Qualcomm @QCOMResearch December 2022

5G NR Release 15

The technology foundation of the 5G evolution

Leading wireless innovation for more than 35 years

Digitized mobile communications

Analog to digital

Redefined computing

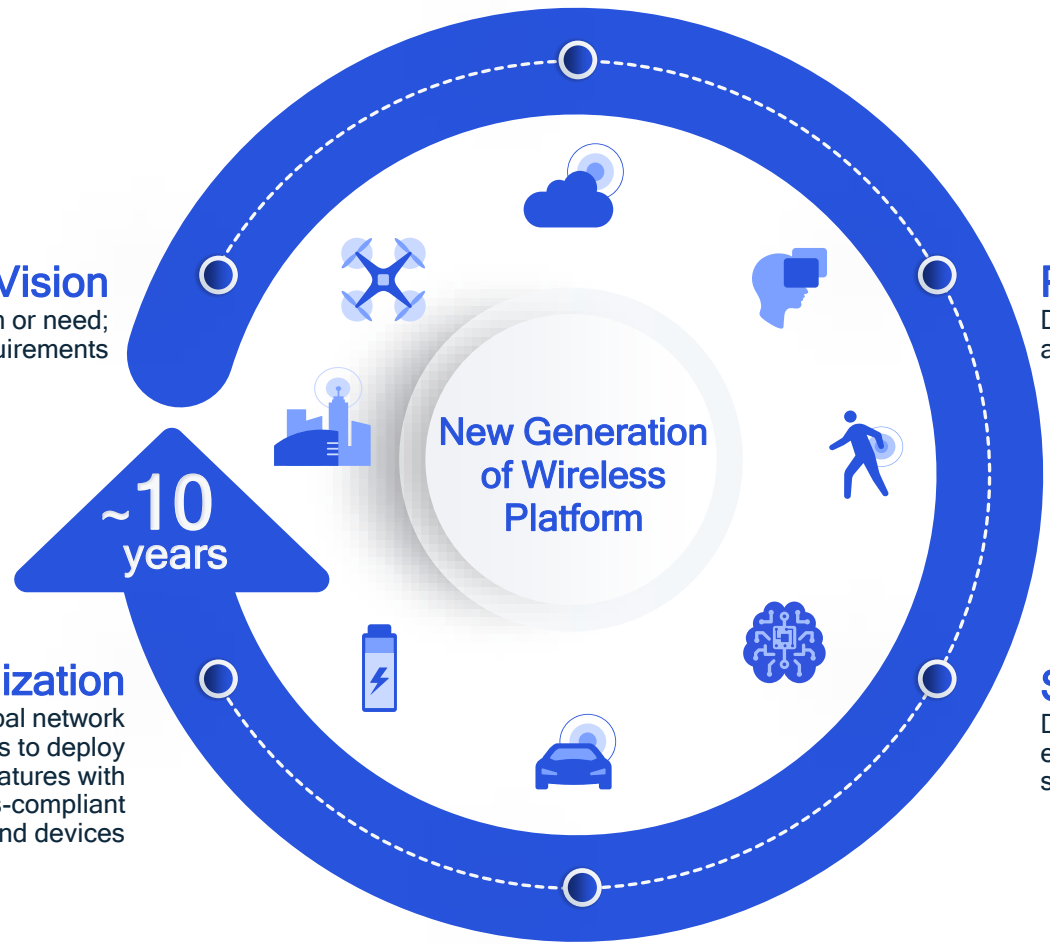
Desktop to smartphones

Transforming industries

Connecting virtually everything

Foundation to “G” leadership is technology leadership

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



Invention
Invent new technologies and e2e system architecture

Proof-of-concept
Deliver end-to-end prototypes and impactful demonstrations

Standardization
Drive e2e design with ecosystem and through standards process

Trials
Collaborate on OTA field trials that track 3GPP standardization and drive ecosystem towards rapid commercialization

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

Vision
Identify a problem or need; establish requirements

Mobile has made a leap every ~10 years

Mobile voice communication

1G

1980s

Analog voice

AMPS, NMT, TACS

Efficient voice to reach billions

2G

1990s

Digital voice

D-AMPS, GSM, IS-95 (CDMA)

Focus shifts to mobile data

3G

2000s

Wireless Internet

CDMA2000/EV-DO WCDMA/HSPA+,

Mobile broadband and emerging expansion

4G

2010s

Mobile broadband

LTE, LTE Advanced, Gigabit LTE

A unified future-proof platform

2020s

Connected intelligent edge

5G New Radio (NR)

Transportation

Manufacturing

Industrial

Retail

Energy

Driving digital transformation across industries

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

Agriculture

Public safety

Smart cities

Healthcare

Entertainment

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

Delivering on the 5G vision

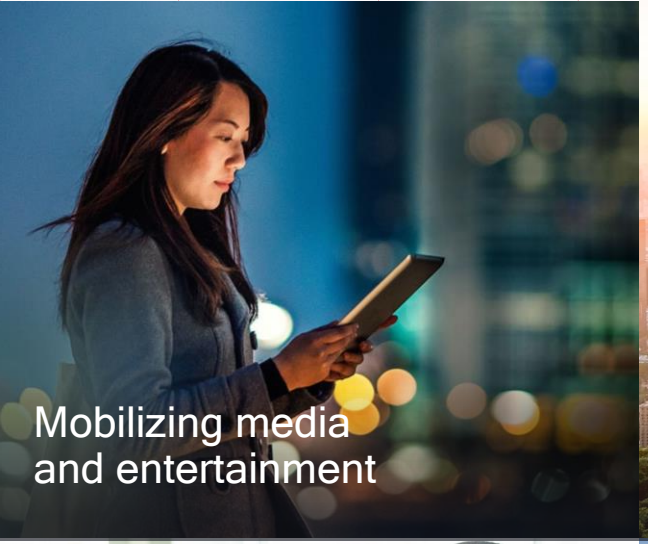
Where virtually everyone and everything is intelligently connected

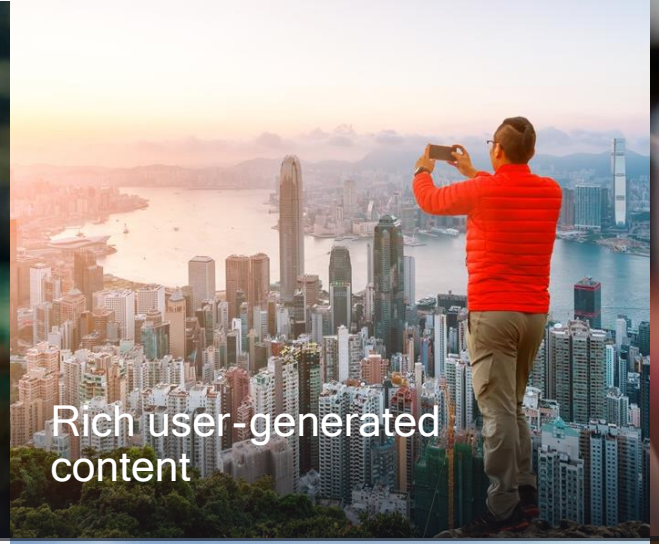
A new kind of network to drive innovation and growth

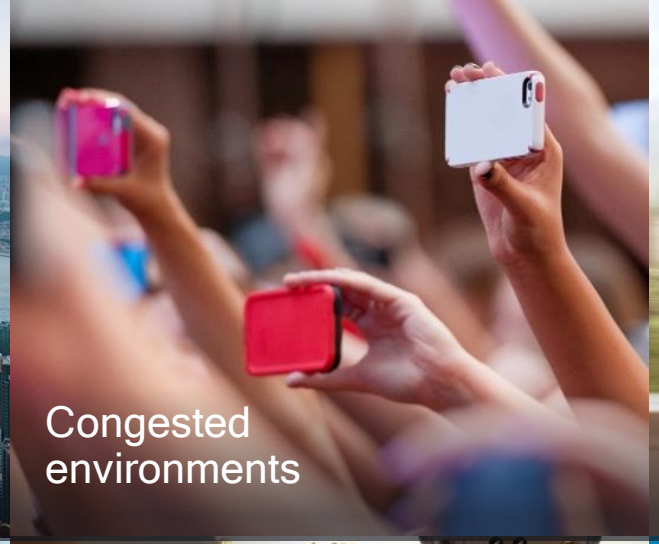
Significant connectivity upgrade

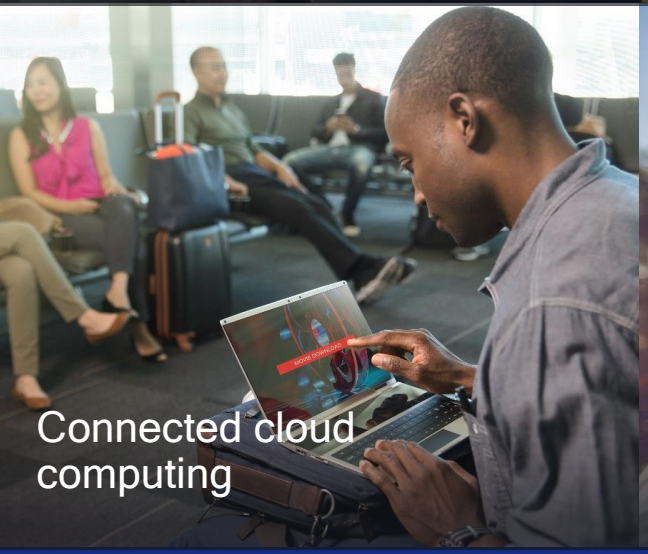
Smartphone tech extending into many industries

