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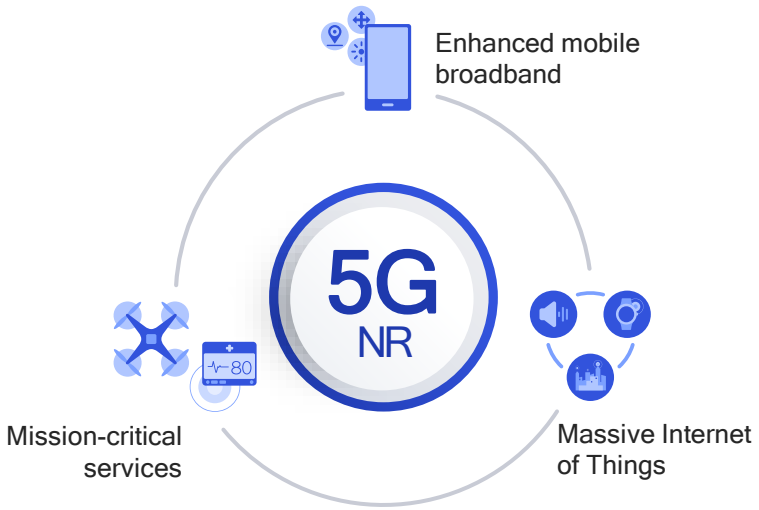
September 2018

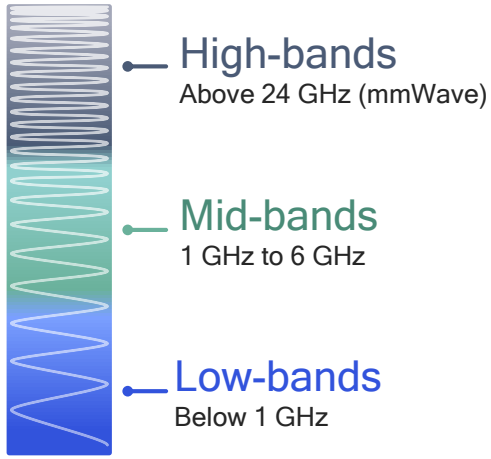
Expanding the 5G NR ecosystem

5G NR roadmap in 3GPP Release 16 and beyond

Designing a unified, more capable 5G air interface



Diverse services



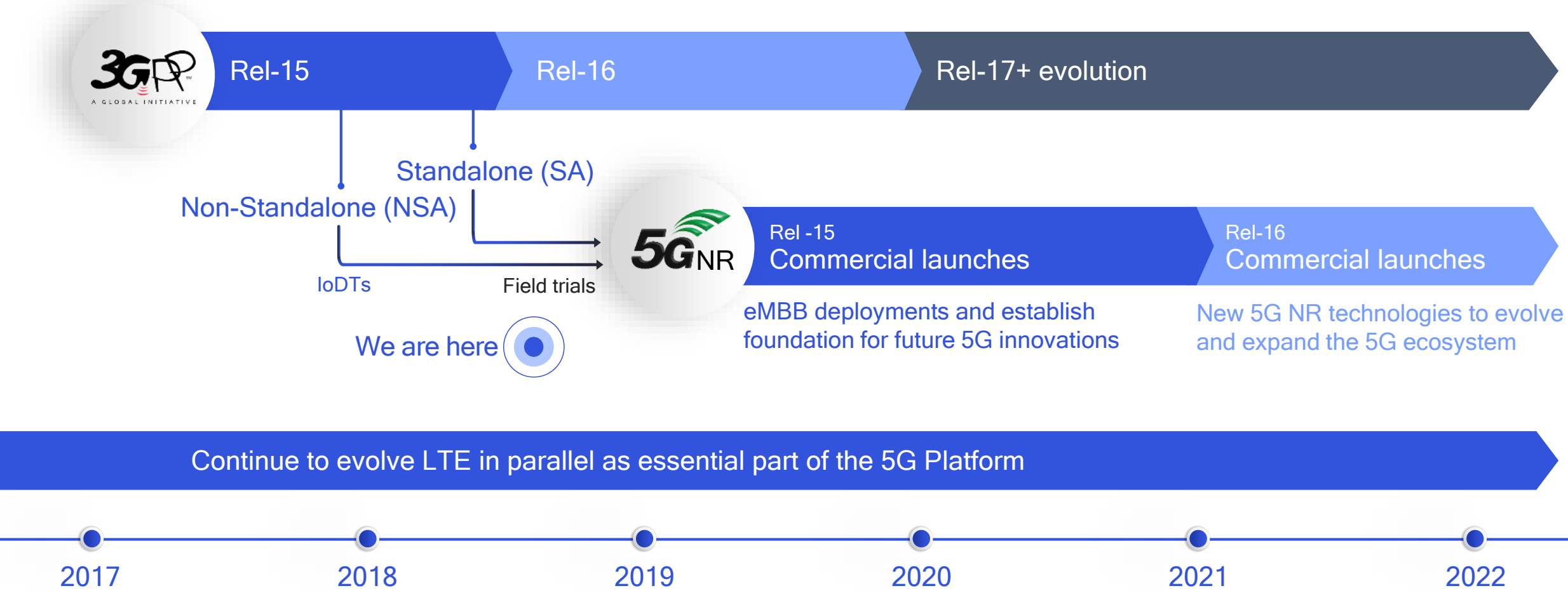
Licensed/shared/unlicensed

Diverse spectrum

Diverse deployments

Existing, emerging, and unforeseen services – a platform for future innovation

Driving the 5G roadmap and ecosystem expansion



5G NR pioneering advanced 5G NR technologies

To meet an extreme variation of 5G NR requirements

Mission-critical services

Cellular Vehicle-to-Everything (C-V2X)

Drone communications | Private Networks

Ultra Reliable Low Latency Comms (URLLC)

Enhanced mobile broadband

Spectrum sharing | Flexible slot-based framework

Scalable OFDM | Massive MIMO | Mobile mmWave

Dual Connectivity | Advanced channel coding

Massive Internet of Things

Enhanced power save modes

Deeper coverage | Grant-free UL

Narrow bandwidth | Efficient signaling

10x Decrease in end-to-end latency

10x Experienced throughput

3x Spectrum efficiency

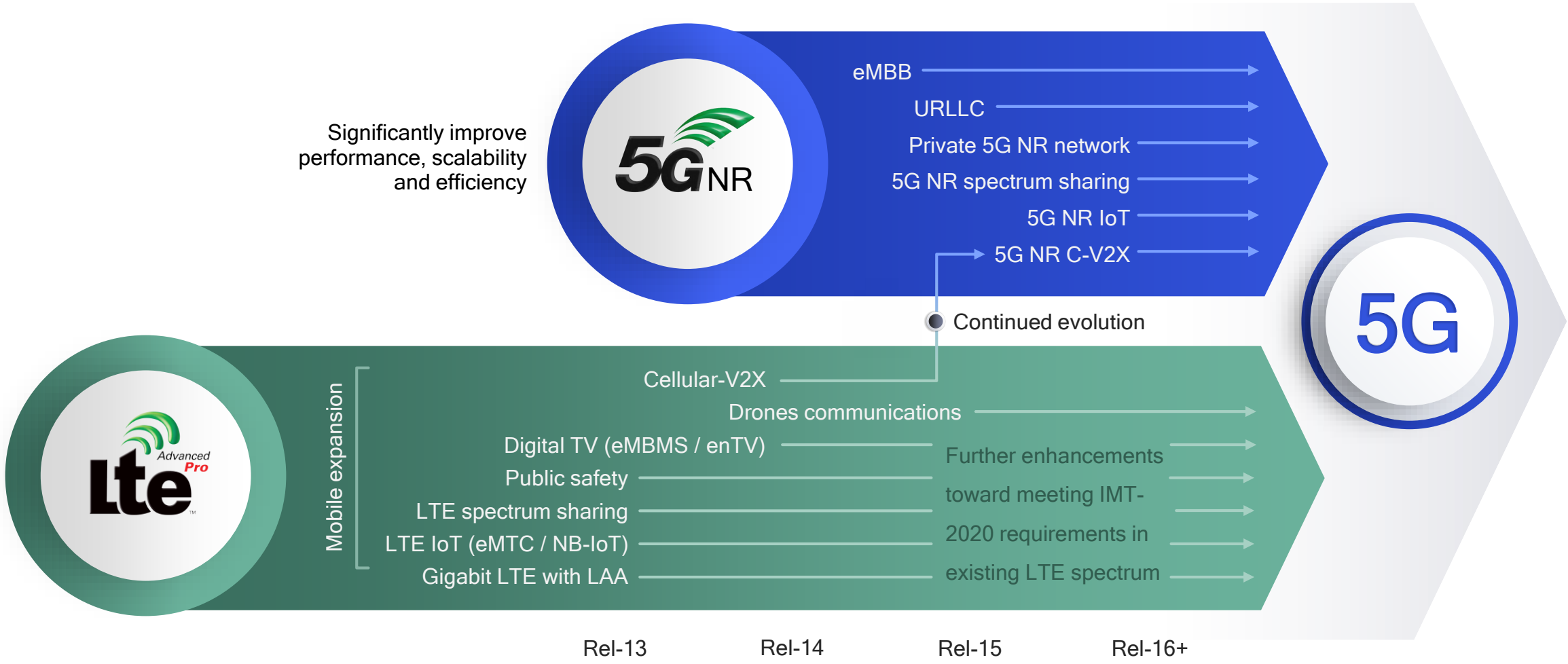
100x Traffic capacity

100x Network efficiency

10x Connection density

Based on ITU vision for IMT-2020 compared to IMT-advanced; URLLC: Ultra Reliable Low Latency Communications; IAB: Integrated Access & Backhaul

A rich and continued roadmap of LTE Advanced Pro advancements is foundational to the 5G evolution



The R&D engine fueling the 5G industry

Early system-level R&D investments

Designing/testing 5G for many years with best-in-class prototype systems

3GPP A GLOBAL INITIATIVE

5G NR

3GPP standards and technology leadership

Our system-level inventions are foundational to 5G NR standard

AT&T BT 中国移动 China Mobile 中国电信 CHINA TELECOM
China unicom中国联通 Deutsche Telekom LG U+ KDDI kt
NTT docomo orange Singtel SK telecom Sprint
TIM verizon Vodafone Group WIND 3
ERICSSON HUAWEI NOKIA SAMSUNG ZTE中兴

Global network experience and ecosystem collaborations

Industry-leading demos, simulations, testing and trials on path to commercialization

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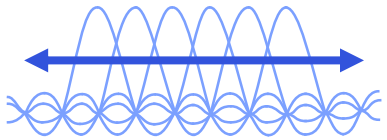
Building on our LTE technology leadership

