Qualcomm®

Making 5G NR a reality
Leading the technology innovations for a unified, more capable 5G air interface

Qualcomm Technologies, Inc.

September, 2016

Transforming our world

through intelligent connected platforms

Last 30 years
Interconnecting people

Next 30 years
Interconnecting their worlds

Utilizing unparalleled systems leadership in connectivity and compute

Mobile fueled the last 30 years—interconnecting people

1G

1980s

Analog voice

AMPS, NMT, TACS

2G

1990s

Digital voice

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

3G

2000s

Mobile broadband

WCDMA/HSPA+, CDMA2000/EV-DO

4G

2010s

Mobile Internet

LTE, LTE Advanced

A unifying connectivity fabric

Always-available, secure cloud access

5G

Enhanced mobile broadband

Mission-critical services

Massive Internet of Things

Unifying connectivity platform for future innovation

Convergence of spectrum types/bands, diverse services, and deployments,
with new technologies to enable a robust, future-proof 5G platform

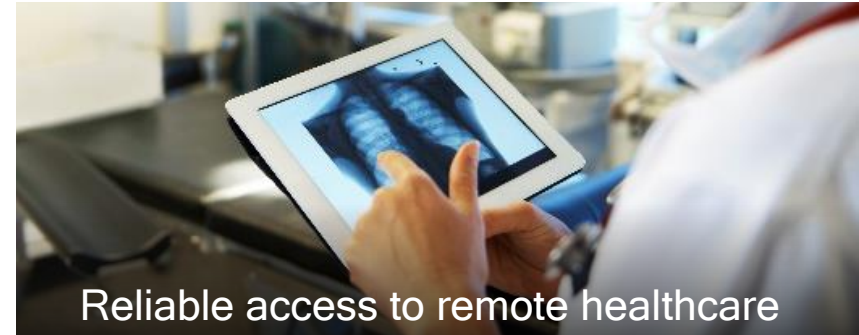# 5G will redefine a wide range of industries

A platform for new connected services - existing, emerging and unforeseen
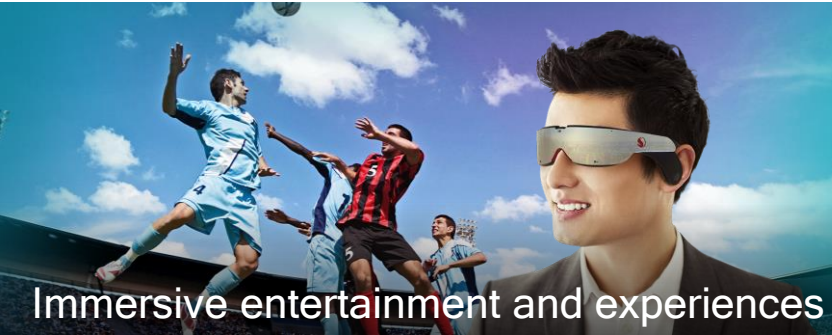
Immersive entertainment and experiences

Safer, more autonomous transportation

Reliable access to remote healthcare

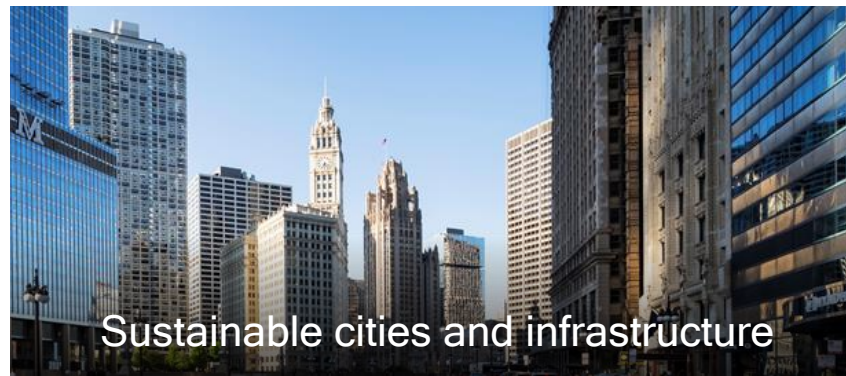Improved public safety and security

Smarter agriculture

More efficient use of energy/utilities

More autonomous manufacturing

Sustainable cities and infrastructure

Digitized logistics and retail

Designing 5G New Radio (NR)

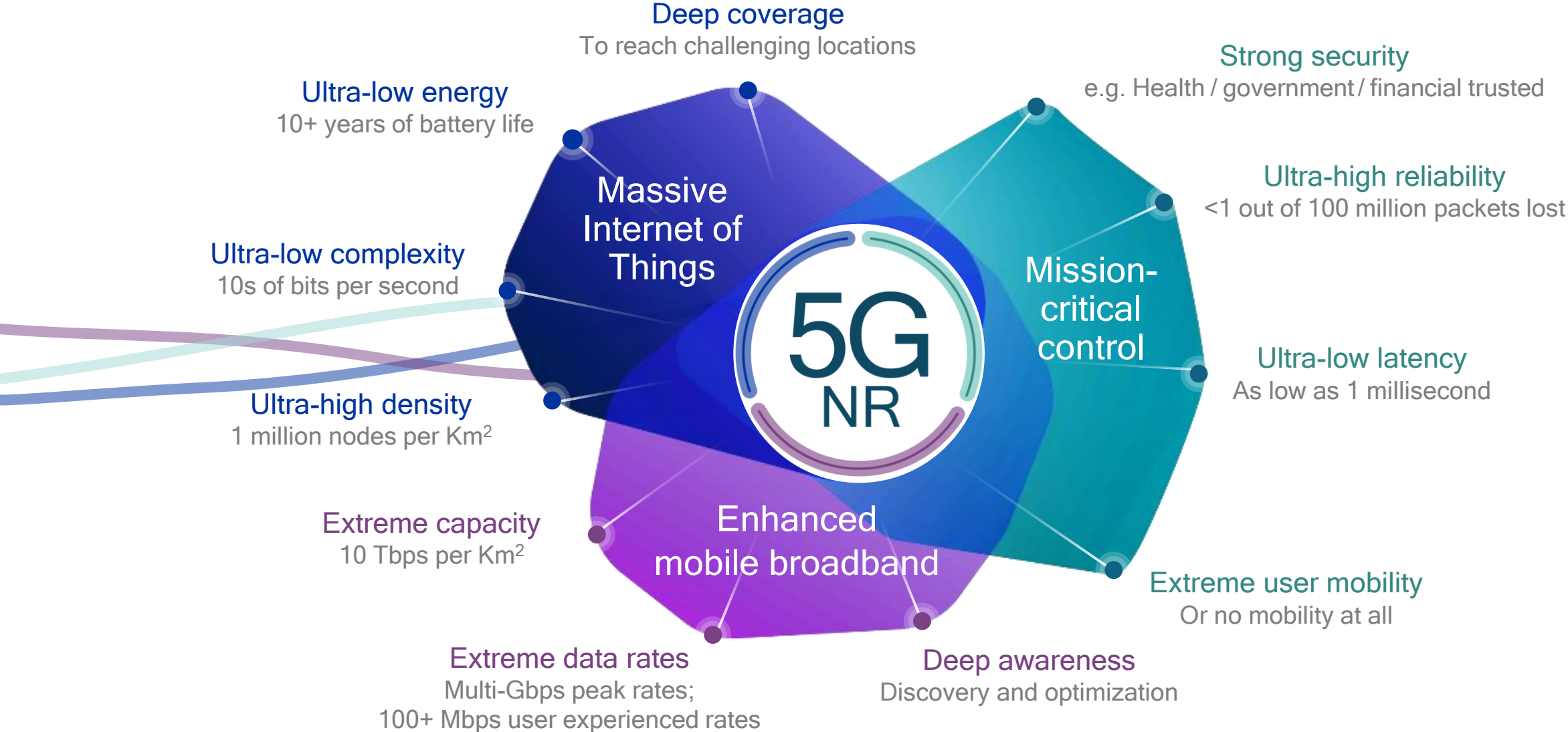An OFDM-based unified, more capable air interface

Diverse deployments

Diverse spectrum

5G NR

Diverse services and devices

Scalability to address diverse service and devices

Deep coverage
To reach challenging locations

Strong security
e.g. Health / government / financial trusted

Ultra-low energy
10+ years of battery life

Ultra-high reliability
<1 out of 100 million packets lost

Ultra-low complexity
10s of bits per second

Massive Internet of Things

Mission-critical control

Ultra-low latency
As low as 1 millisecond

Ultra-high density
1 million nodes per Km^2

5G NR

Extreme capacity
10 Tbps per Km^2

Enhanced mobile broadband

Extreme user mobility
Or no mobility at all

Extreme data rates
Multi-Gbps peak rates;
100+ Mbps user experienced rates

Deep awareness
Discovery and optimization

Getting the most out of every bit of diverse spectrum

5G NR

Low bands below 1 GHz: longer range for e.g. mobile broadband and massive IoT
e.g. 600 MHz, 700 MHz, 850/900 MHz

Mid bands 1 GHz to 6 GHz: wider bandwidths for e.g. eMBB and mission-critical
e.g. 3.4-3.8 GHz, 3.8-4.2 GHz, 4.4-4.9 GHz

High bands above 24 GHz (mmWave): extreme bandwidths
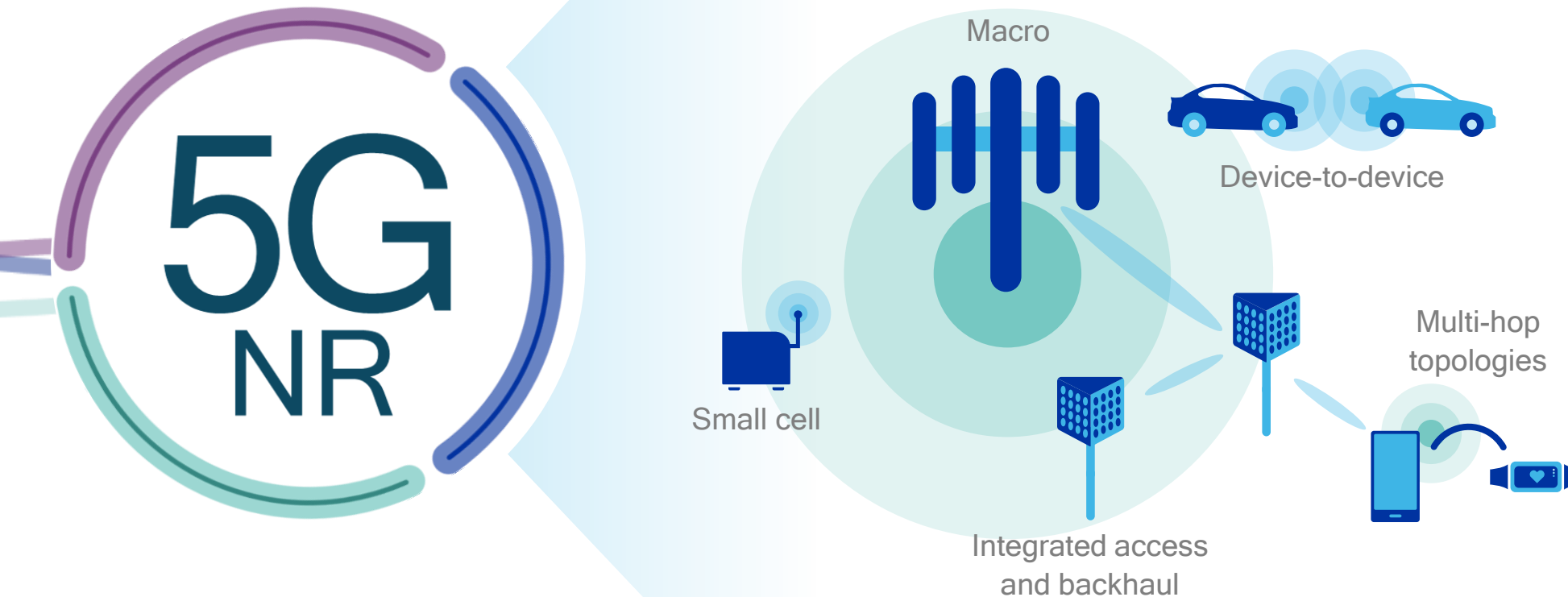e.g. 24.25-27.5 GHz, 27.5-29.5, 37-40, 64-71 GHz

Licensed Spectrum
Exclusive use

Shared Spectrum
New shared spectrum paradigms

Unlicensed Spectrum
Shared use

Adaptable to diverse deployments and topologies

Macro

Device-to-device

Multi-hop topologies

Small cell

Integrated access
and backhaul

5G will be deployed and managed by a variety of entities

Mobile operator networks provide ubiquitous coverage—the backbone of 5G

Pioneering new technologies to meet 5G NR requirements

Hyper dense deployments

Mobilizing mmWave

Ultra-reliable links

Massive MIMO

Integrated access and backhaul

Beam forming

Advanced channel coding, e.g. LDPC

Multi-connectivity

Redundant links

Wide bandwidths

Coordinated spatial techniques

Narrowband Internet of Things

Dynamic, low-latency TDD/FDD

Multicast

V2N

New shared spectrum paradigms

Multi-hop

Advanced receivers

Grant-free uplink transmissions, e.g. RSMA

V2V

Device-centric mobility

New levels of capability and efficiency

10x experienced throughput	10x decrease in end-to-end latency	10x connection density	3x spectrum efficiency	100x traffic capacity	100x network efficiency

Simplifying 5G deployments with multi-connectivity

Fully leveraging 4G LTE and Wi-Fi investments for a seamless user experience

Small cell

5G / 4G / 3G / Wi-Fi multimode device

Macro

5G Carrier aggregation

5G above 6GHz

5G below 6GHz

4G LTE, LTE Unlicensed and Wi-Fi

5G below 6GHz

4G LTE

5G above 6GHz

4G below 6GHz

Wi-Fi

4G/5G below 6GHz

4G/5G Macro

4G Macro
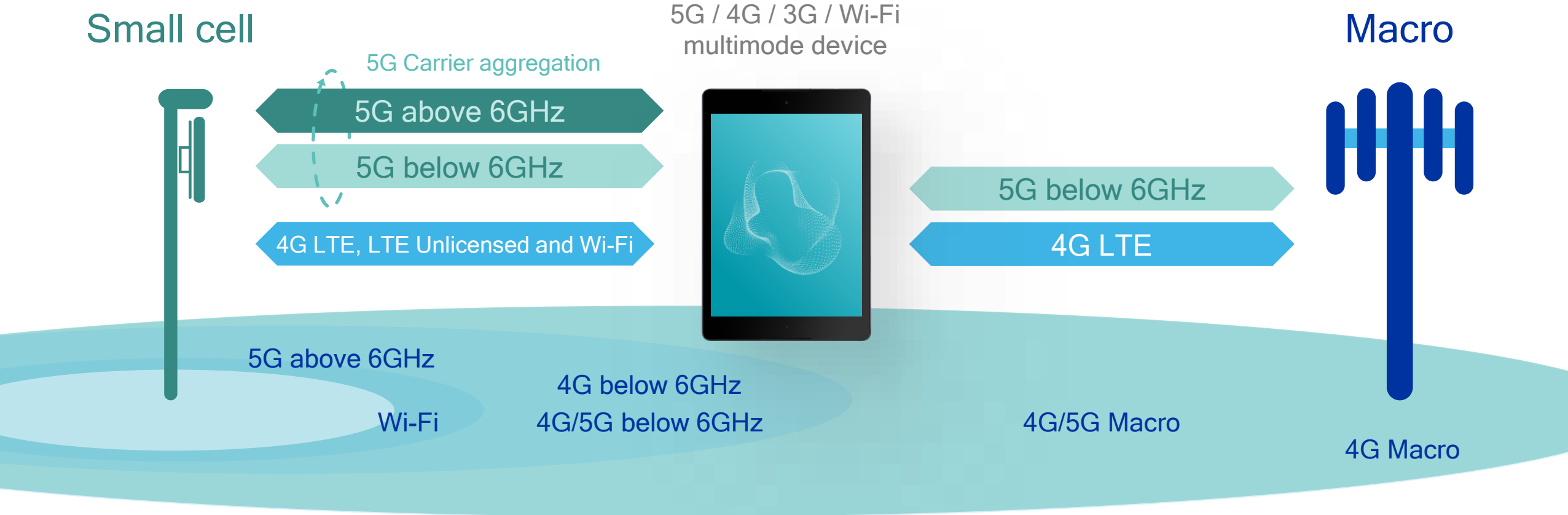
5G NR radio access designed to utilize LTE anchor for mobility management (non-standalone) or operate stand-alone with new multi-access 5G NextGen Core Network (NGCN)

The path to 5G includes a strong LTE foundation

Advanced MIMO

Shared spectrum

Significantly improve performance, cost and energy efficiency

256QAM

Gigabit-class LTE

Massive MIMO

5G NR

Rel-15 and beyond
5G NR

Carrier aggregation

NB-IoT

Low Latency

Enhanced broadcast

Device-to-device

C-V2X

Further backwards-compatible enhancement

5G

Rel-10/11/12
LTE Advanced

Rel-13 and beyond
LTE Advanced Pro

2010

2015

2020

Note: Estimated commercial dates. Not all features commercialized at the same time

12

Anyone can talk about 5G.
We are creating it.