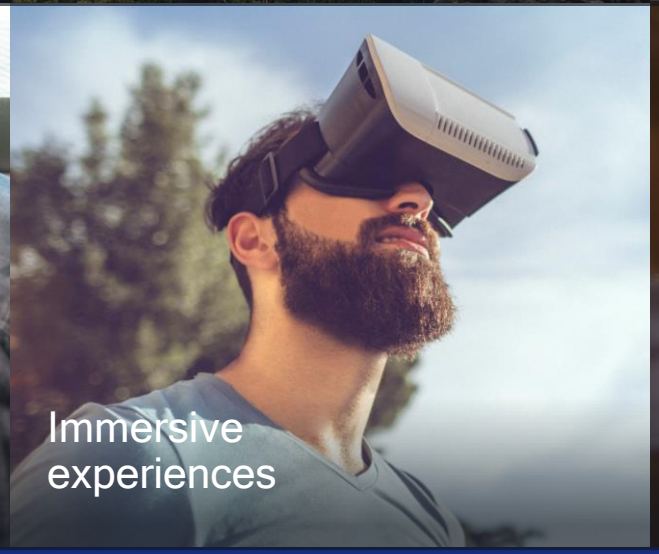
Consumers want 5G smartphones

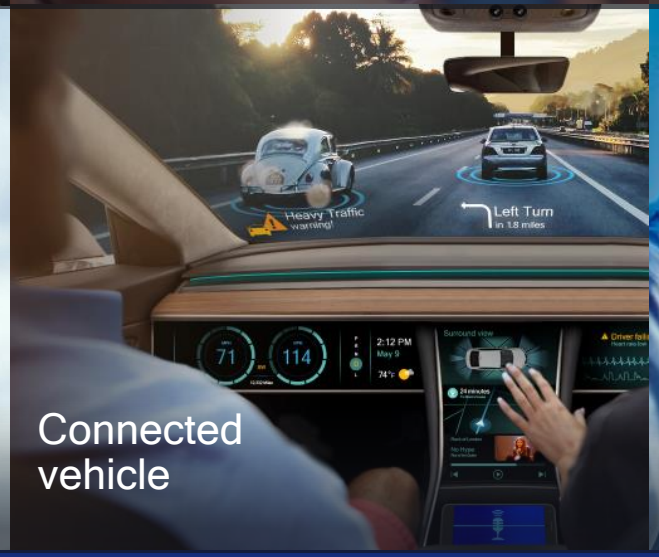










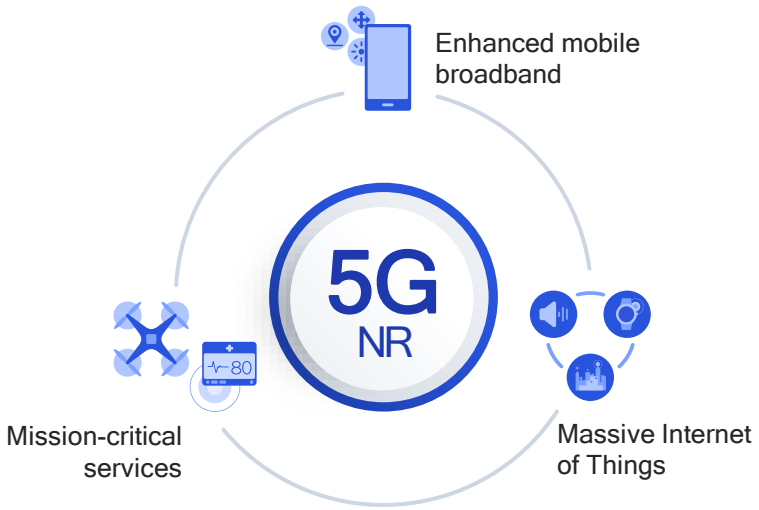


5G

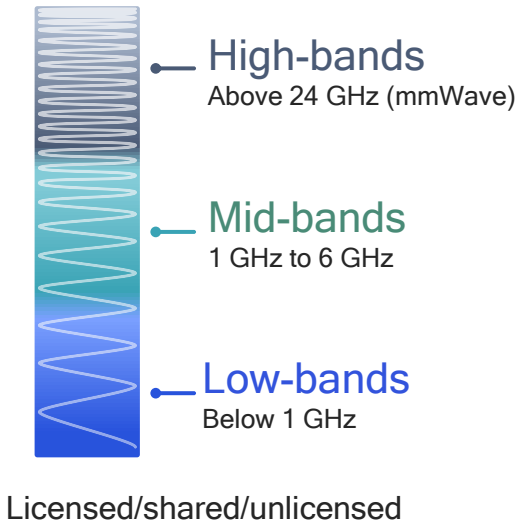
5G is essential for next generation mobile experiences

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

5G NR is a unified, more capable air interface



Diverse services



Licensed/shared/unlicensed

Diverse spectrum

Diverse deployments

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

5G NR pioneering advanced 5G NR technologies

Mission-critical services

Cellular Vehicle-to-Everything (C-V2X)

Drone communications | Private Networks

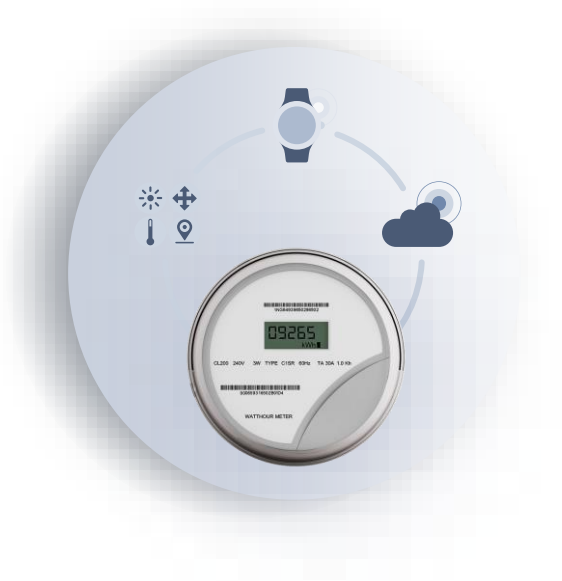
Ultra Reliable Low Latency Comms (URLLC)

Enhanced mobile broadband

Spectrum sharing | Flexible slot-based framework

Scalable OFDM | Massive MIMO | Mobile mmWave

Dual Connectivity | Advanced channel coding

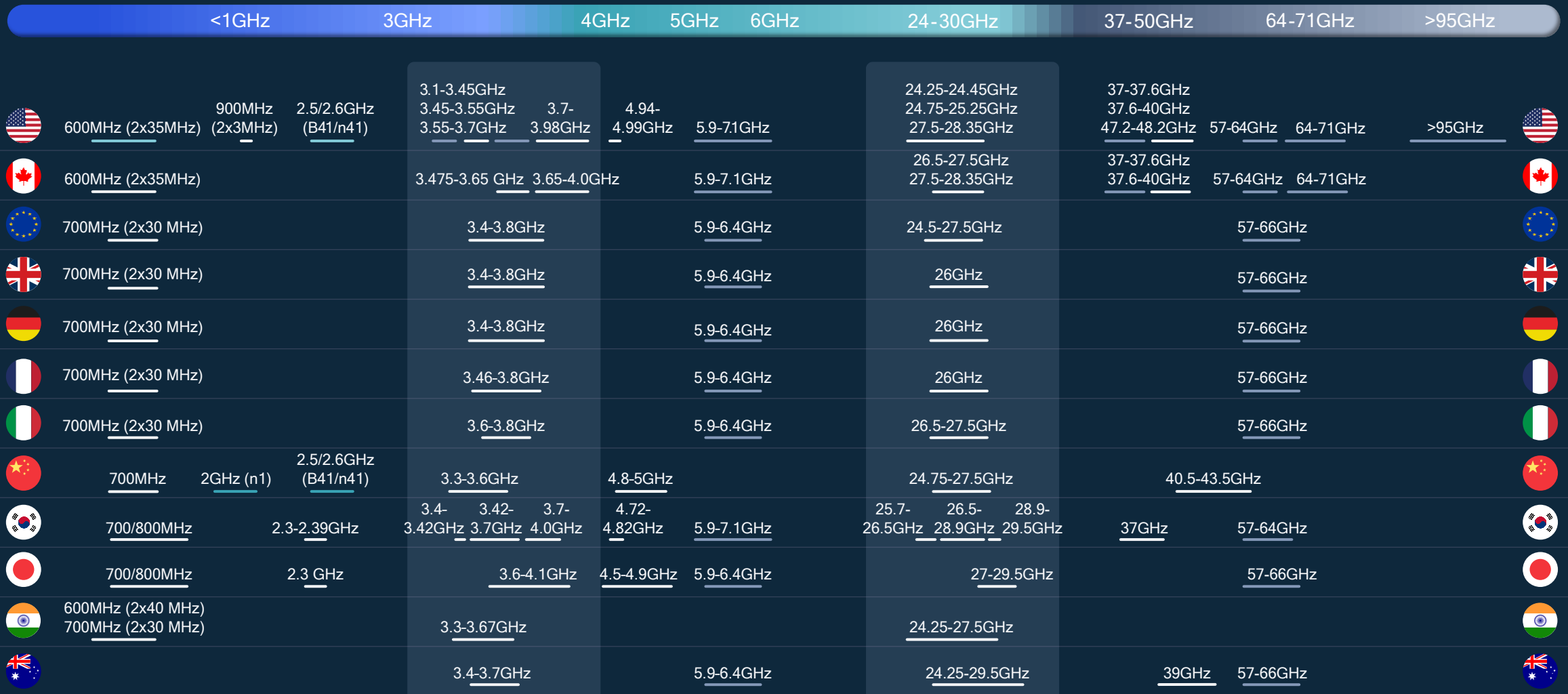


Massive Internet of Things

Enhanced power save modes

Deeper coverage | Grant-free UL

Narrow bandwidth | Efficient signaling



Global snapshot of allocated/targeted 5G spectrum

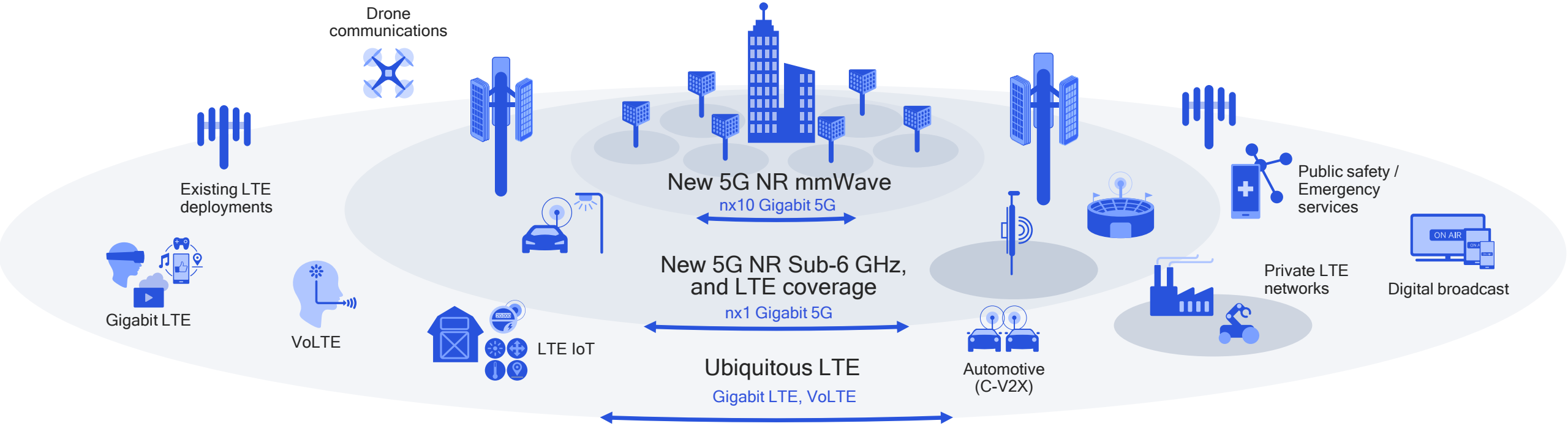
5G is being designed for diverse spectrum types/bands