Our technology inventions drove Rel-15 specifications

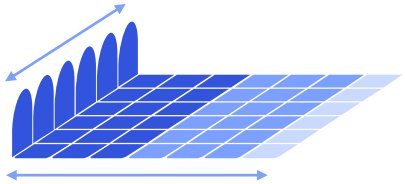
Scalable OFDM-based air interface



Scalable OFDM numerology

Address diverse services, spectrum, deployments

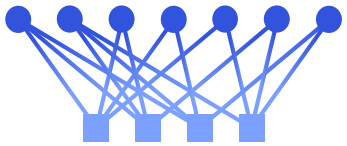
Flexible slot-based framework



Self-contained slot structure

Low latency, URLLC, forward compatibility

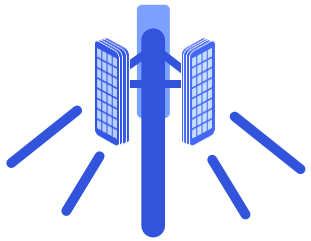
Advanced channel coding



Multi-Edge LDPC and CRC-Aided Polar

Support large data blocks, reliable control channel

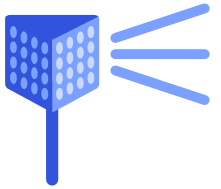
Massive MIMO



Reciprocity-based MU-MIMO

Large # of antennas to increase coverage/capacity

Mobile mmWave



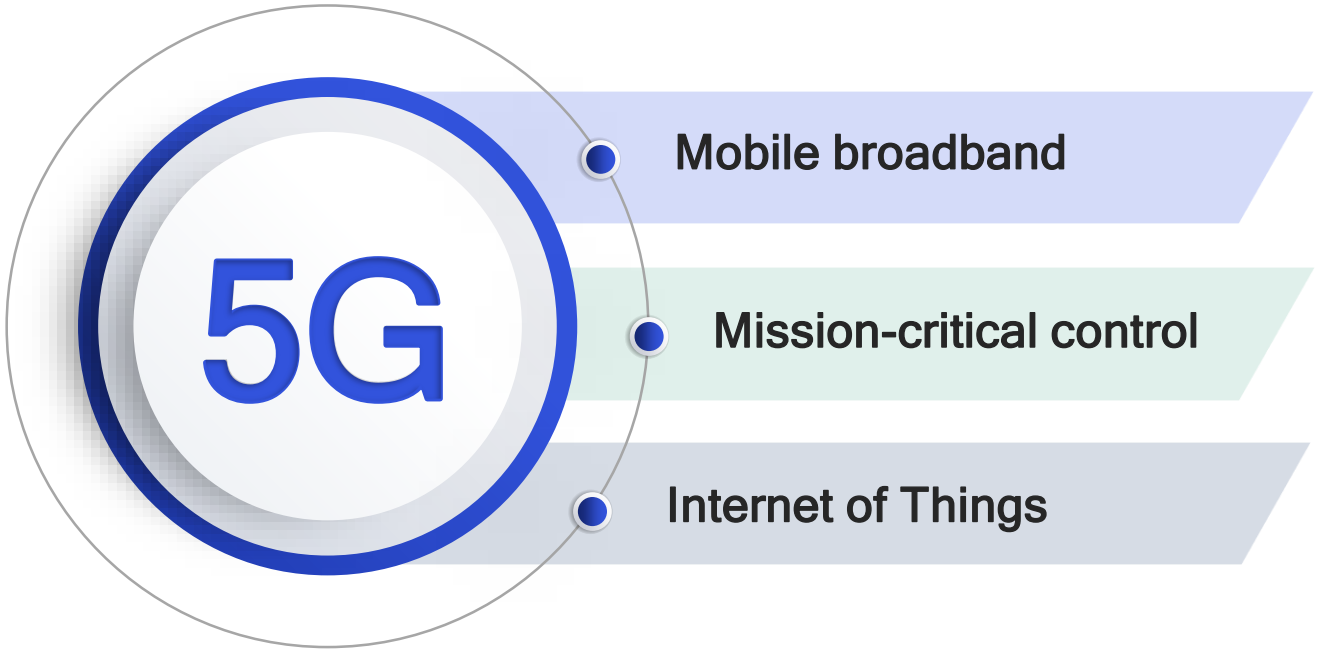
Beamforming and beam-tracking

For extreme capacity and throughput

Early R&D investments | Best-in-class prototypes | Fundamental contributions to 3GPP

5G next Gen Core (NGC) also part of 3GPP Rel-15

Increased flexibility through NFV and SDN – essential to 5G NR expansion



Configurable end-to-end connectivity per vertical

Modular, specialized network functions per service

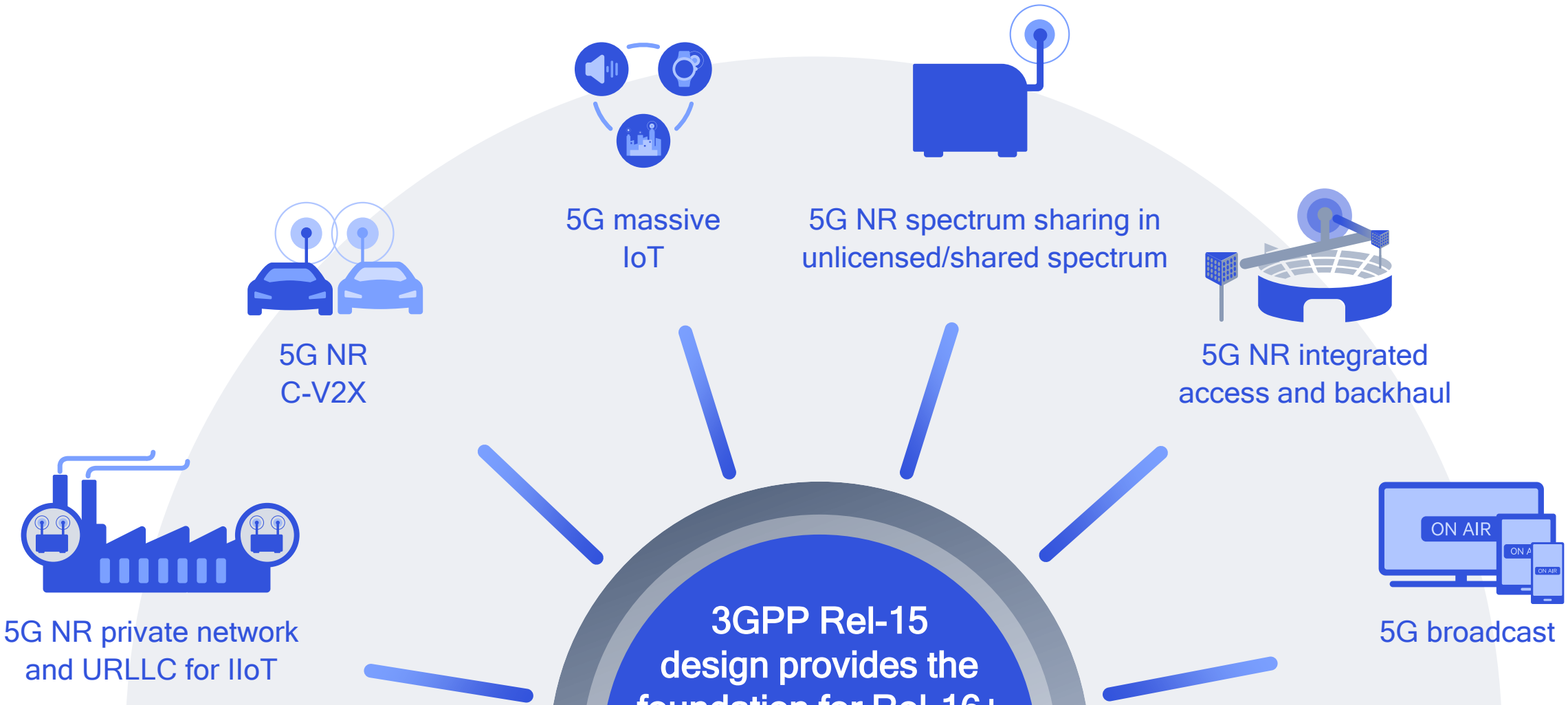
Flexible subscription models

Dynamic control and user planes with more functionality at the edge

NFV: Network Functions Virtualization; SDN: Software Defined Networking

Better cost/energy efficiency | Optimized performance | Flexible biz models and deployments | Dynamic creation of services

Driving a rich 5G roadmap in Release 16 and beyond



Spectrum sharing valuable for wide range of deployments

Licensed spectrum aggregation

Better user experience with higher speeds

Enhanced local broadband

Neutral host, neighborhood network

Private 5G networks

Industrial IoT, Enterprise

Enhancing existing deployments

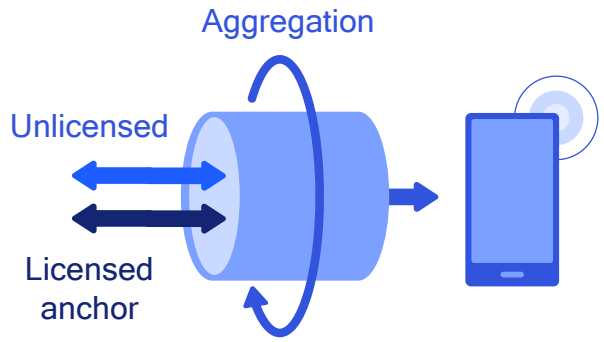
New types of deployments

Examples today: Gigabit LTE with LAA[1]

Examples today: Private LTE networks

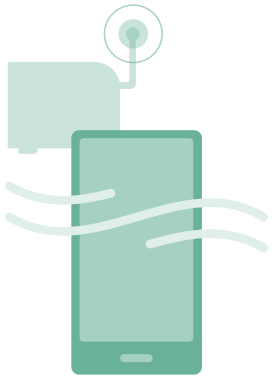
1. Licensed-Assisted Access (LAA);

3GPP study on 5G NR operation in unlicensed spectrum



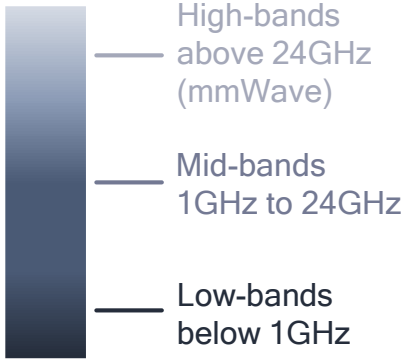
NR-based LAA

NR in unlicensed aggregated with LTE (dual connectivity) or NR (carrier-aggregation) in licensed spectrum



Standalone unlicensed

NR operating standalone in unlicensed spectrum. This will become the MulteFire™ evolution path to 5G.



