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September 26th, 2018

Leading the world to 5G
and its expansion to new industries

Dr. John Smee

Vice President, Engineering
Qualcomm Technologies, Inc.

Agenda

1

5G vision and 5G NR overview

A unified, more capable air interface for the next decade and beyond

2

5G NR design and technologies

Based on the 3GPP Release 15 global standard

3

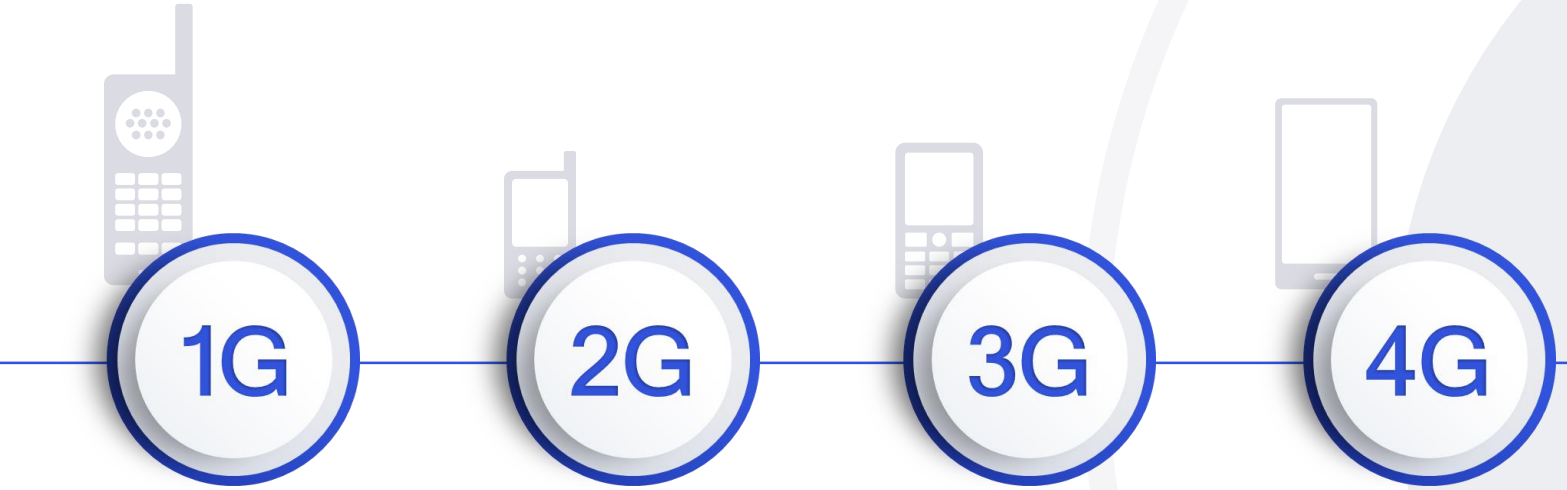
5G NR evolution and expansion

Driving 5G NR beyond mobile broadband in 3GPP Release 16 and beyond

4

Q&A

Mobile is the largest technology platform in human history

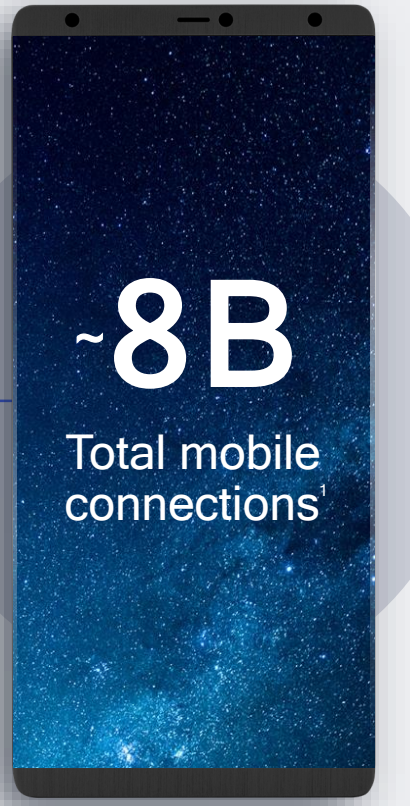


1980s
Analog voice
AMPS, NMT, TACS

1990s
Digital voice
D-AMPS, GSM, IS-95 (CDMA)

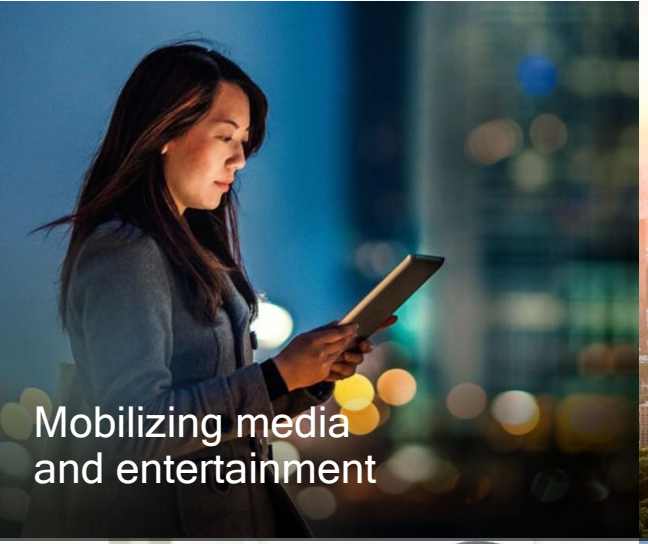
2000s
Mobile data
WCDMA/HSPA+, CDMA2000/EV-DO

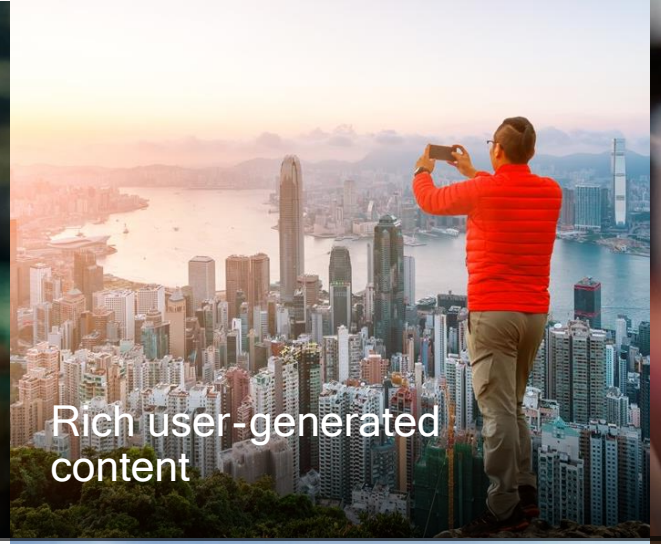
2010s
Mobile broadband
LTE, LTE Advanced, Gigabit LTE

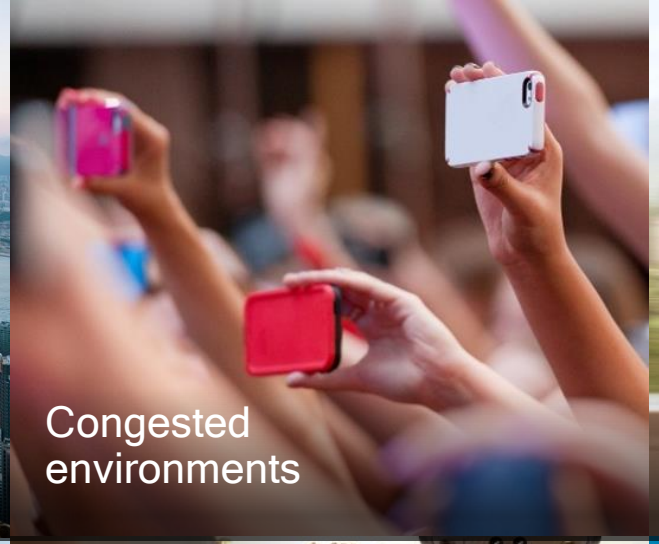


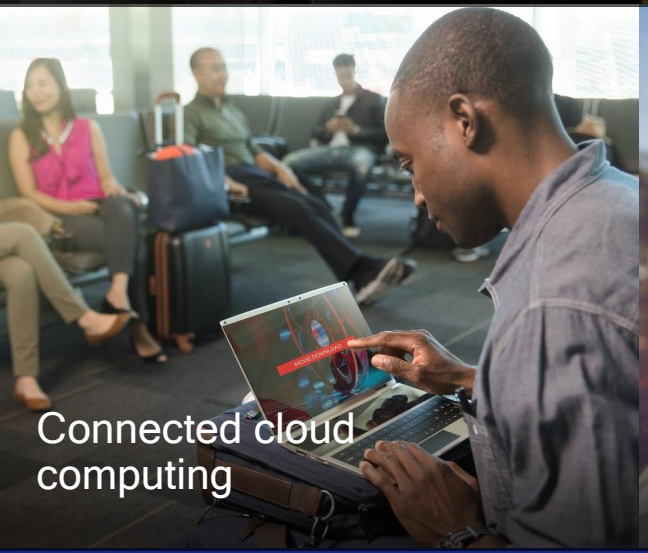
1. GSMA Intelligence, July 2018, excluding licensed cellular IoT

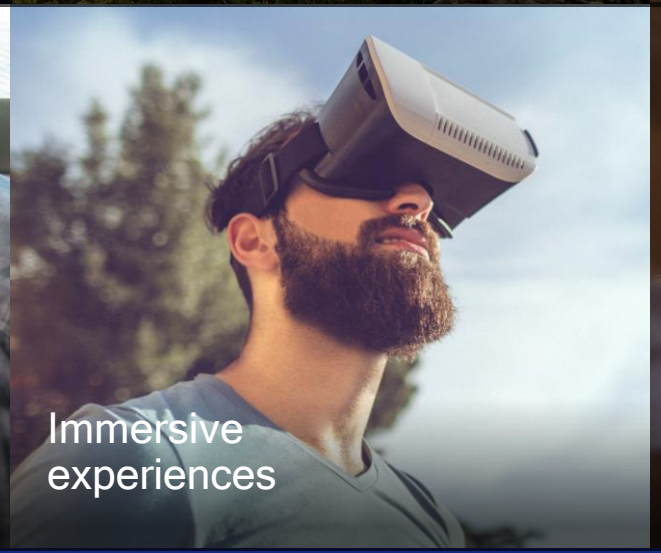

A unifying connectivity fabric for society
Like electricity, you will just expect it everywhere
5G
Multi-gigabit speed
Scalable to extreme simplicity
Ultra-low latency
Virtually unlimited capacity
Extreme reliability
On-device intelligence