New 5G band
- Licensed
- Unlicensed / shared
- Existing band

Note for Japan: All cellular bands are available for 5G; 5.9-6.4 GHz is in the final stage of regulatory process for the update expected in August 2022

Our LTE advancements are essential to 5G

Providing ubiquitous coverage and essential services that complement 5G NR

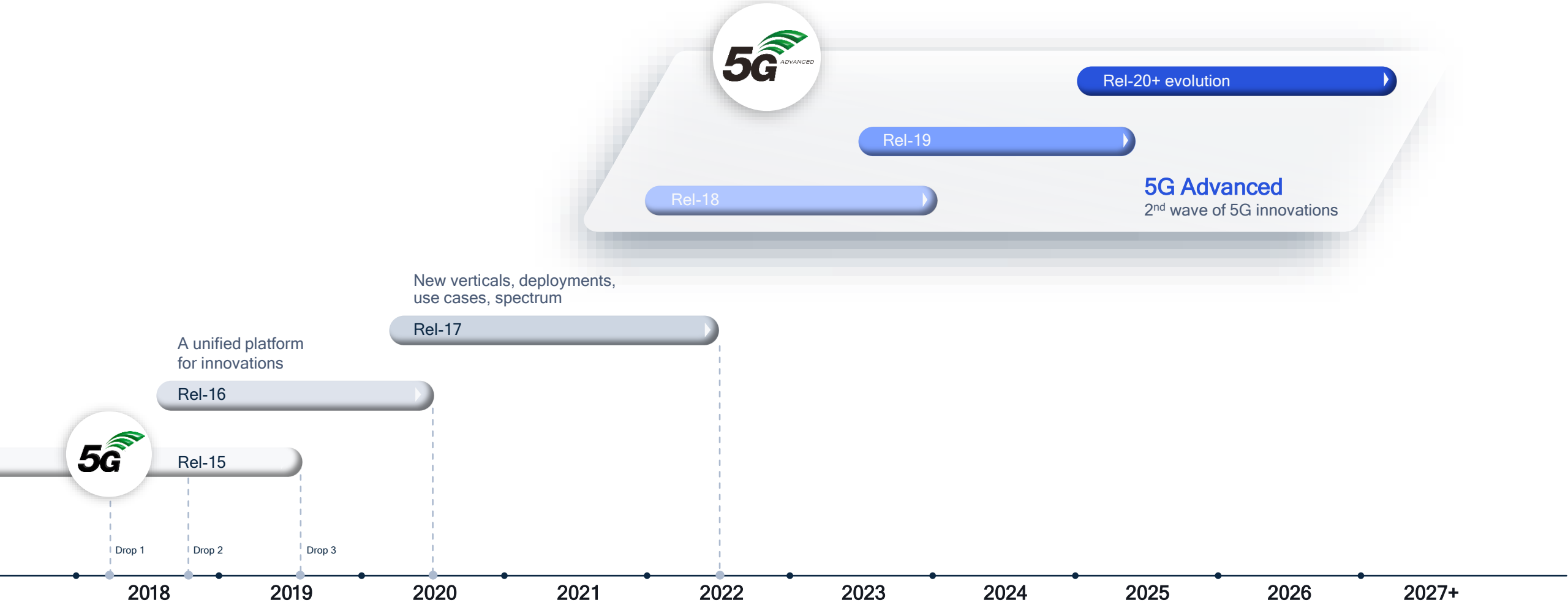


Gigabit LTE is here now and delivers a virtually seamless 5G mobile experience

LTE IoT, private LTE network, C-V2X are enabling new mobile use cases today

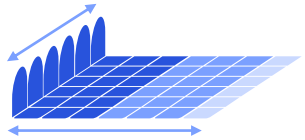
LTE Advanced Pro leadership is essential to success in the 5G Era

Embarking on the 5G evolution to fulfill the 5G vision



Our technology inventions drove 5G Rel-15 specifications

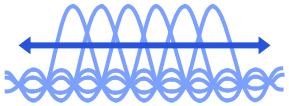
Flexible slot-based framework



Scalable OFDM numerology

Address diverse services, spectrum, deployments

Scalable OFDM-based air interface



Self-contained slot structure

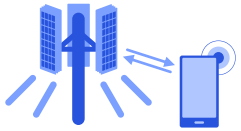
Low latency, URLLC, forward compatibility

Advanced channel coding

Multi-Edge LDPC and CRC-Aided Polar

Support large data blocks, reliable control channel

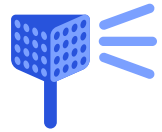
Massive MIMO



Reciprocity-based MU-MIMO

Large # of antennas to increase coverage/capacity

Mobile mmWave



Beamforming and beam-tracking

For extreme capacity and throughput

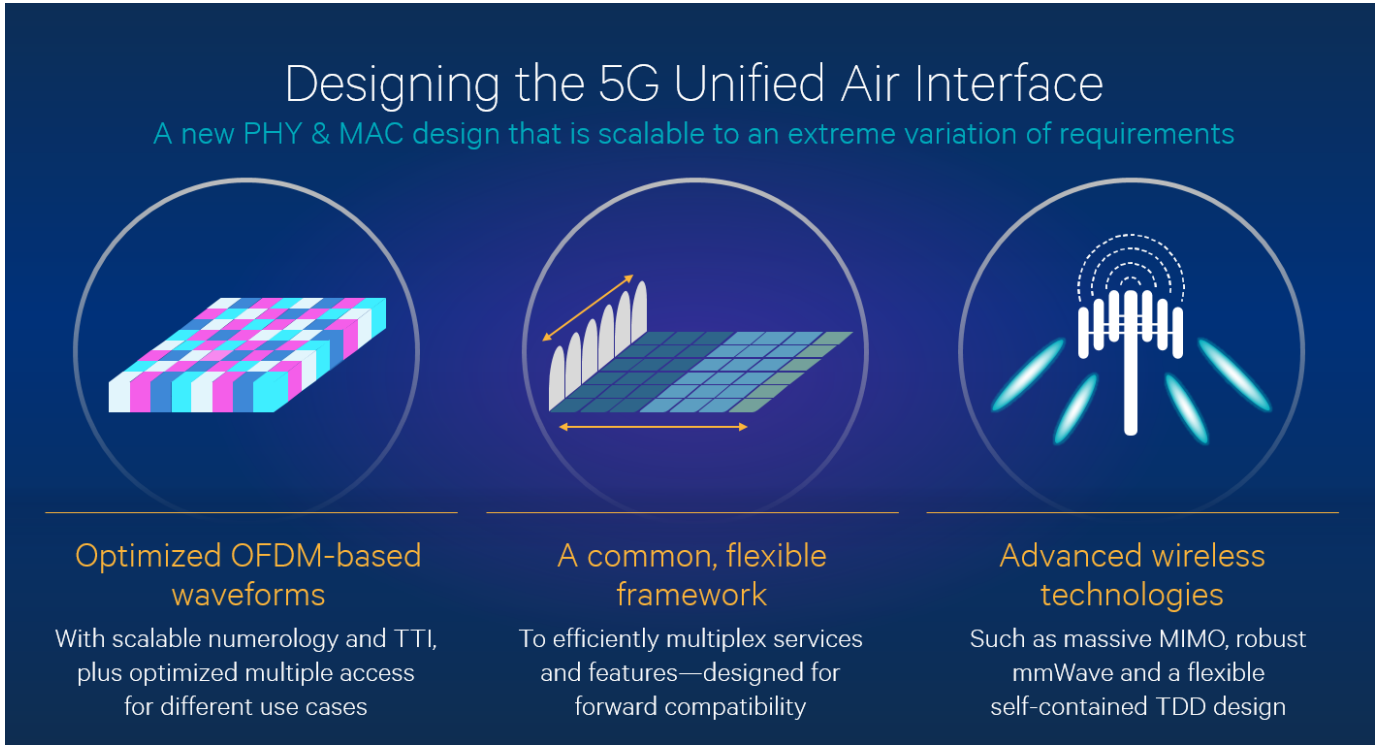
Early R&D investments | Cutting-edge prototypes | Fundamental contributions to 3GPP

5G NR standard aligned with our early 5G design

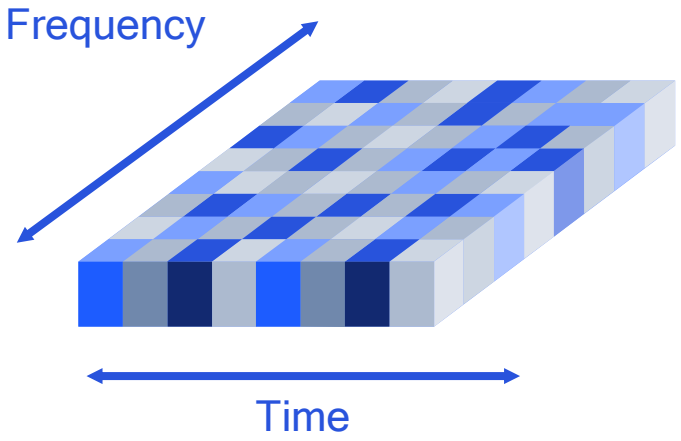
A testament to the impact of our early 5G R&D and fundamental contributions to 3GPP

November 2015

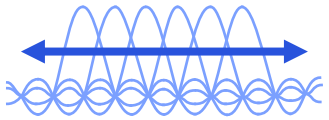
Qualcomm Technologies' 5G Analyst Day



Scalable OFDM-based 5G NR air interface

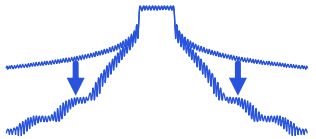


Scalable numerology



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]