Across spectrum bands

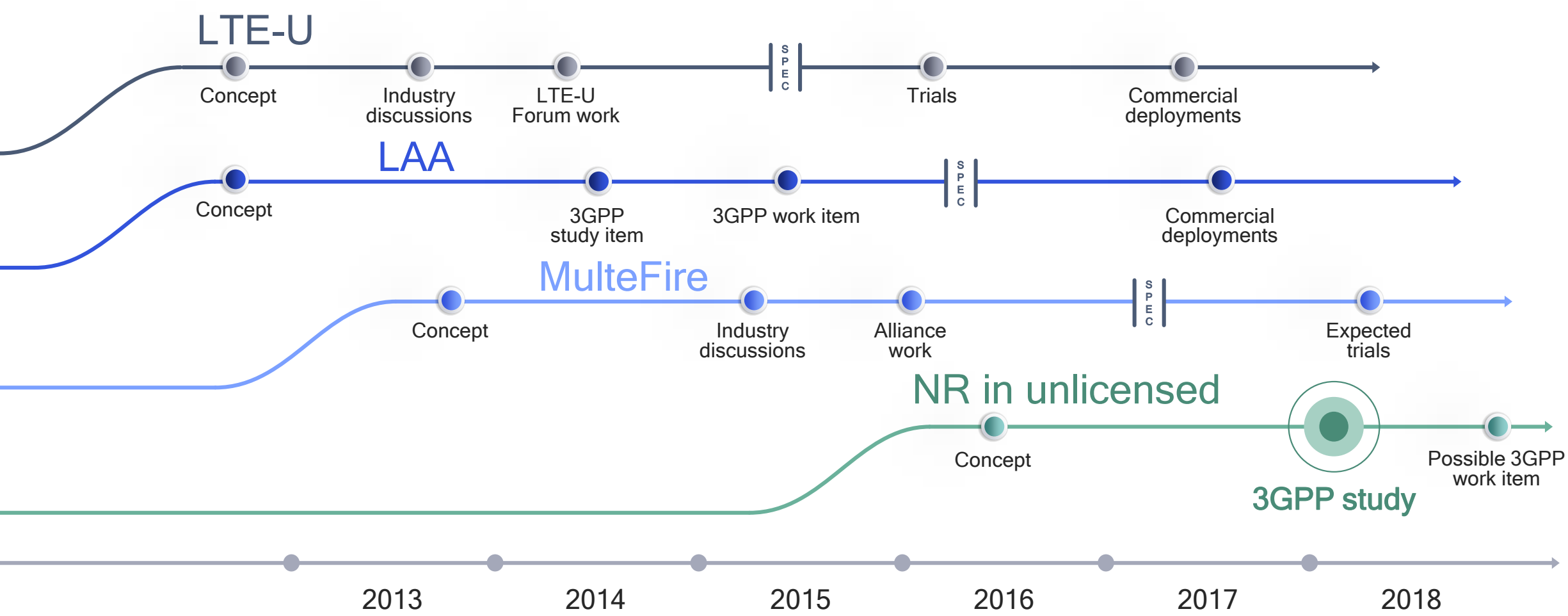
Both below and above 6 GHz, e.g., 5GHz, 37GHz, 60GHz* (*assuming no change to waveform)

1 Study item in Rel. 15 (RP-170828), which could be followed by a work item that is completed in Rel. 16.

Designing with fair co-existence in any unlicensed spectrum: NR/NR, NR/LTE, NR/Wi-Fi

Many years in the making to lead up to NR in unlicensed

Work started over 5 years ago when we first envisioned LTE in unlicensed



5G NR – opportunity for new spectrum sharing paradigms

Building on spectrum sharing technologies that we are pioneering today for LTE

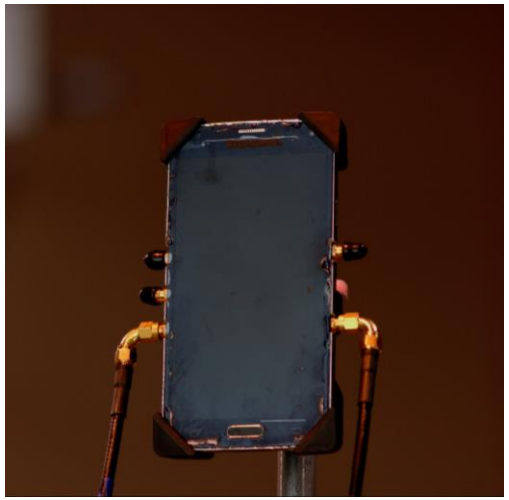
Evolution Path

- LTE-U / LAA
- LWA
- MulteFire
- CBRS / LSA

5G NR Spectrum Sharing

Revolution Path

- Flexible NR framework
- Time synch. and coordinated sharing
- Guaranteed QoS
- Exploiting spatial domain
- Vertical & horizontal sharing



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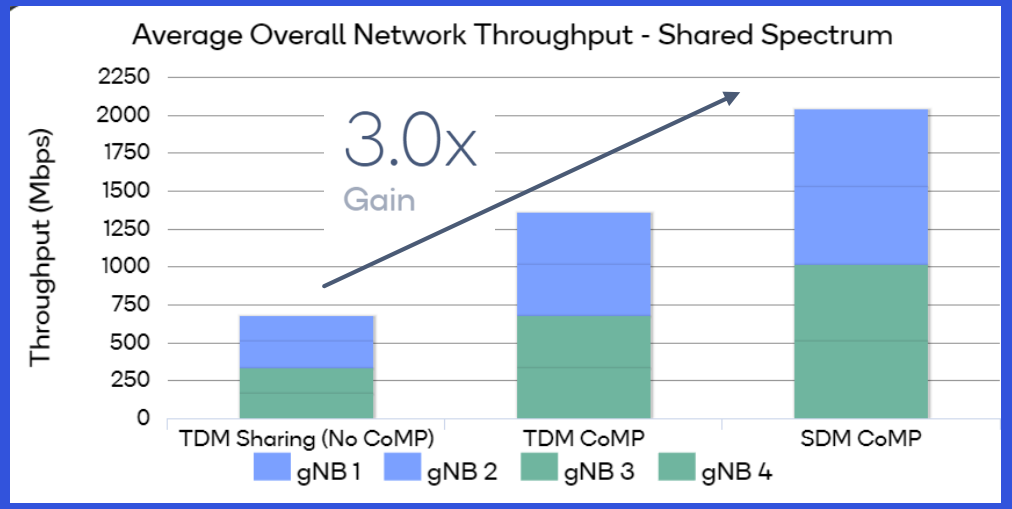
Demonstrating the potential new 5G NR spectrum sharing paradigms

Utilizes 5G NR spectrum sharing prototype – designed to also support testing of 5G NR in unlicensed spectrum

Significant performance gains utilizing advanced intra-operator CoMP and inter-operator SDM techniques



COMP = Coordinated Multi-Point
SDM = Spatial Domain Multiplexing

5G NR URLLC for new mission-critical services

A platform for tomorrow's more autonomous world

Ultra-low 1 ms e2e latency

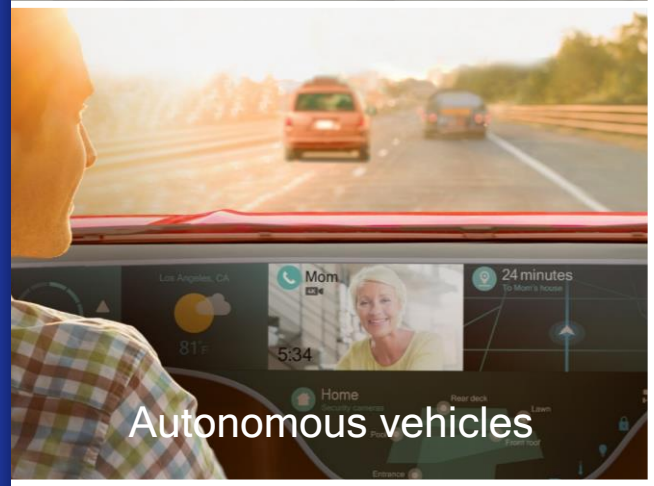
Qualcomm Research locations

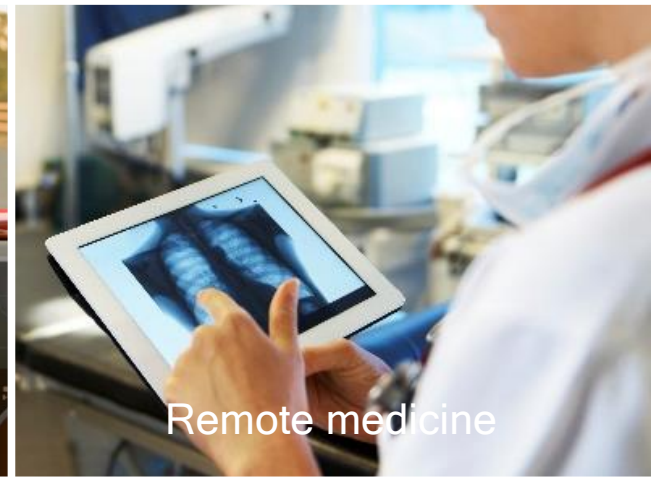
High reliability targeting 10-5 BLER1

Ultra reliable transmissions that can be time multiplexed with nominal traffic through puncturing

