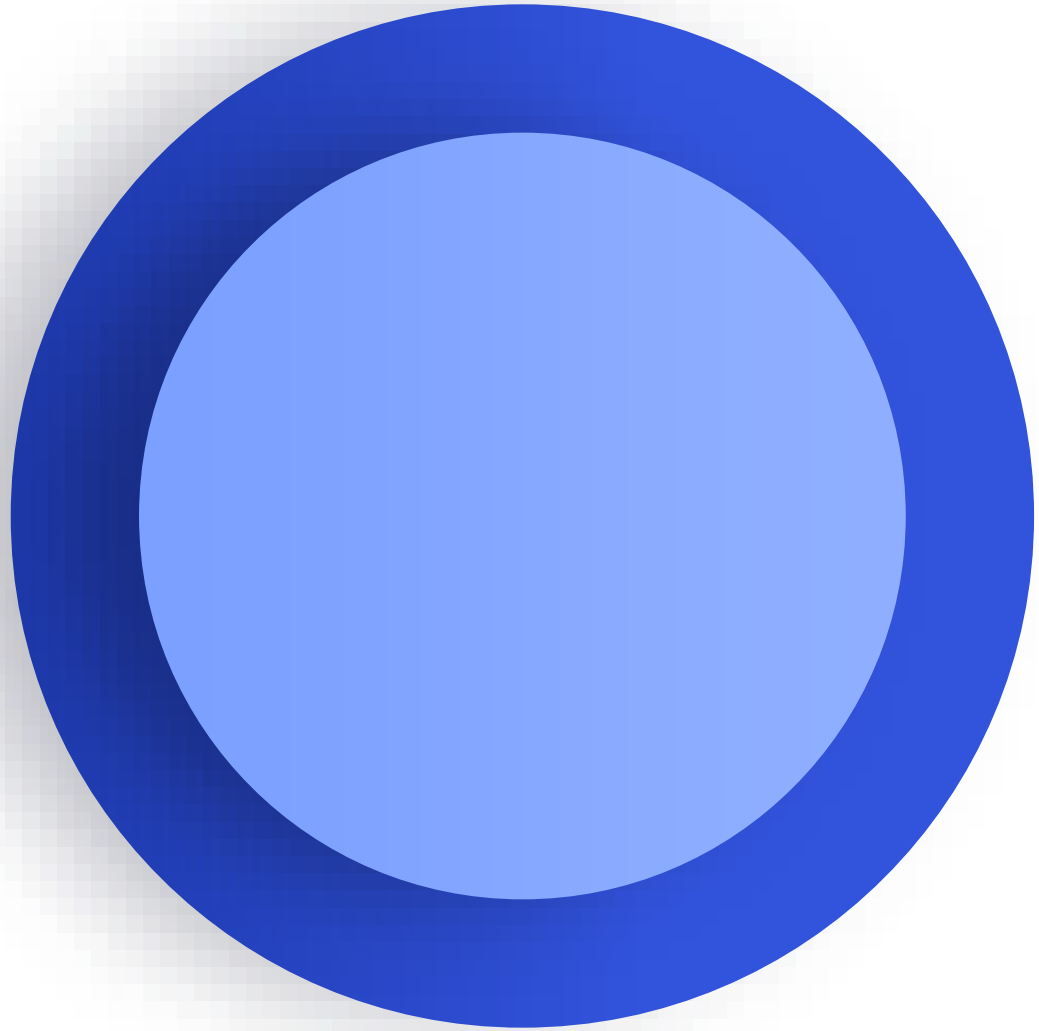
Rel-17: Possible candidates

Definition in progress.
Lesson learned & further expansion and evolution

Continued 5G NR evolution to deliver on the 5G vision

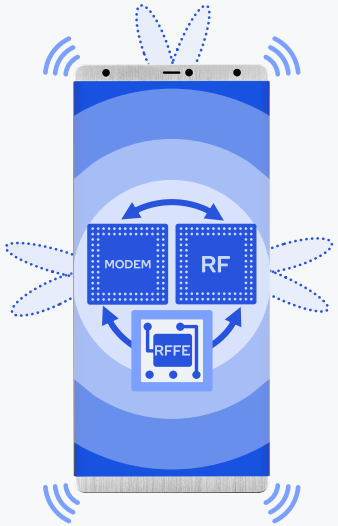
1. Enhancing Rel-14 LTE enTV to meet 5G requirements; 2. eMTC/NB-IOT in-band 5G NR and connected to 5G core; 3. MIMO, power consumption, mobility, MR DC/CA, interference management and more; 4. Non-terrestrial networks, non-public networks (private networks), NR SON/MDT and more; 5. further improvements to capacity, coverage, mobility, power consumption, spectral