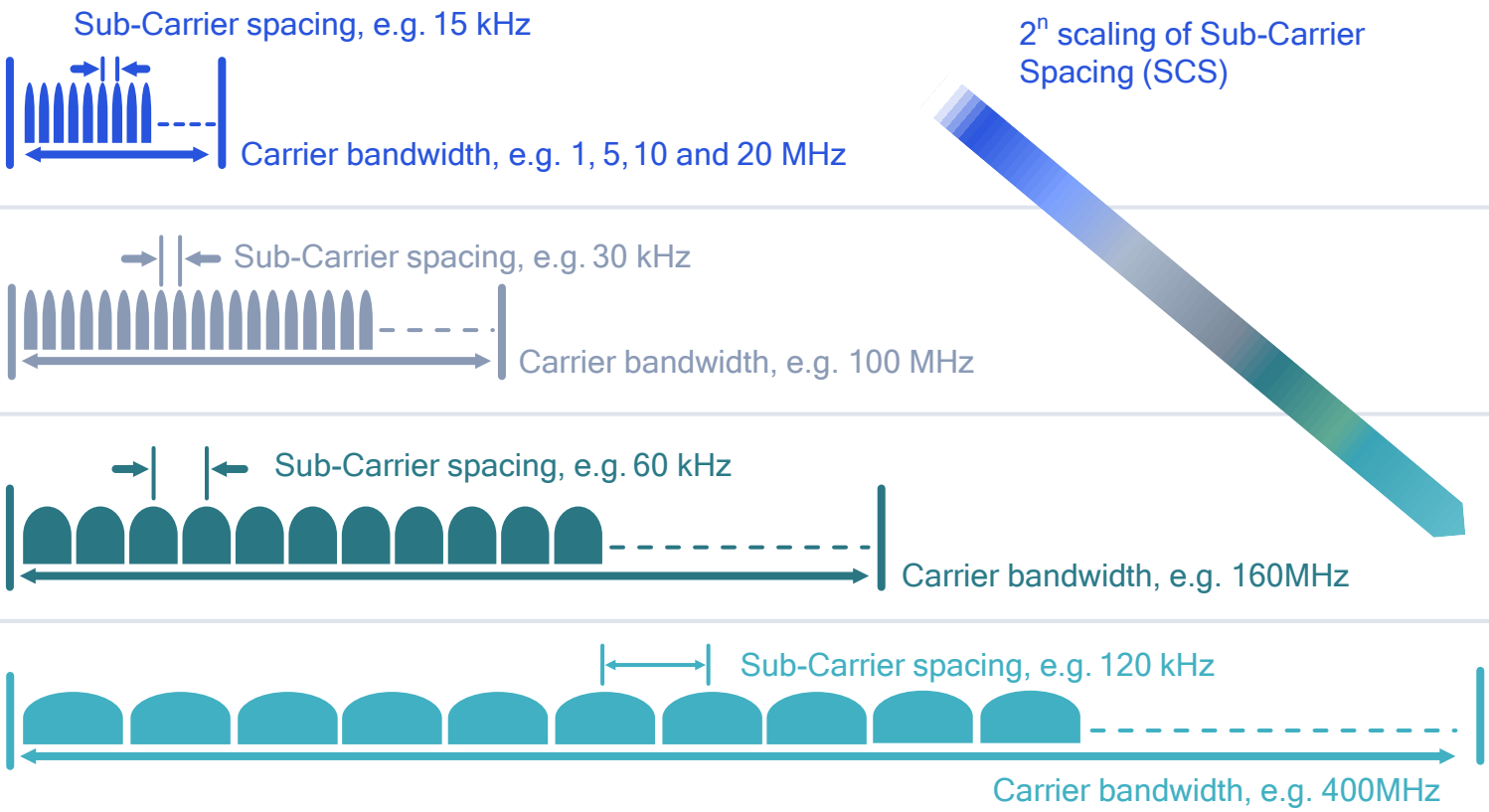
Scalable 5G NR OFDM numerology–examples

Outdoor macro coverage
e.g., FDD 700 MHz

Outdoor macro and small cell
e.g., TDD 3-5 GHz

Indoor wideband
e.g., unlicensed 6 GHz

mmWave
e.g., TDD 28 GHz



Efficiently address 5G diverse spectrum, deployments and services

Scaling reduces FFT processing complexity for wider bandwidths with reusable hardware

Expanding 5G with the flexible slot-based framework

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

Scalable slot duration

Efficient multiplexing of diverse latency and QoS requirements

Broadcast/ enTV (Rel-16+)

Cellular V2X – network side (Rel-16+)

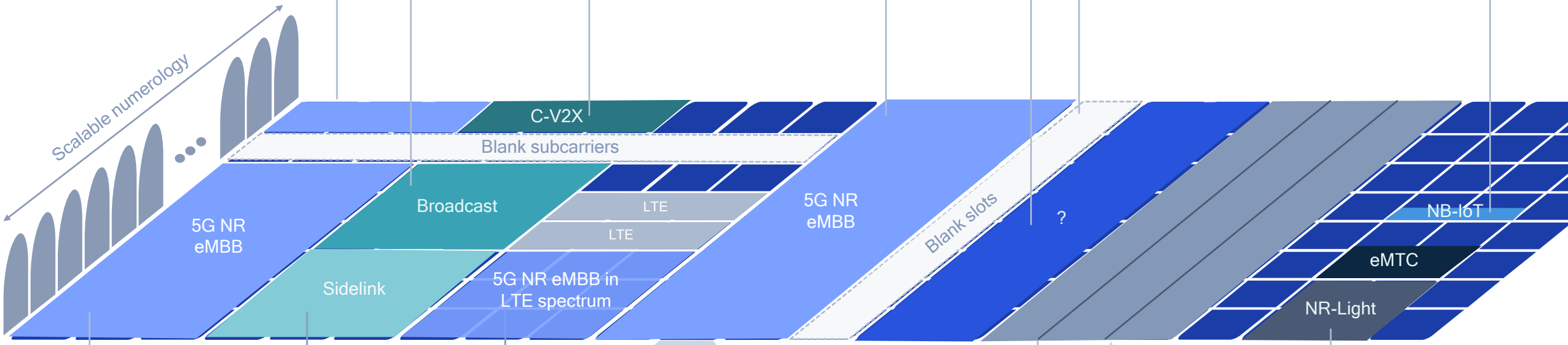
Integrated access & backhaul (Rel-16+)

Unknown service not yet defined

Forward compatibility

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

Massive IoT (Rel-16+)



Enhanced mobile broadband (Rel-15+)

Sidelink (Rel-17+), e.g., for offloading

Dynamic spectrum sharing (Rel-15+)

Wide-area mission-critical (Rel-15/16+)

NR-Light (Rel-17+)