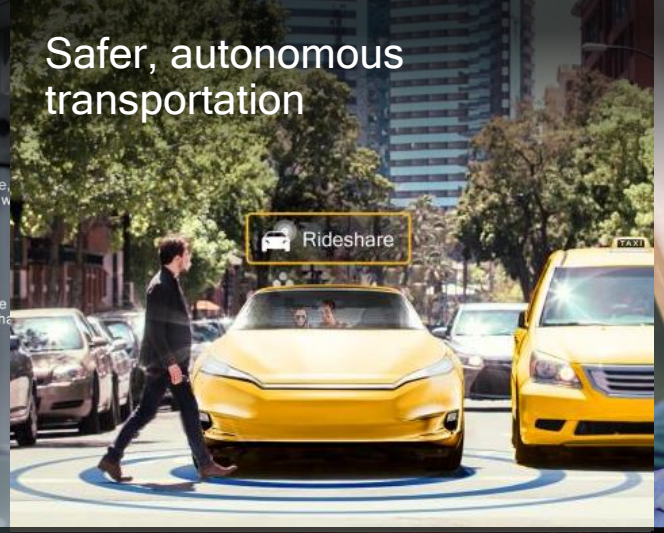


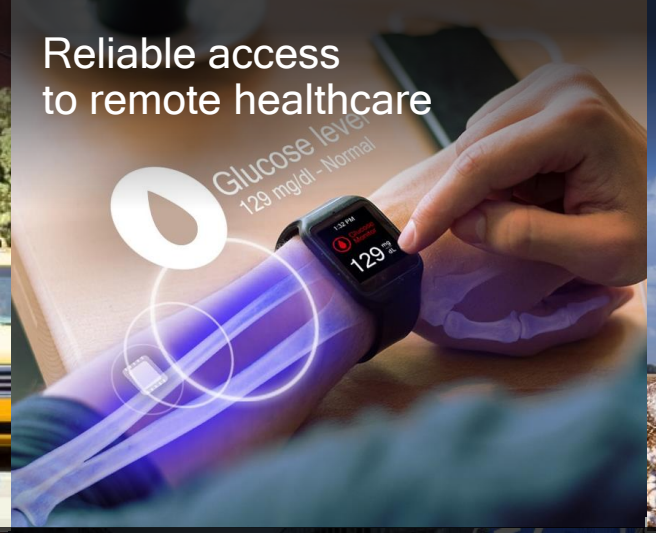


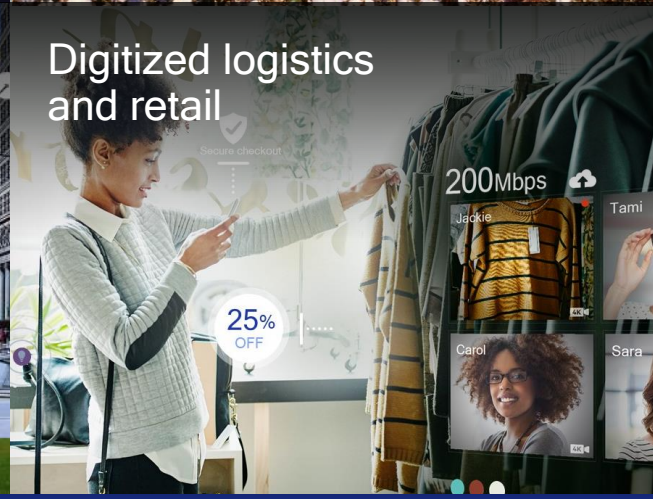
5G

5G is essential for next generation mobile experiences

- Fiber-like data speeds
- Low latency for real-time interactivity
- More consistent performance
- Massive capacity for unlimited data







5G

5G will expand the mobile ecosystem to new industries

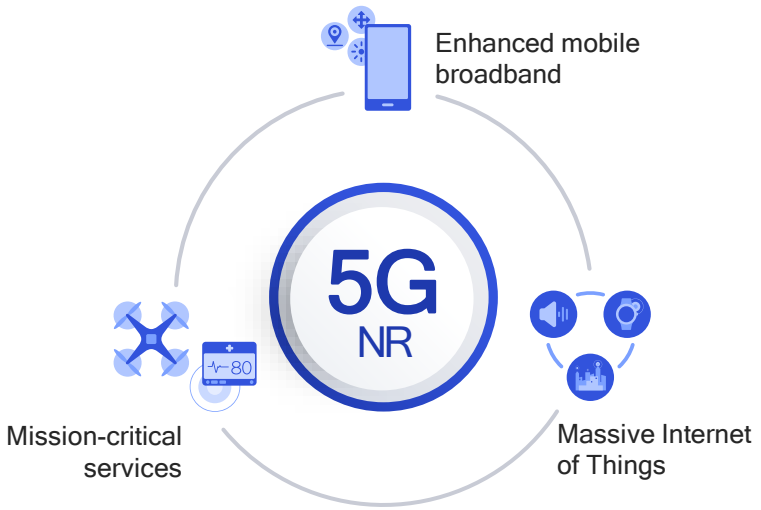
Powering the digital economy

>$12 Trillion

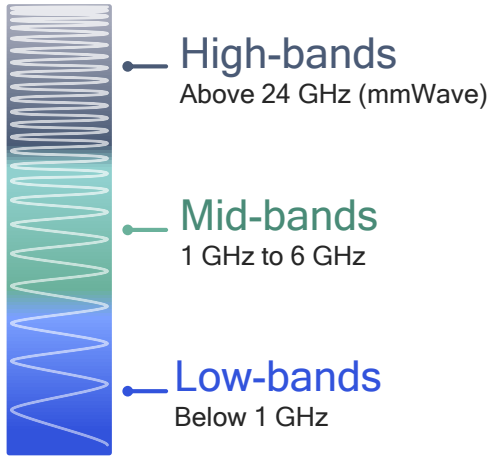
In goods and services by 2035*

* The 5G Economy, an independent study from IHS Markit, Penn Schoen Berland and Berkeley Research Group, commissioned by Qualcomm

Designing a unified, more capable 5G air interface



Diverse services



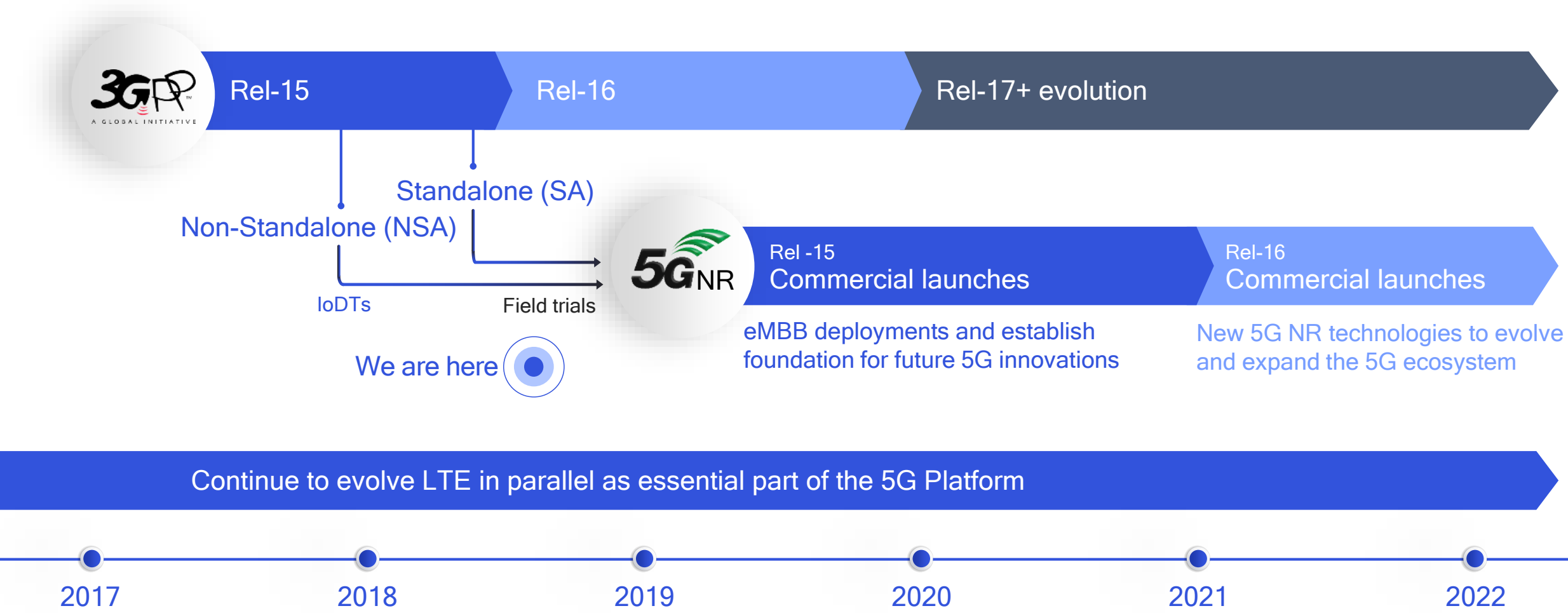
Licensed/shared/unlicensed

Diverse spectrum

Diverse deployments

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

Driving the 5G roadmap and ecosystem expansion



World’s first 5G NR milestones led by Qualcomm

ZTE中兴

World’s first interoperable 5G NR sub-6 GHz data connection

November 2017

ERICSSON

World’s first interoperable 5G NR mmWave data connection

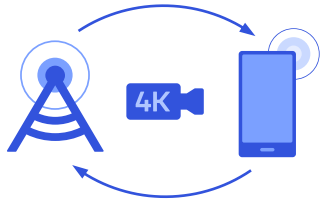
December 2017

NOKIA

Successful multi-band 5G NR interoperability testing

February 2018

SAMSUNG HUAWEI



GSMA MOBILE WORLD CONGRESS

Interoperable 5G NR sub-6 GHz & mmWave connections with 5 vendors

MWC 2018

大唐移动 DTmobile

5G NR interoperability testing preparing for the Chinese mass market

June 2018

Qualcomm snapdragon X50 5G modem

Rel-15 5G NR trials based on Snapdragon™ X50 modem chipset

2H-2018

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

Driving the 5G ecosystem towards 2019 launches in collaboration with 18+ global mobile network operators and 20+ device manufacturers

X50

5G Modem family

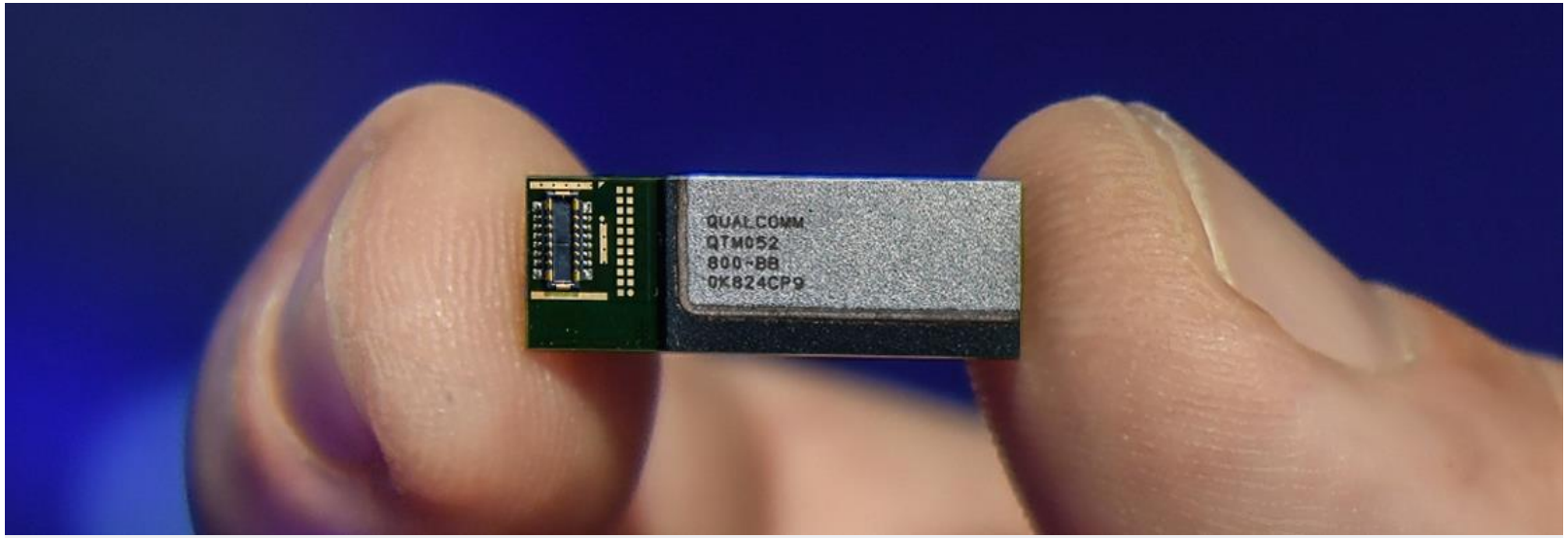
World's first 5G NR multimode modems

- 5G NR standards compliant
- Sub-6 + mmWave
- Premium-tier smartphones in 2019

Qualcomm®

QTM052 mmWave antenna modules

For pairing with the Qualcomm Snapdragon X50 5G modem to deliver modem-to-antenna capabilities across spectrum bands



Smartphone form factor

Suitable for compact smartphone industrial designs with four mmWave modules

Fully-integrated mmWave RF

Including transceiver, PMIC, RF front-end components, and a phased antenna array

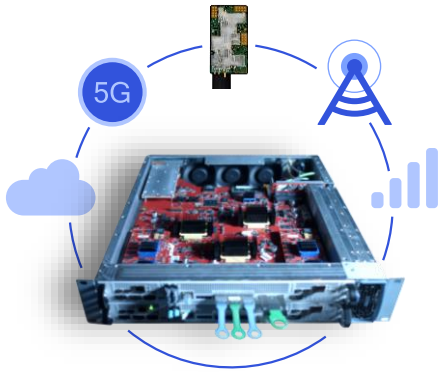
Newly supported mmWave bands

Supporting for up to 800 MHz of bandwidth in n257, n260, and n261 5G NR mmWave bands