efficiency; 6. mixed-mode multicast, small data transmission, multi-SIM, satellite, multimedia

System RF front-end

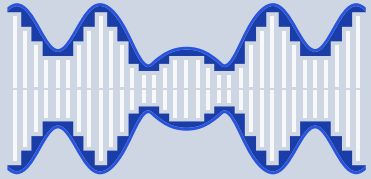


Achievements made possible by approaching challenges with a **systems** perspective

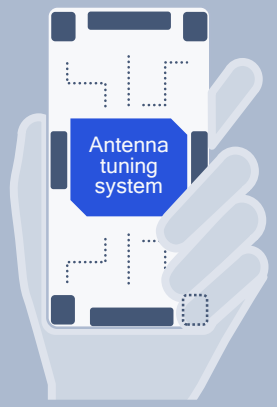
Qualcomm®
mmWave
for mobile



Qualcomm®
Smart Transmit™



Qualcomm®
Wideband
Envelope Tracking



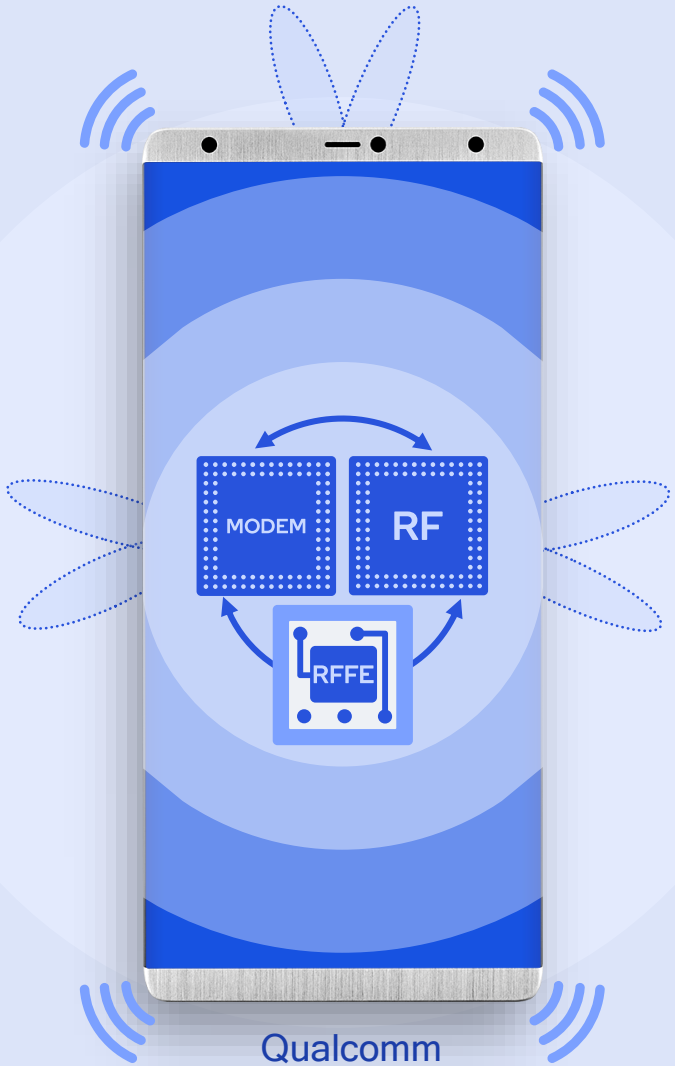
Qualcomm®
Signal Boost

Qualcomm®
5G PowerSave

Qualcomm® Smart Transmit™

Multi-radio management system for highly optimized uplink while complying with RF transmit power limits