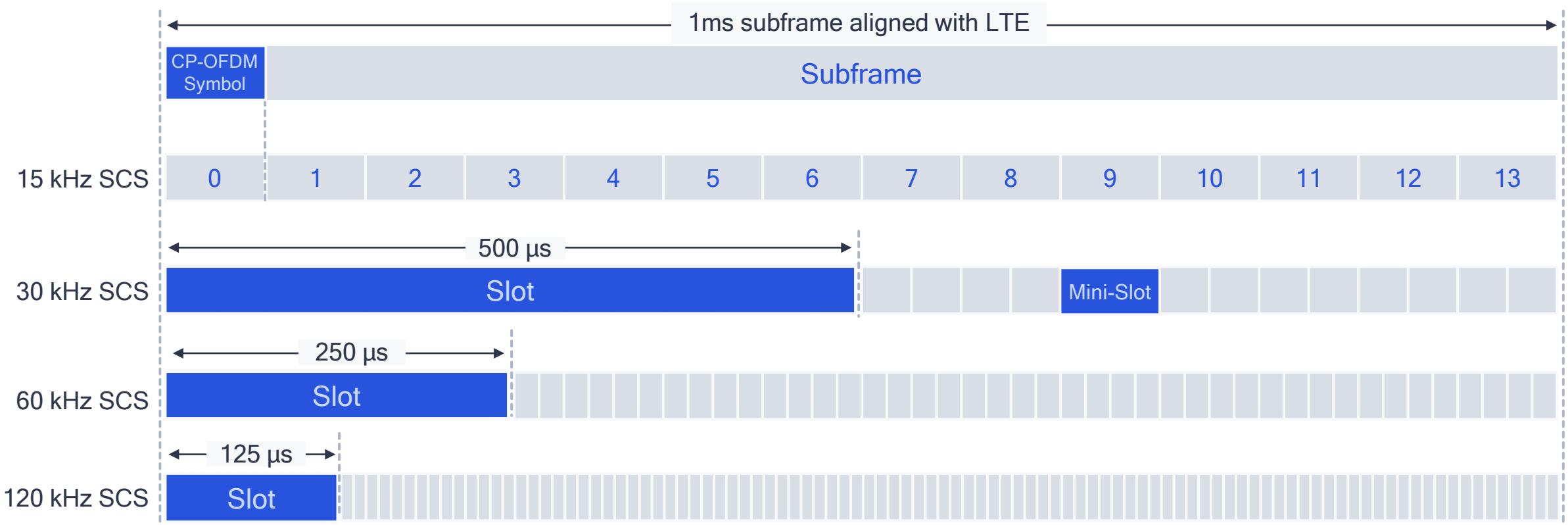
Self-contained slot structure

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



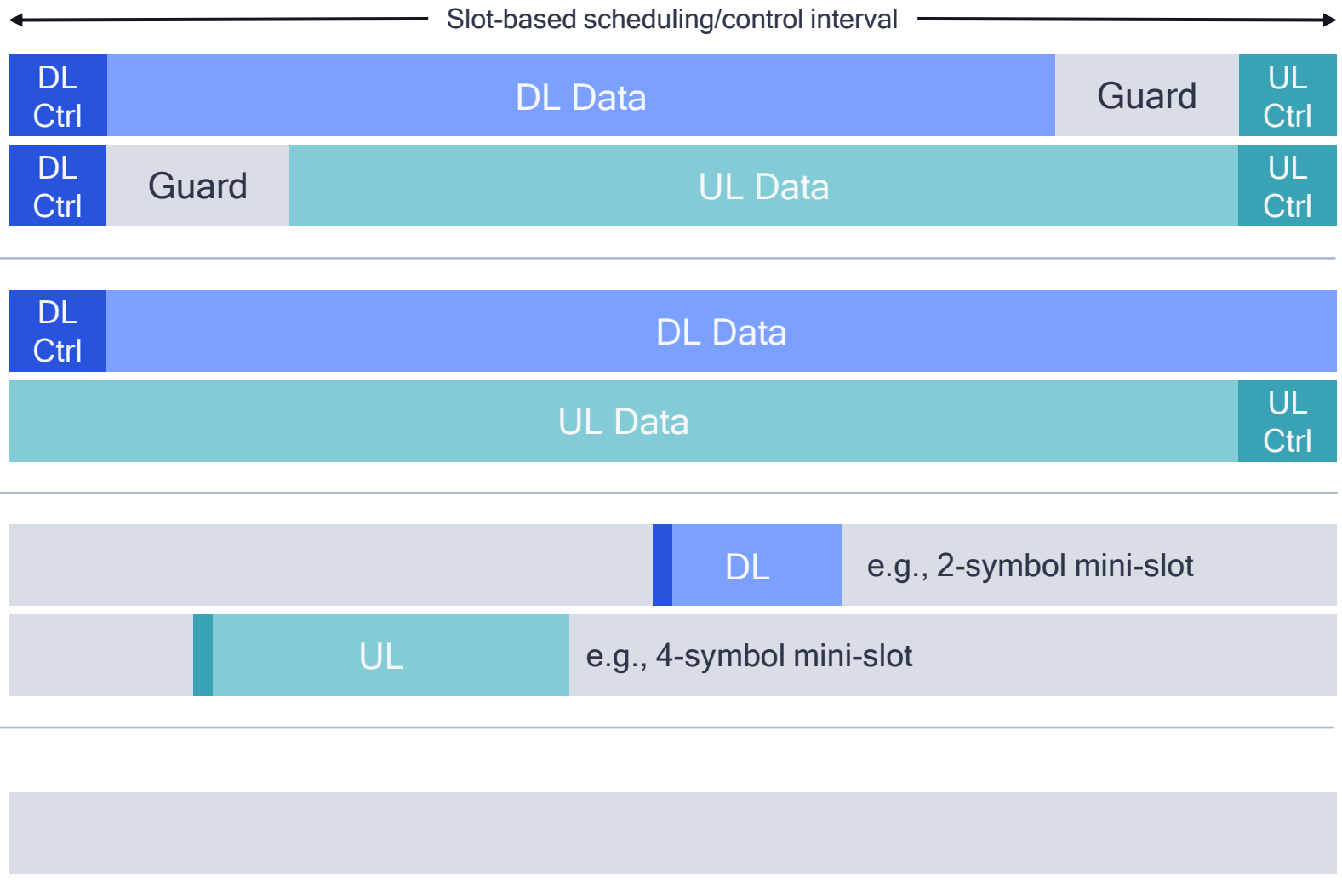
14 OFDM symbols per slot with mini-slot (2, 4, or 7 symbols) for shorter transmissions[1]

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

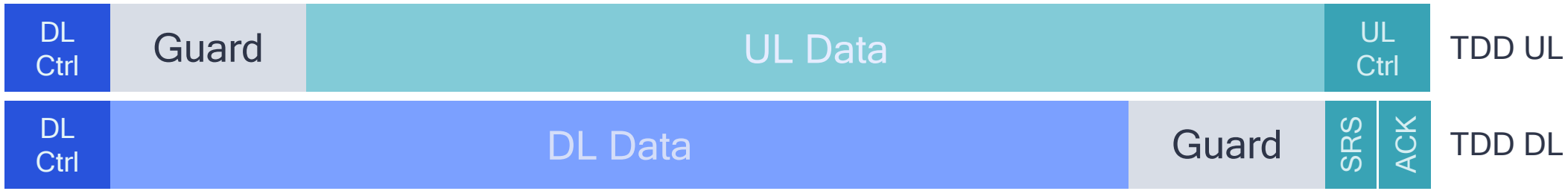
Much faster, more flexible TDD switching and turn-around than 4G LTE

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

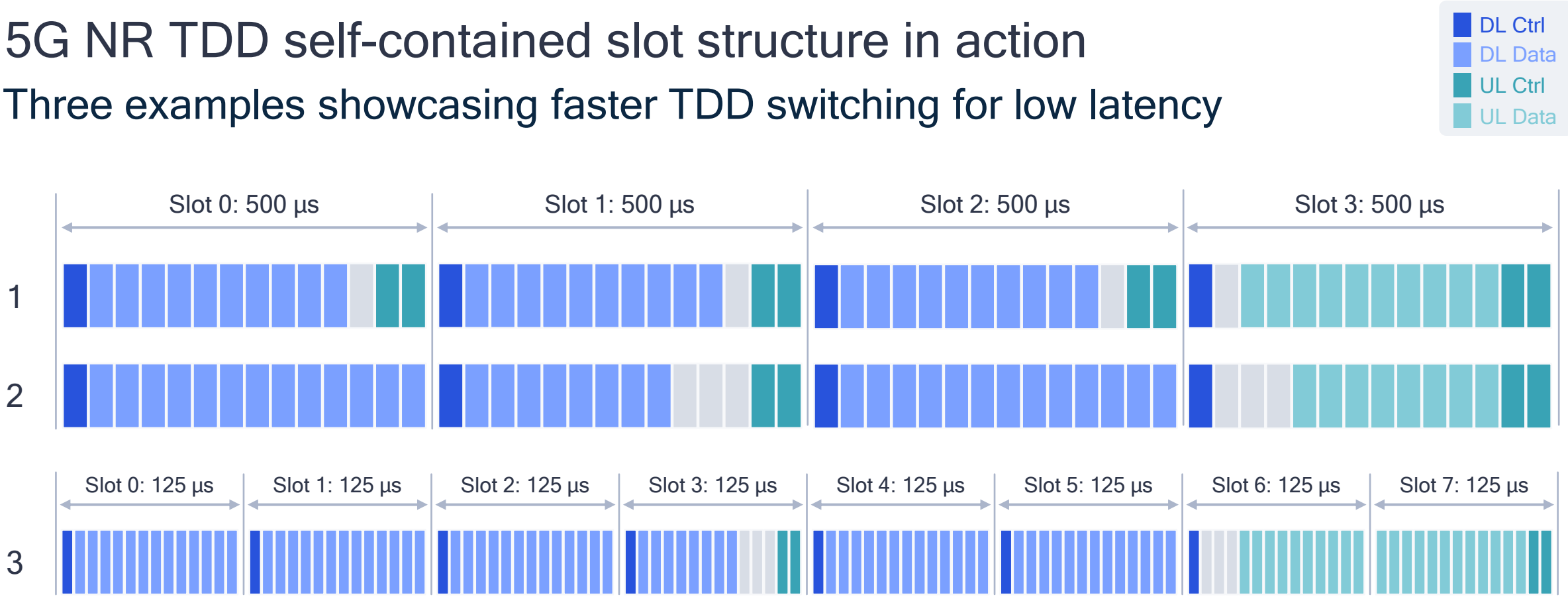
Efficient massive MIMO

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

1. Sounding Reference Signal

5G NR TDD self-contained slot structure in action

Three examples showcasing faster TDD switching for low latency



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

1. Indoor (sub-6 or mmWave)

- Shorter guard for indoor deployment
- Fast turn-around (DL/UL switch per slot)
- Ultra-low latency possible on every slot
- Maximum flexibility for UL/DL allocation

2. Outdoor (sub-6 or mmWave)

- Larger guard for outdoor deployment
- DL/UL switch per 1ms (5x faster than LTE)
- Slot 1 opportunity for ultra-low latency
- Bulk of UL traffic goes on Slot 3

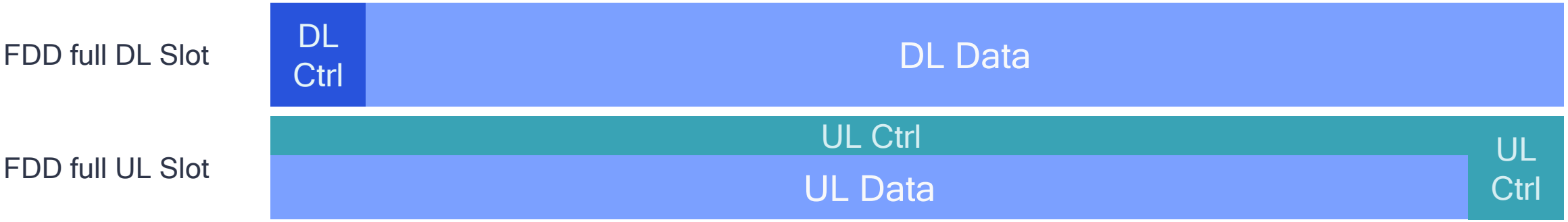
3. Outdoor mmWave

- Larger guard for outdoor deployment
- 6:2 configuration every 1ms (120kHz SCS)
- Slot 3 opportunity for ultra-low latency
- Bulk of UL traffic goes on Slots 6 & 7

5G NR flexible FDD slot structure

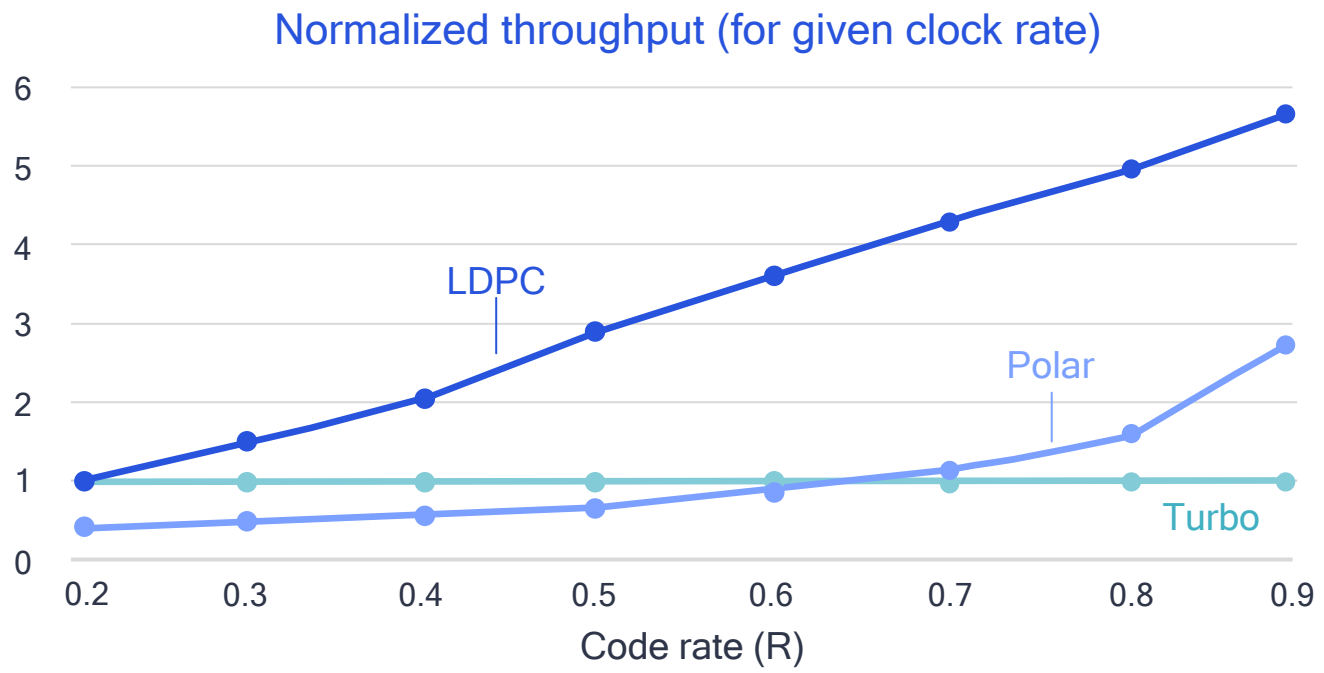
Delivering low latency, extended coverage, and forward compatibility