Advanced mobility features

Supporting beamforming, beam steering, and beam tracking for bi-directional mmWave communications

Making 5G NR a commercial reality for 2019



Best-in-class 5G prototype systems

Designing and testing 5G technologies for many years

3GPP™ A GLOBAL INITIATIVE

5G NR standards and technology leadership

Our technology inventions are driving the 5G NR standard

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

5G NR interoperability testing and trials

Leveraging prototype systems and our leading global network experience

Qualcomm snapdragon X50 5G modem

Modem and RFFE leadership

Announced the Qualcomm Snapdragon X50 5G modem family

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

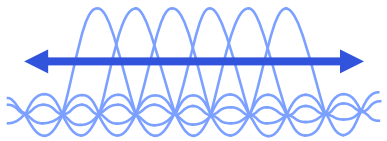
LTE foundational technologies

5G NR design and technologies

3GPP Release 15

Our technology inventions drove Rel-15 specifications

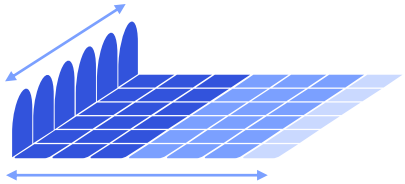
Scalable OFDM-based air interface



Scalable OFDM numerology

Address diverse services, spectrum, deployments

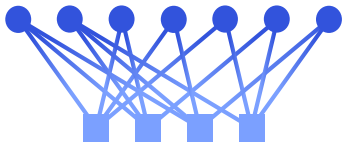
Flexible slot-based framework



Self-contained slot structure

Low latency, URLLC, forward compatibility

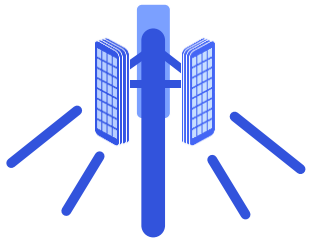
Advanced channel coding



Multi-Edge LDPC and CRC-Aided Polar

Support large data blocks, reliable control channel

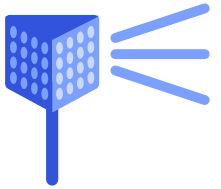
Massive MIMO



Reciprocity-based MU-MIMO

Large # of antennas to increase coverage/capacity

Mobile mmWave

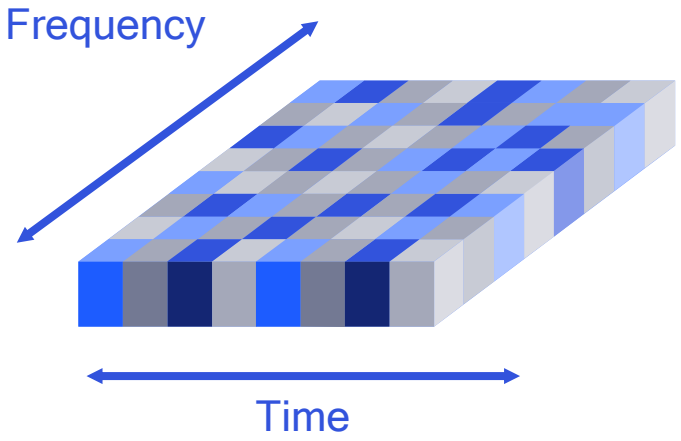


Beamforming and beam-tracking

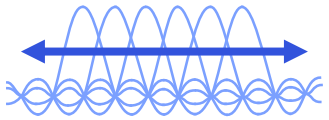
For extreme capacity and throughput

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

Scalable OFDM-based 5G NR air interface

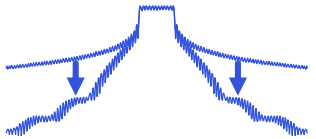


Scalable numerology



2^n scaling of sub-carrier spacing to efficiently support wider bandwidths

Frequency localization



Windowing[1] can effectively minimize in-band and out-of-band emissions

Lower power consumption

Single-carrier[2] OFDM utilized for efficient uplink transmissions

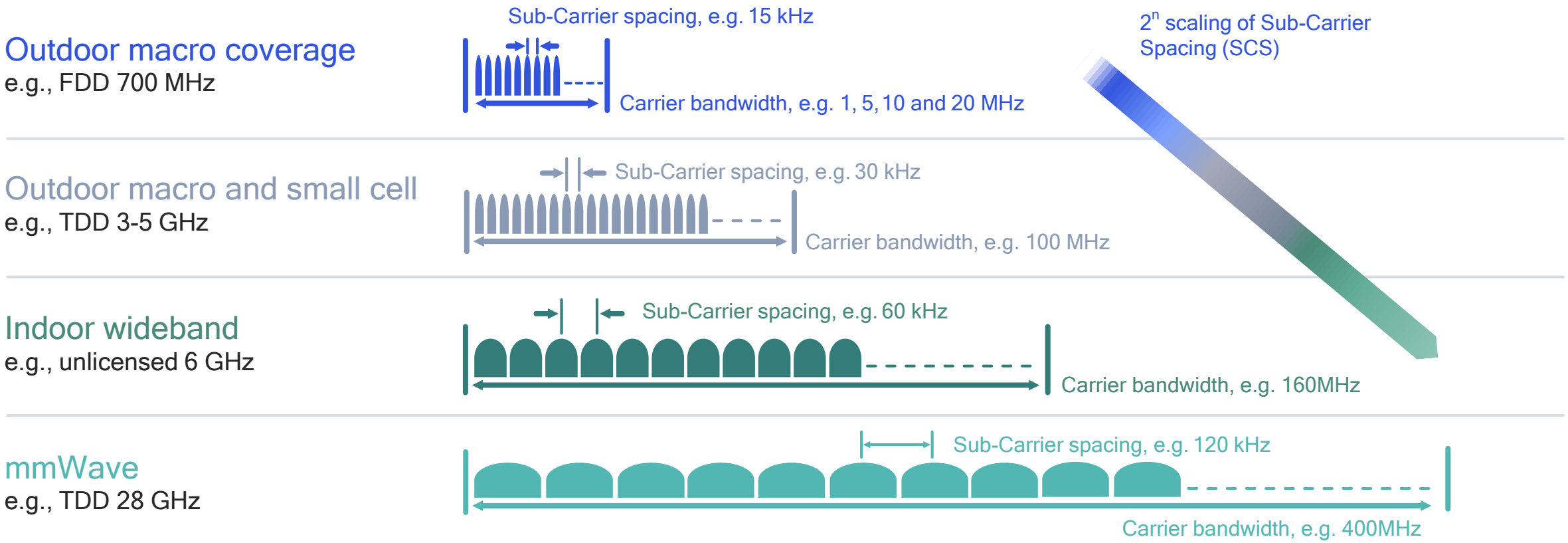
Asynchronous multiple access

Can co-exist with optimized waveforms and multiple access for IoT UL[3]

Qualcomm Research is a division of Qualcomm Technologies, Inc.
1. Such as Weighted Overlap Add (WOLA) utilized in LTE systems today. 2. DFT-Spread (DFT-S) OFDM. 3. Such as non-orthogonal Resource Spread Multiple Access (RSMA)

3GPP Rel-15 specifications aligned with Qualcomm Research whitepaper published Nov 2015 [link]

Scalable 5G NR OFDM numerology–examples



Efficiently address 5G diverse spectrum, deployments and services

Scaling reduces FFT processing complexity for wider bandwidths with reusable hardware

Flexible slot-based 5G NR framework

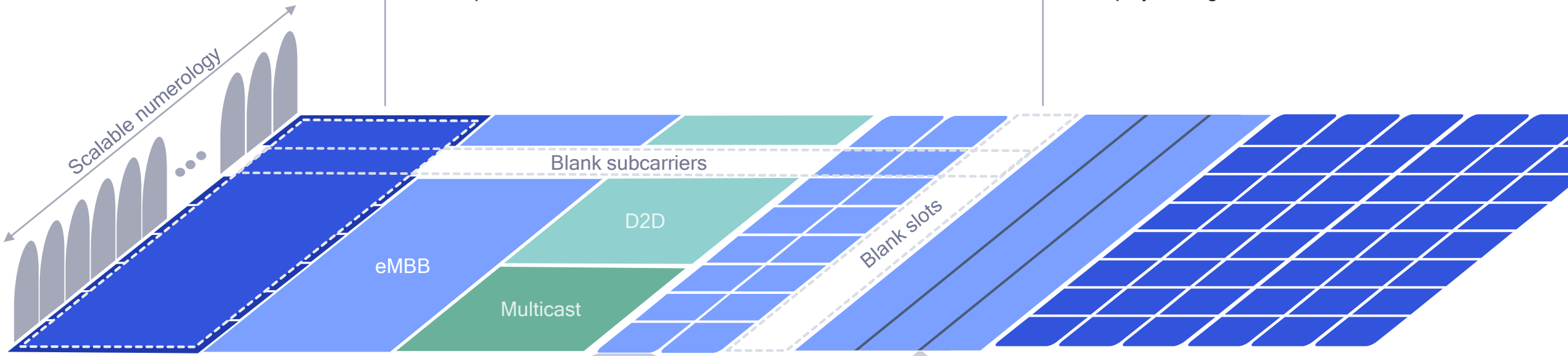
Efficiently multiplex envisioned and future 5G services on the same frequency

Scalable slot duration

Efficient multiplexing of diverse latency and QoS requirements

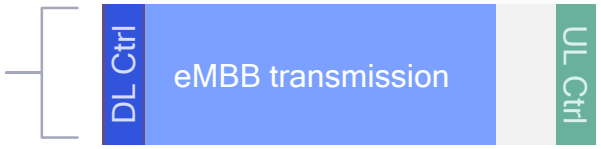
Forward compatibility

Transmissions well-confined in time/frequency to simplify adding new features in future



Self-contained slot structure

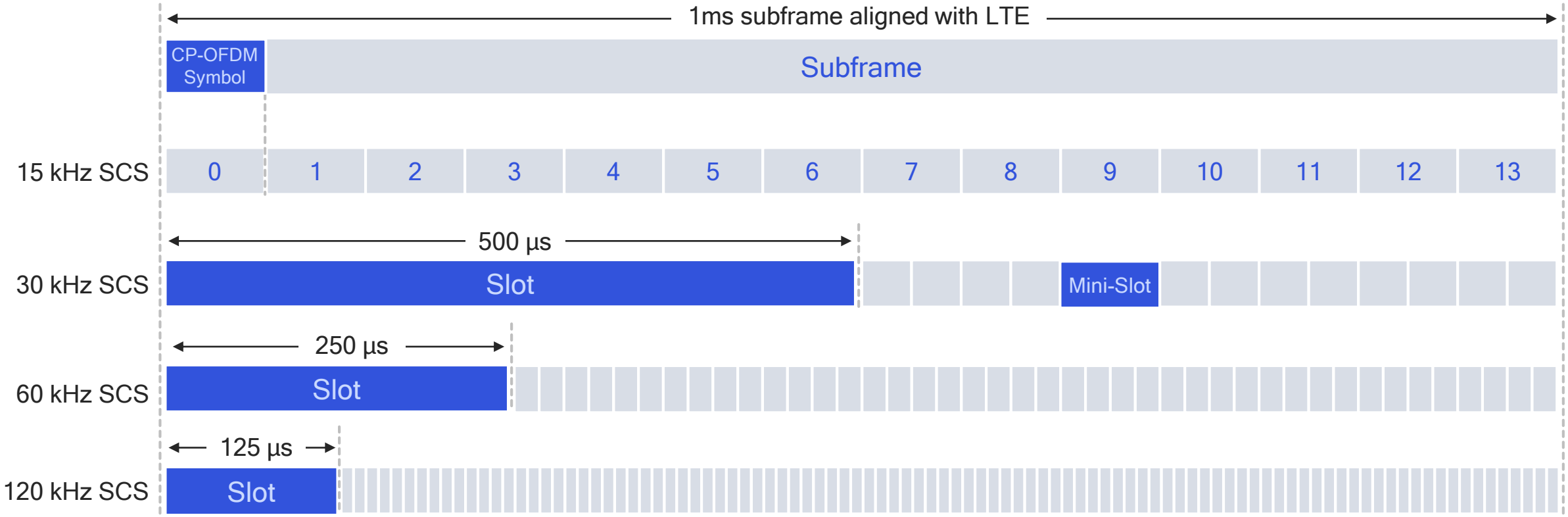
Ability to independently decode slots and avoid static timing relationships across slots