High availability

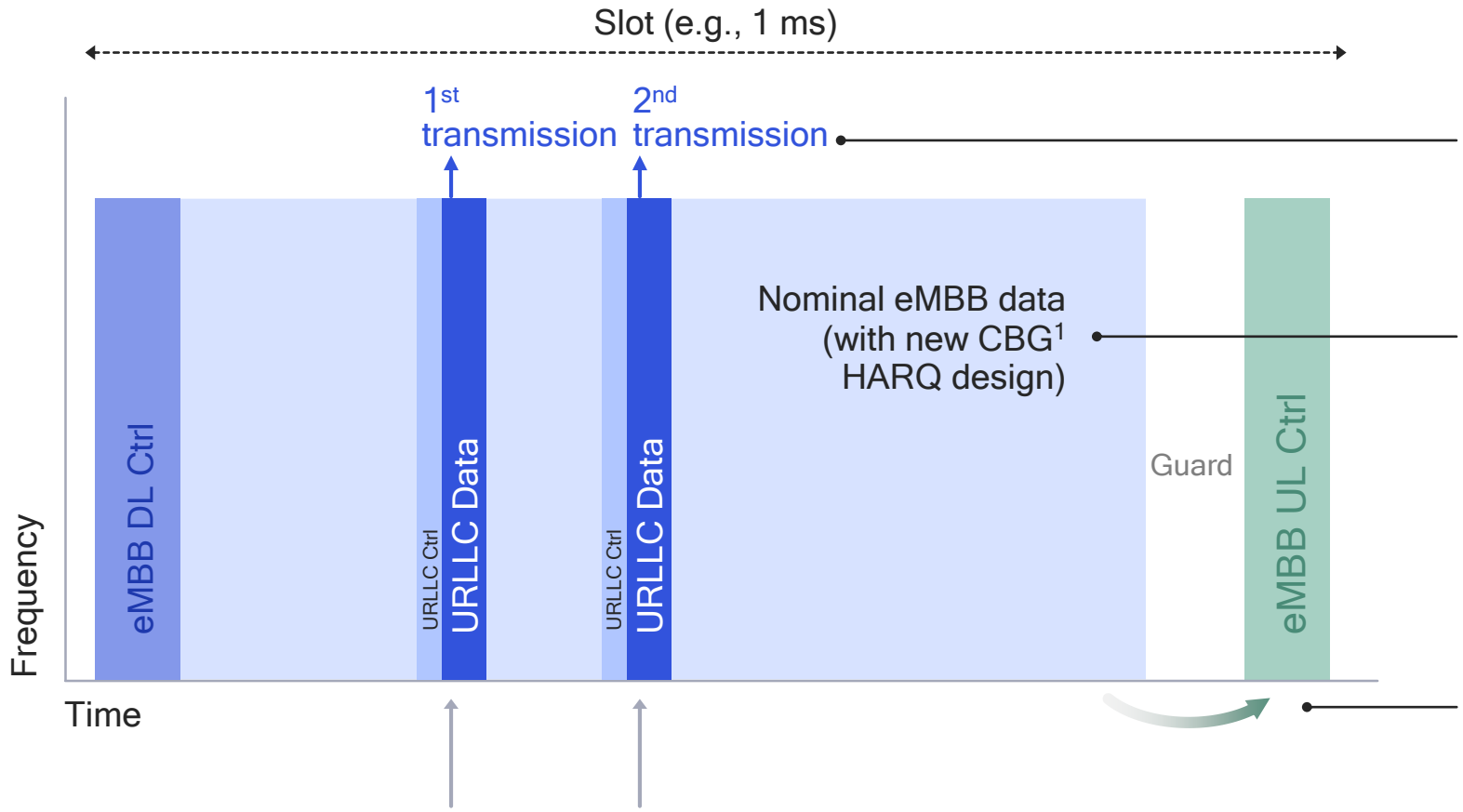
Simultaneous links to both 5G and LTE for failure tolerance and extreme mobility





New slot structure enables low latency communication

Efficient multiplexing with other services – more flexible than dedicated resources



Time-bounded retransmissions help to achieve higher reliability with specified latency limit

Design such that other traffic can sustain puncturing from mission-critical transmission

Self-contained TDD slot structure can enable lower slot latency and quicker link adaptation (e.g., faster SRS/CQI feedback)

Mini-slots optimized for short data transmissions; can start at anytime – no need to wait for scheduling

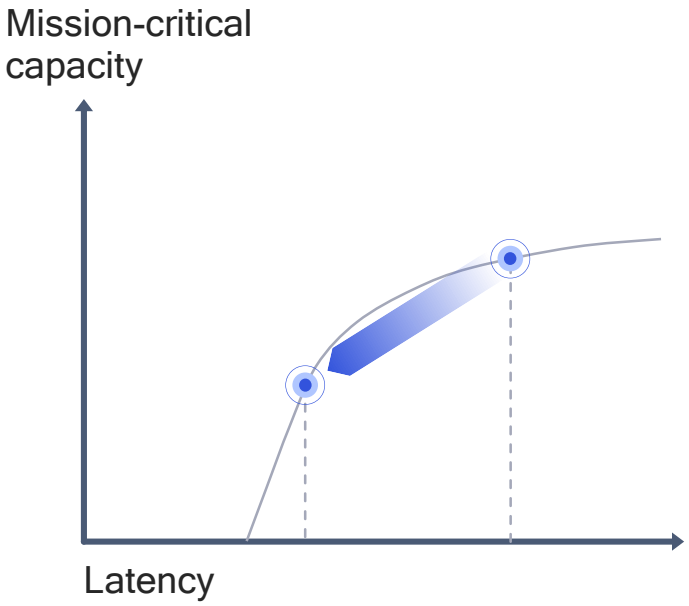
Opportunity for uplink RSMA non-orthogonal access using OFDM waveforms

1 Code Blog Group

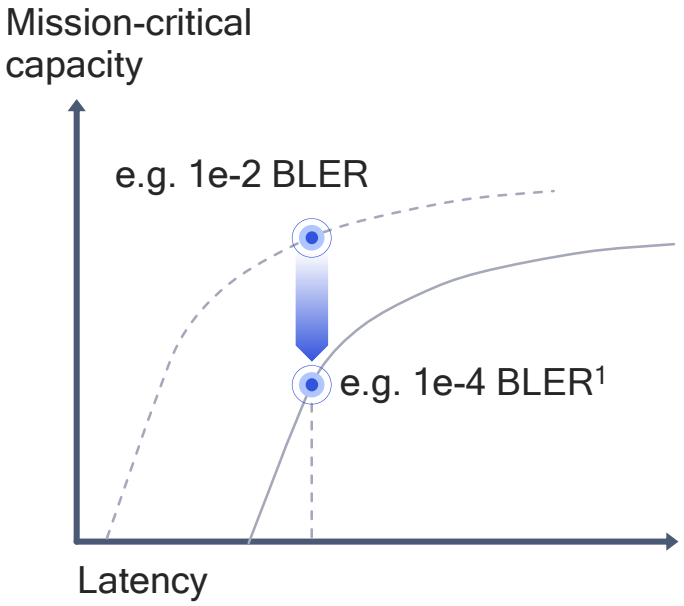
New 5G NR design allows for optimal trade-offs

E.g., leveraging wider bandwidths to offset mission-critical capacity reductions

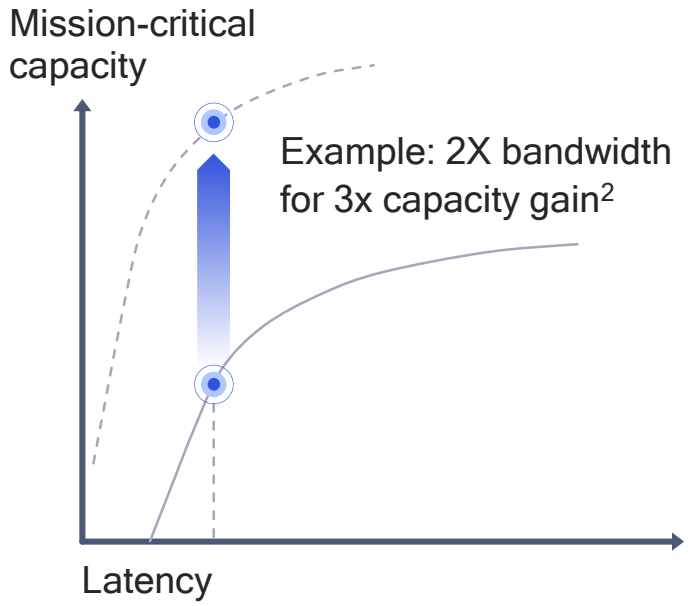
Latency vs. capacity…



Reliability vs. capacity…



But wider bandwidth can offset reductions

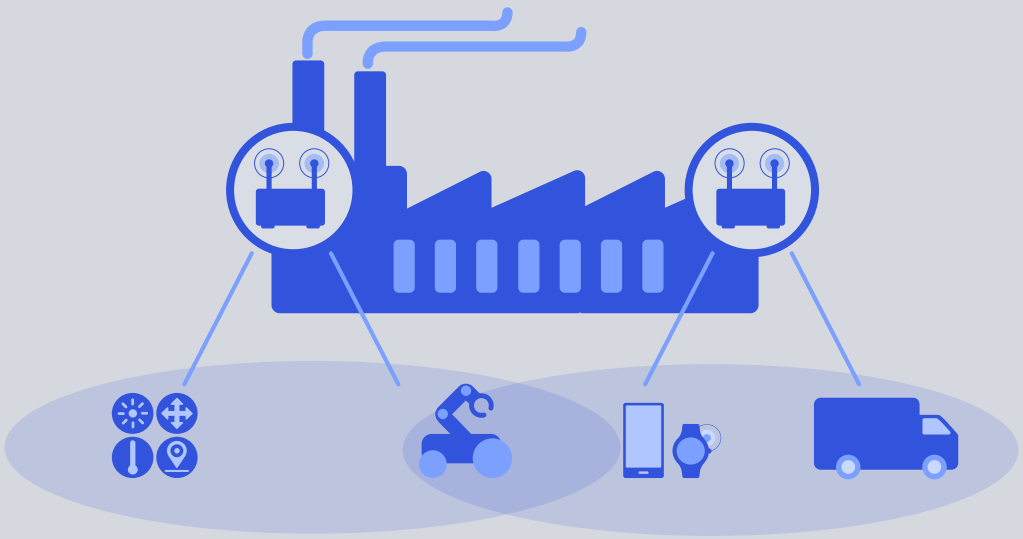


1 Low BLER Block Error Rate, required to achieve high reliability with a hard delay bound; 2 All data based on Qualcomm simulations with approximate graphs and linear scales; 3x gain when increasing from 10 to 20MHz for 1e-4 BLER

Private 5G NR networks for Industrial IoT use cases

Optimizing LTE for the industrial IoT

Scalable from Gigabit LTE to LTE IoT



New opportunities with 5G NR capabilities

Advanced capabilities in 3GPP Release 15 Study Items[1]

- Ultra-reliable low-latency
- Time-sensitive networking
- mmWave for extreme eMBB
- Wireless industrial ethernet

1. TR 22.821 Feasibility Study on LAN Support in 5G and TR 22.804 Study on Communication for Automation in Vertical Domain