FDD baseline for continuous transmission and extended coverage



FDD partial slot for faster DL/UL turn-around and efficient half-duplex FDD implementation

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

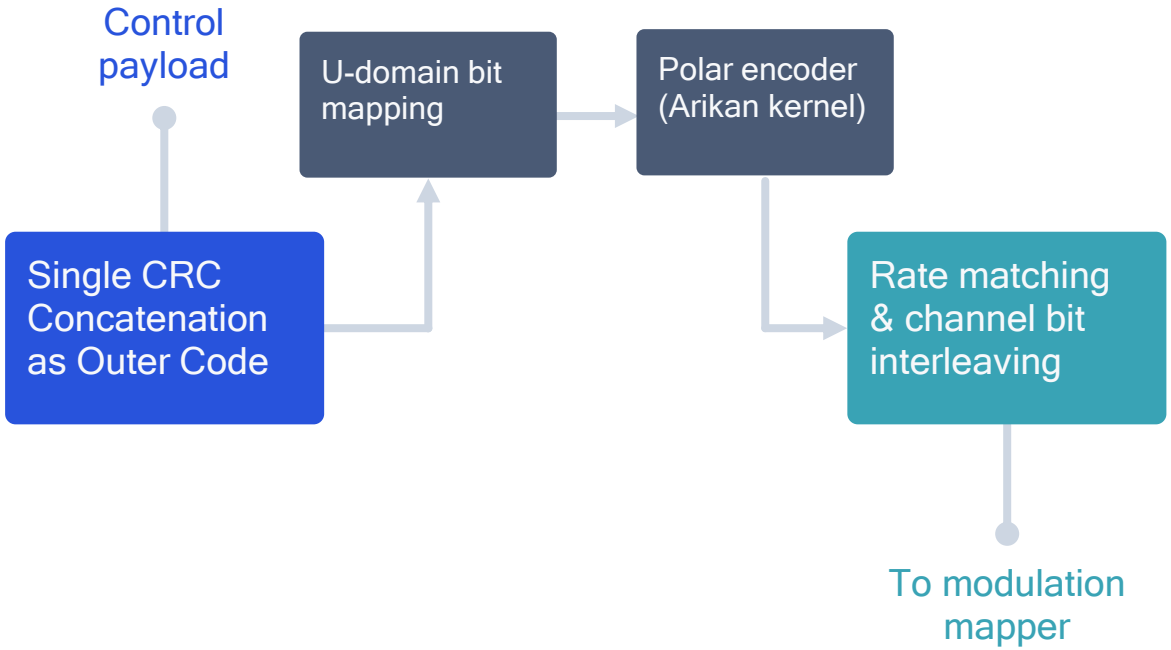
1. Multi-Edge Low-Density Parity-Check

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

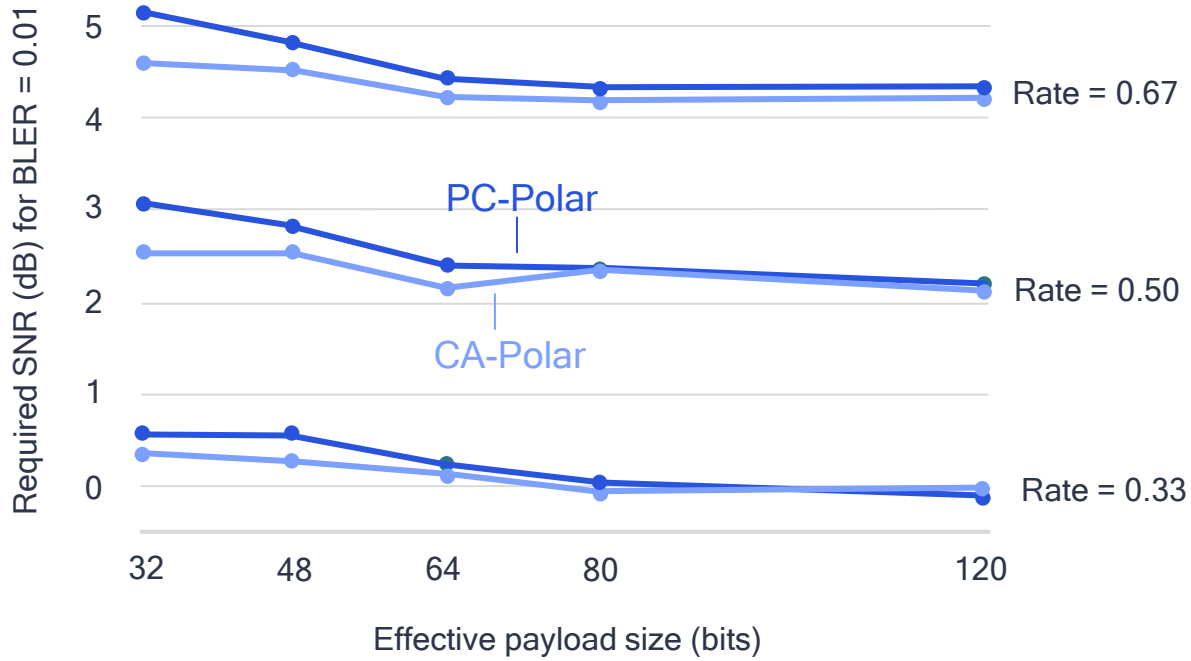
5G NR CRC-Aided (CA-Polar) design

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



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

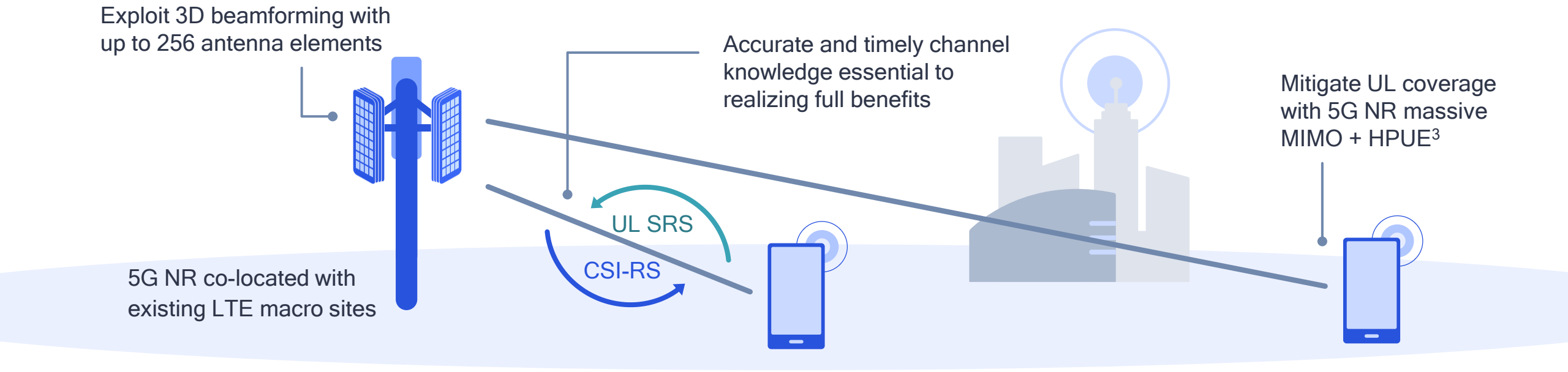
Versus PC-Polar[1] (lower is better)



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



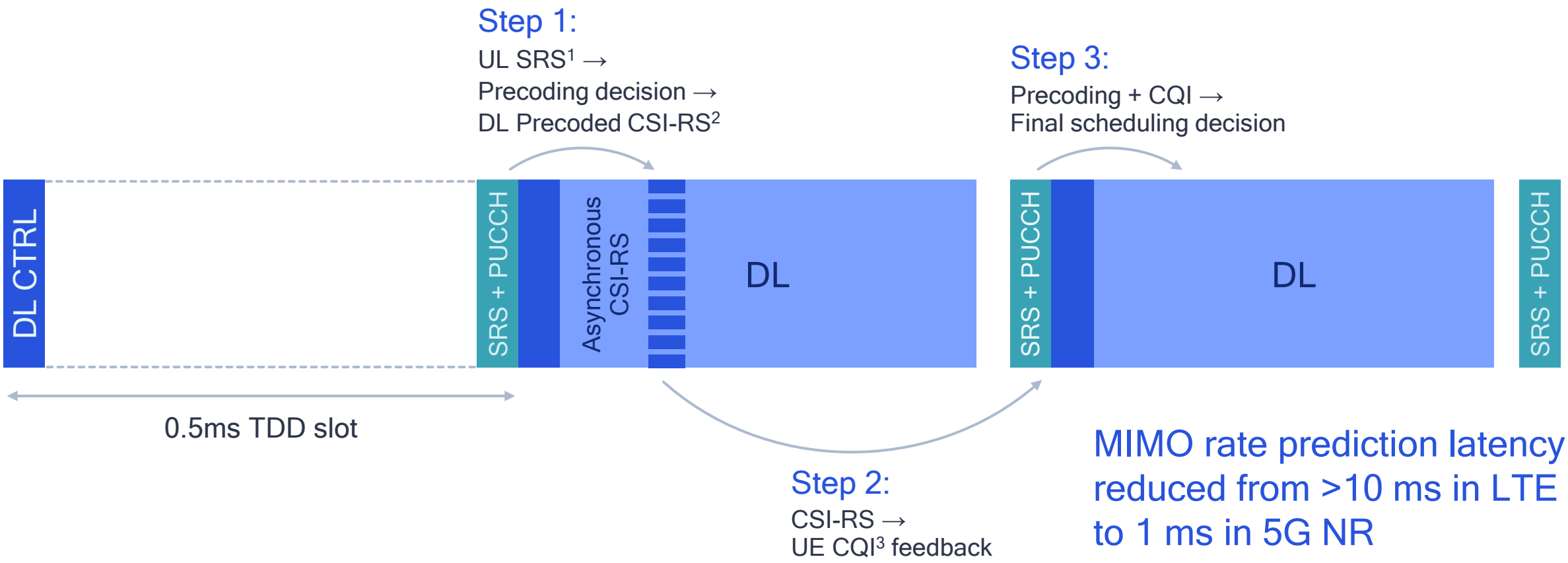
Enabled through an advanced 5G NR end-to-end Massive MIMO design (network and device)