Nominal traffic puncturing

To enable URLCC transmissions to occur at any time using mini-slots

Scalable 5G NR slot duration for diverse latency/QoS



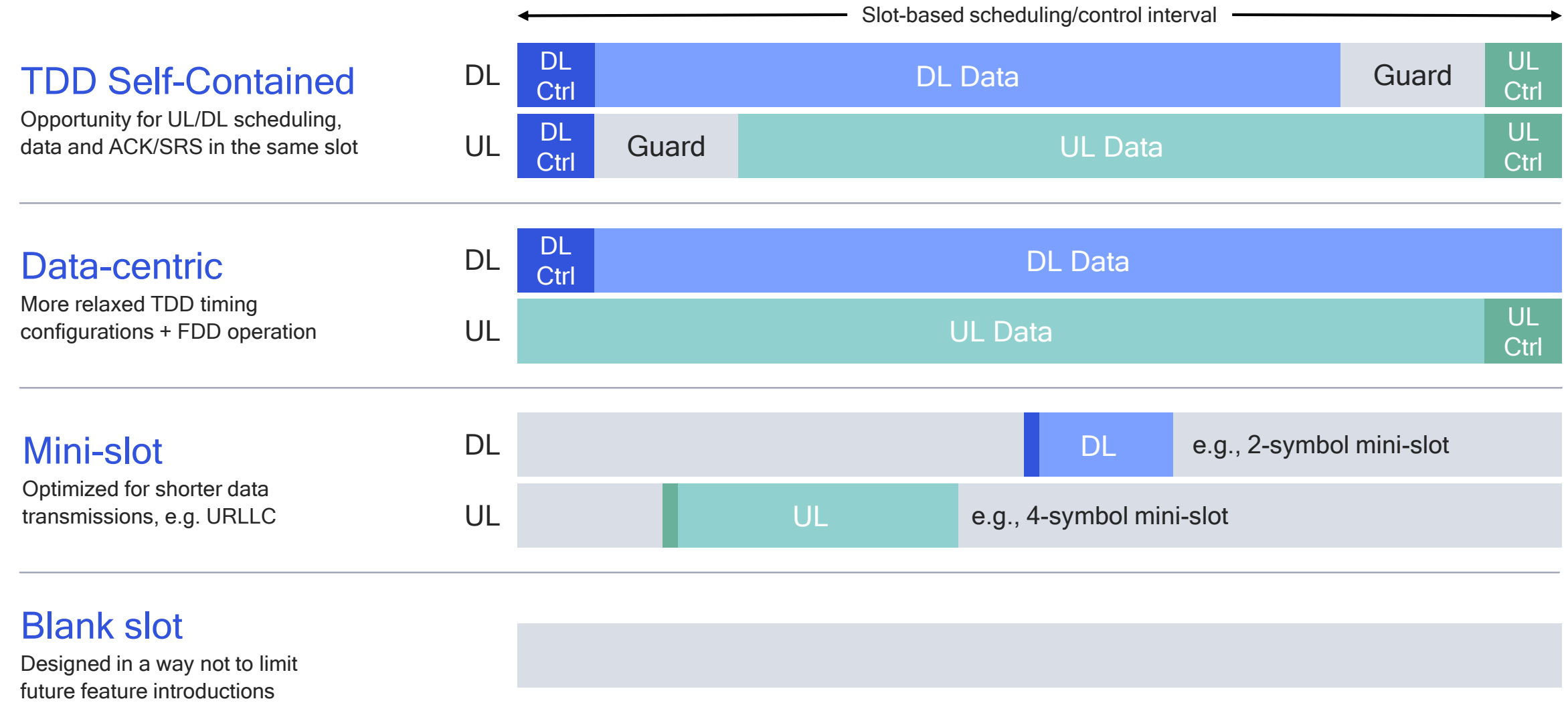
14 OFDM symbols per slot with mini-slot (2, 4, or 7 symbols) for shorter transmissions[1]

Supports slot aggregation for data-heavy transmissions

Efficient multiplexing of long and short transmissions[2]

1. As low as two symbols per mini-slot; 2. Symbols across numerologies align at symbol boundaries and transmissions span an integer # of OFDM symbols

Flexible 5G NR slot structures – Examples



DL reference signals (DL DMRS) & UL Reference + Sounding (UL DSMR, SRS) not showed for simplicity

Benefits of the 5G NR TDD self-contained slot

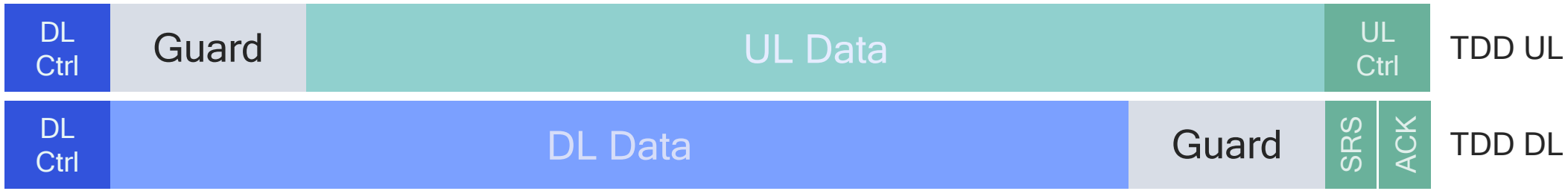
Much faster, more flexible TDD switching and turn-around than 4G LTE

Flexibility for additional headers

E.g., channel reservation header for unlicensed/shared spectrum

More adaptive UL/DL

Faster TDD switching allows for more flexible capacity allocation



Low latency

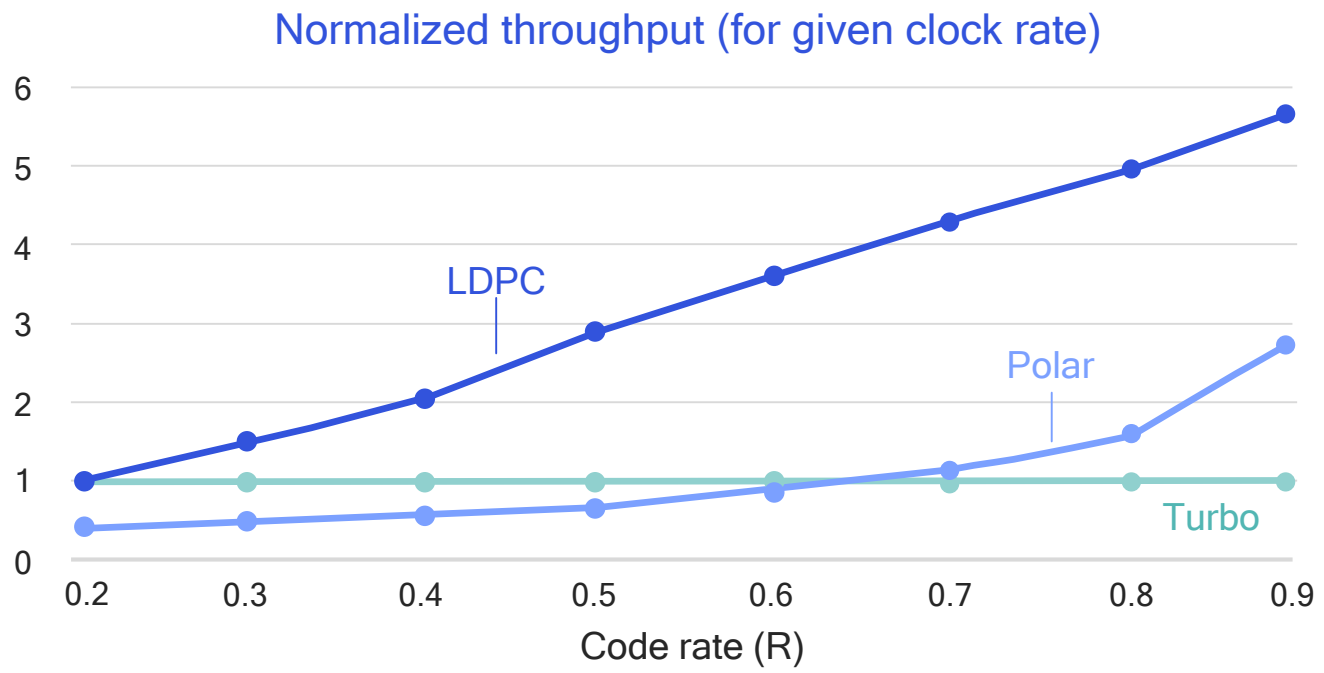
Faster TDD turn-around, with opportunity for UL/DL scheduling, data and ACK in the same slot

Efficient massive MIMO

Optimized TDD channel reciprocity with opportunity for SRS[1] every slot

1. Sounding Reference Signal

Advanced ME-LDPC[1] channel coding is more efficient than LTE Turbo code at higher data rates



High efficiency

Significant gains over LTE Turbo–particularly for large block sizes suitable for MBB

Low complexity

Easily parallelizable decoder scales to achieve high throughput at low complexity

Low latency

Efficient encoding/decoding enables shorter transmission time at high throughput

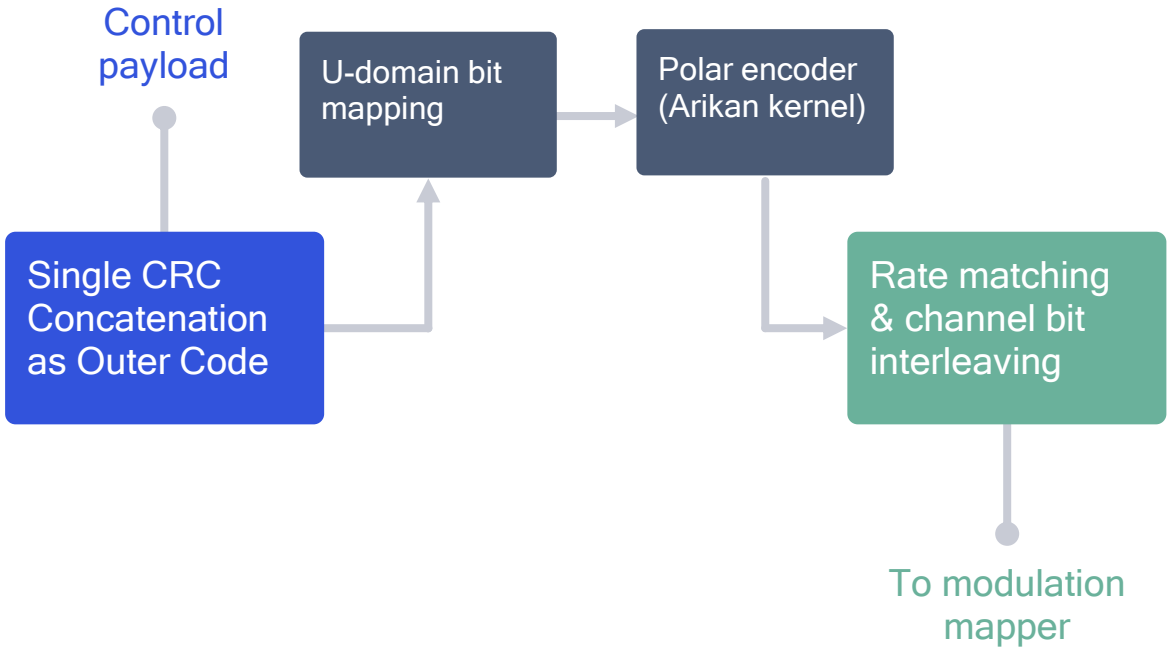
1. Multi-Edge Low-Density Parity-Check

Selected as 5G NR eMBB data channel as part of 3GPP Release-15

Performance gains of CRC-Aided Polar channel coding led to its adoption across many 5G NR control use cases