We are driving technology innovations to mobilize mmWave

Working with operators on trials & early deployments starting late 2017/early 2018[1]

802.11ad 60 GHz chipset commercial for mobile devices

1.79 cm

0.71 cm
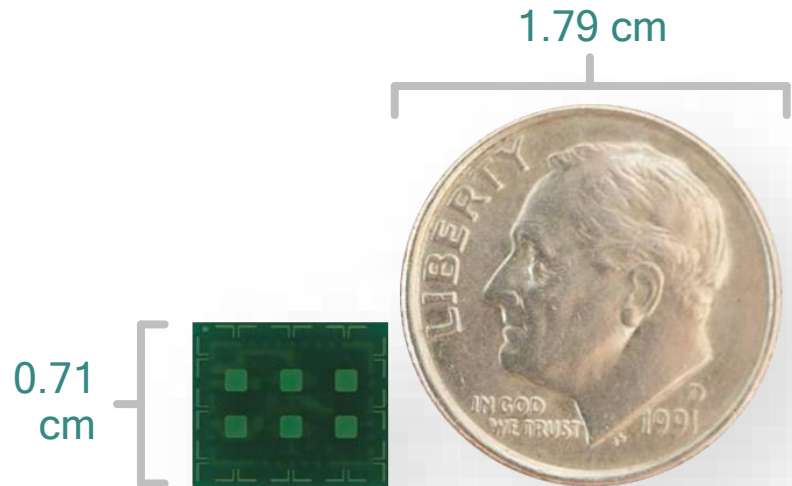
Qualcomm® VIVE™ 802.11ad 60 GHz technology with a 32-antenna array

5G mmWave prototype system and trial platform
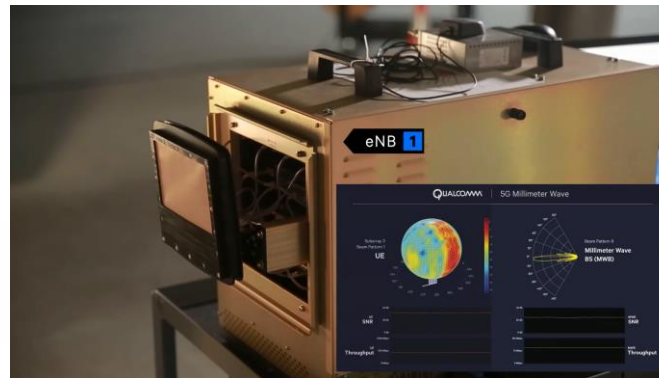
End-to-end system operating at 28 GHz demonstrating NLOS operation and robust mobility

28 GHz mmWave RFIC development
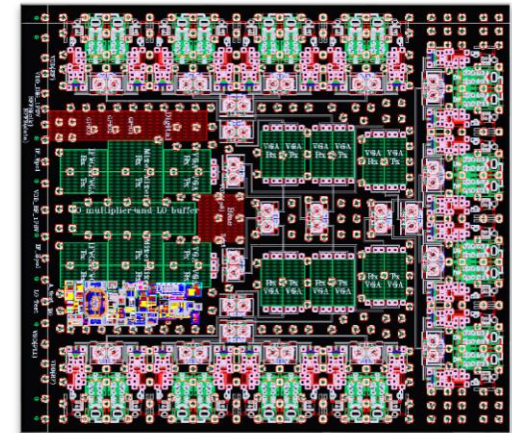
With integrated PA, LNA, phase shifter, power splitters for beamforming

Bringing new level of performance for sub-6 GHz

5G NR sub-6 GHz prototype system and trial platform

160MHz carrier bandwidth
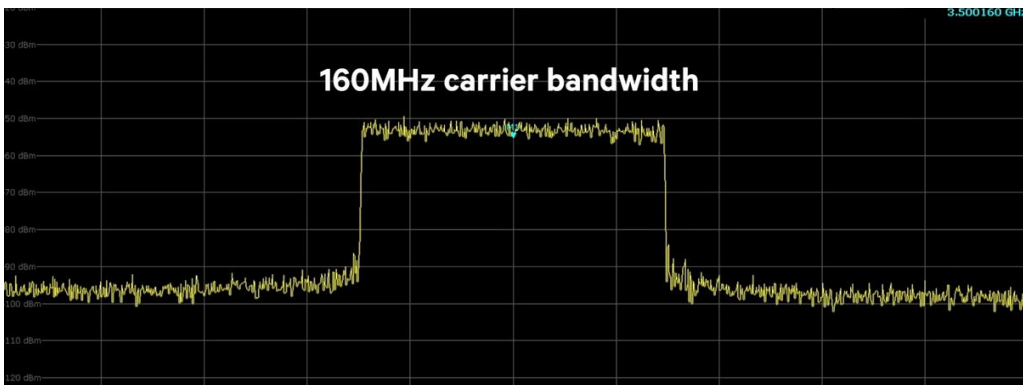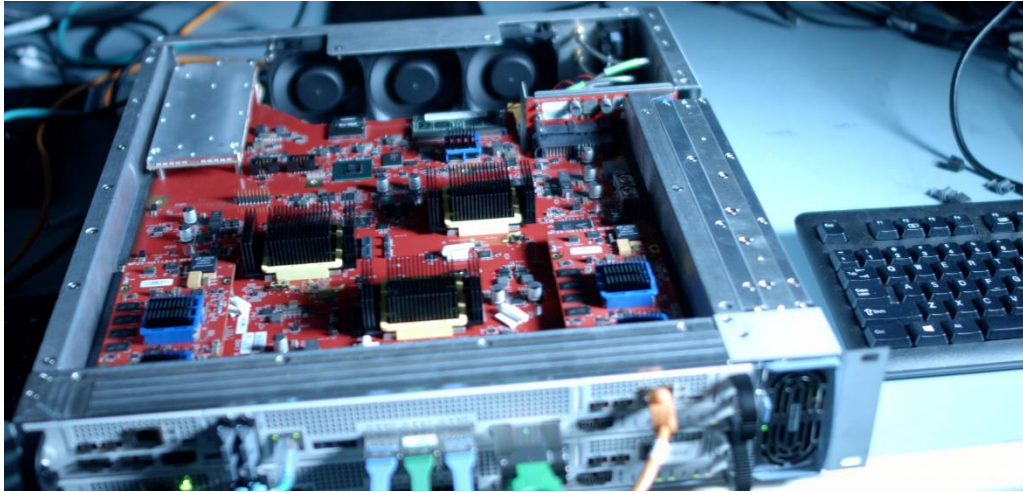
Operating in sub-6 GHz spectrum bands

Allows for flexible deployments with ubiquitous network coverage and a wide range of use cases

Achieving multi-Gbps at low latency

Showcases innovative Qualcomm 5G designs to efficiently achieve multi-gigabit per second data rates and low latency

Driving standardization on 5G NR

OFDM-based designs implemented on the prototype system are being utilized to drive 3GPP standardization

Will enable impactful 5G NR trials

Designed to flexibly track 3GPP standardization and be utilized as a trial platform for impactful and timely 5G NR trials

Watch the demo video at: https://www.qualcomm.com/videos/5g-nr-sub-6ghz-prototype-system

We are accelerating the path to 5G NR

Best-in-class 5G prototype systems and testbeds

5G standards, technology and research leadership

Impactful trials and early deployments with network operators

Modem and RFFE leadership to solve 5G complexity
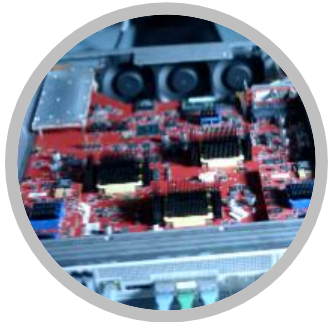
Test, demonstrate and verify our innovative 5G designs to contribute to and drive standardization

Such as advanced channel coding, self-contained subframe, mobilizing mmWave, …

Over-the-air interoperability testing leveraging prototype systems and our leading global network experience

Roadmap to 5G significantly more complex and faster moving–builds upon our rich history of industry firsts

5G NR standardization progressing for 2019 launches
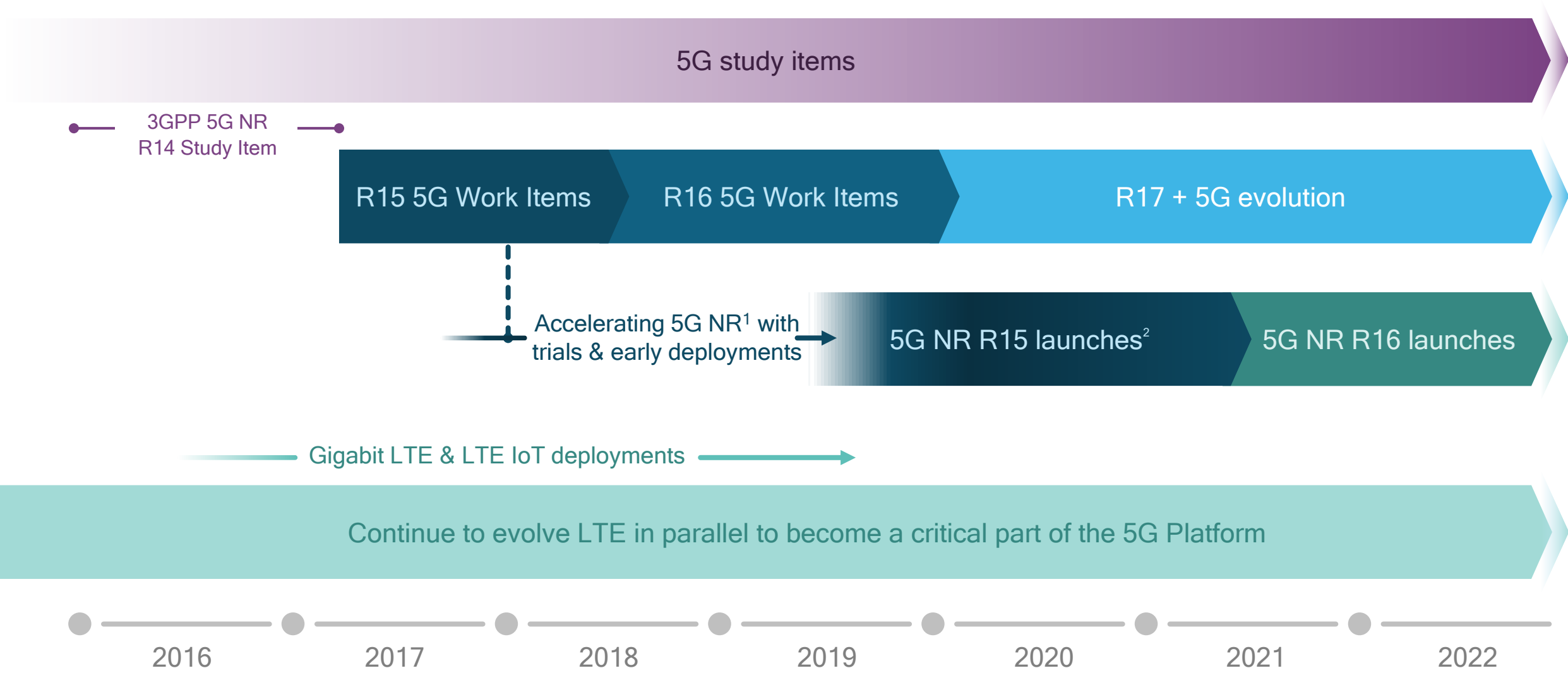
5G study items

3GPP 5G NR
R14 Study Item

| R15 5G Work Items | R16 5G Work Items | R17 + 5G evolution |

Accelerating 5G NR[1] with trials & early deployments

5G NR R15 launches[2]

5G NR R16 launches

Gigabit LTE & LTE IoT deployments

Continue to evolve LTE in parallel to become a critical part of the 5G Platform

2016   2017   2018   2019   2020   2021   2022

5G NR R15[1] will establish the 5G foundation

For enhanced mobile broadband and beyond

Optimized OFDM-based waveforms

With scalable numerology and TTI, plus optimized multiple access for different use cases
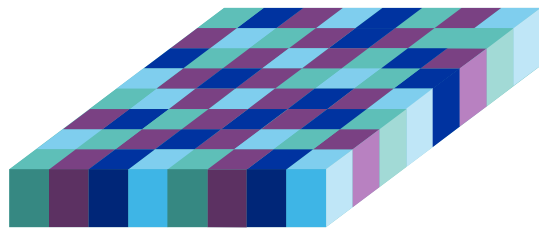
A common, flexible framework

To efficiently multiplex services and features with a dynamic, low-latency TDD/FDD design
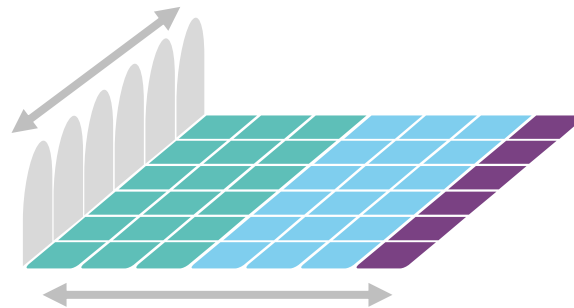
Advanced wireless technologies

Such as massive MIMO, robust mmWave, advanced channel coding, and device-centric mobility
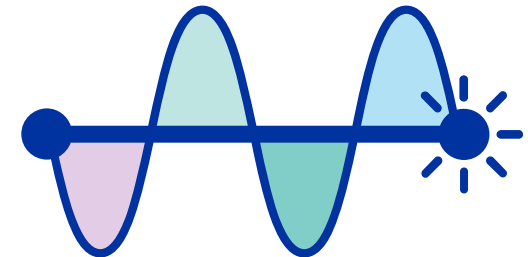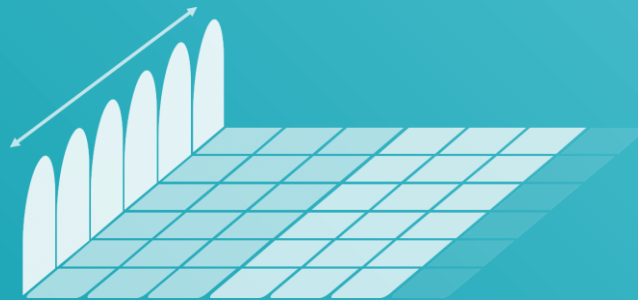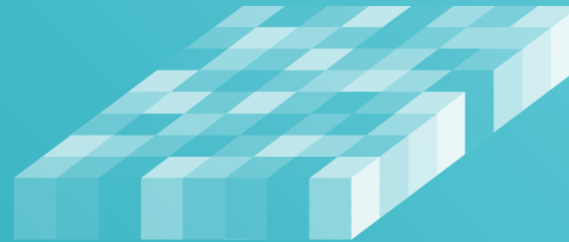
Unified design across spectrum types and bands

For licensed and shared/unlicensed spectrum bands both below 6 GHz and above 6 GHz[2]
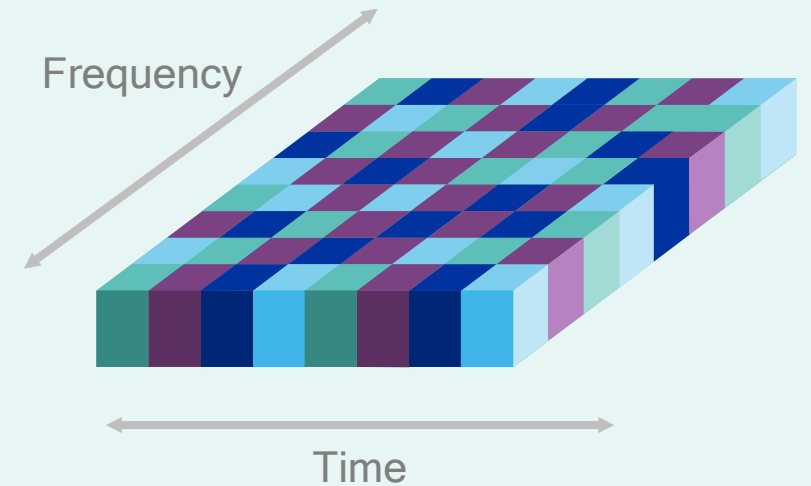
Designing
5G NR

Leading the technology innovations for
a unified, more capable 5G air interface

OFDM family is the right choice for 5G mobile broadband and beyond

Adapted for scaling to an extreme variations of 5G requirements

Frequency

Time

Spectral efficiency

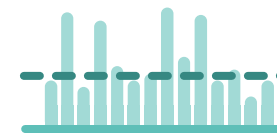Efficient framework for MIMO spatial multiplexing

Low complexity

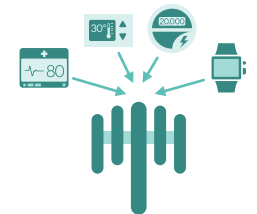Low complexity receivers even when scaling to wide bandwidths

Frequency localization

Windowing can effectively minimizes in-band and out-of-band emissions

Lower power consumption

Single-carrier OFDM well suited for efficient uplink transmissions
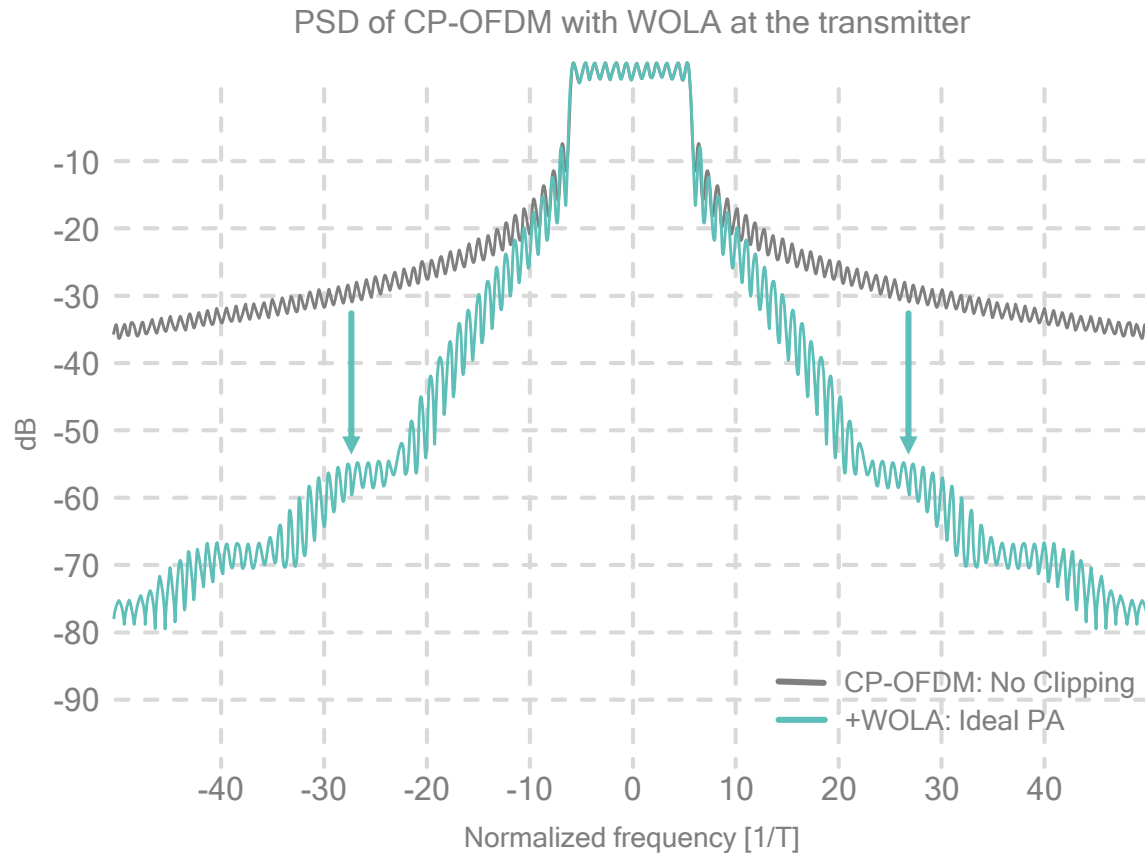
Asynchronous multiplexing