Optimized

Tailored for industrial applications, e.g., QoS, latency, security

Dedicated

Easy to deploy small-cells, hosted or self-contained core network

On-premise

Locally managed, sensitive data stays local

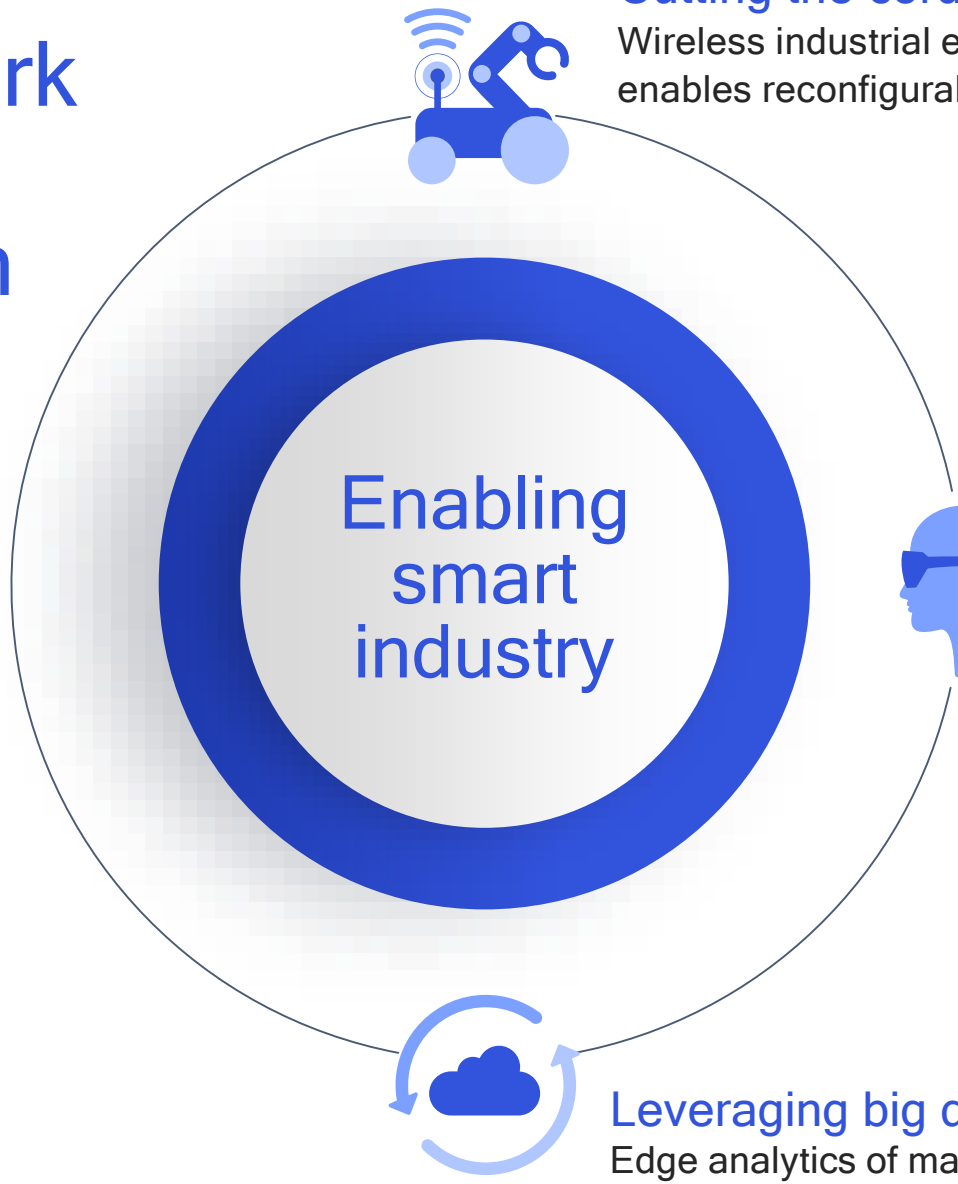
Private 5G NR network enables the next Industrial Revolution

New capabilities
- URLLC – ultra-reliable, low-latency
- Time sensitive networking

Large cellular ecosystem
- Global solutions
- Certified interoperability

More spectrum
- Licensed, shared, unlicensed
- Low, mid, mmWave spectrum

Single network for the entire factory
- Multimode network supporting LTE & 5G NR
- Scalable to all connectivity needs



Cutting the cord
Wireless industrial ethernet enables reconfigurable factories

Enabling new use cases
Such as operators using Augmented Reality (AR) glasses

Leveraging big data analytics
Edge analytics of massive real-time data collection increases productivity

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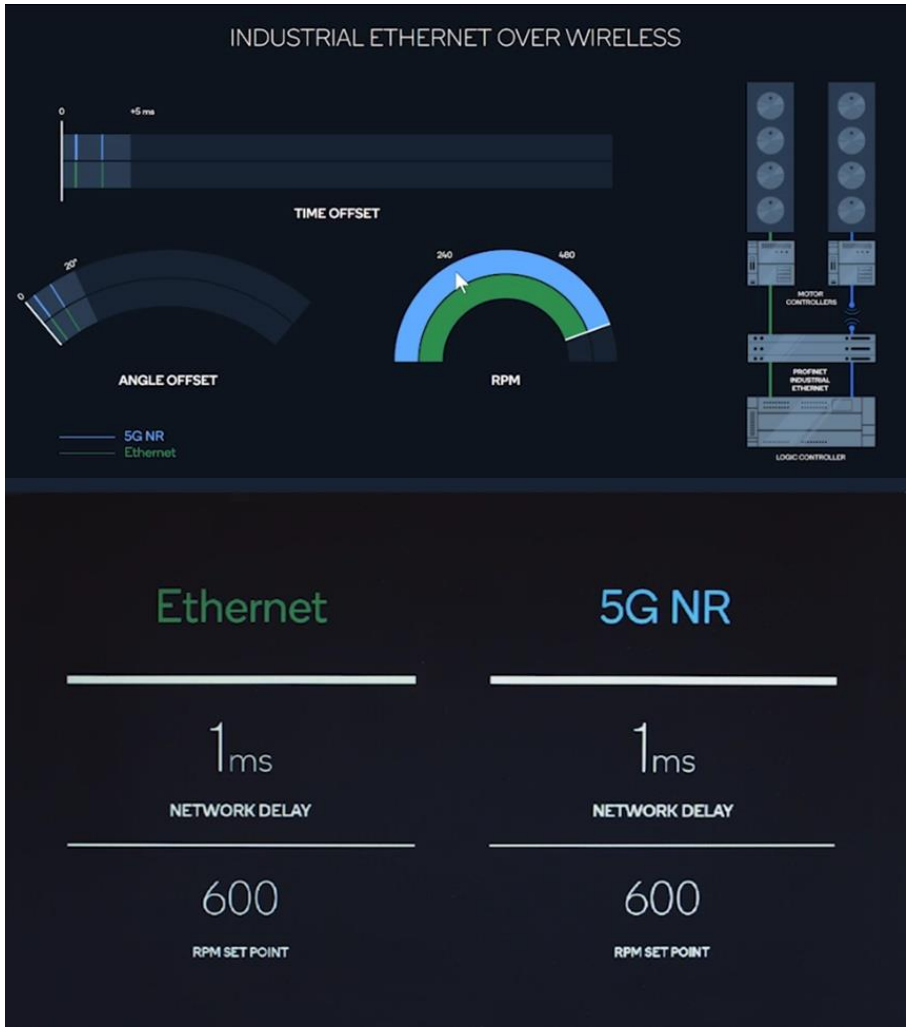
Industry-first demo of wireless PROFINET Industrial Ethernet over 5G NR

Showcases precise command-and-control of high-demand factory apps

Previews new use cases for 5G NR URLLC with sub-millisecond latencies

Highlights factory automation use case with 5G NR Private Networks

Enables wireline replacement and reconfigurable factories: a key concept of Industry 4.0



Long range

To reach challenging locations by achieving device link budget of 164 dB[1]

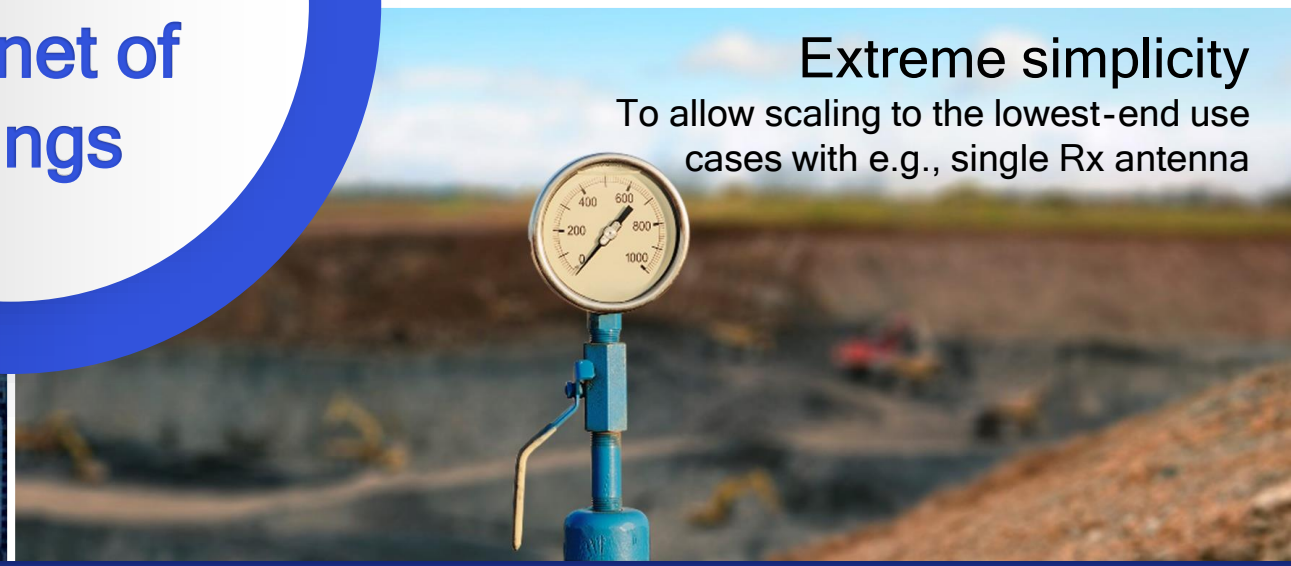
Power efficient

To realize10+ year device battery life[2] and 100x network energy efficiency[3]