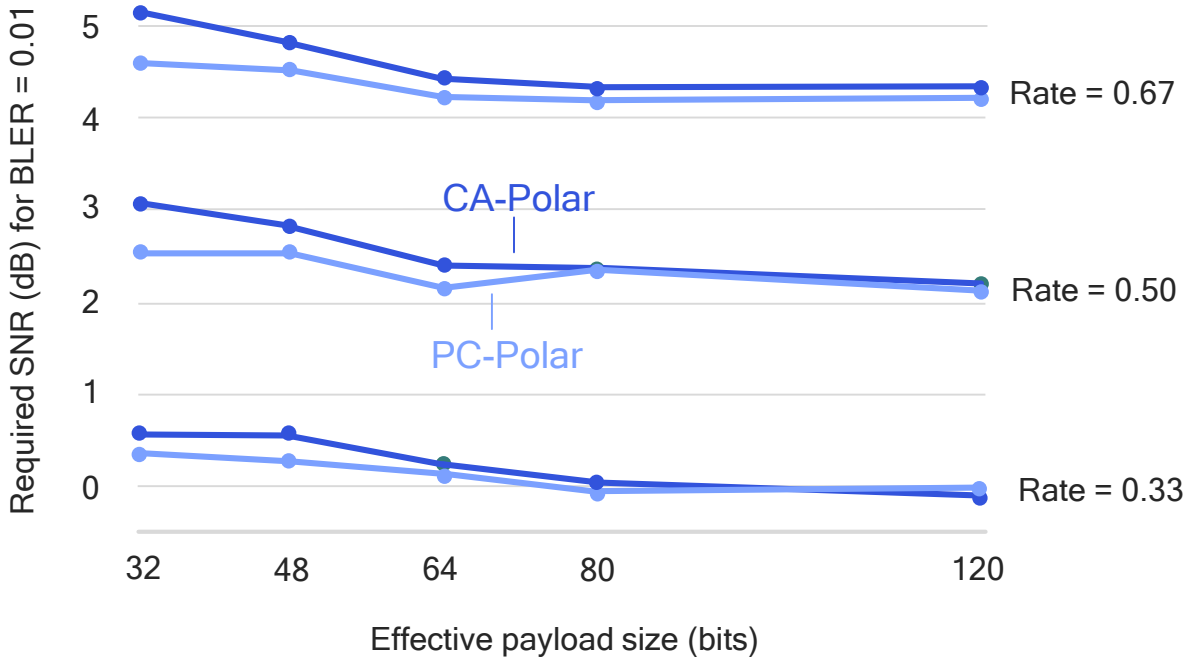
5G NR CRC-Aided (CA-Polar) design

Efficient construction based on single Cyclic Redundancy Check (CRC) for joint detection and decoding



Link-level gains of 5G NR CA-Polar design

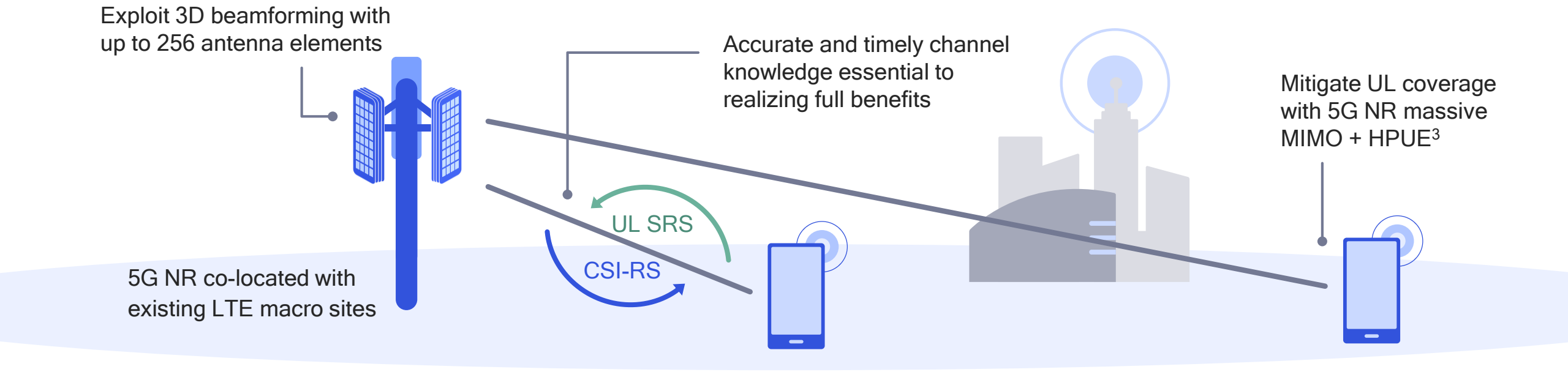
Versus PC-Polar[1] (lower is better)



1. Parity-Check Polar channel coding

5G NR optimized design for massive MIMO

Key enabler for using higher spectrum bands, e.g. 4 GHz, with existing LTE sites



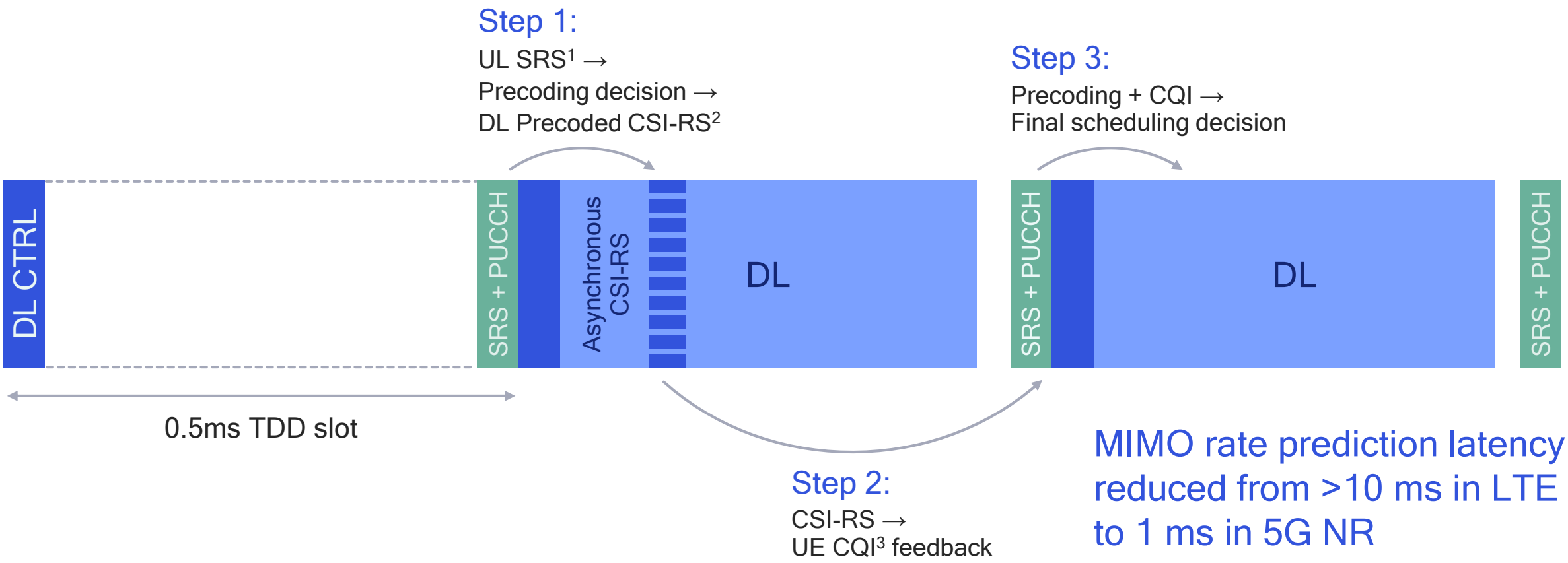
Enabled through an advanced 5G NR end-to-end Massive MIMO design (network and device)

- Optimized design for TDD reciprocity procedures utilizing UL SRS[1]
- Enhanced CSI-RS[2] design and reporting mechanism
- Advanced, high-spatial resolution codebook supporting up to 256 antennas
- New features, such as distributed MIMO

C1. Sounding Reference Signal. 2. Channel State Information Reference Signal; 3. High-Power User Equipment (HPUE) Tx power gains

5G NR optimized design for TDD reciprocity procedures

5G NR slot structure and enhanced Ref Signals enable fast/accurate feedback



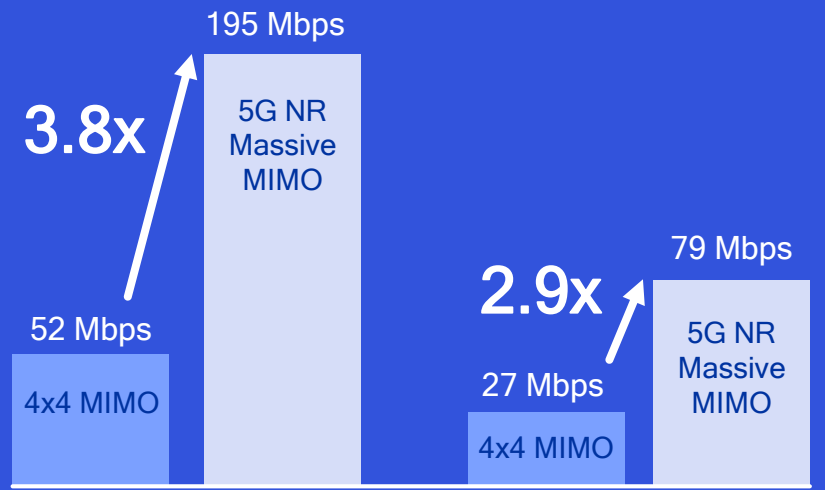
MIMO rate prediction latency reduced from >10 ms in LTE to 1 ms in 5G NR

*Sub-6 GHz, macro cell numerology, 30 kHz tone spacing; Channel sounding opportunity increases from <= 200 Hz with LTE to 2 kHz with 5G NR.
1. Sounding Reference Signal. 2. Channel State Information Reference Signal. 3. Channel Quality Indicator

Qualcomm | 5G NR Massive MIMO

5G NR massive MIMO increases coverage & capacity

Faster, more uniform data rates throughout cell



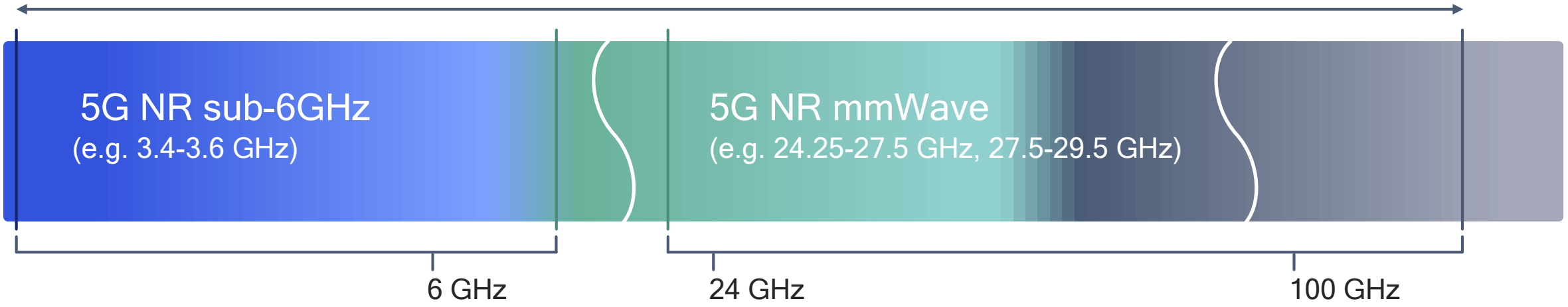
Assumptions: carrier frequency 4GHz; 200m ISD, 200MHz total bandwidth; base station: 256 antenna elements (x-pol), 48dBm Tx power; UE: 4 Tx/Rx antenna elements, 23dBm max. Tx power; full buffer traffic model, 80% indoor and 20% outdoor UEs.