Co-exist with optimized waveforms and multiple access for wide area IoT

Efficient service multiplexing with windowed OFDM

OFDM with WOLA[1] windowing
Substantially increases frequency localization

PSD of CP-OFDM with WOLA at the transmitter

Legend:
- CP-OFDM: No Clipping
- +WOLA: Ideal PA

y-axis: dB (-10, -20, -30, -40, -50, -60, -70, -80, -90)
x-axis: Normalized frequency [1/T] (-40, -30, -20, -10, 0, 10, 20, 30, 40)

Key for 5G service multiplexing
Mitigate interference between flexible sub-carriers

Wideband (e.g. eMBB)   Narrowband (e.g. IoT)   Large CP (e.g. broadcast)

Frequency
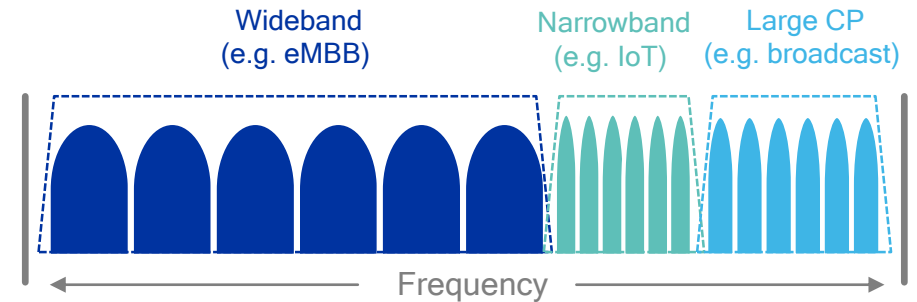
OFDM with WOLA windowing

Effectively reduces in-band and out-of-band emissions

Windowed OFDM proven in LTE system today

Alternative OFDM-approaches, such as FBMC and UFMC, add complexity with marginal benefits

[1] Weighted Overlap Add

Source: Qualcomm Research, assuming 12 contiguous data tones, 60 symbols per run, 1000 runs. CP length is set to be roughly 10% of the OFDM symbol length. For Tx-WOLA, raised-cosine edge with rolloff α≈0.078 is used.

Optimizing for diverse services and deployments

5G NR Downlink
Unified downlink design
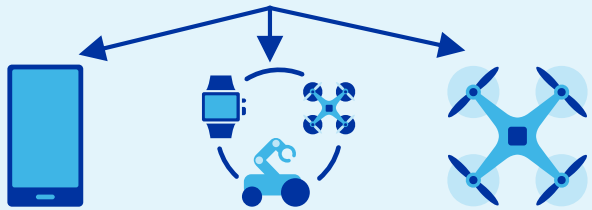
Mobile Broadband   Massive IoT   Mission-critical

CP-OFDM[1] + OFDMA

Also recommended for D2D and inter-cell communications to maximize Tx/Rx design reuse

5G NR Uplink
Optimized for different deployments

Macro cell
SC-OFDM[1] + SC-FDMA
To maximize device energy efficiency

Small cell
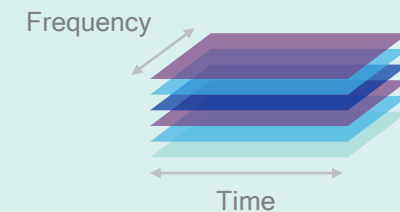CP-OFDM[1] + OFDMA
To maximize spectral efficiency

Optimized for different services

Massive IoT
Low energy single-carrier[2]

Mission-critical
CP-OFDM / SC-OFDM[1]

+

Frequency

Time

Resource Spread Multiple Access (RSMA)[3]

Grant-free transmissions efficient for sporadic transfer of small data bursts with asynchronous, non-orthogonal, contention-based access

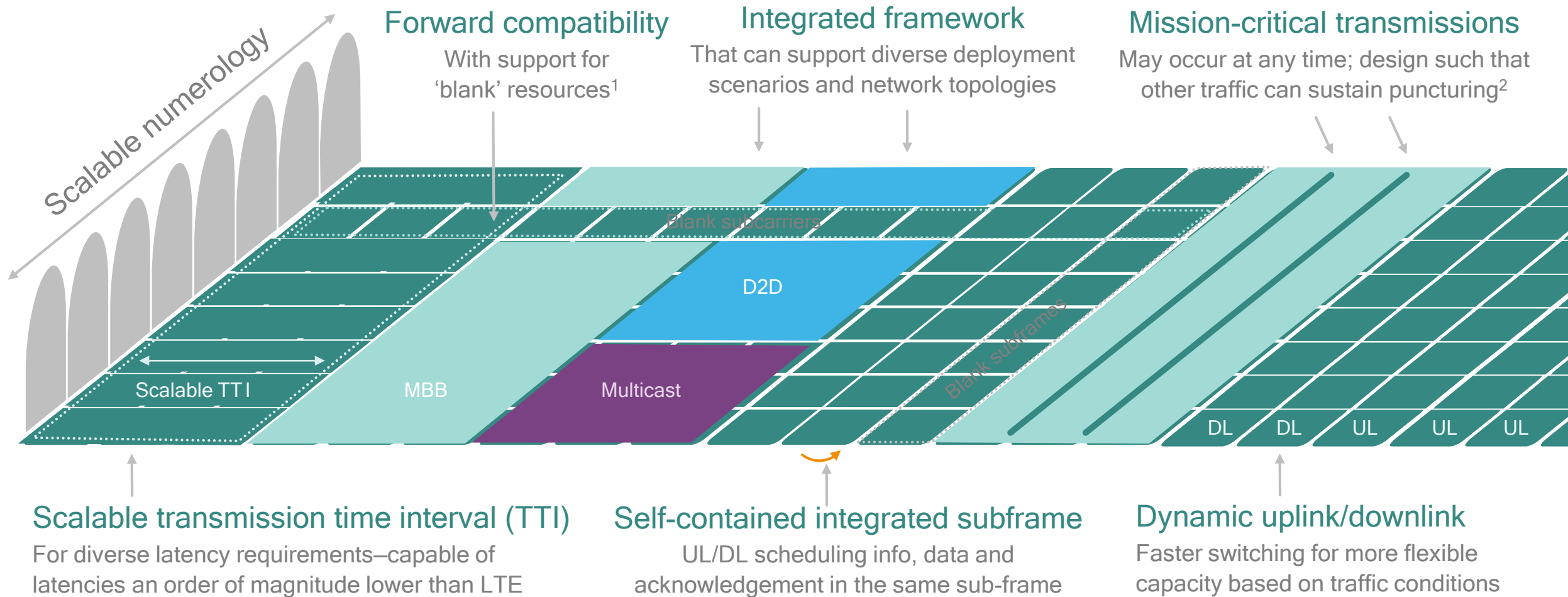Download Qualcomm Research whitepaper for detailed analysis:
https://www.qualcomm.com/documents/5g-research-waveform-and-multiple-access-techniques

1 With time domain windowing as common in LTE systems today; 2 Such as SC-FDE and GMSK; 3 Mission-critical service may also use OFDMA/SC-FDMA for applications that may be scheduled

A flexible framework with forward compatibility

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

Scalable numerology

Forward compatibility
With support for 'blank' resources[1]

Integrated framework
That can support diverse deployment scenarios and network topologies

Mission-critical transmissions
May occur at any time; design such that other traffic can sustain puncturing[2]

Blank subcarriers

D2D

Blank subframes

Scalable TTI

MBB

Multicast

DL   DL   UL   UL   UL

Scalable transmission time interval (TTI)
For diverse latency requirements—capable of latencies an order of magnitude lower than LTE

Self-contained integrated subframe
UL/DL scheduling info, data and acknowledgement in the same sub-frame

Dynamic uplink/downlink
Faster switching for more flexible capacity based on traffic conditions

[1] Blank resources may still be utilized, but are designed in a way to not limit future feature introductions; [2] Nominal 5G access to be designed such that it is capable to sustain puncturing from mission-critical transmission or bursty interference
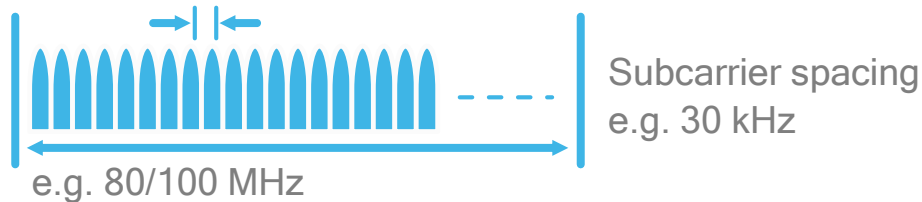
Scalable numerology with scaling of subcarrier spacing

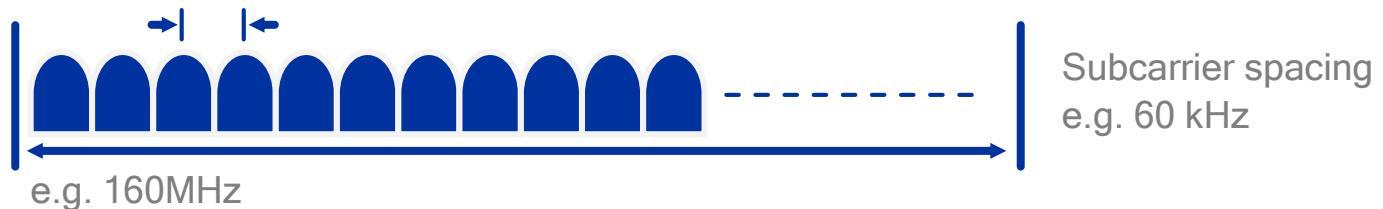## Efficiently address diverse spectrum, deployments and services
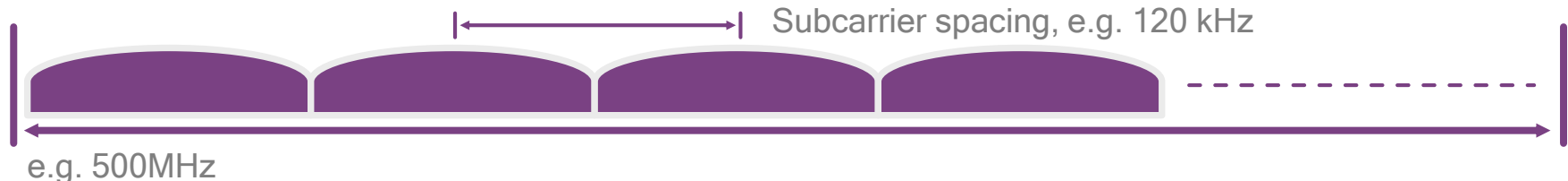
Outdoor and macro coverage
FDD/TDD <3 GHz

Subcarrier spacing
e.g. 15 kHz

e.g. 1, 5, 10 and 20 MHz
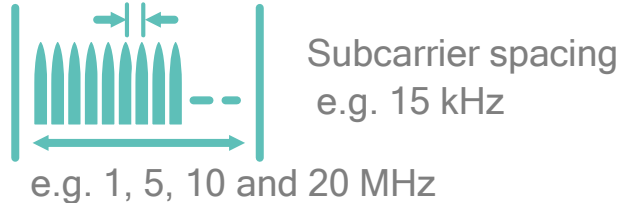
Outdoor and small cell
TDD > 3 GHz

Subcarrier spacing
e.g. 30 kHz

e.g. 80/100 MHz

Indoor wideband
TDD e.g. 5 GHz (Unlicensed)

Subcarrier spacing
e.g. 60 kHz

e.g. 160MHz

mmWave
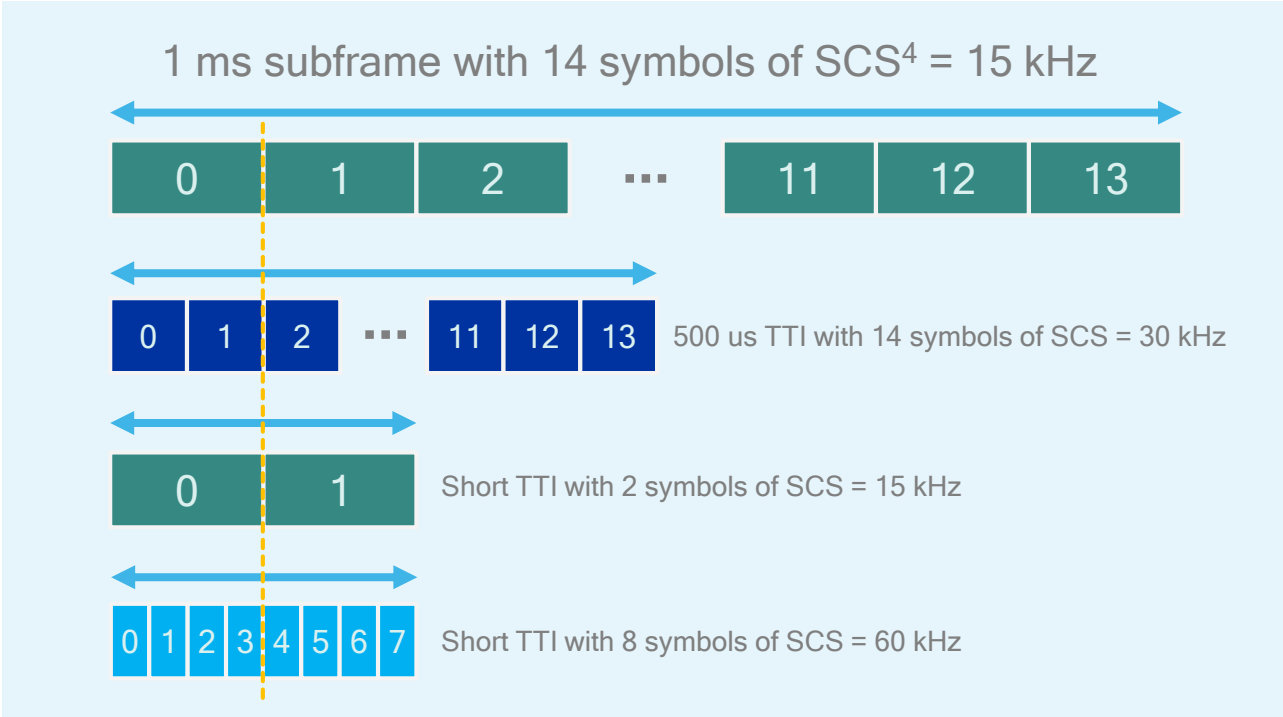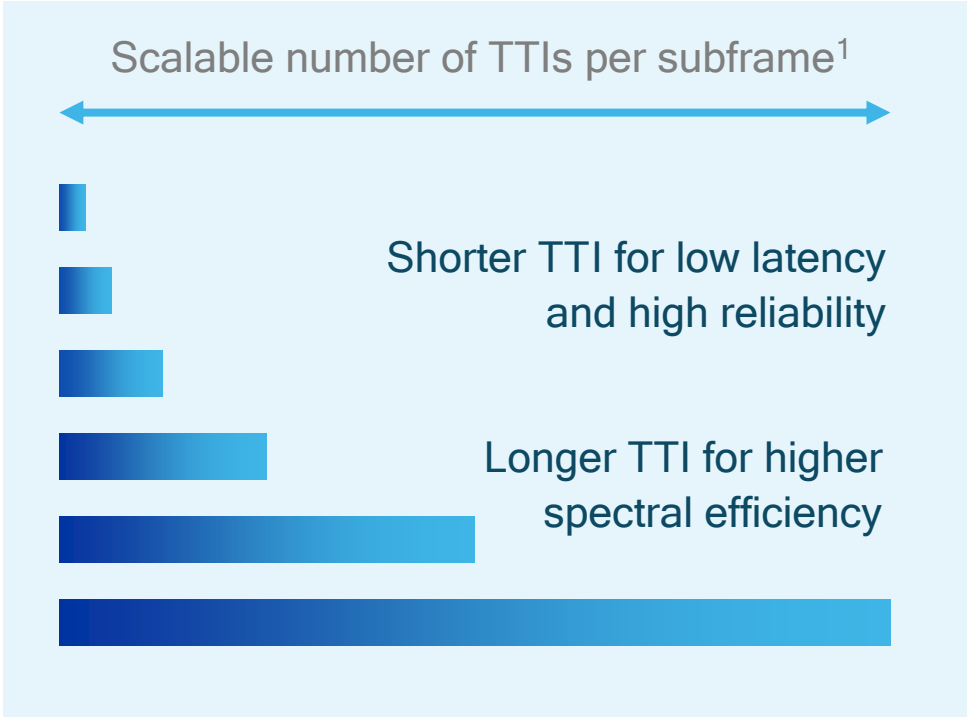TDD e.g. 28 GHz