Scaling for the massive Internet of Things

Massive scale

To efficiently support dense connections of 1+ million devices/km^2



Extreme simplicity

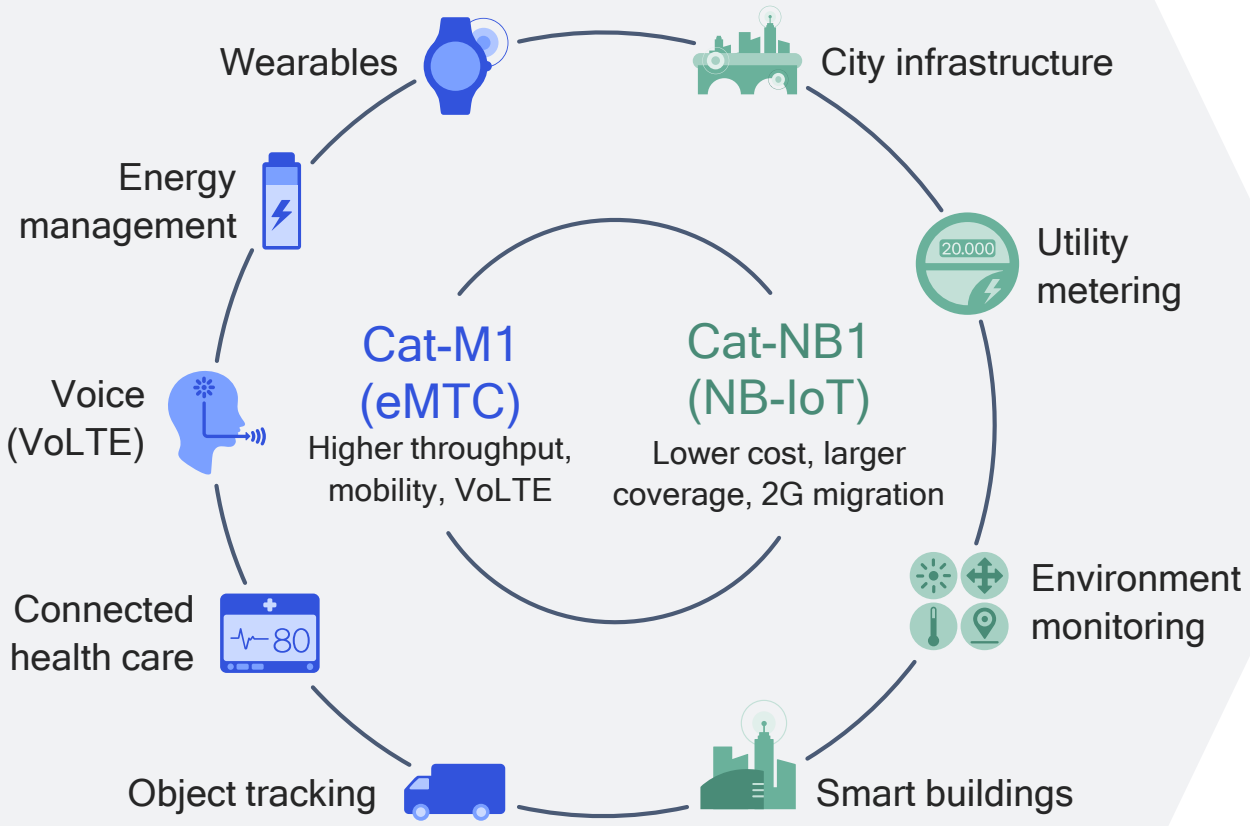
To allow scaling to the lowest-end use cases with e.g., single Rx antenna

Addressing the growing needs of low-power, wide-area IoT use cases

1. Maximum Coupling Loss, assuming data rate of 160bps; 2. Assuming 200B UL + 20B DL per day at 164 MCL with 5Wh battery; 3. Compared to IMT-Advanced

LTE IoT starts to connect the massive IoT today

50+ commercial Cat-M1 and/or Cat-NB1 networks in over 30 countries



MDM9206

Flexible LTE IoT chipset platform for Cat-M1 / Cat-NB1 / E-GPRS

- Global dual-mode solution: single SKU
- Pre-certified modules commercially available today
- Multiple design wins across industry-leading OEMs

QUECTEL Wireless Module Expert · ZTE Welink · Telit · LONGSUNG 龙尚科技 · Neoway 有方 · SIMCom A company of SIM Tech · MobileTek · u-blox · WNC · mobike

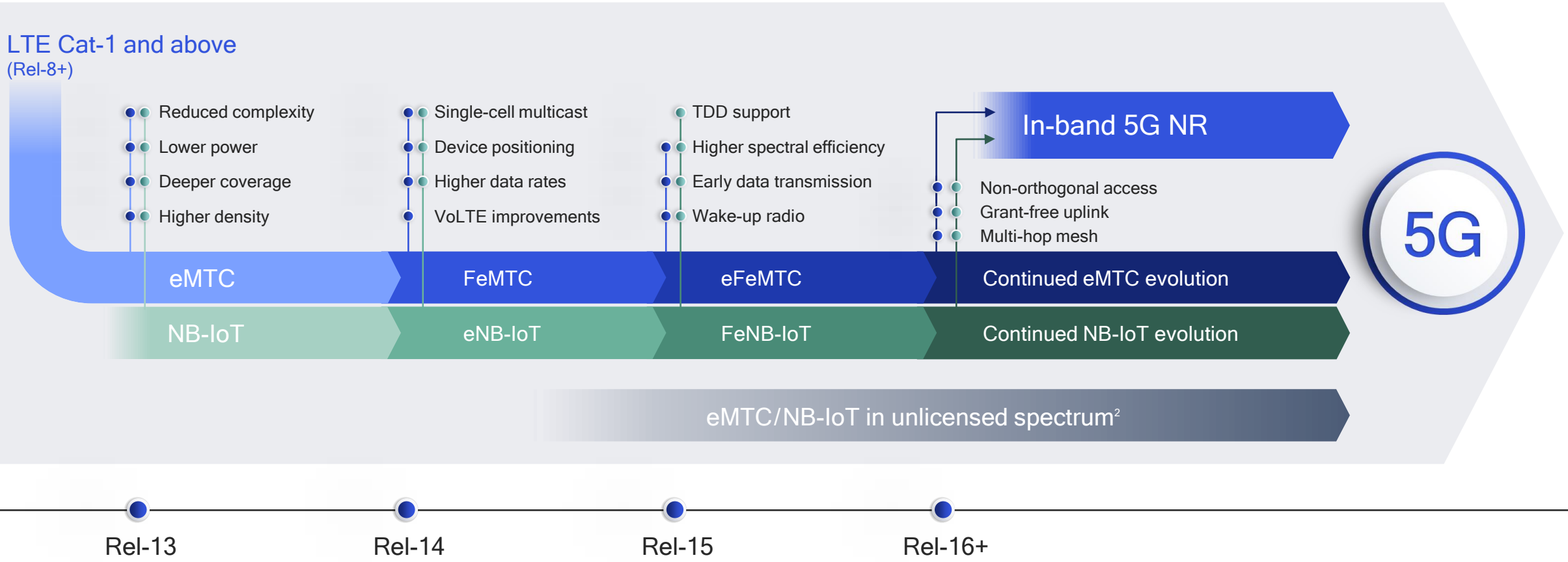
...and many more

Qualcomm MDM9206 is a product of Qualcomm Technologies, Inc. and/or its subsidiaries

Sources: GSA NB-IoT and LTE-M: Global Market Status, March, 2018

Continued evolution to meet tomorrow's massive IoT needs

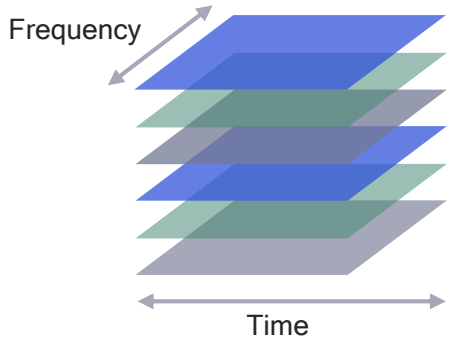
Essential to 5G – LTE IoT to be submitted to meet IMT-2020[1] requirements



1. Defined in ITU Recommendation ITU-R M.2083-0, September, 2015; 2. Standardization in MulteFire Alliance

Pioneering tomorrow's massive IoT technologies

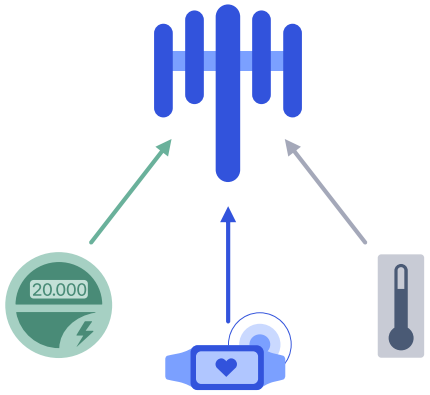
Applies to LTE IoT and 5G NR IoT evolution – potential for 3GPP Rel-16+



Non-orthogonal multiple access

Even higher connection density

- NOMA is part of 5G NR Rel-15 Study Item
- Can be either scheduled or grant-free
- Increases device density and network efficiency

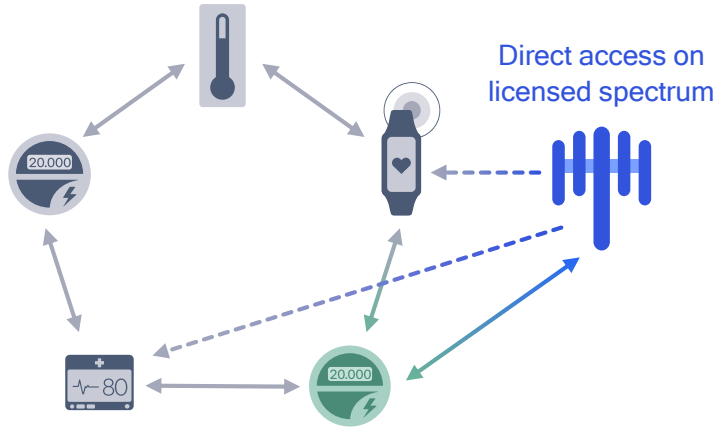


Grant-free uplink

Autonomous mode transmission

- Contention-based access for IoT devices
- For sporadic uplink of small data bursts
- Also key enabler of mission-critical communication

Mesh on unlicensed or partitioned with uplink licensed spectrum[1]