The large bandwidth opportunity for mmWave

The new frontier of mobile broadband

5G NR

Unified design across diverse spectrum bands/types

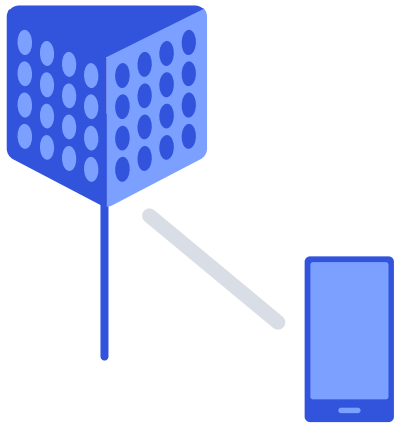


Multi-Gbps data rates
With large bandwidths (100s of MHz)

Much more capacity
With dense spatial reuse

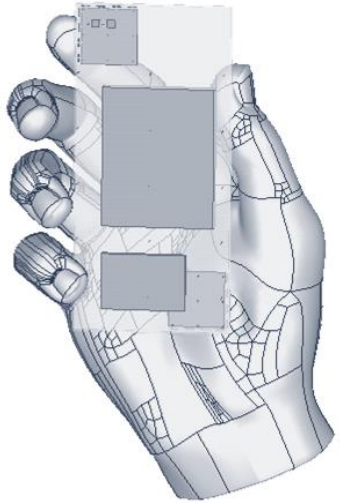
Excels in wider bandwidths
Opens up new opportunities

Overcoming numerous challenges to mobilize mmWave



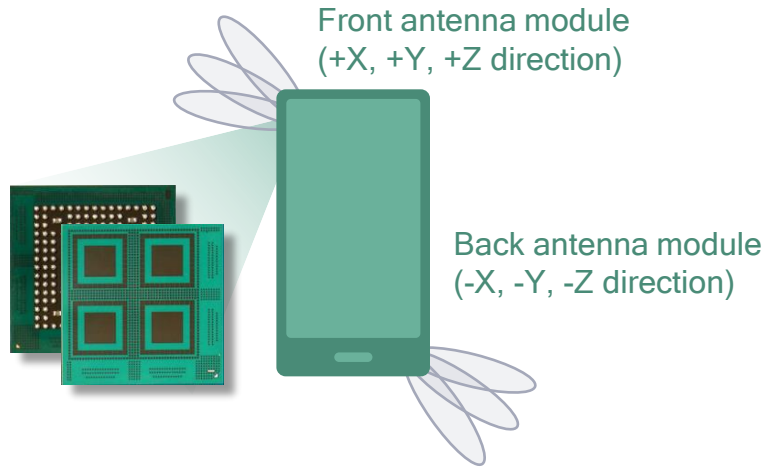
Coverage

Analog beamforming with narrow beamwidth to overcome significant path loss in bands above 24 GHz



Robustness

Adaptive beam steering and switching to overcome blockage from hand, head, body and foliage

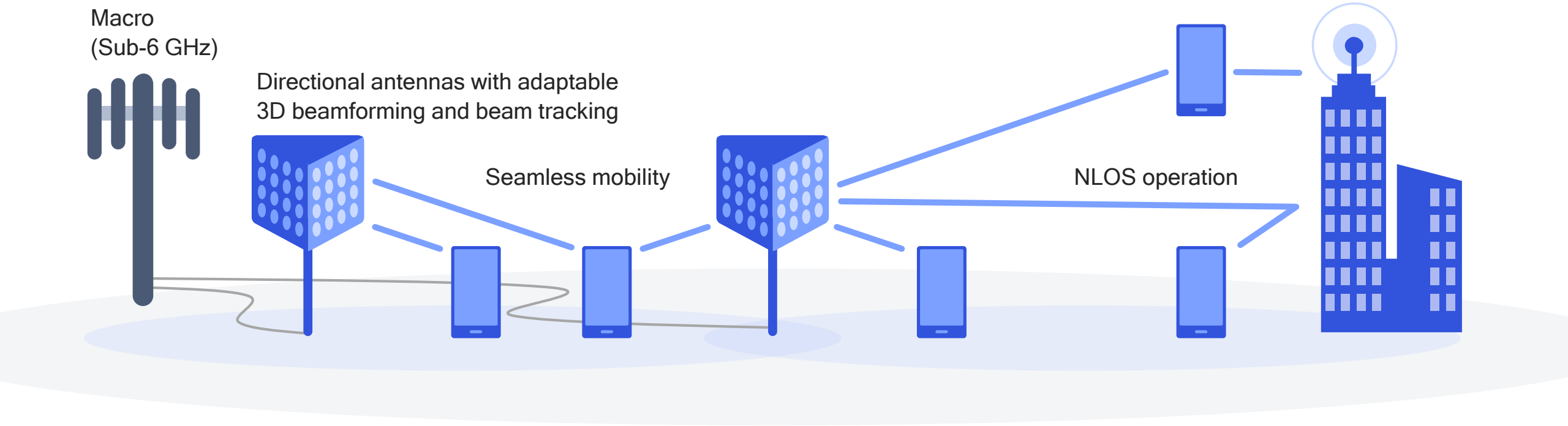


Device size/power

Different antenna configurations (face/edge) to fit mmWave design in smartphone form factor and thermal constraints

Mobilizing mmWave with 5G NR technologies

Key properties for robust mmWave operation in a NLOS mobile environment



Very dense network topology and spatial reuse (~150-200m ISD)

Fast beam steering and switching within an access point

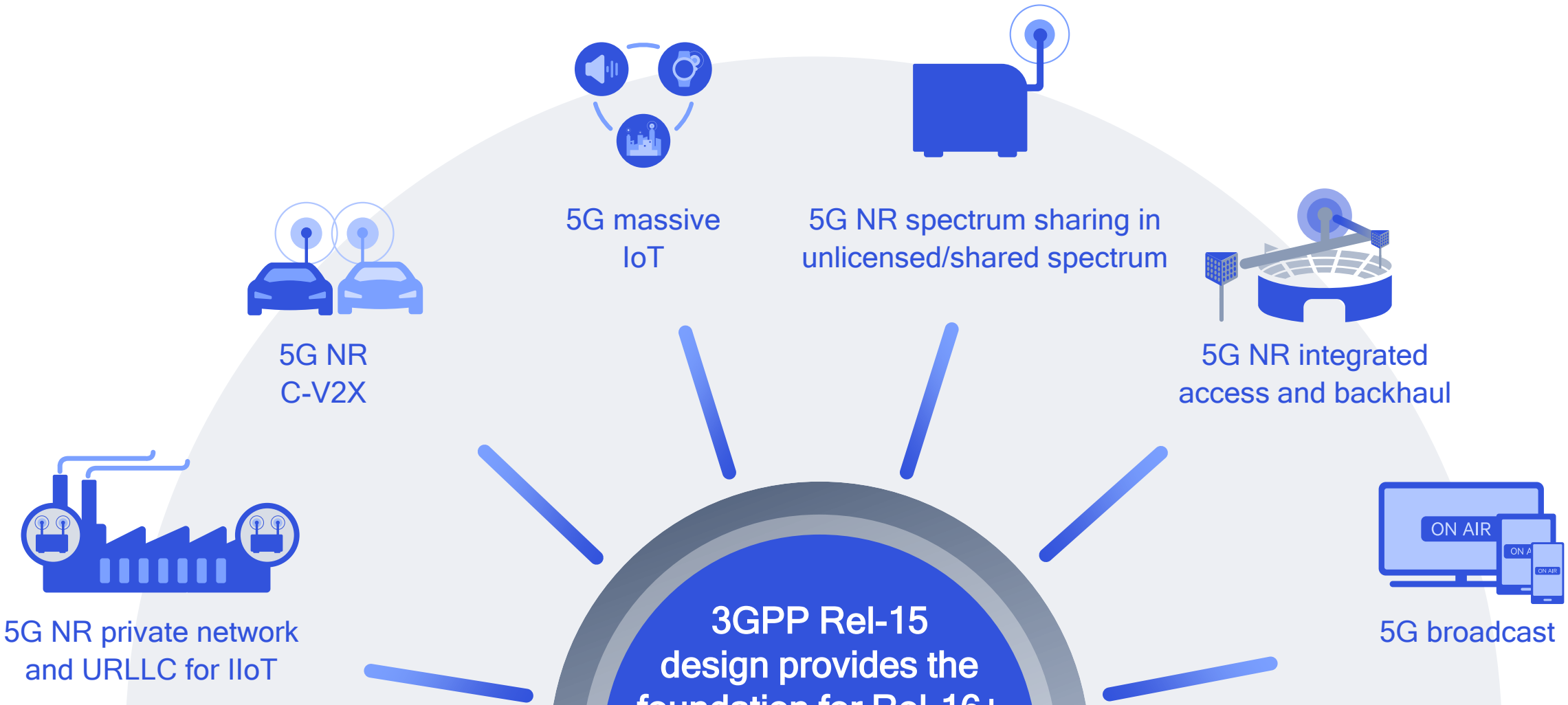
Architecture that allows for fast beam switching across access points

Tight integration with sub-6 GHz (LTE or NR)

Driving 5G NR evolution and expansion

3GPP Release 16 and beyond

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);

5G NR – opportunity for new spectrum sharing paradigms

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

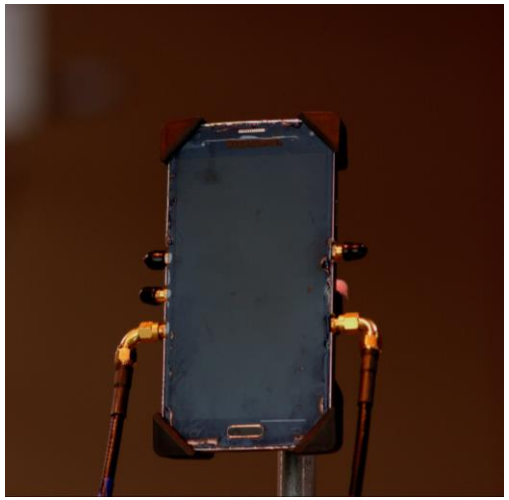
Evolution Path

- 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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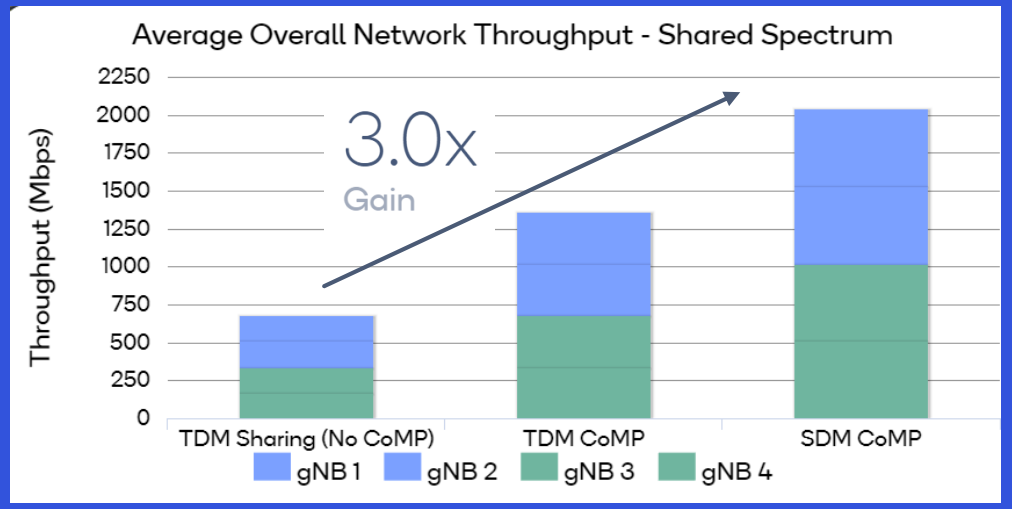
Demonstrating the potential new 5G NR spectrum sharing paradigms