Subcarrier spacing, e.g. 120 kHz

e.g. 500MHz

Example usage models and channel bandwidths

Scalable Transmission Time Interval (TTI)
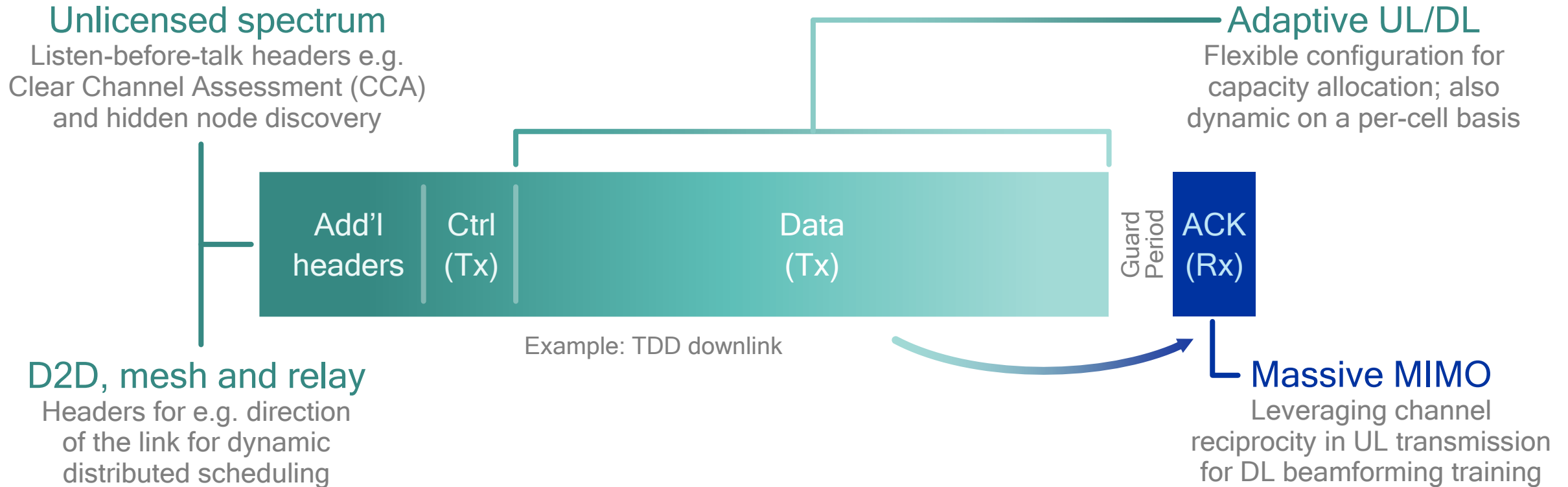
Scalable TTI for diverse latency and QoS requirements

Scalable number of TTIs per subframe[1]

Shorter TTI for low latency and high reliability

Longer TTI for higher spectral efficiency

Efficient multiplexing of long & short TTIs to allow transmissions to start on symbol boundaries[2,3]

1 ms subframe with 14 symbols of SCS[4] = 15 kHz

| 0 | 1 | 2 | ... | 11 | 12 | 13 |

| 0 | 1 | 2 | ... | 11 | 12 | 13 | 500 us TTI with 14 symbols of SCS = 30 kHz

| 0 | 1 | Short TTI with 2 symbols of SCS = 15 kHz

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Short TTI with 8 symbols of SCS = 60 kHz

Self-contained integrated subframe design

UL/DL scheduling info, data and acknowledgement in the same sub-frame

Unlicensed spectrum
Listen-before-talk headers e.g. Clear Channel Assessment (CCA) and hidden node discovery

Adaptive UL/DL
Flexible configuration for capacity allocation; also dynamic on a per-cell basis

| Add'l headers | Ctrl (Tx) | Data (Tx) | Guard Period | ACK (Rx) |

Example: TDD downlink

D2D, mesh and relay
Headers for e.g. direction of the link for dynamic distributed scheduling

Massive MIMO
Leveraging channel reciprocity in UL transmission for DL beamforming training

Faster, more flexible TDD switching and turn around,
plus support for new deployment scenarios and forward compatibility

New self-contained TDD design enables new use cases

Eliminates control channel interference to allow for robust, dynamic DL/UL switching

TDD DL

| DL CTRL | DL DATA[1] | | UL CTRL |

No DL ←→ UL interference between control channels

Common UL burst

TDD UL

DL CTRL	UL DATA[1] (User 1)	UL CTRL
	UL DATA (User 2)	
	UL DATA (User 3)	
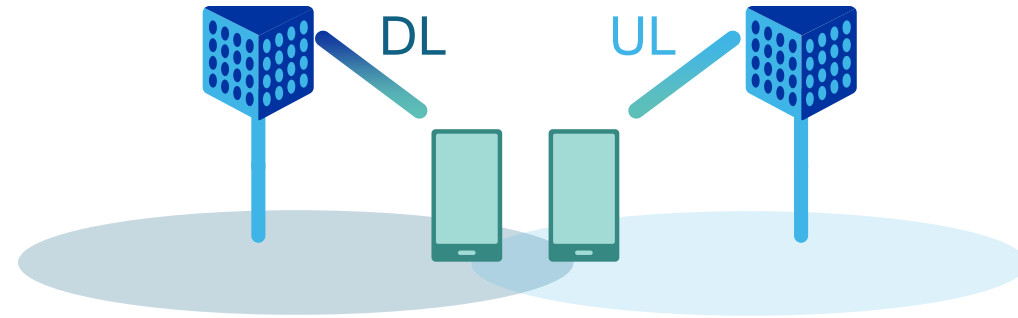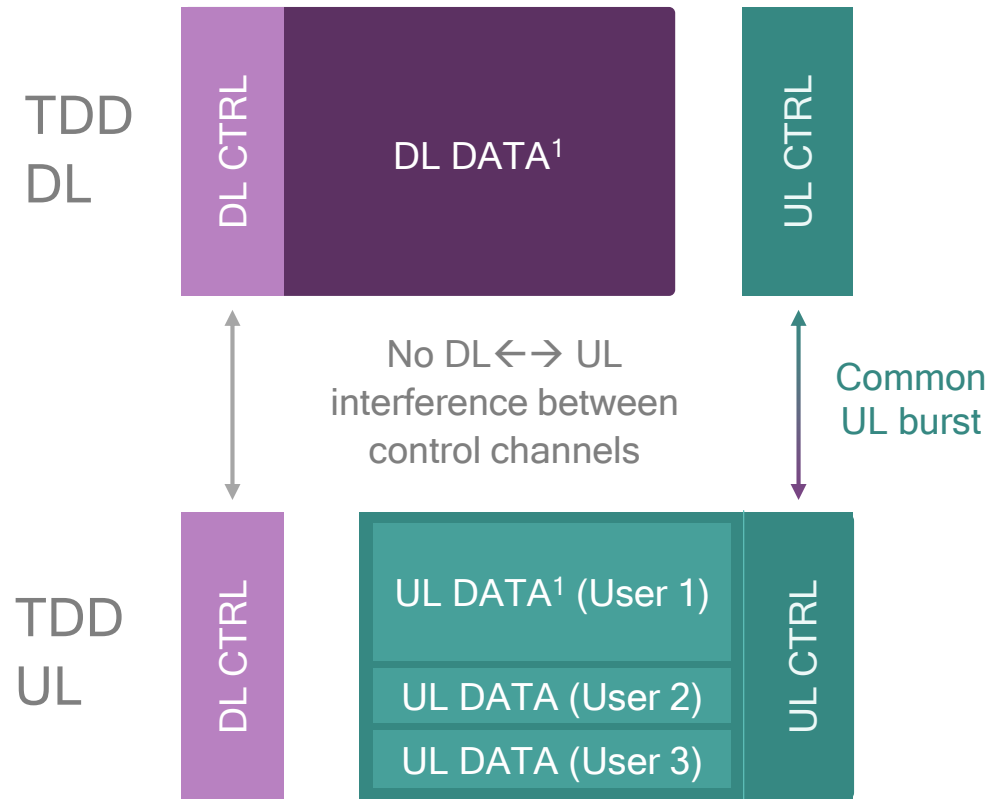
DL   UL

- Allows for robust, dynamic DL/UL switching driven by different loading and traffic types

- Enables integrated access and backhaul co-channel deployments for mmWave

5G NR design innovations across diverse services

Massive IoT

- Low complexity narrowband
- Low power modes for deep sleep
- Efficient signaling
- Grant-free uplink transmissions
- Optimized link budget
- Managed multi-hop mesh

Mission-Critical Control

- Low-latency with bounded delay
- Efficient multiplexing with nominal traffic
- Grant-free uplink transmissions
- Simultaneous redundant links
- Reliable device-to-device links
- Optimized PHY/pilot/HARQ

5G
NR

Enhanced Mobile Broadband

- Wider bandwidths
- Mobilizing mmWave
- Shared spectrum
- Device-centric mobility

- Dynamic, low-latency TDD/FDD
- Massive MIMO
- Advanced channel coding
- Native HetNet and multicast support

5G Enhancing mobile broadband

Extreme throughput
Ultra-low latency
Uniform experience

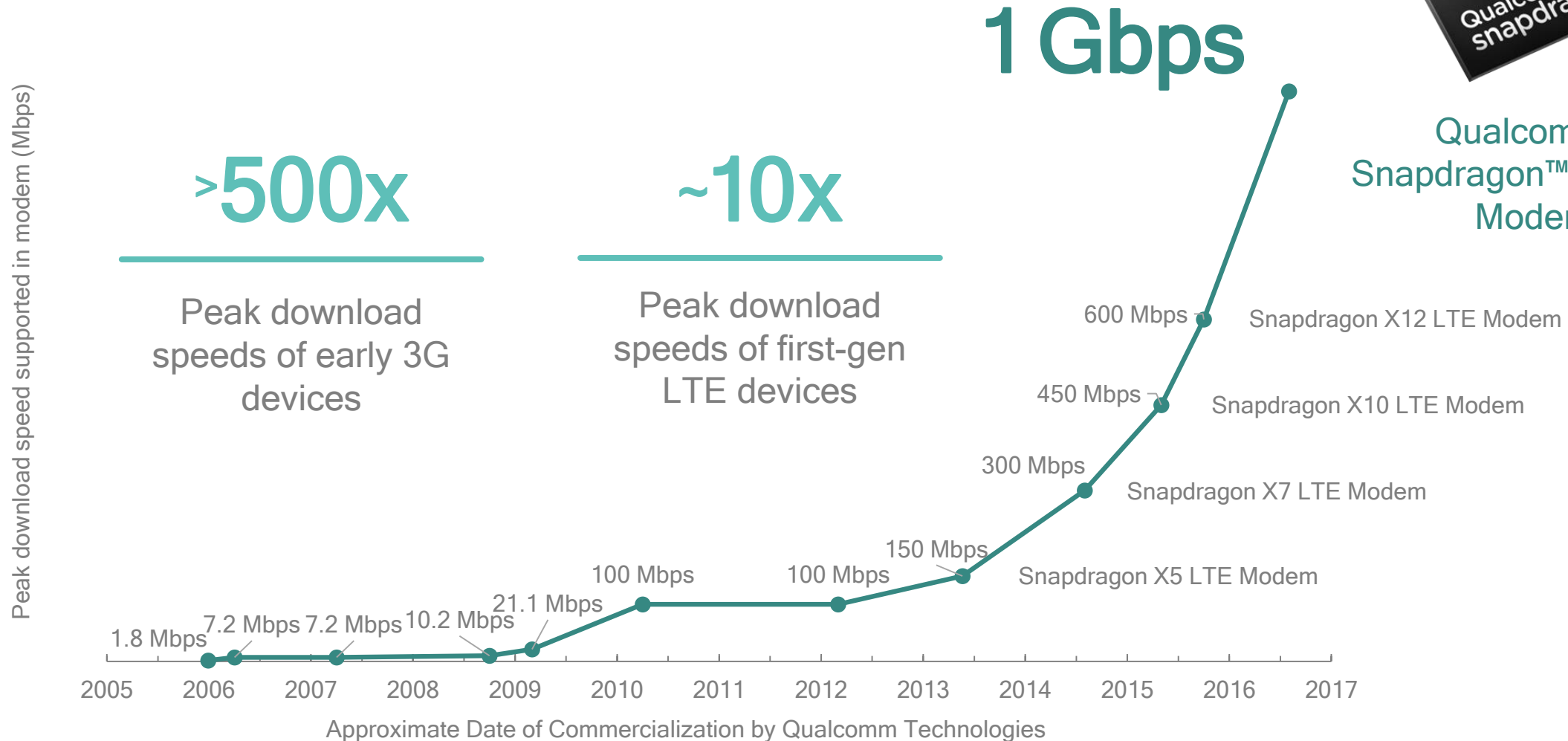# Breaking the Gigabit barrier in LTE today

The first real glimpse of our 5G future

1 Gbps

Qualcomm® Snapdragon™ X16 LTE Modem

Peak download speed supported in modem (Mbps)

>500x

Peak download speeds of early 3G devices

~10x

Peak download speeds of first-gen LTE devices

600 Mbps — Snapdragon X12 LTE Modem

450 Mbps — Snapdragon X10 LTE Modem

300 Mbps — Snapdragon X7 LTE Modem

150 Mbps — Snapdragon X5 LTE Modem

100 Mbps

100 Mbps

21.1 Mbps

10.2 Mbps

1.8 Mbps 7.2 Mbps 7.2 Mbps

2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017

Approximate Date of Commercialization by Qualcomm Technologies

Continuing to evolve LTE for enhanced mobile broadband

Pioneering 5G technologies and ensuring a consistent user experience as 5G rolls out

Gbps+ peak rates

More uniform experience

Better coverage

Significantly lower latencies

Carrier Aggregation evolution–wider bandwidths
Aggregating more carriers, diverse spectrum types and across different cells

LTE in unlicensed spectrum
Make the best use of the vast amounts of unlicensed spectrum available

TDD/FDD evolution–faster, more flexible
Enable significantly lower latency, adaptive UL/DL configuration, and more

Many more antennas–path to massive MIMO
Exploit 3D beamforming (FD-MIMO) to increase capacity and coverage

Designing 5G NR for significantly lower latency

10x lower latency than today's LTE networks

FDD

Fewer (variable) interlaces for HARQ[1]

TDD

Self-contained design reduces RTT
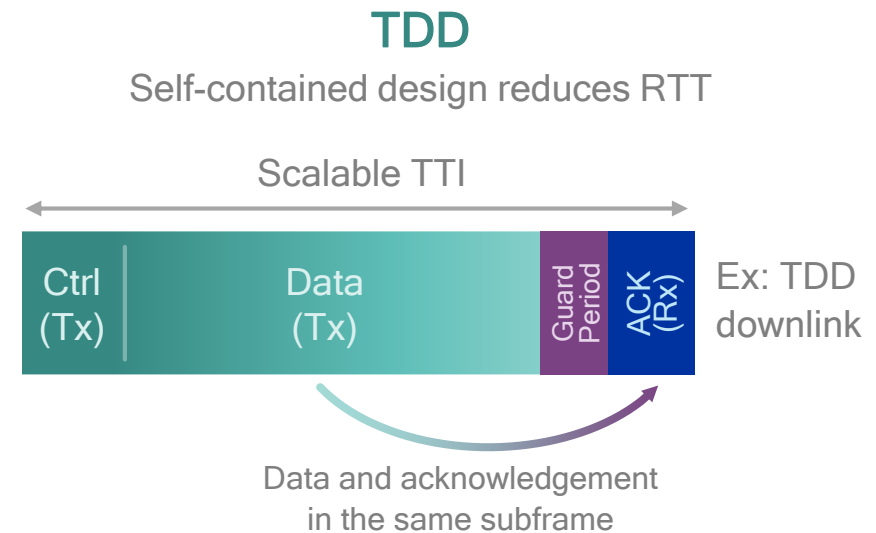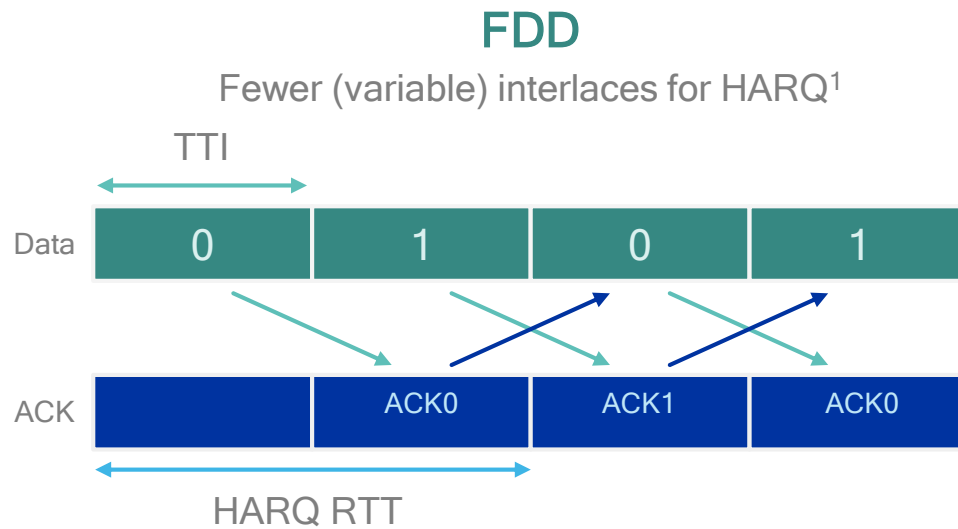
Improved performance by addressing TCP/UDP throughput limitations