Mesh networking

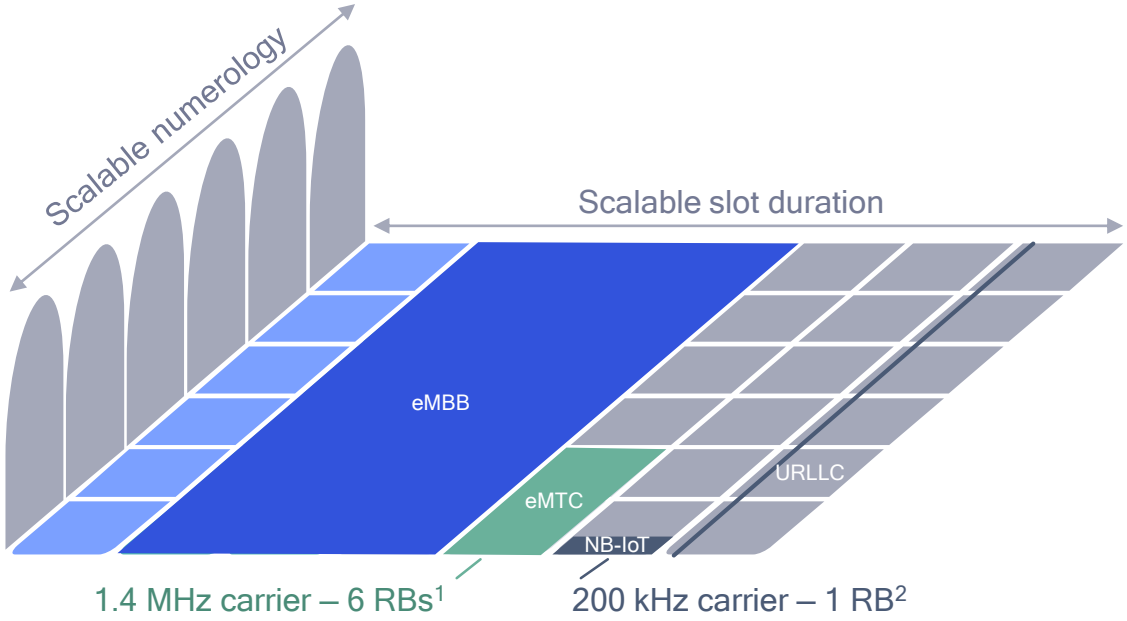
Multi-hop mesh with WAN management

- For low-power devices with challenging placements
- Especially uplink data relayed via nearby devices
- Expands on LTE Device-to-Device (D2D)

1. Greater range and efficiency when using licensed spectrum, e.g. protected reference signals. Network time synchronization improves peer-to-peer efficiency

5G NR IoT to fully leverage the LTE IoT evolution

Enabled by in-band deployment of LTE IoT in 5G NR spectrum



In-band eMTC / NB-IoT support in Rel-16

5G NR 2^n scaling of 15 kHz subcarrier spacing is natively compatible with eMTC and NB-IoT numerologies

Agnostic to core networks

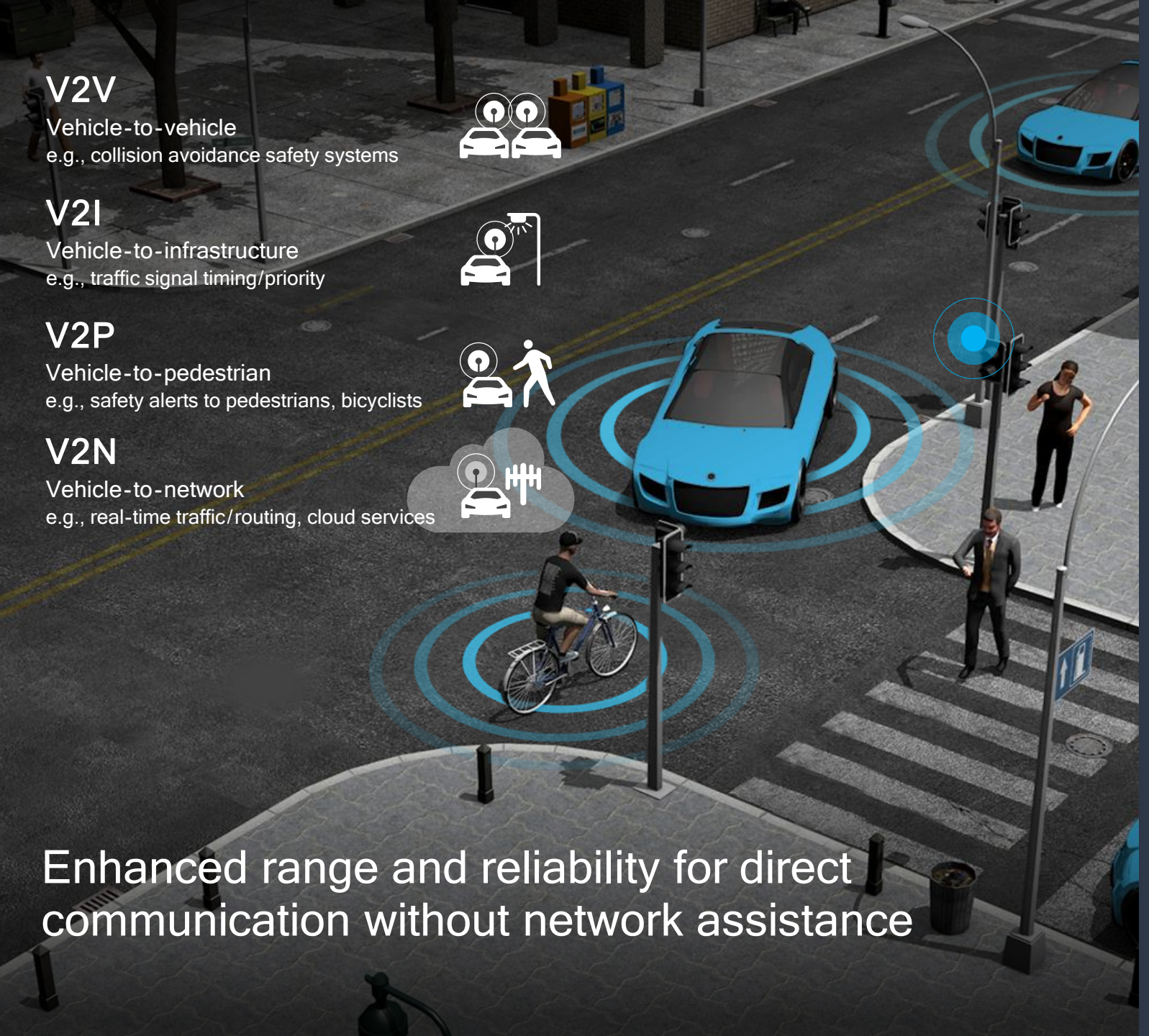
Both 5G NR deployment options – NSA with LTE EPC and SA with 5G core – support eMTC and NB-IoT evolution

Advanced features coming in Rel-16+

Non-orthogonal access, grant-free uplink, and multi-hop mesh will deliver even better performance and efficiency

1. Cat-M1 uses 6 Resource Blocks (RBs) with 12 tones per RB at 15 kHZ SCS; 2. Cat-NB1 uses 1 Resource Block (RB) with 12 tones with 12 tones per RB at 15 kHz SCS, single-tone option also available

5G NR Flexible framework designed to support future evolution addressing even broader IoT use cases such as latency sensitive applications



C-V2X

Establishes the foundation for safety use cases and a continued 5G NR C-V2X evolution for future autonomous vehicles

- C-V2X Release 14 completed in 2017
- Broad industry support – 5GAA
- Global trials started in 2017
- Our 1st announced C-V2X product in September, 2017

Learn more at: https://www.qualcomm.com/c-v2x

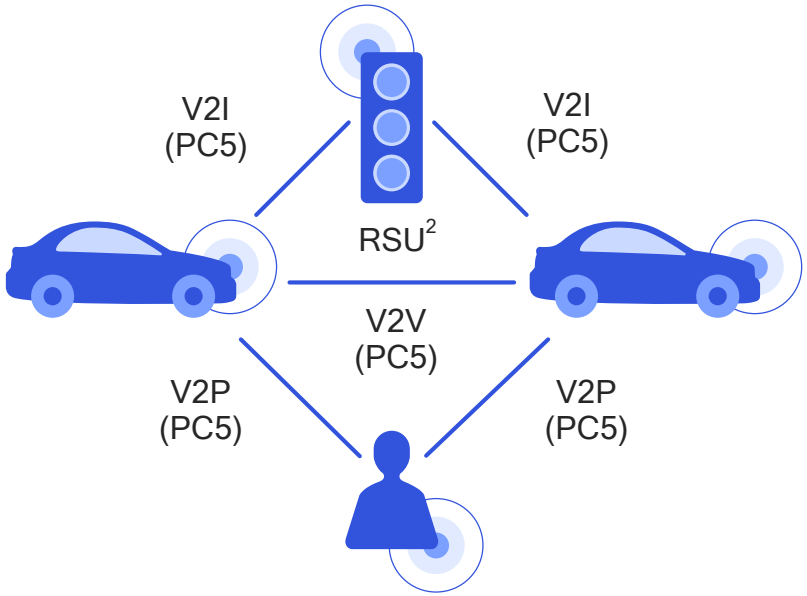
C-V2X enables network independent communication

Direct safety communication independent of cellular network

Low latency Vehicle to Vehicle (V2V), Vehicle to Infrastructure (V2I), and Vehicle to Person (V2P) operating in ITS bands (e.g. 5.9 GHz)

Direct PC5 interface

e.g. location, speed, local hazards

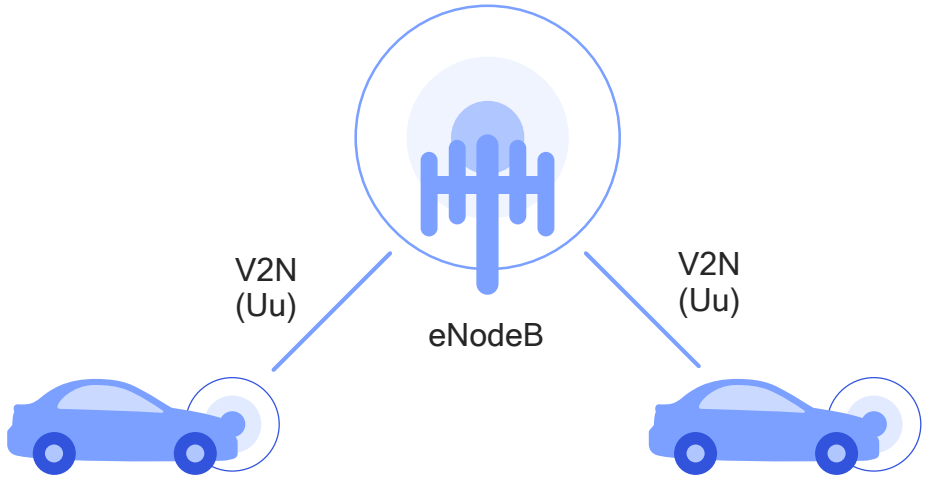


Network communications for complementary services

Vehicle to Network (V2N) operates in a mobile operator's licensed spectrum

Network Uu interface

e.g. accident 2 kilometer ahead



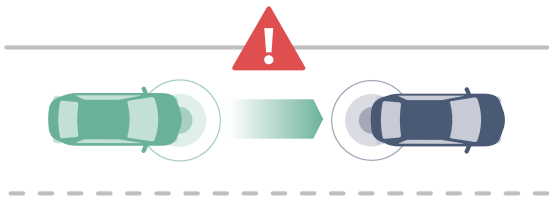
1. PC5 operates on 5.9GHz; whereas, Uu operates on commercial cellular licensed spectrum 2. RSU stands for roadside unit.1. 3GPP also defines a mode, where eNodeB helps coordinate C-V2X Direct Communication; 2. GNSS is required for V2X technologies, including 802.11p, for positioning. Timing is calculated as part of the position calculations and it requires smaller number of satellites than those needed for positioning