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

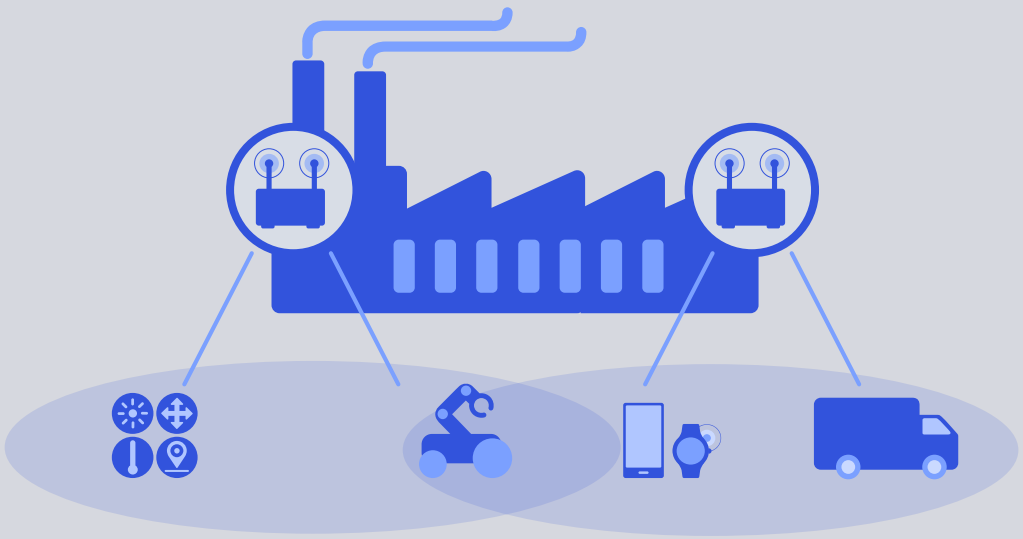


COMP = Coordinated Multi-Point
SDM = Spatial Domain Multiplexing

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

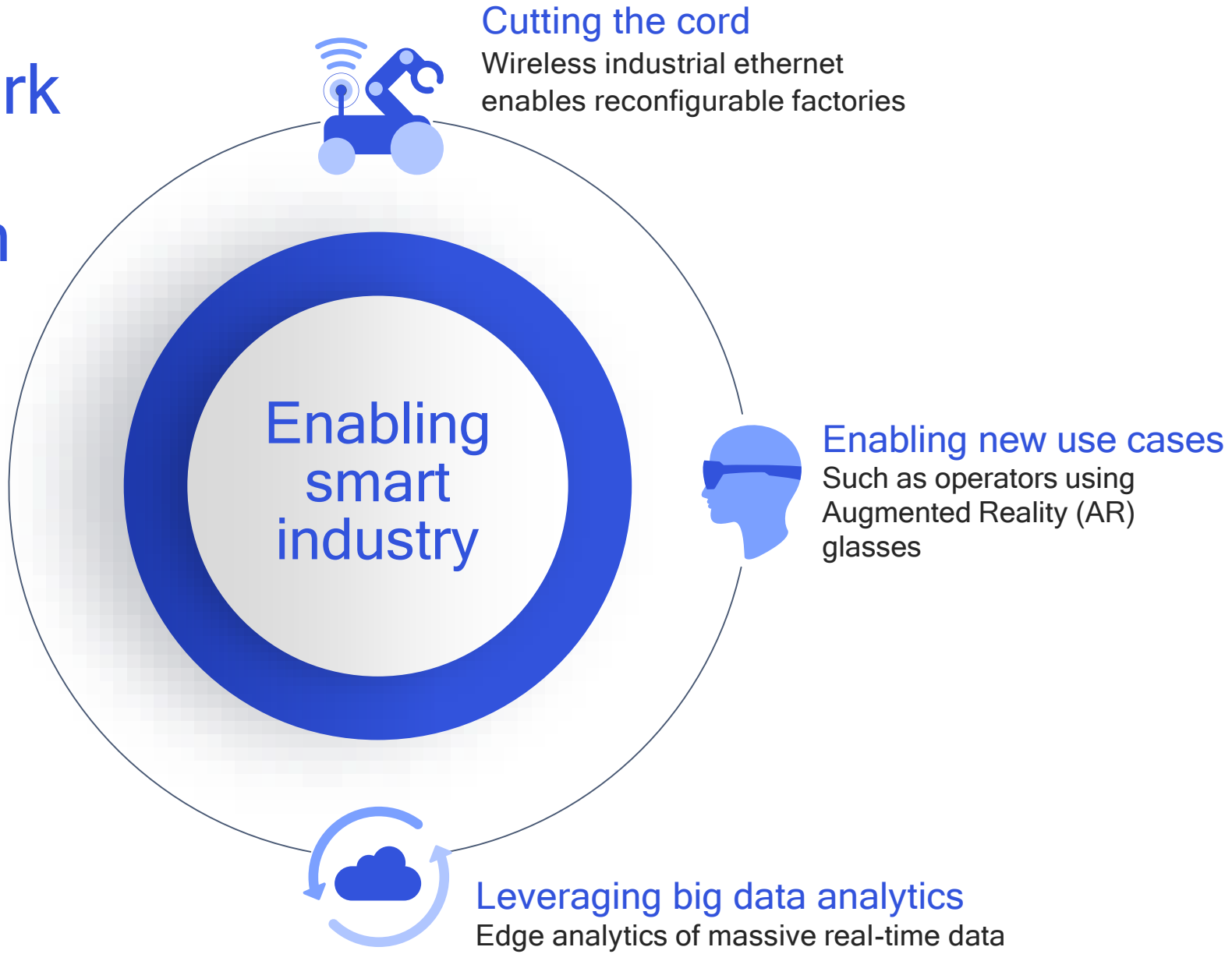
Private 5G NR network enables the next Industrial Revolution

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



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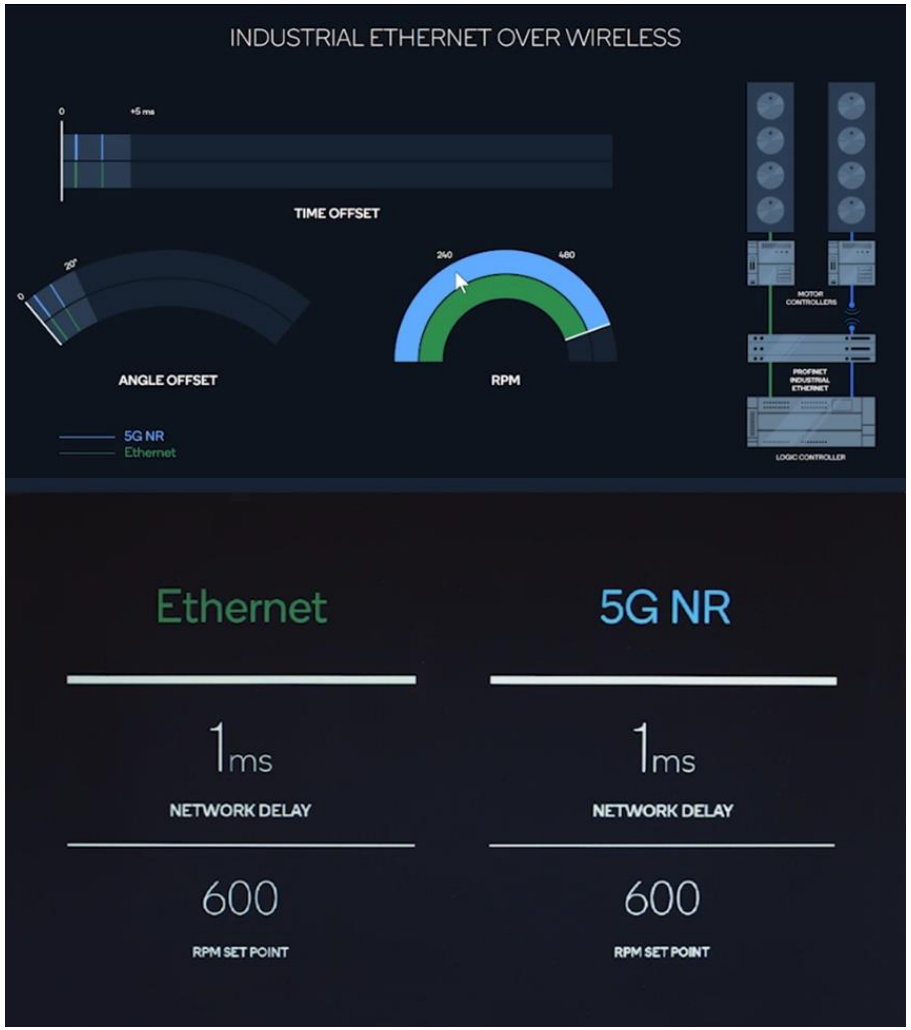
Industry-first demo of wireless PROFINET Industrial Ethernet over 5G NR

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]

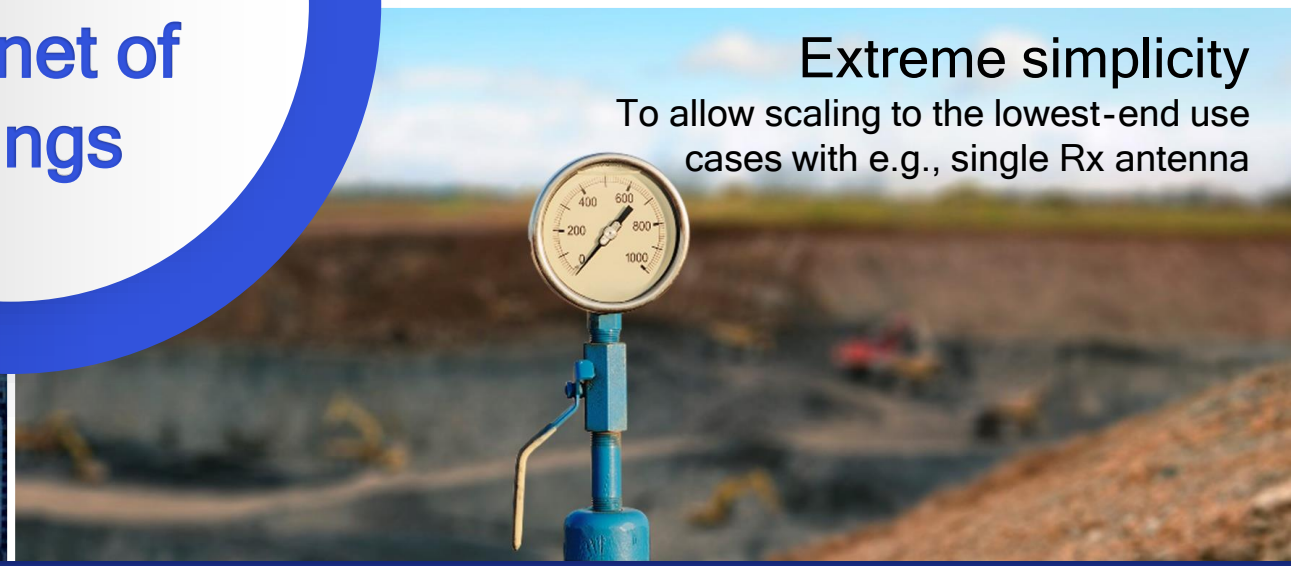
Power efficient

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

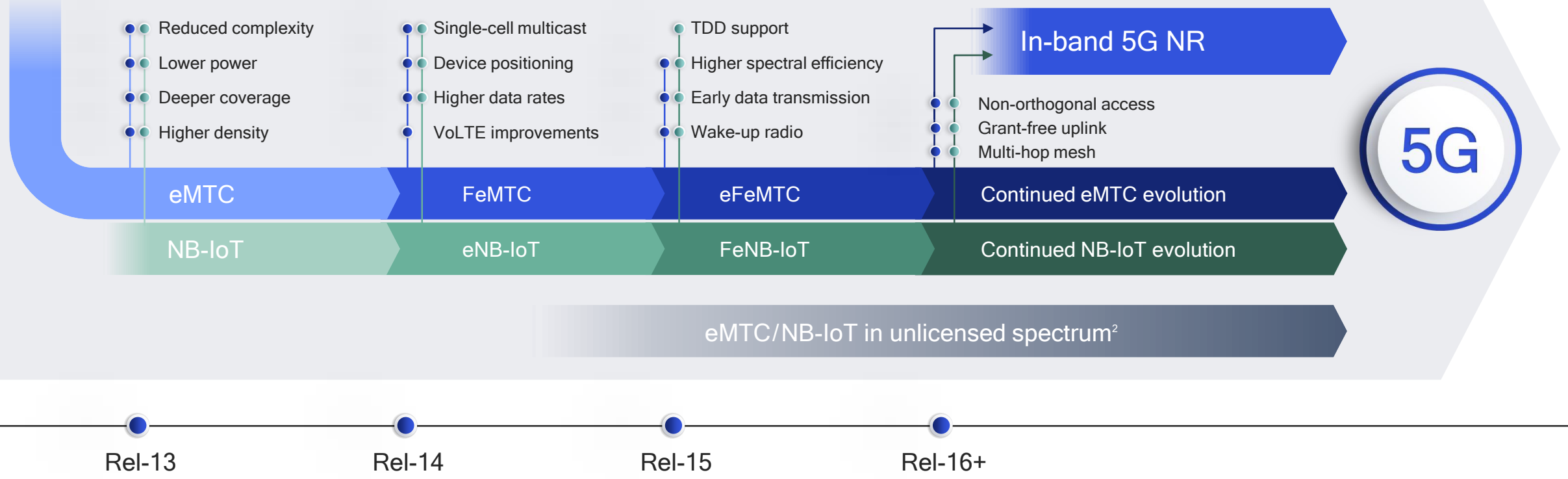
To allow scaling to the lowest-end use cases with e.g., single Rx antenna