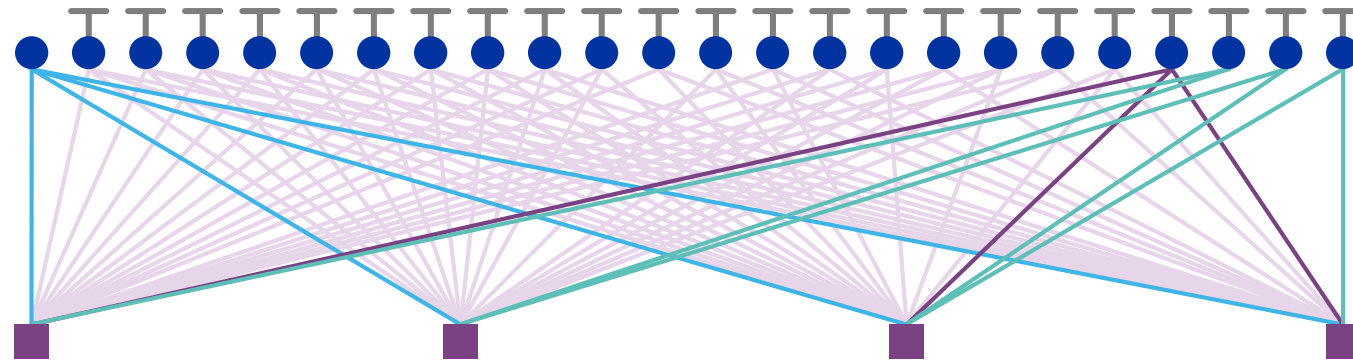**Better user experience for real-time applications such as Video-over-IP applications**

Address new latency-critical apps such as command-and-control of drones

Delivering advanced 5G NR channel coding

ME-LDPC[1] codes more efficient than today's LTE Turbo codes at higher data rates

Example ME-LDPC Basegraph

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
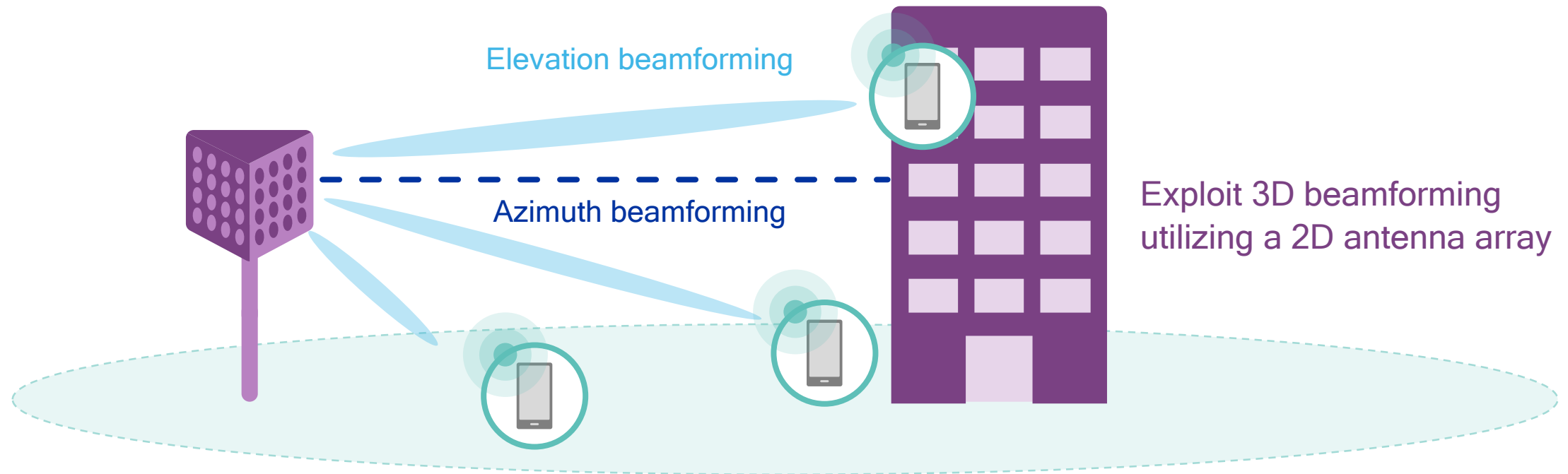
Low Latency
Efficient encoding/decoding enables shorter TTI

Also exploring alternative channel coding for mission-critical and massive IoT traffic[2]

[1] Multi-Edge Low-Density Parity-Check; [2] such as Polar or TBCC

Many more antennas to increase coverage and capacity

Evolving towards Massive MIMO

Elevation beamforming

Azimuth beamforming

Exploit 3D beamforming
utilizing a 2D antenna array

LTE Today
Fixed codebook for up to
8-antenna elements with
azimuth beamforming only

LTE Rel. 13 (FD-MIMO)
2D codebook support for 8-, 12- and
16-antenna elements with Reference
Signal enhancements for beamforming

5G NR Rel. 15 (Massive MIMO)
Support even larger # of antenna elements
(up to 256) with new features, e.g. hybrid
beamforming, distributed MIMO

Massive MIMO is a key enabler for higher spectrum bands

Allows reuse of existing sites and same transmit power at e.g. 4 GHz

Macro site

- 1.7 km inter-site distance
- 46 dBm transmit power

10 users per cell

— 2x4 MIMO, 20 MHz @ 2 GHz
— 2x4 MIMO, 80 MHz @ 4 GHz
— 24x4 MIMO, 80 MHz @ 4 GHz

Significant capacity gain: Average cell throughput = 808 Mbps in 80 MHz

3.4x   4.1x

2.7x   3.9x

Significant gain in cell edge user throughput

CDF (y-axis)

Shared/unlicensed spectrum is important for 5G

Unlocking more spectrum

Shared spectrum can unlock spectrum that is lightly used by incumbents
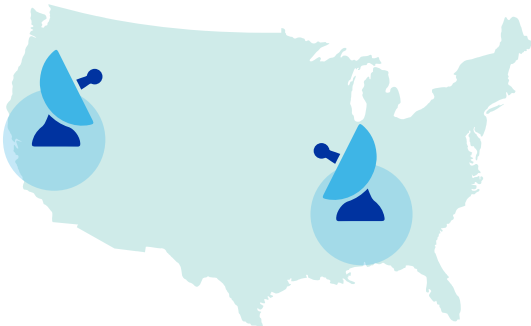
High spectrum utilization

Spectrum sharing has the potential to increase spectrum utilization

Spectrum

Time
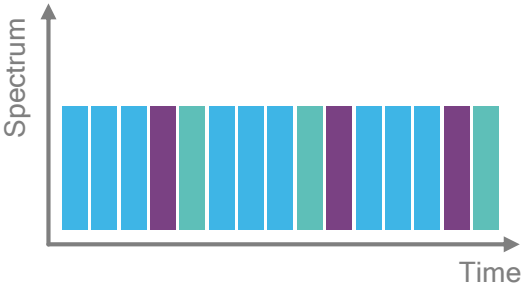
A lot of spectrum may be shared/unlicensed

FCC recent decision on high-band spectrum included a significant portion of shared/unlicensed[1]

- Licensed
- Shared/Unlicensed
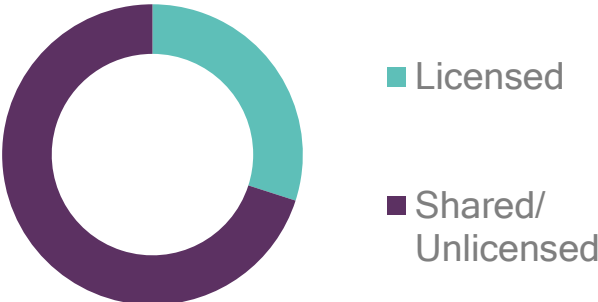
1) FCC ruling FCC 16-89 on 7/14/2016 allocated 3.25 MHz of licensed spectrum and 7.6 MHz of shared/unlicensed spectrum.

We are pioneering 5G shared spectrum today

Building on LTE-U/LAA, LWA, CBRS/LSA and MulteFire[1]
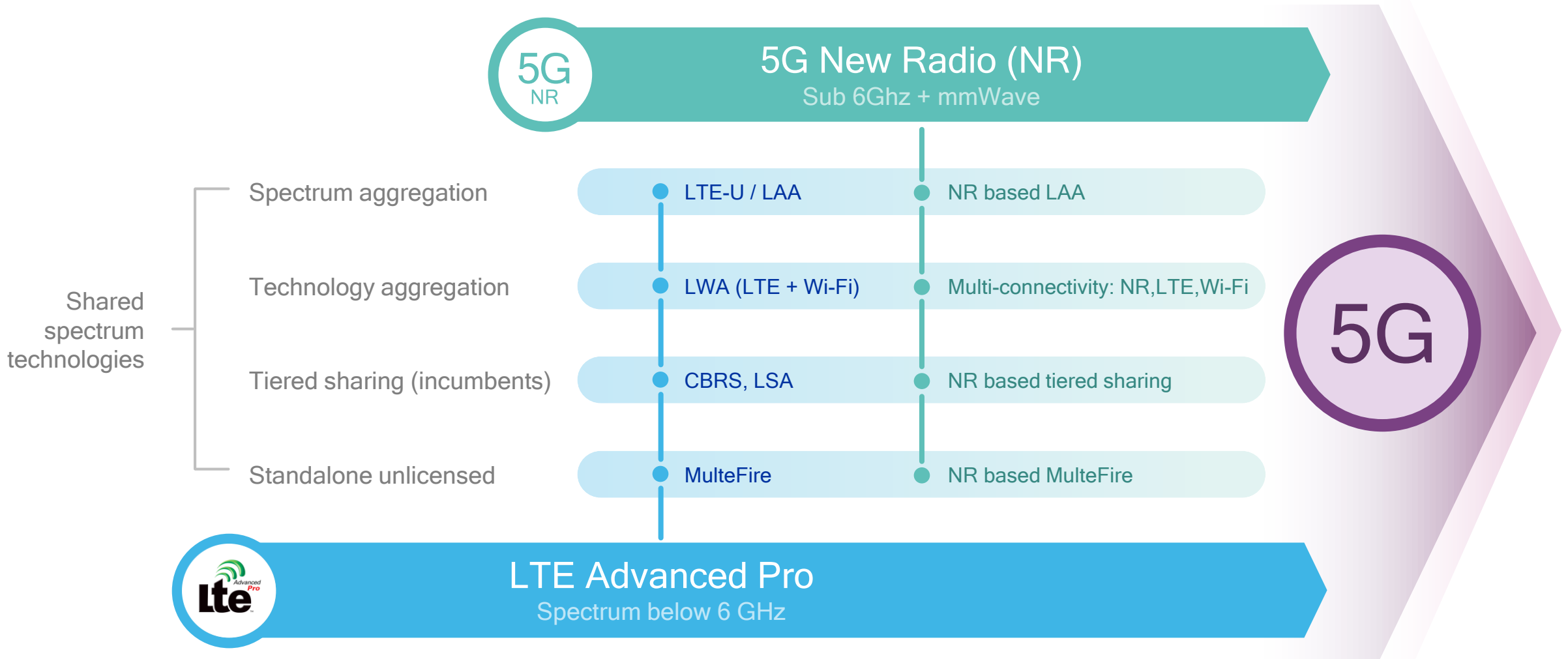
5G NR

5G New Radio (NR)
Sub 6Ghz + mmWave

Shared spectrum technologies

Category		
Spectrum aggregation	LTE-U / LAA	NR based LAA
Technology aggregation	LWA (LTE + Wi-Fi)	Multi-connectivity: NR,LTE,Wi-Fi
Tiered sharing (incumbents)	CBRS, LSA	NR based tiered sharing
Standalone unlicensed	MulteFire	NR based MulteFire

5G

lte Advanced Pro

LTE Advanced Pro
Spectrum below 6 GHz

Pioneered shared/unlicensed spectrum in 4G LTE

LSA[1]

LTE-U

LAA[2]

MULTEFIRE™

CBRS[3]

Incumbents
PAL
GAA
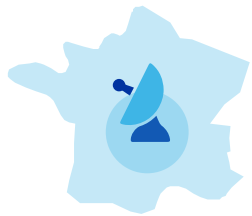
Technically extensive pilot in France with Ericsson and Red in Jan 2016

We designed the original proposal, commercialized by the LTE-U forum

Performed world's first over-the-air LAA trial with Deutsche Telekom Nov 2015

A founder of the MulteFire Alliance and a key contributor to its specification
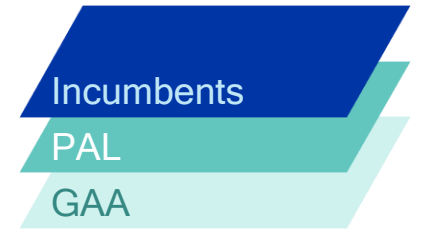
A founder of the CBRS Alliance and a key contributor to coexistence

Realizing the mmWave opportunity for mobile broadband

Extreme bandwidth opportunity

- Extreme bandwidths capable of Multi-Gbps data rates
- Flexible deployments (integrated access/backhaul)
- High capacity with dense spatial reuse

Mobilizing mmWave challenge

- Robustness due to high path loss and susceptibility to blockage
- Device cost/power and RF challenges at mmWave frequencies

5G NR

Smart beamforming and beam tracking
Increase coverage and minimize interference
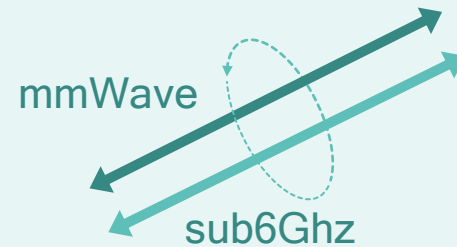
mmWave

sub6Ghz

Tight interworking with sub 6 GHz
Increase robustness, faster system acquisition
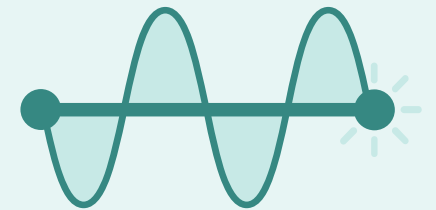
Optimized mmWave design for mobile
To meet cost, power and thermal constraints

Learn more at: www.qualcomm.com/documents/promise-5g-mmwave-how-do-we-make-it-mobile

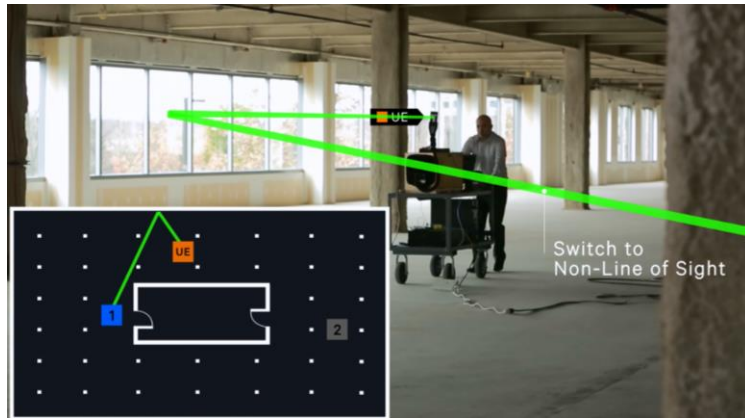# Mobilizing mmWave–live demonstration of our prototype

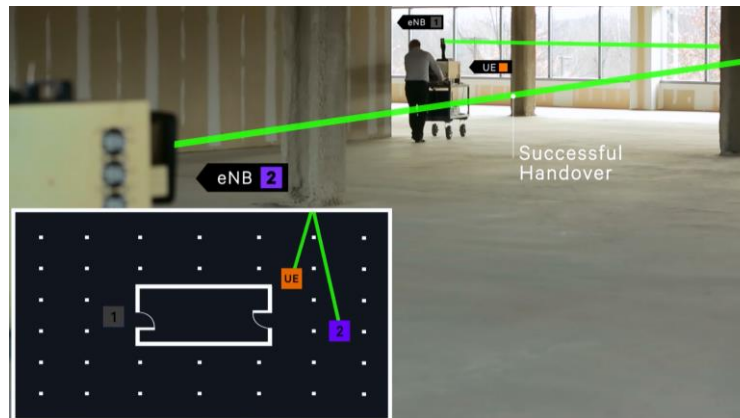**Millimeter Wave UE**

Millimeter wave base station
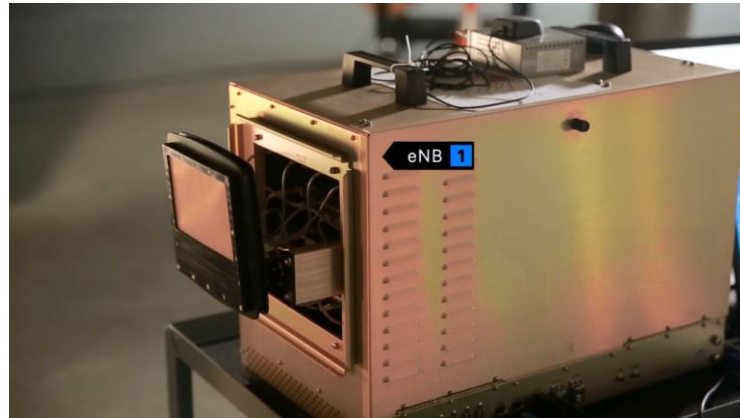
Beamforming and scanning

Non-line-of-sight through reflection

Handover

Outdoor

Learn more at: www.qualcomm.com/videos/mobilizing-mmwave-5g
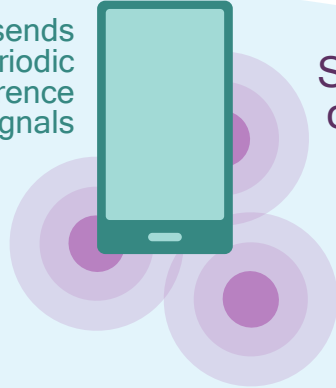
Device-centric mobility management in 5G NR