- Manage Tx power across all radios in real time
- Increase UL throughput and coverage
- Smart multi-beam management



Qualcomm Smart Transmit

- Support 2G-5G including mmWave
- Commercialized in some 5G mmWave devices in 2019 (US)

Qualcomm 5G PowerSave

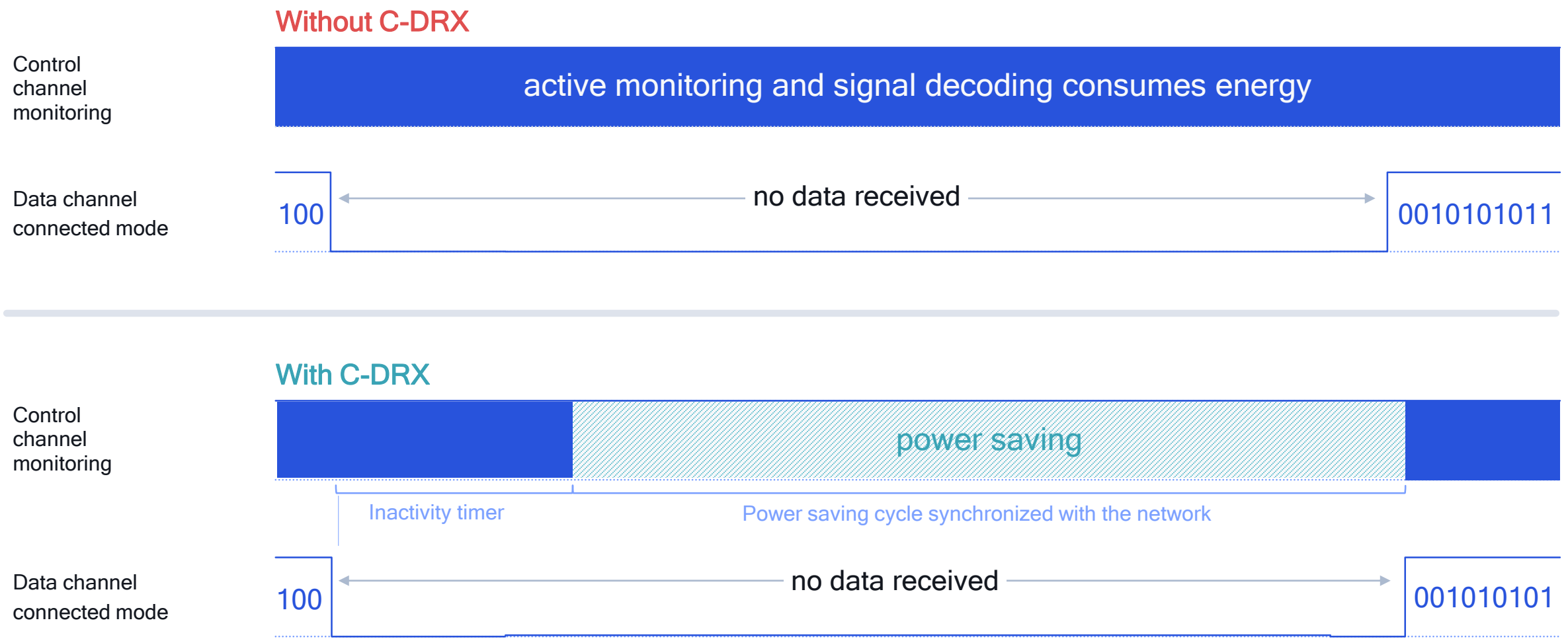
Comprehensive solution designed to bring **all-day battery life** to 5G devices

Qualcomm Technologies introduced related inventions in 4G, made **Gigabit LTE practical**

System-level optimization with features spanning network and device

Connected-mode Discontinuous Reception (C-DRX)

One of the key features in Qualcomm 5G PowerSave



* Connected-Mode Discontinuous Reception

Qualcomm

Thank you

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