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

Continued evolution to meet tomorrow's massive IoT needs

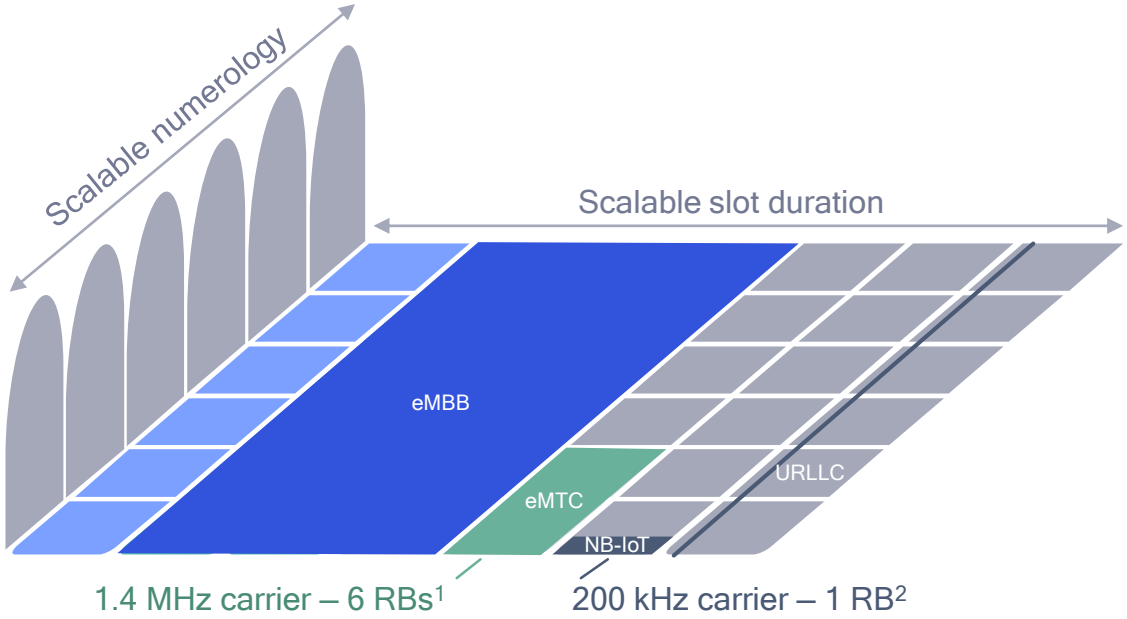
Essential to 5G – LTE IoT to be submitted to meet IMT-2020[1] requirements



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

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

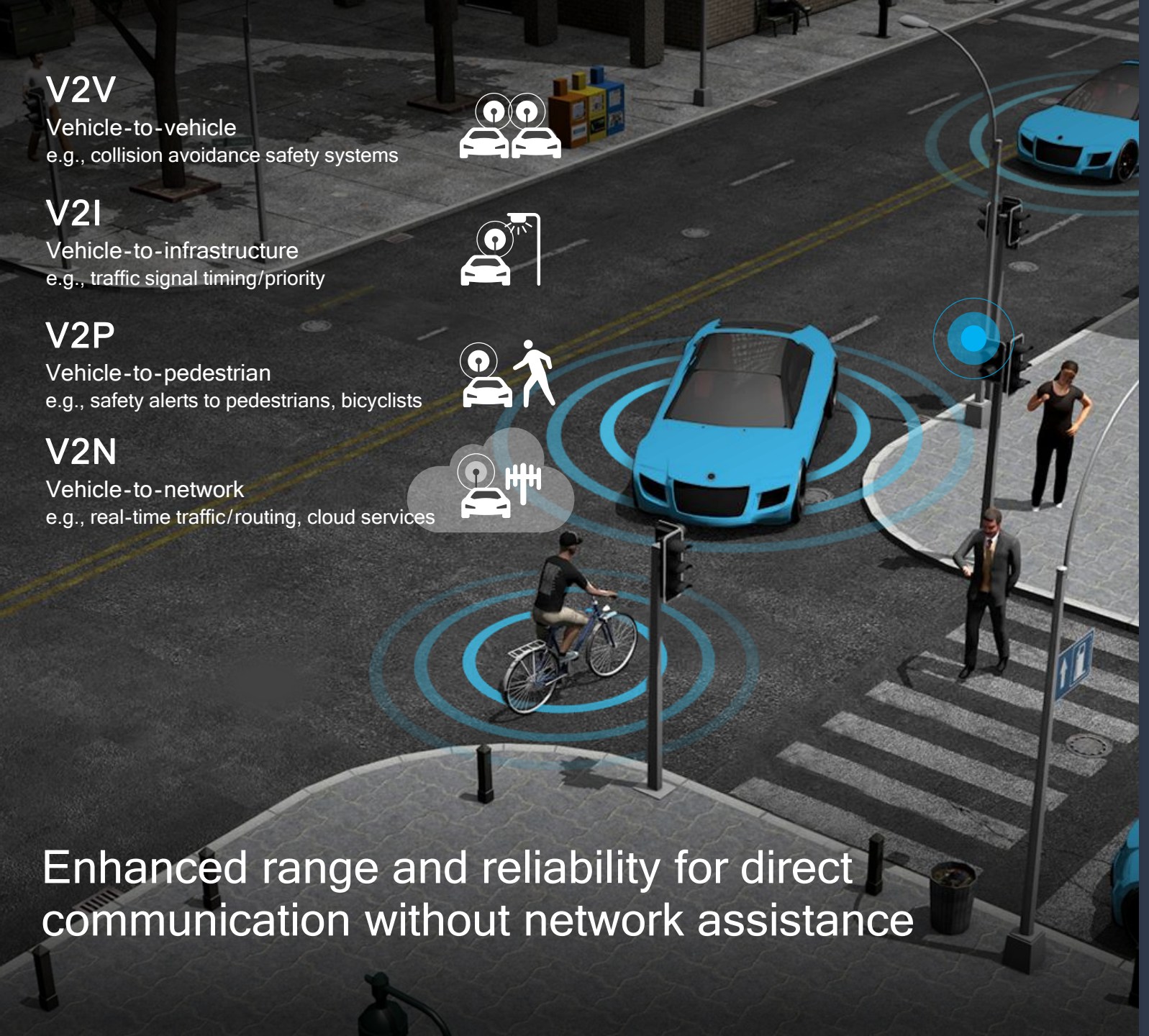
Both 5G NR deployment options – NSA with LTE EPC and SA with 5G core – support eMTC and NB-IoT evolution

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

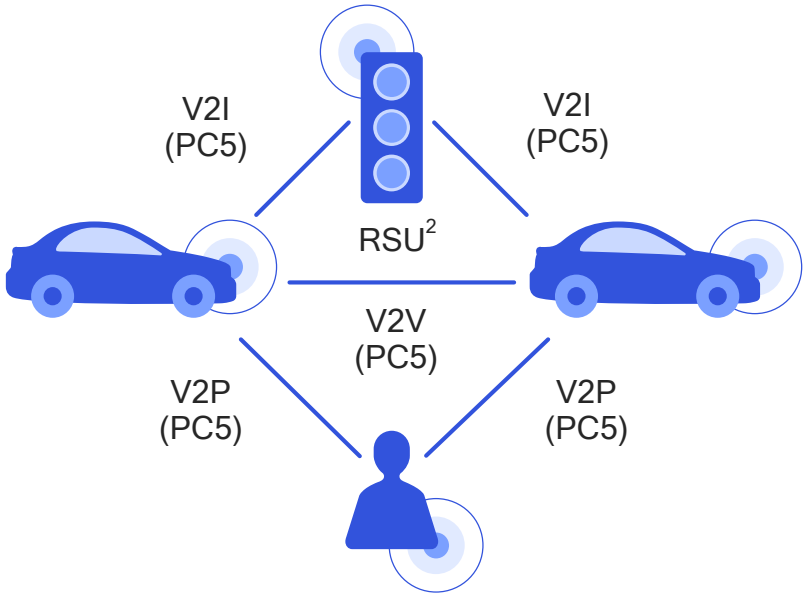
C-V2X enables network independent communication

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

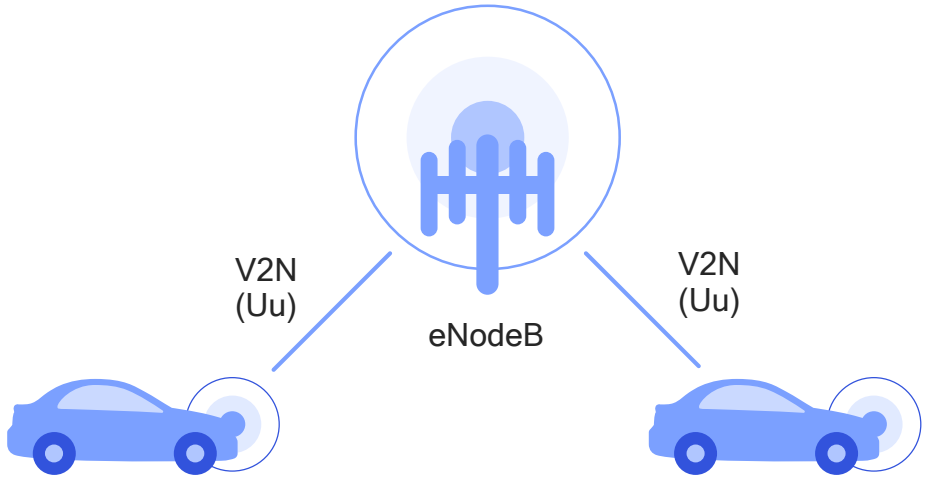


Network communications for complementary services

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

Network Uu interface

e.g. accident 2 kilometer ahead



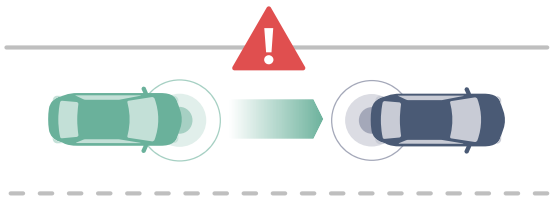
1. PC5 operates on 5.9GHz; whereas, Uu operates on commercial cellular licensed spectrum 2. RSU stands for roadside unit.1. 3GPP also defines a mode, where eNodeB helps coordinate C-V2X Direct Communication; 2. GNSS is required for V2X technologies, including 802.11p, for positioning. Timing is calculated 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

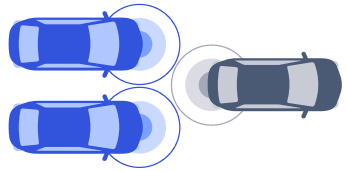


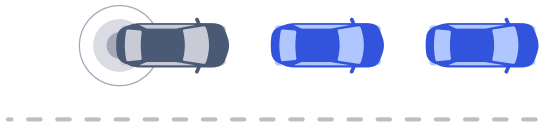
Basic and enhanced safety
C-V2X Rel-14/Rel-15 with enhanced range and reliability

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





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5G NR

5G is the foundation to what's next. We are the foundation to 5G.

Learn more at www.qualcomm.com / 5G

Making 5G NR a commercial reality for 2019 eMBB deployments

Driving the expansion of 5G NR ecosystem and opportunity

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Thank you!

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