Control plane improvements to improve energy and overhead efficiency

UE sends periodic reference signals

Serving cluster

Network triggers cell reselection/handover based on measurement of UE signals

Edgeless mobility zone
(area of tightly coordinated cells)

Lightweight mobility for device energy savings

- Apply COMP-like[1] concepts to the control plane
- Intra-zone mobility transparent to the device

Less broadcast for network energy savings

- Low periodic beacon for initial discovery of device(s)
- On-demand system info (SIB) when devices present[2]
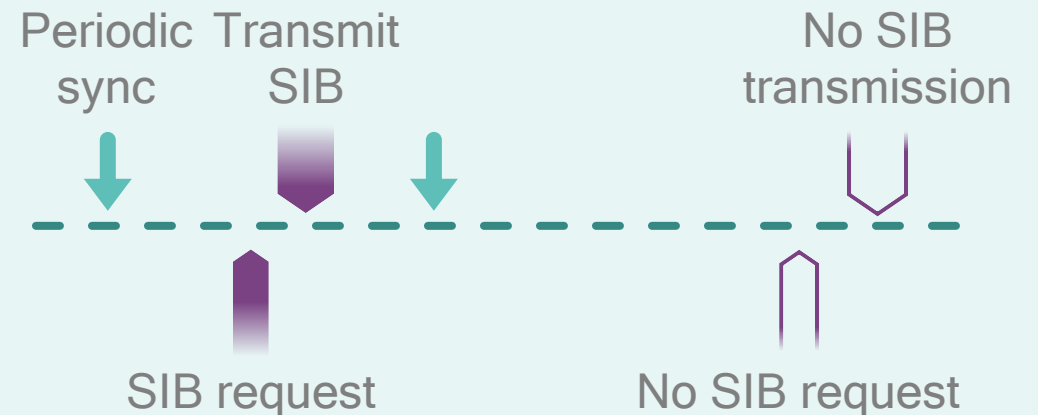
Periodic sync   Transmit SIB

No SIB transmission

SIB request

No SIB request

5G Connecting massive
Internet of Things

Power efficient

Low complexity

Long range

Cellular technologies enable a wide range of IoT services

Smart cities
Lighting, traffic sensors, smart parking,…

Mobile health
Wearables, gateways, remote patient,…

Smart utilities
Smart grid, gas/water/ electric meters

Environmental monitoring
Agriculture, forecast fire/ air pollution sensors,…

>5B
IoT connections by 2025[1]

Connected building
Security, video surveillance, smoke detectors,…

Connected industrial
Process/equipment monitoring, HVAC, …

Connected retail
Vending machines, ATM, digital ads,…

Asset tracking
Fleet management, pet/kid trackers, shipping,…

Ubiquitous coverage

Always-on connectivity

Reliable and secure

Global ecosystem

We are evolving LTE for the Internet of Things

Paving the path to Narrowband 5G for massive IoT

Scaling up in performance and mobility

Scaling down in complexity and power

Today

New narrowband IoT technologies (3GPP Release 13+)

LTE Cat-4 and above
>10 Mbps
n x 20 MHz

LTE Cat-1
Up to 10 Mbps
20 MHz

LTE Cat-M1 (eMTC)
Variable rate up to 1 Mbps
1.4 MHz narrowband

Cat-NB1 (NB-IoT)
10s of kbps
200 kHz narrowband

Mobile

Video security

Wearables

Object tracking

Utility metering

Environment monitoring

Connected car

Energy management

Connected healthcare

City infrastructure

Smart buildings

5G NR will bring new capabilities for the massive IoT

## NB-IoT continuing to evolve beyond Release 13—foundation of Narrowband 5G

eMTC

Scales down LTE to address the broadest range of IoT use cases

NB-IoT

Optimizes to lowest cost/power for delay-tolerant, low-throughput IoT use cases; evolving with new features such as VoLTE and positioning support

NB-5G

3GPP 5G NR further enhances massive IoT with new capabilities such as RSMA[1] & multi-hop mesh
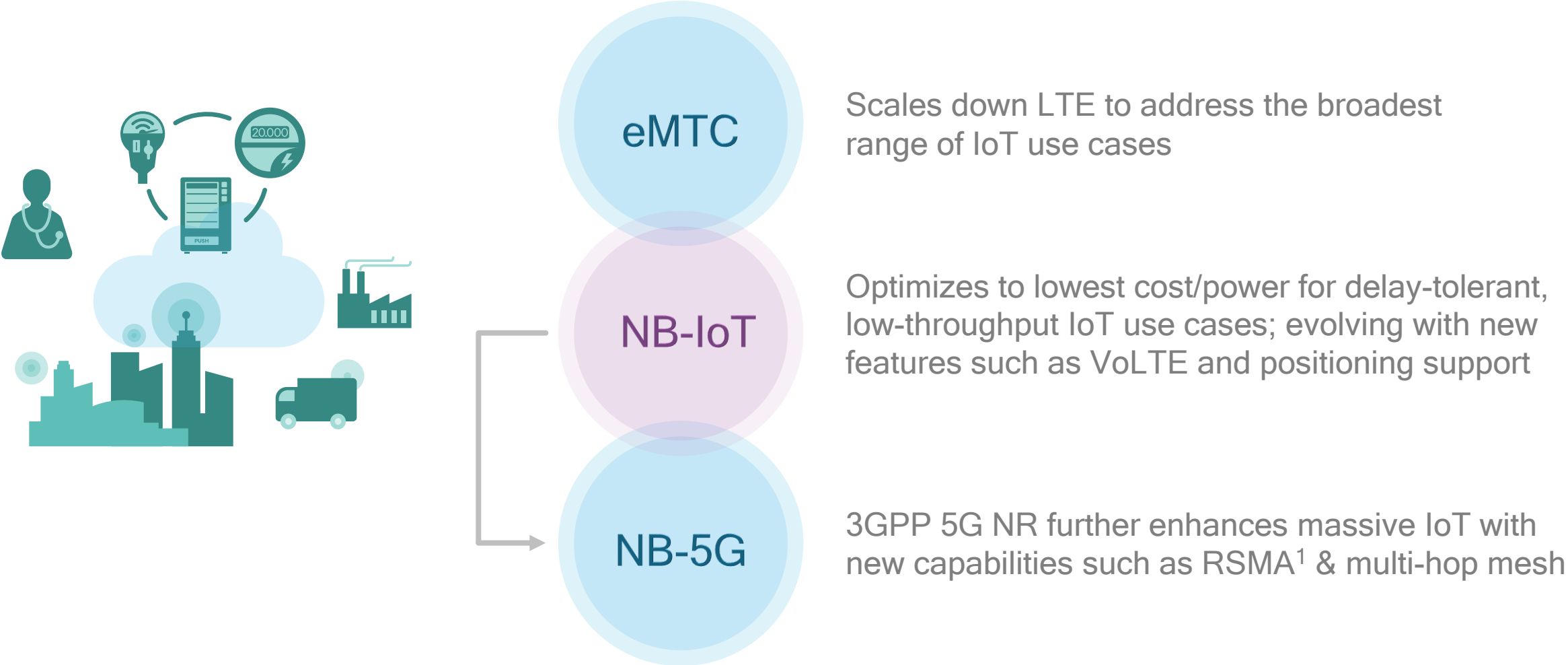
Non-orthogonal RSMA for efficient IoT communications

Characterized by small data bursts in uplink where signaling overhead is a key issue

Grant-free transmission of small data exchanges

- Eliminates signaling overhead for assigning dedicated resources

- Allows devices to transmit data asynchronously
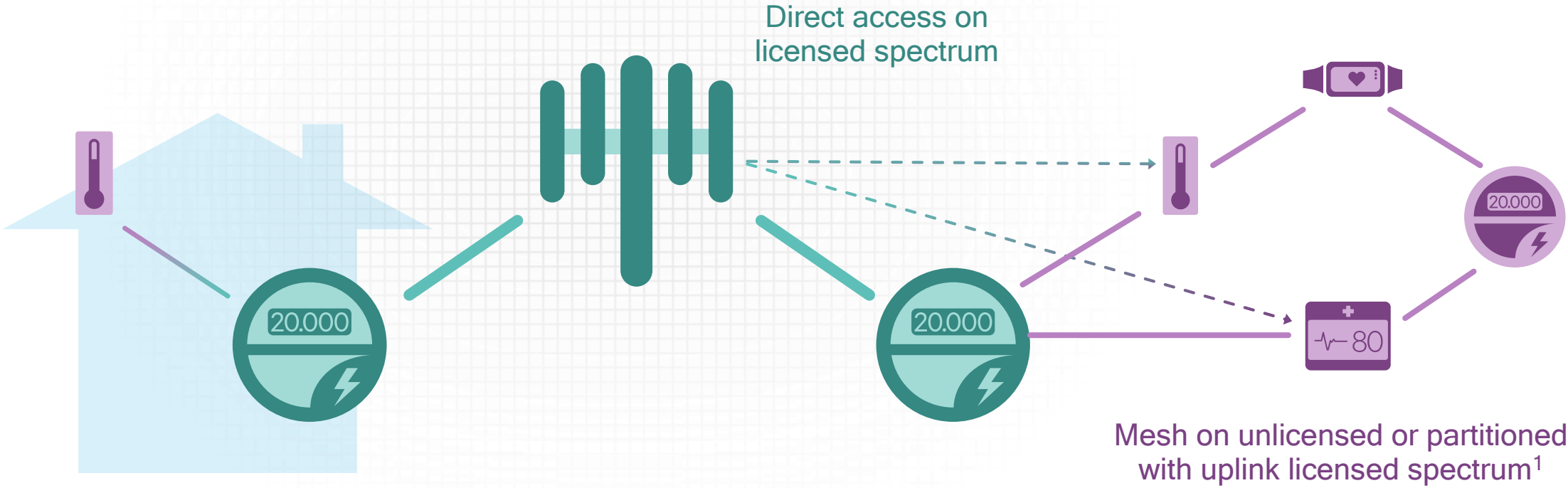
- Capable of supporting full mobility

Downlink remains OFDM-based for coexistence with other services
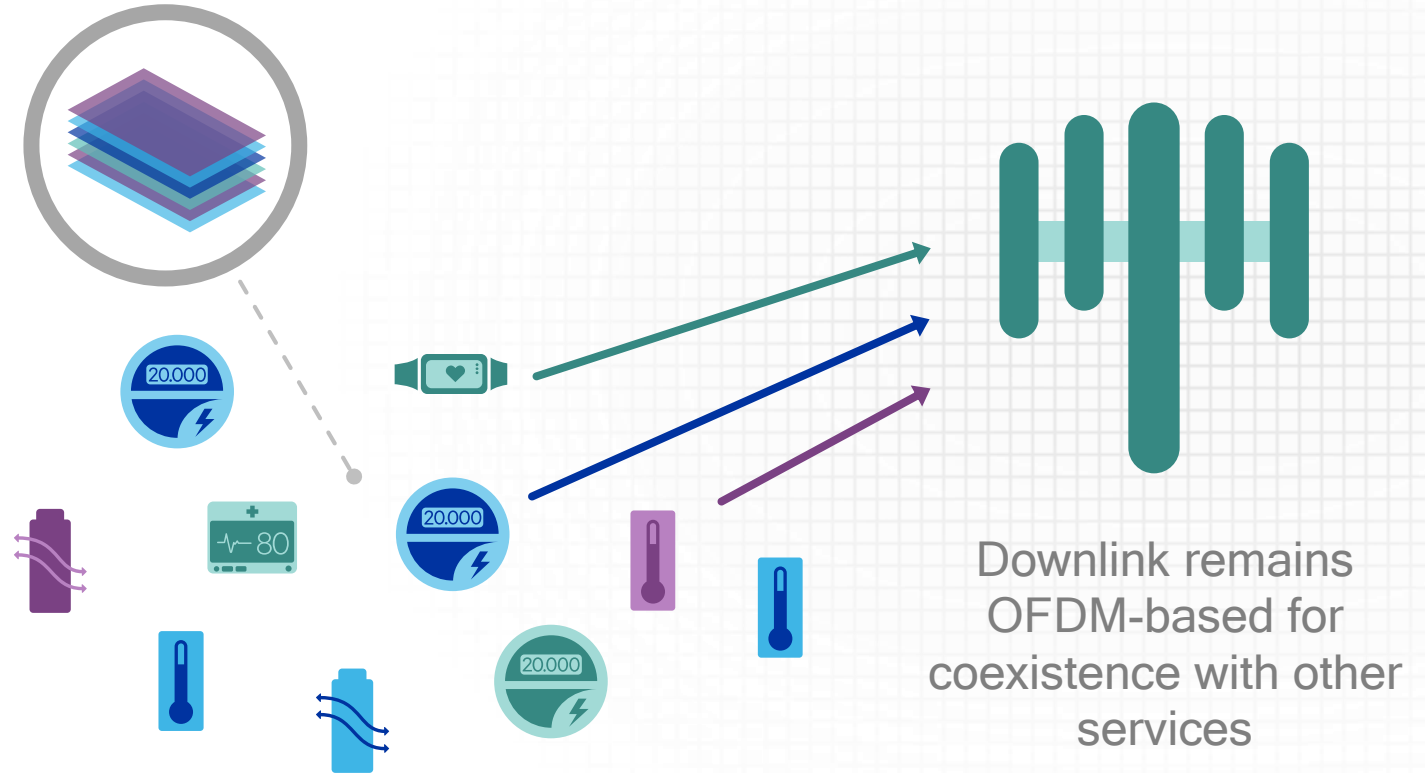
Increased battery life

Scalability to massive # of things

Better link budget

Support for multi-hop mesh with WAN management

Direct access on licensed spectrum

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

Problem: Uplink coverage
Due to low power devices and challenging placements, in e.g. basement

Solution: Managed uplink mesh
Uplink data relayed via nearby devices–uplink mesh but direct downlink.

5G Enabling mission-critical services

High reliability
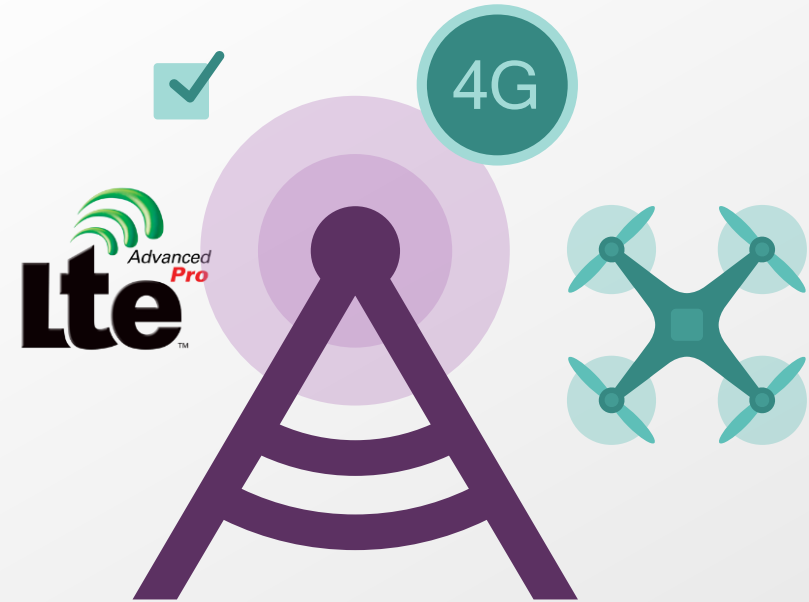Ultra-low latency
High availability

We are pioneering mission-critical services with LTE today
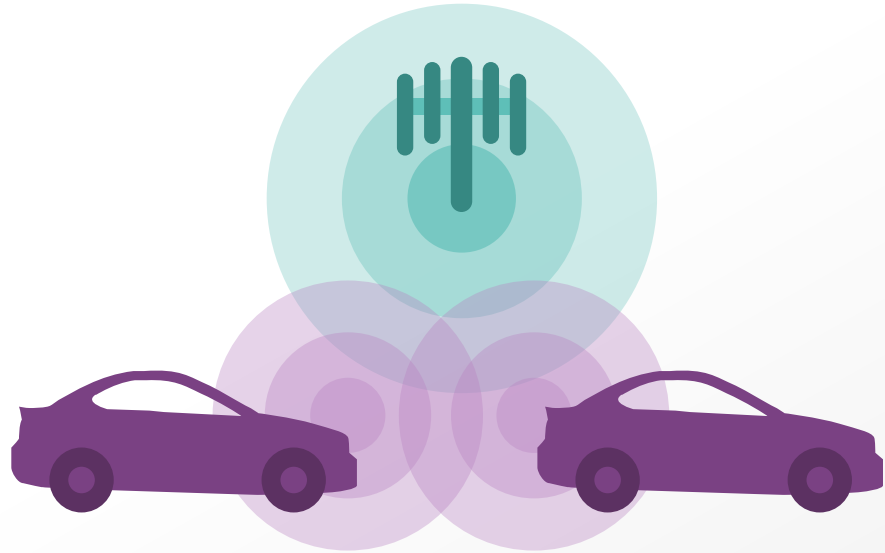
Cellular Vehicle-to-Everything (C-V2X)