- 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

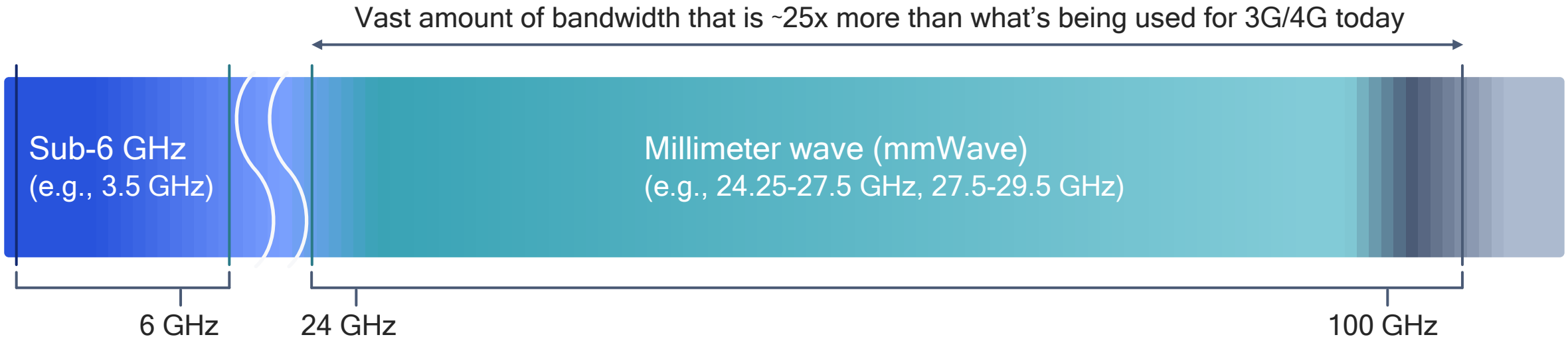
5G NR slot structure and enhanced Ref Signals enable fast/accurate feedback



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

New frontier of mobile broadband – mobilizing mmWave



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

Much more capacity
With dense spatial reuse

Lower latency
Bringing new opportunities

We are overcoming the mobile mmWave challenge

Proving the skeptics wrong about mmWave can never be used for mobile

Limited coverage and too costly

Significant path loss means coverage limited to just a few hundred feet, thus requiring too many small cells

Significant coverage with co-siting

Analog beamforming w/ narrow beam width to overcome path loss. Comprehensive system simulations reusing existing sites.

Works only line-of-sight (LOS)[1]

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

Operating in LOS and NLOS[1]

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

Only viable for fixed use

As proven commercial mmWave deployments are for wireless backhauls and satellites

Supporting robust mobility

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

Requiring large formfactor

mmWave is intrinsically more power hungry due to wider bandwidth with thermal challenges in small formfactor

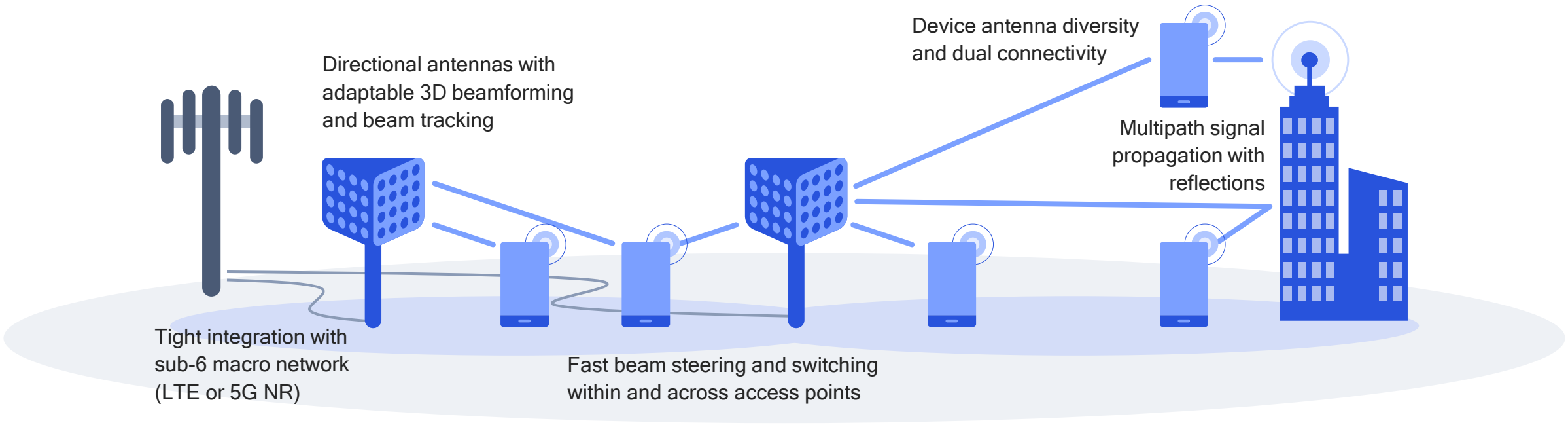
Commercializing smartphone

Announced modem, RF, and antenna products to meet formfactor and thermal constraints, plus device innovations.

1 LOS: Line of sight, NLOS: Non-line-of-sight

Mobilizing mmWave with 5G NR technologies

Deploying a dense mmWave network with spatial reuse – ~150 - 200m ISD

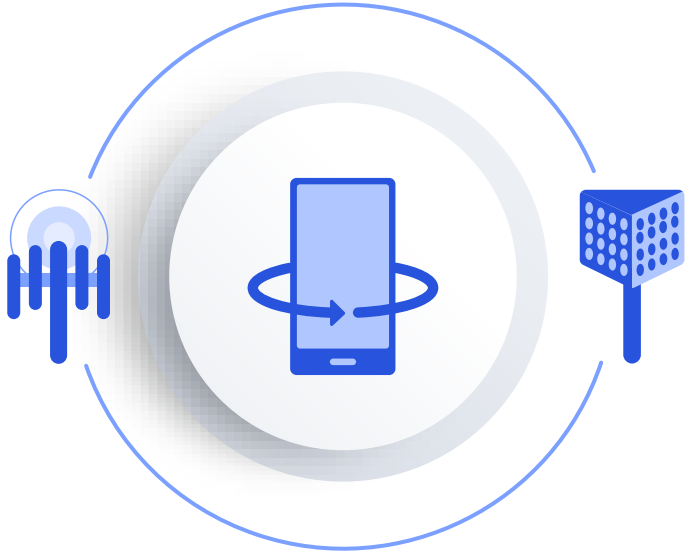


Delivering robust NLOS connectivity

Supporting seamless mobility

Complementing macro area coverage

Spectrum aggregation essential to 5G NR deployments



Carrier Aggregation (CA) and Dual Connectivity enable deployments with tightly and loosely coordinated cells

Dual Connectivity across LTE and NR

Fully leveraging LTE investments and coverage, including NSA operation for early 5G NR deployments

CA across spectrum bands

E.g., tight CA between 5G NR mmWave and sub-6 GHz to address mmWave coverage gaps

CA across FDD and TDD bands

Sub-1 GHz and mid/high band aggregation; supplemental uplink for better coverage, supplemental downlink for capacity

CA across spectrum types

E.g., Licensed and unlicensed with 5G NR Licensed Assisted Access (LAA) – approved Rel-15 Study Item

Building on solid LTE CA and Dual Connectivity foundation

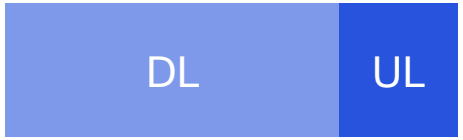
LTE Rel-10+	5G NR Rel-15+
Supplemental DL	LTE/5G NR NSA
FDD/TDD CA	Supplemental UL
LAA CA	Supplemental DL
Dual Connectivity	FDD/TDD CA
	NR LAA CA
	Dual Connectivity

5G NR FDD/TDD CA to support mid-band deployments

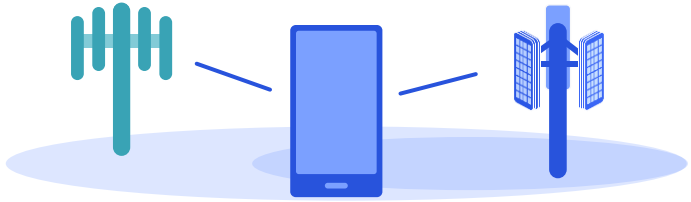
Low-band FDD can help increase 5G NR TDD UL data rate/range[1]

5G NR mmWave
e.g., TDD 28 GHz

5G NR mid-band
e.g., TDD 3-5 GHz



Low-band
e.g., FDD 700 MHz



Non-Standalone (NSA)

Low-band LTE or NR UL can help increase UL data rate/range

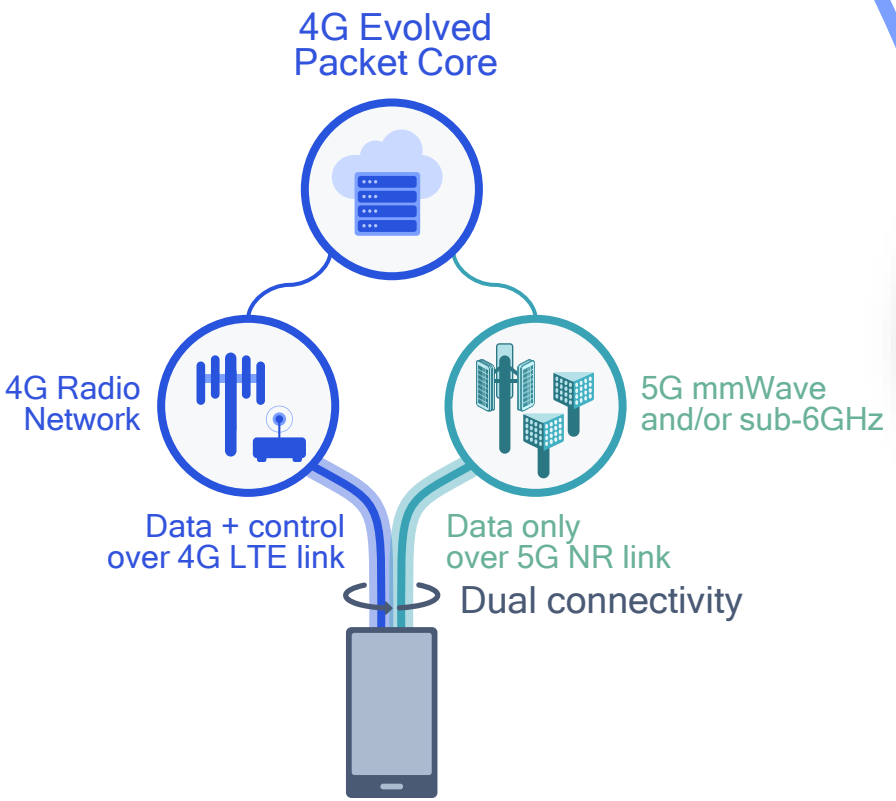
e.g. <1 GHz | LTE Anchor | NR TDD, e.g. 3.5 GHz