C-V2X has a strong evolution path towards 5G NR

While maintaining backward capabilities

Evolution to 5G NR, while being backward compatible
C-V2X Rel-14 is necessary and operates with Rel-16

Basic safety
IEEE 802.11p

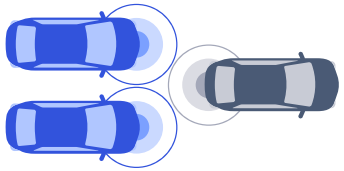


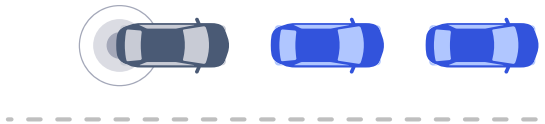
Basic and enhanced safety
C-V2X Rel-14/Rel-15 with enhanced range and reliability

Autonomous driving use cases
5G NR C-V2X Rel-16

Backward compatible with Rel-14/Rel-15 enabled vehicles

Higher throughput
Higher reliability
Wideband ranging/positioning
Lower latency





5G NR C-V2X complements Rel-14 with new capabilities

Targeting new use cases for autonomous driving

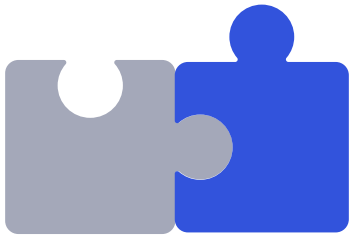
Rel-14 C-V2X

Automotive safety

Do not pass warning (DNPW)

Intersection movement assist (IMA) at a blind intersection

Blind curve / Local hazard warning



Rel-16 5G NR C-V2X

Autonomous driving

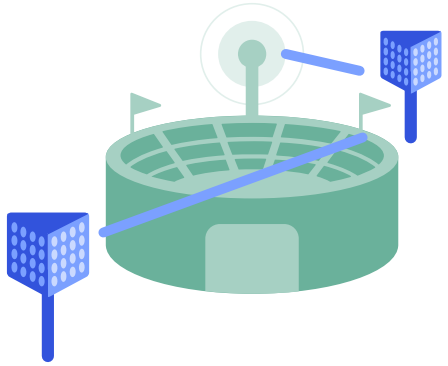
Local high definition maps / “Bird’s eye view”

Intention / Trajectory sharing

High throughput sensor sharing

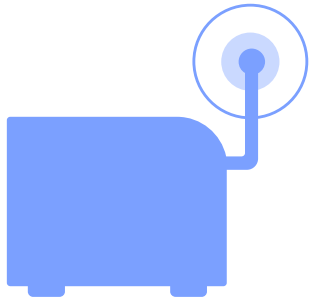
Wideband ranging and positioning

5G NR mmWave continuing to evolve beyond R15



Integrated Access and Backhaul

Rel-15 Study Item on enabling easy/low-cost deployment of small cells using mmWave spectrum for access and backhaul



Unlicensed Spectrum

Rel-15 Study Item for both LAA and standalone operation (aka 5G MulteFire™) in sub-6 GHz and mmWave spectrum bands

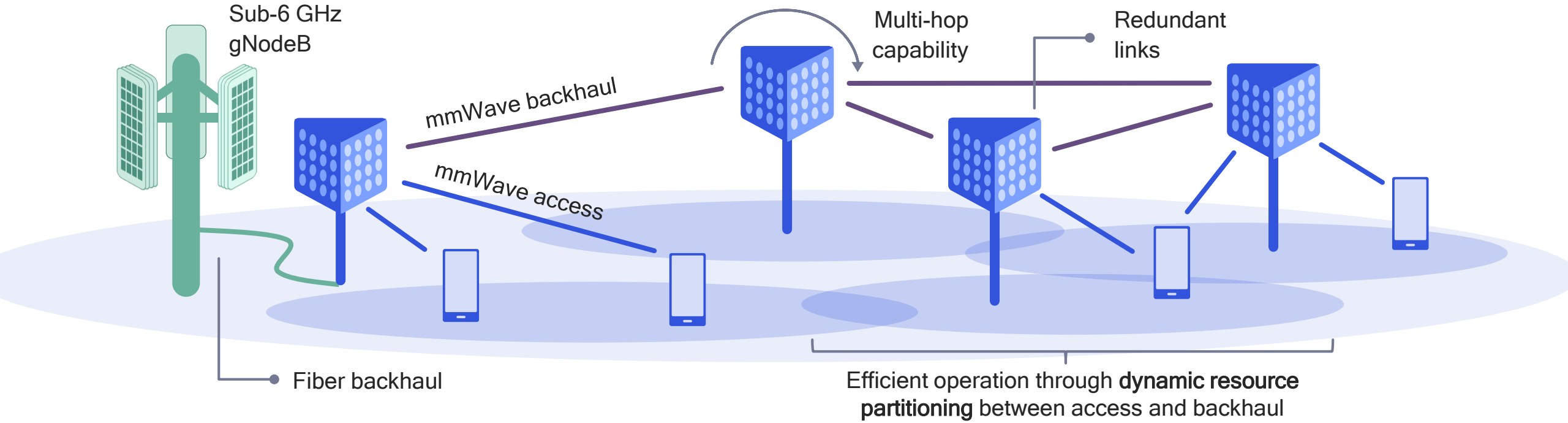
Higher spectrum bands

Exploring the use of spectrum bands above ~40 GHz, including unlicensed spectrum in the 57 GHz to 71 GHz band

Bringing new capabilities, new spectrum bands and new deployment opportunities

5G NR mmWave IAB[1] for cost-efficient dense deployments

Improves coverage and capacity, while limiting backhaul cost



1 Integrated Access & Backhaul

Traditional fiber backhaul can be expensive for mmWave cell sites

- mmWave access inherently requires small cell deployment
- Running fiber to each cell site may not be feasible and can be cost prohibitive
- mmWave backhaul can have longer range compared to access

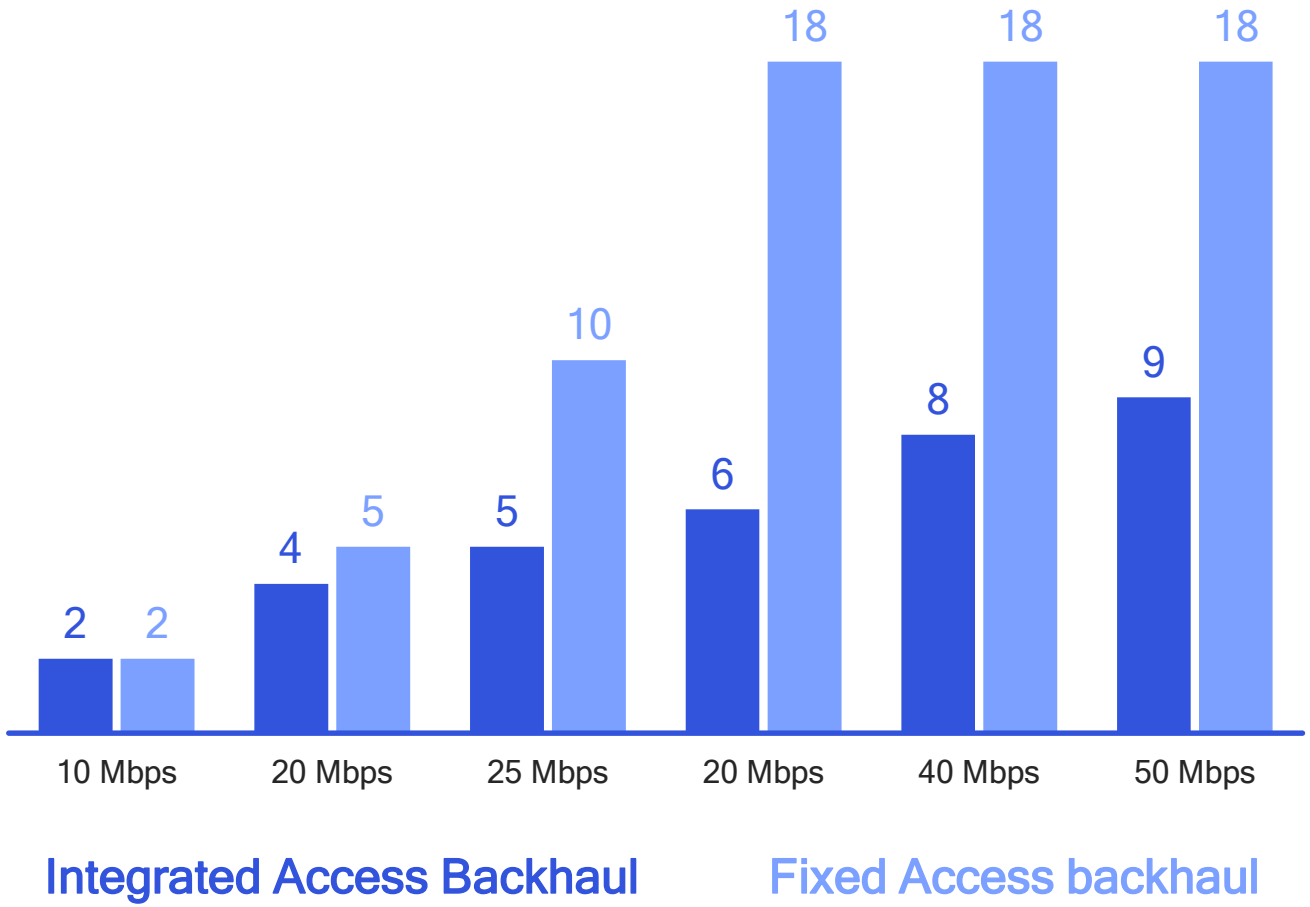
5G NR Integrated Access & Backhaul

Supports more flexible deployments and reduces network cost

Fewer fiber drop points needed compared to fixed backhaul for a given traffic demand

Dynamically adjusts to changes in fiber drop locations and numbers

Number of fiber drops needed



*Assumptions: 28 GHz band, 1GHz b/w, 18 base-stations; 200m ISD; 600 devices, uniform distribution; results obtained without any constraint on the number of hops

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5G NR

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Making 5G NR a commercial reality for 2019 eMBB deployments

Driving the expansion of 5G NR ecosystem and opportunity

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