Actively driving C-V2X 3GPP Release 14 Work Item and beyond, building upon our leadership in LTE Direct and LTE Broadcast
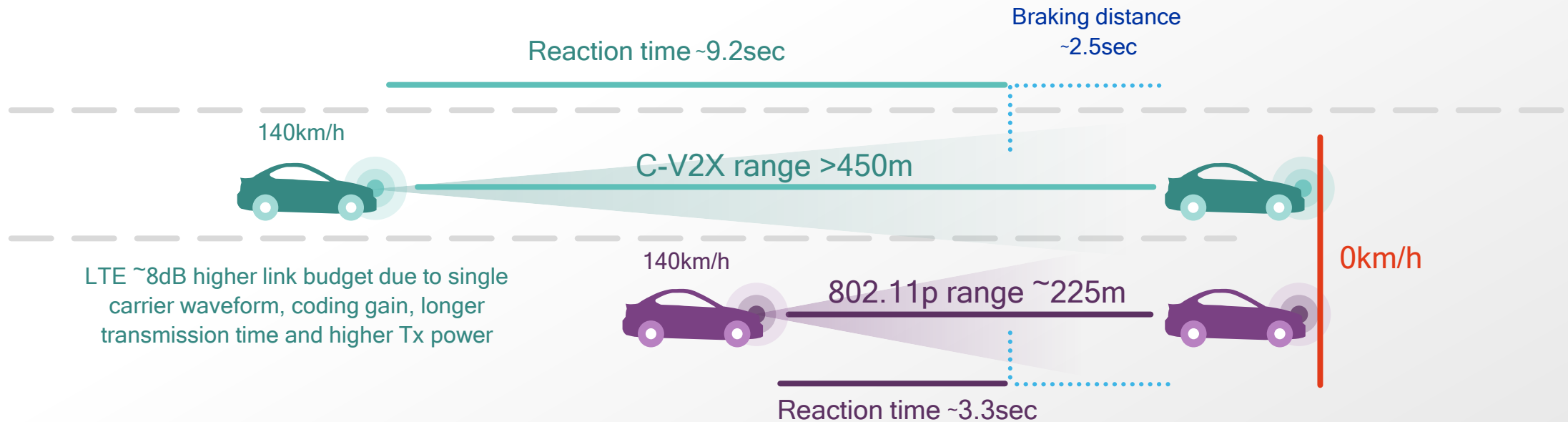
Cellular drone communications

Testing drone operation on commercial 4G LTE networks at FAA-authorized UAS Flight Center, representing "real world" conditions

Pioneering C-V2X with rich roadmap to 5G

C-V2X increases reaction time over 802.11p/DSRC for improved safety use cases

Braking distance ~2.5sec

Reaction time ~9.2sec

140km/h

C-V2X range >450m

0km/h

LTE ~8dB higher link budget due to single carrier waveform, coding gain, longer transmission time and higher Tx power

140km/h

802.11p range ~225m

Reaction time ~3.3sec

Safer driving experience
Increased driver reaction time

Support for high speeds
Relative speeds up to 500km/h

Increased situational awareness
Gather data from further ahead

Based on link level curves and the 3GPP LOS path loss model @ 10% Packet Error - Actual performance varies significantly with vehicle density and environment

Testing drone operation over commercial LTE networks

To optimize LTE networks and advance 5G for mission critical services

Controlled Airspace Class B

- FAA-authorized test environment
- Repressing real world" conditions with mix of commercial, residential and rural

Early findings

- Drones at altitude are served by multiple base stations
- Drones demonstrated seamless handovers with zero link failures

Opportunities for optimization

- Interference management
- Handover optimization
- LTE Drone Specific Requirements

5G NR will enable new mission-critical control services

A platform for tomorrow's more autonomous world

Autonomous vehicles

Robotics
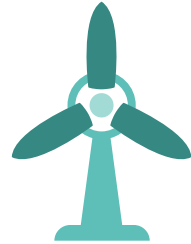
Energy/ Smart grid

Aviation

Industrial automation

Medical

1ms e2e latency
Faster, more flexible frame structure; also new non-orthogonal uplink access

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

Ultra-high availability
Simultaneous links to both 5G and LTE for failure tolerance and extreme mobility

Strong e2e security
Security enhancements to air interface, core network, & service layer across verticals[1]

[1] Also exploring alternative roots of trust beyond the SIM card

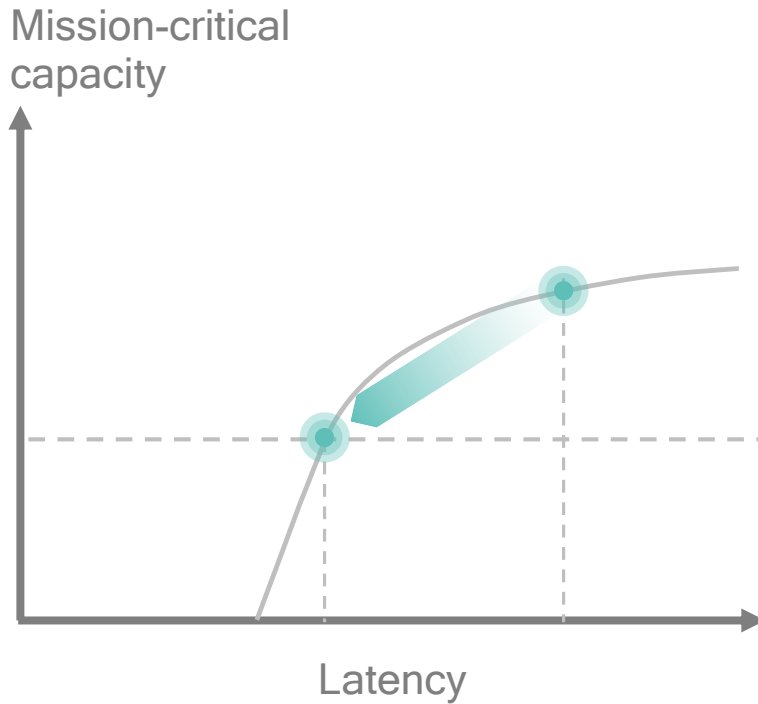# Efficient mission-critical multiplexing with other services

A more flexible design as compared to dedicated mission-critical resources (e.g. FDM)

One TTI

1st transmission

2st transmission

Nominal traffic
(with new FEC and HARQ design)

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

Frequency

Time

Mission-critical transmission
may occur at any time and cannot wait for scheduling

Opportunity for uplink RSMA non-orthogonal access using OFDM waveforms
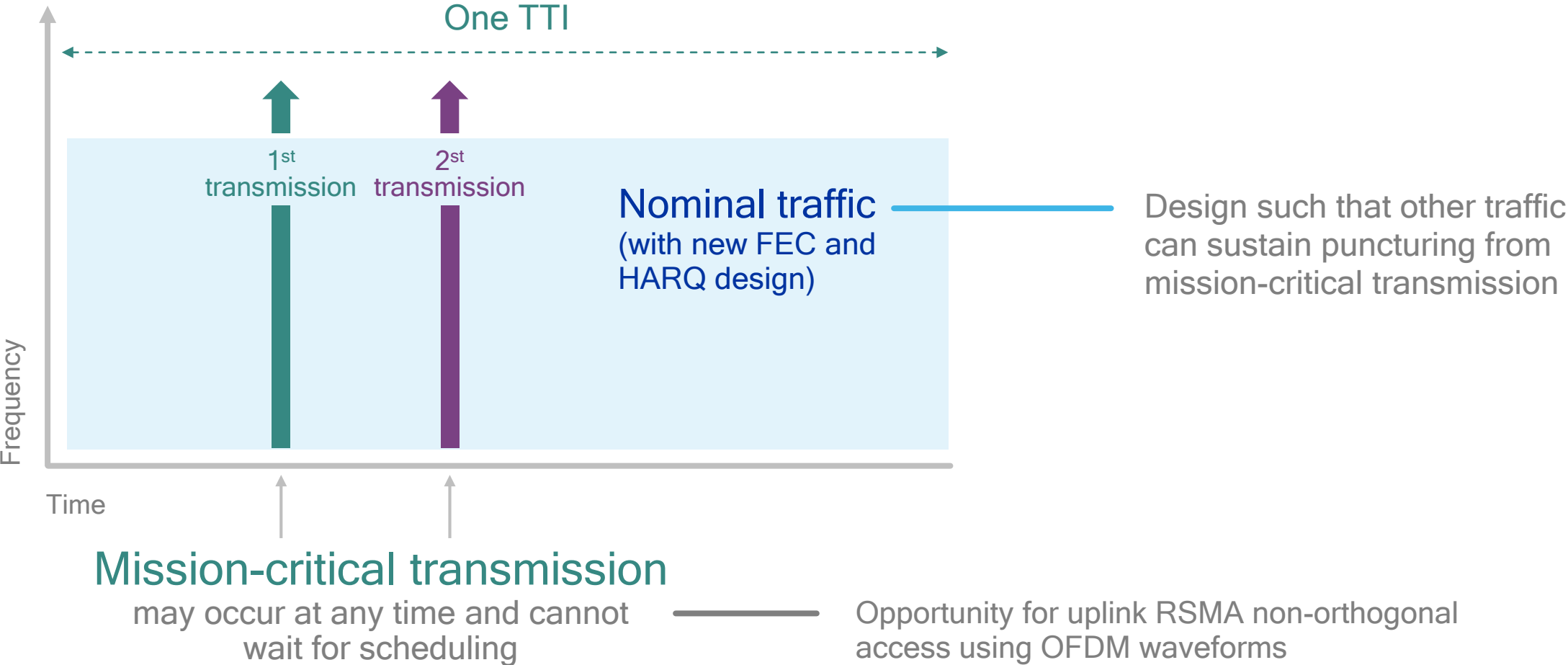
New 5G design allows for optimal trade-offs

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

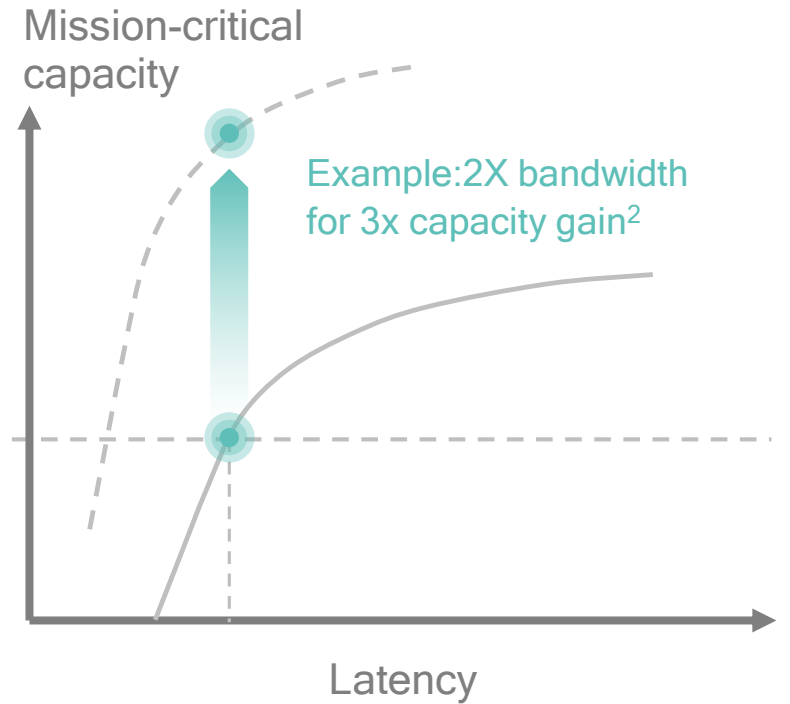### Latency vs. capacity…

Mission-critical capacity

Latency

Reliability vs. capacity…

Mission-critical capacity

e.g. 1e-2 BLER

e.g. 1e-4 BLER1

Latency
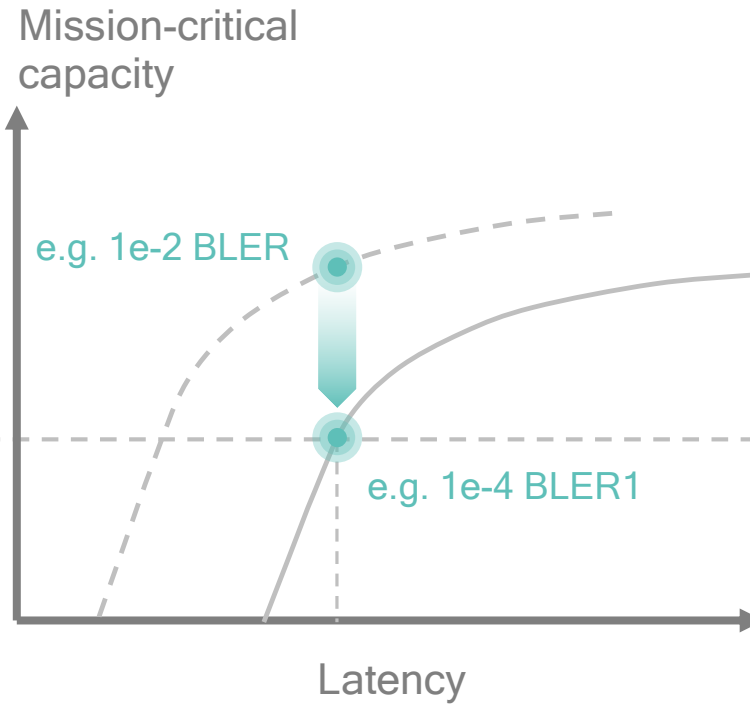
But wider bandwidth can offset reductions

Mission-critical capacity

Example:2X bandwidth for 3x capacity gain[2]

Latency

[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 10Mhz to 20Mhz for 1e-4 BLER.
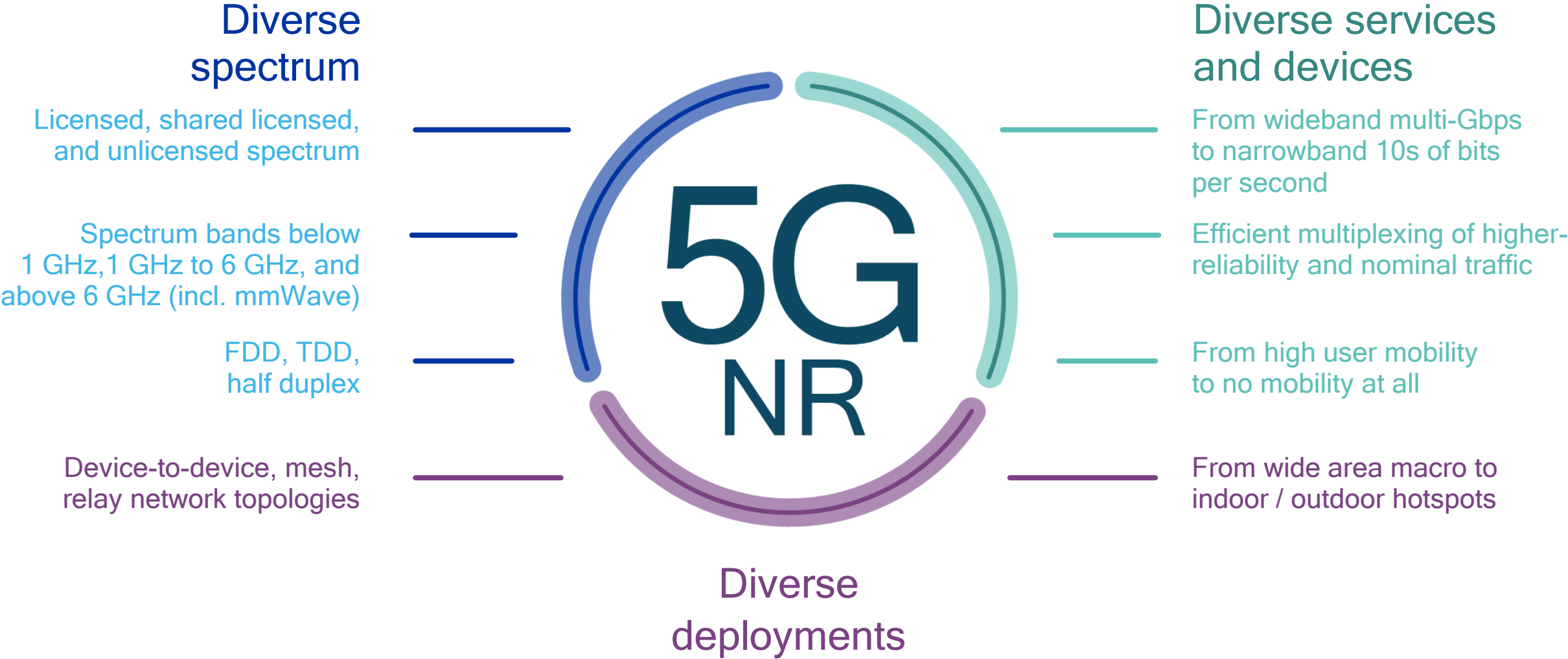
As we did in 3G and 4G, Qualcomm is leading the world to 5G

Making 5G NR a reality

3G
4G
5G
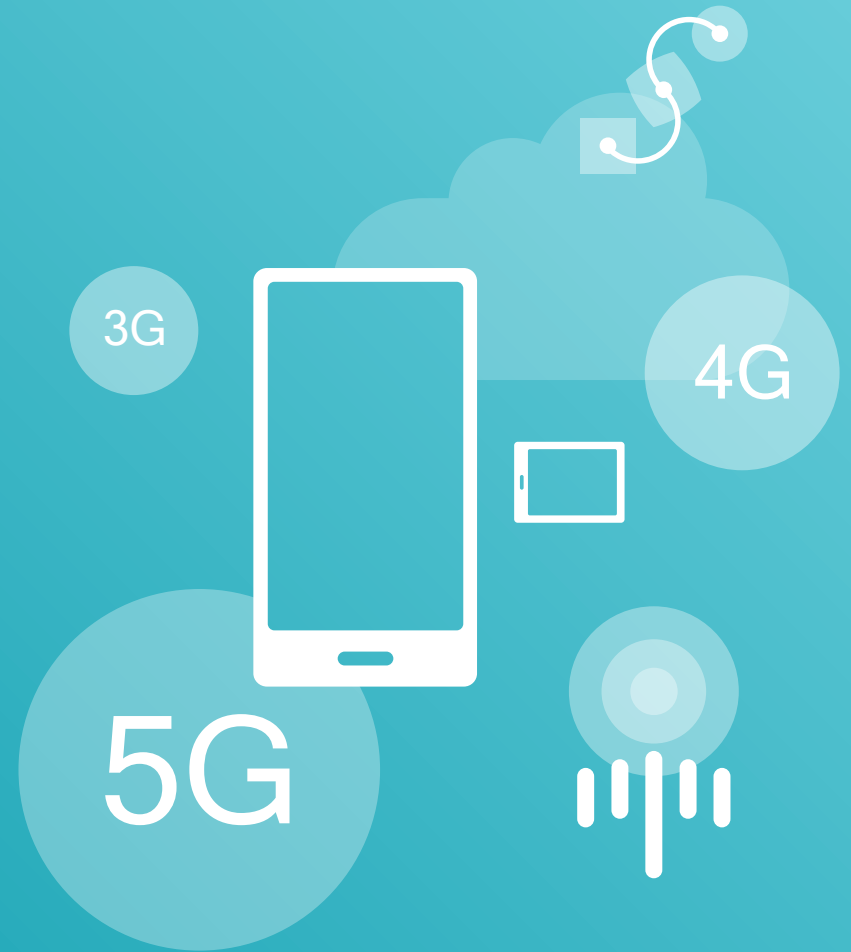
We are designing a unified, more capable 5G air interface