Standalone (SA)

NR low-band can carry NR uplink control and data for edge cell users

e.g. <1 GHz | NR TDD, e.g. 3.5 GHz

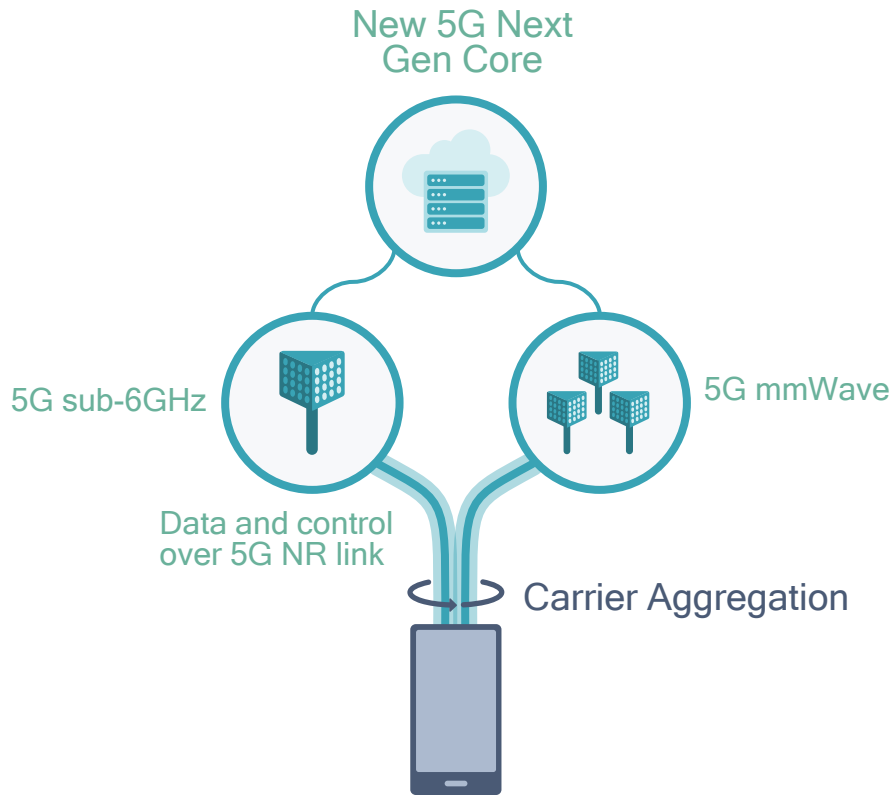
Non-Standalone (NSA) stepping stone to new core



Fast-to-launch | VoLTE & CS voice

5G NR

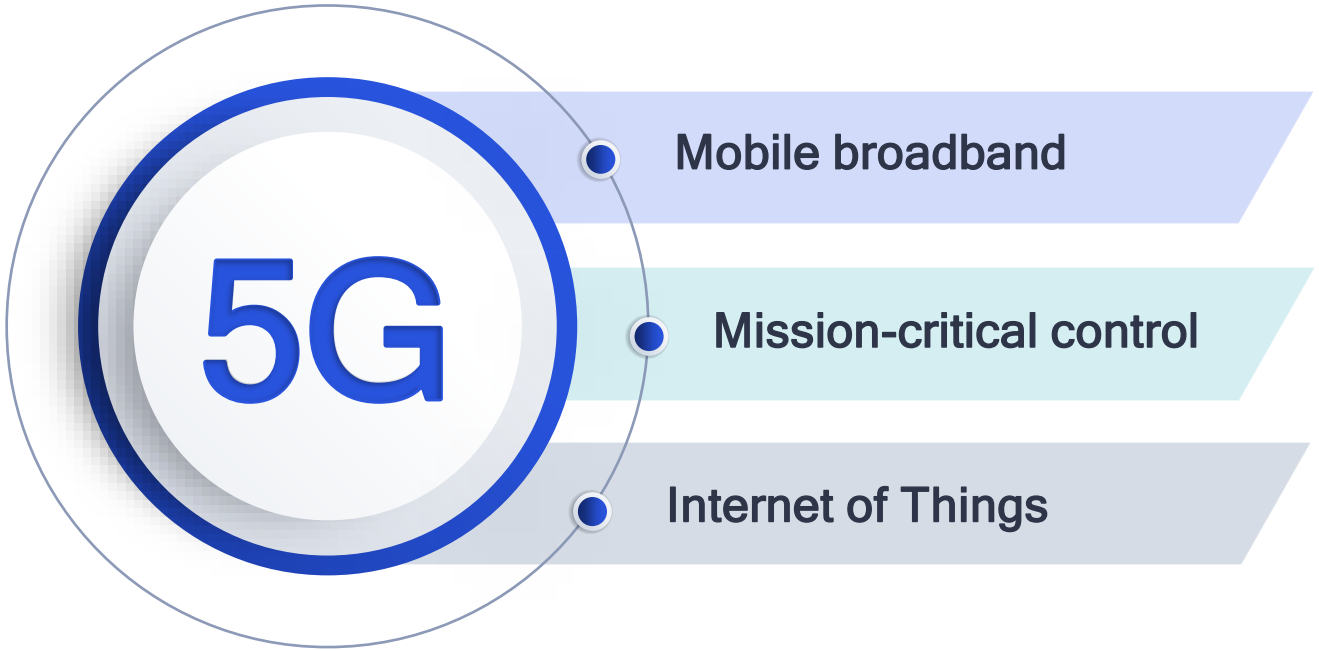
Standalone (SA) for new core benefits



NFV and SDN | VoNR & fallback to VoLTE

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

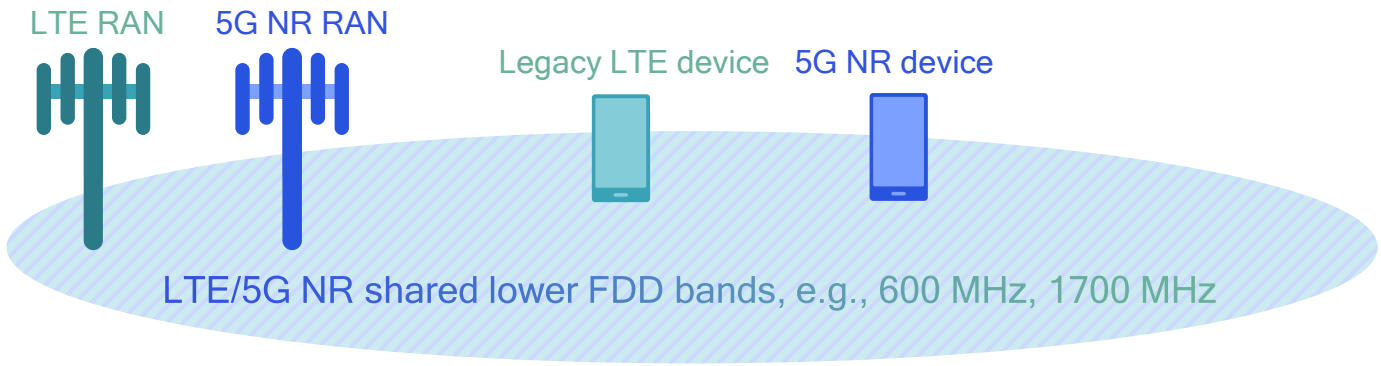
Dynamic control and user planes with more functionality at the edge

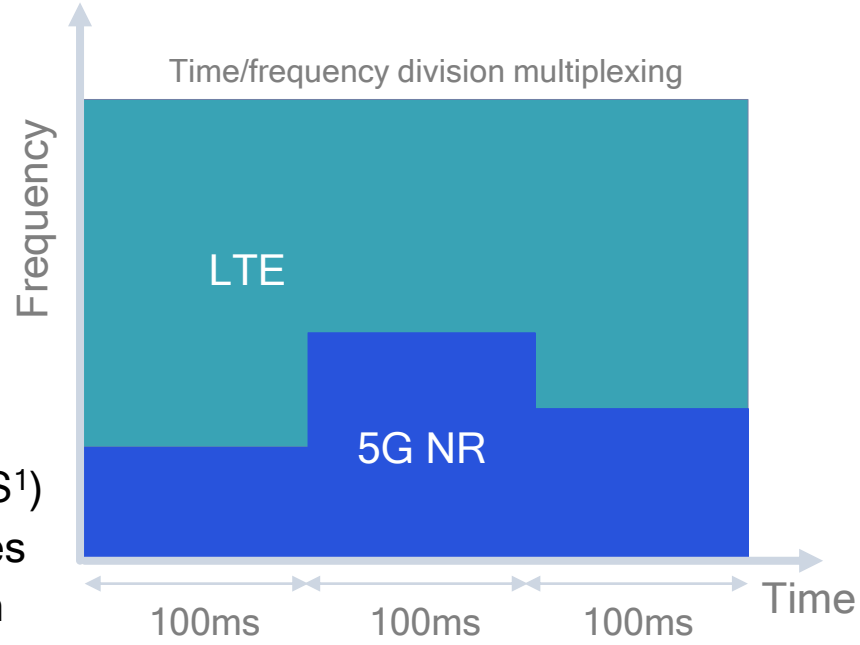
NFV: Network Functions Virtualization; SDN: Software Defined Networking

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

Dynamic Spectrum Sharing (DSS) in 3GPP Release 15

For supporting 5G NR in lower FDD bands for NSA and SA deployments





- LTE controlled sharing – 5G NR to avoid resources used by LTE (e.g., LTE CRS[1])
- No impact to legacy LTE devices – DSS support only required for 5G NR devices
- System efficiency depends on LTE/5G NR traffic volume and device penetration

1 Cell Specific Reference Signal

Supports 5G NR in LTE bands today with “soft refarming”

Efficient use of spectrum with low sharing overhead

DSS & carrier aggregation are key enablers for SA migration

Thank you

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