Diverse spectrum

Licensed, shared licensed, and unlicensed spectrum

Spectrum bands below 1 GHz, 1 GHz to 6 GHz, and above 6 GHz (incl. mmWave)

FDD, TDD, half duplex

Device-to-device, mesh, relay network topologies

5G NR

Diverse services and devices

From wideband multi-Gbps to narrowband 10s of bits per second

Efficient multiplexing of higher-reliability and nominal traffic

From high user mobility to no mobility at all

From wide area macro to indoor / outdoor hotspots

Diverse deployments

Also designing a flexible 5G network architecture

Leveraging virtualized network functions to create optimized network slices

Mobile broadband

Internet of Things

Mission-critical control

5G
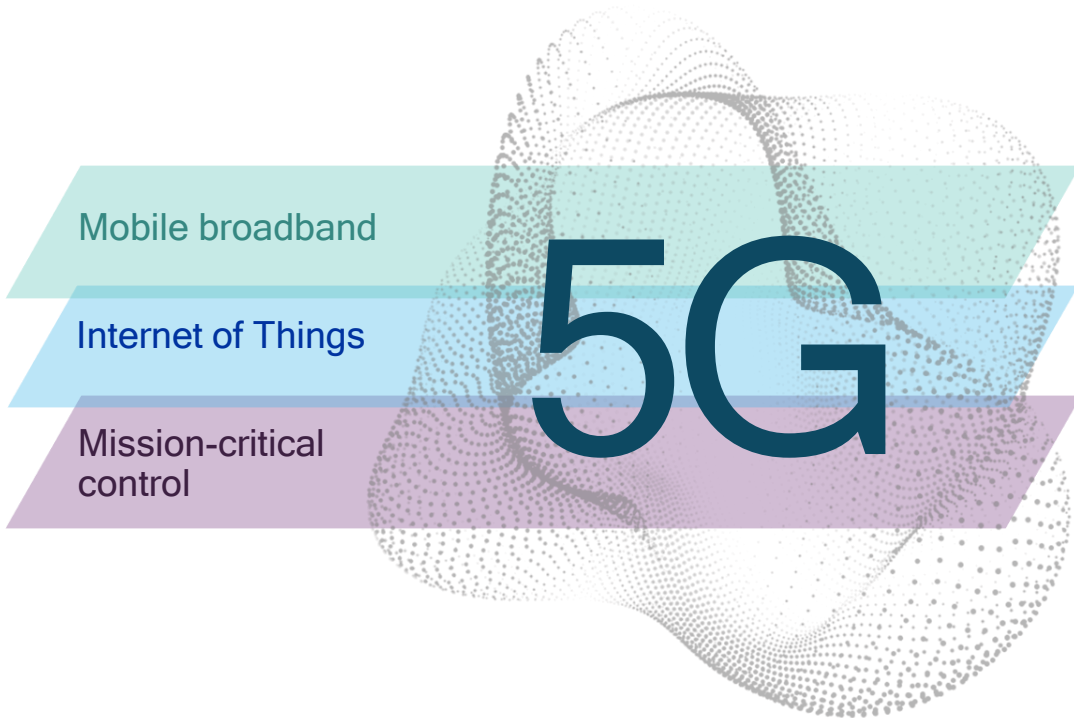
- Configurable end-to-end connectivity per vertical

- Modular, specialized network functions per services

- Flexible subscription models

- Dynamic control and user planes with more functionality at the edge

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

Pioneering new 5G technologies today

With our leadership and expertise in LTE and Wi-Fi

Breaking the gigabit barrier

Solving the 1000x data challenge

Enabling new spectrum paradigms

Mobilizing mmWave spectrum bands

Bringing new ways to connect

Optimizing for the Internet of Things

5G NR

Pioneering new 5G technologies today

With our leadership and expertise in LTE and Wi-Fi

Breaking the gigabit barrier
Qualcomm® Snapdragon™ X16 LTE modem industry's first Gigabit Class LTE modem (4x CA, LAA, 4x4 MIMO, 256-QAM)

1000X Solving the 1000x data challenge
Technologies for hyper-densification, e.g. Qualcomm UltraSON™ self-organization and converged LTE / Wi-Fi solutions

Enabling new spectrum paradigms
New technologies such as LSA for sharing with incumbents, LTE-U, LWA, LAA, MulteFire™ for over-the-air sharing

Mobilizing mmWave spectrum bands
Qualcomm® VIVE 802.11ad 60 GHz chipset commercial for mobile devices with a 32-antenna array element

Bringing new ways to connect
LTE Direct and LTE Broadcast (including digital TV), and new standard for Cellular V2X (C-V2X) communications

Optimizing for the Internet of Things
New LTE IoT technologies (eMTC, NB-IoT), and optimizing technologies for cellular drone communications

5G NR

Our modem and RF leadership is critical to 5G

Roadmap to 5G is significantly more complex and faster moving

Wi-Fi, 3G, 2G
technologies

50+ spectrum bands
450 MHz–5.8 GHz
(licensed and unlicensed)

~200 Carrier Aggregation
combinations

4G LTE OFDM-based
waveforms, transmission
modes, and UE categories

New LTE services, e.g.
LTE Broadcast, VoLTE
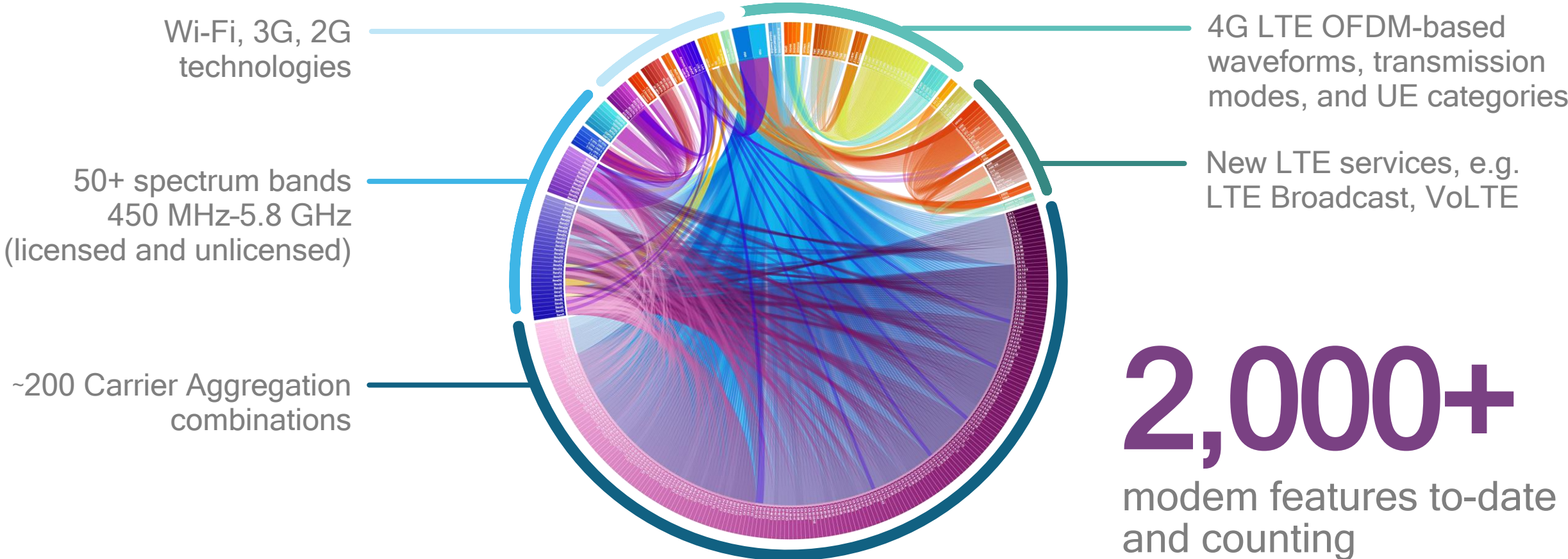
2,000+
modem features to-date
and counting

LTE multi-mode today

Our modem and RF leadership is critical to 5G

Roadmap to 5G is significantly more complex and faster moving

Device-to-device, mesh, relay

Wideband to narrowband

More diverse deployment scenarios
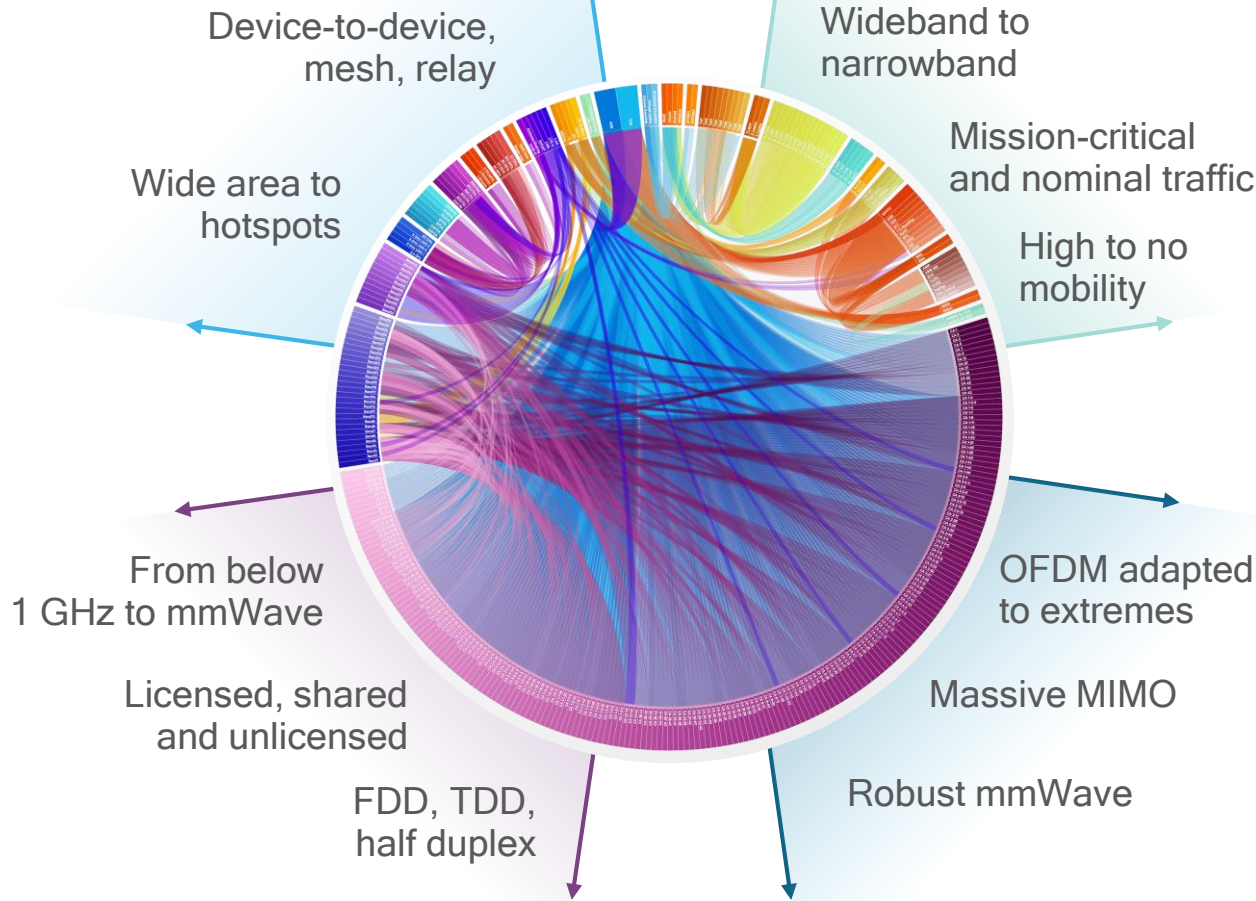
A much wider variation of use cases

Wide area to hotspots

Mission-critical and nominal traffic

High to no mobility

From below 1 GHz to mmWave

OFDM adapted to extremes

Many more spectrum bands / types

Advanced wireless technologies

Licensed, shared and unlicensed

Massive MIMO

FDD, TDD, half duplex

Robust mmWave

Roadmap to 5G

Qualcomm Research 5G NR prototype systems

Testbed for 5G designs to drive standardization and timely commercialization

Sub-6 GHz for flexible deployments across a wide range of use cases

End-to-end system operating sub-6 GHz and showcasing innovations to efficiently achieve large bandwidths capable of multi-Gbps rates at low latency

Robust mmWave for extreme mobile broadband
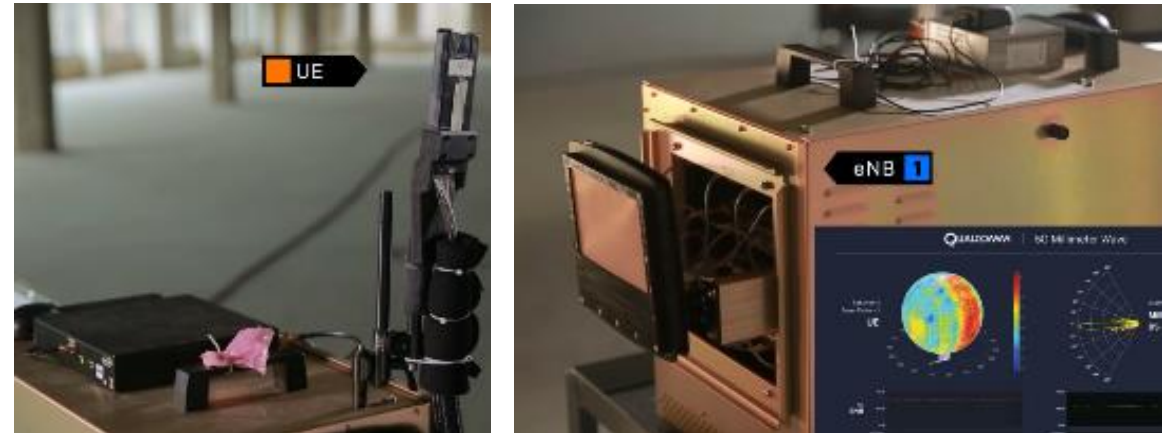
End-to-end system operating at 28 GHz, demonstrating beam forming and scanning to address non-line-of-sight scenarios, improve indoor/outdoor range, and provide robust mobility

Anyone can talk about 5G. We are creating it.

Investing in 5G for many years—building upon our leadership foundation

Wireless/OFDM technology and chipset leadership

Pioneering new 5G technologies to meet extreme requirements
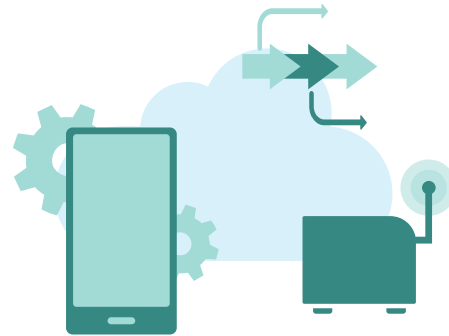
End-to-end system approach with advanced prototypes

Driving 5G from standardization to commercialization
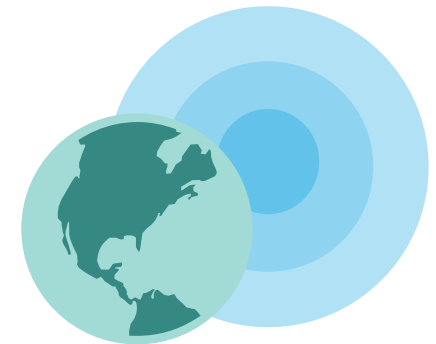
Leading global network experience and scale

Providing the experience and scale that 5G demands

Learn more at www.qualcomm.com/5G

Questions? - Connect with Us

www.qualcomm.com/wireless

www.qualcomm.com/news/onq

@Qualcomm_tech

http://www.youtube.com/playlist?list=PL8AD95E4F585237C1&feature=plcp

http://www.slideshare.net/qualcommwirelessevolution
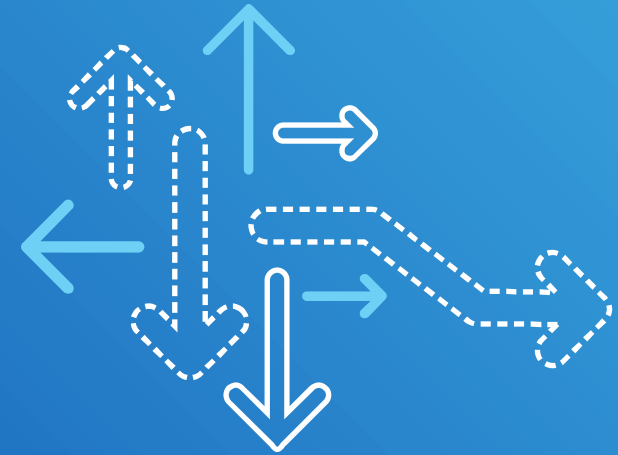
Thank you

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