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

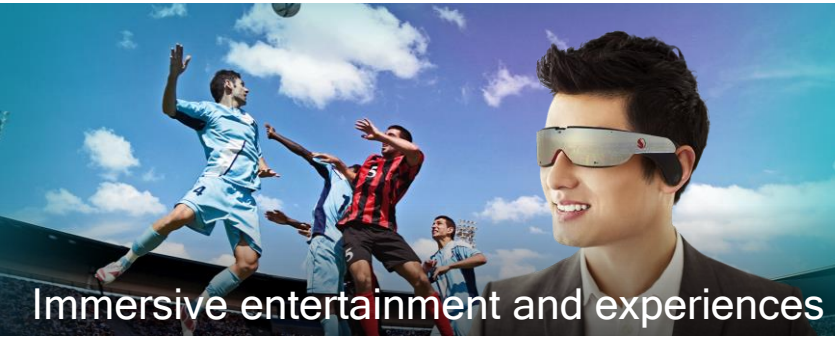
Massive Internet of Things

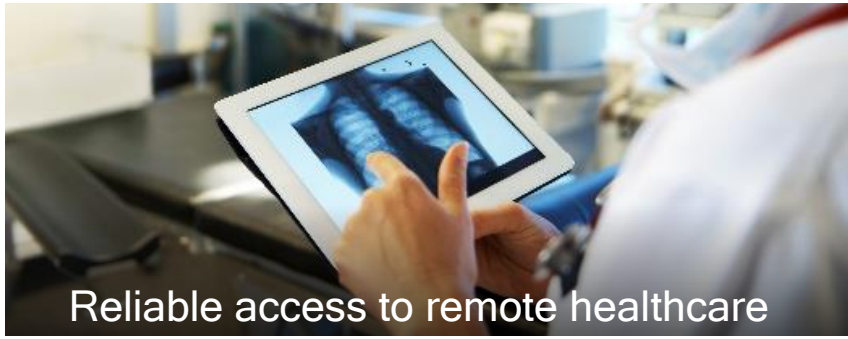
Unifying connectivity platform for future innovation

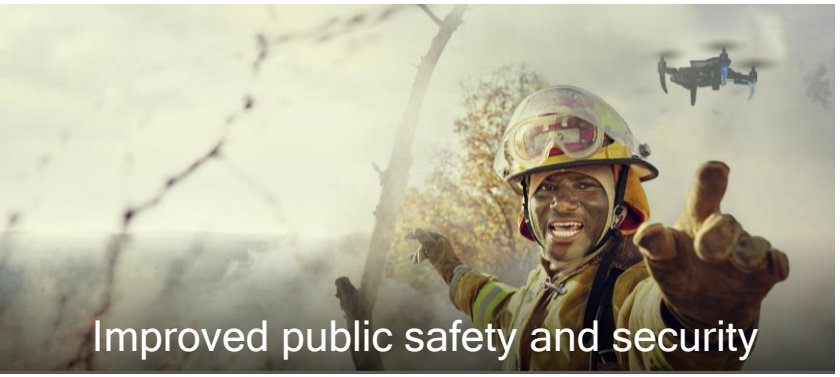
Convergence of spectrum types/bands, diverse services, and deployments, with new technologies to enable a robust, future-proof 5G platform

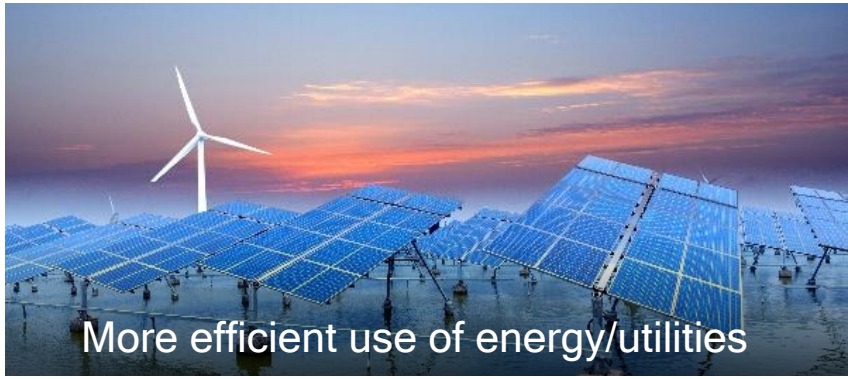
5G will redefine a wide range of industries

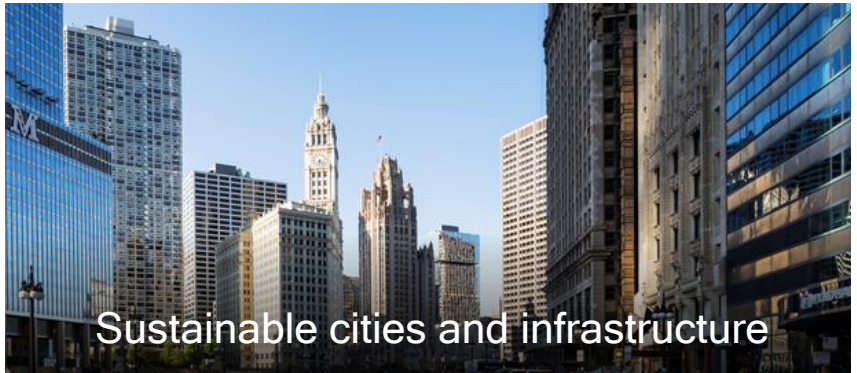
A platform for new connected services – existing, emerging and unforeseen



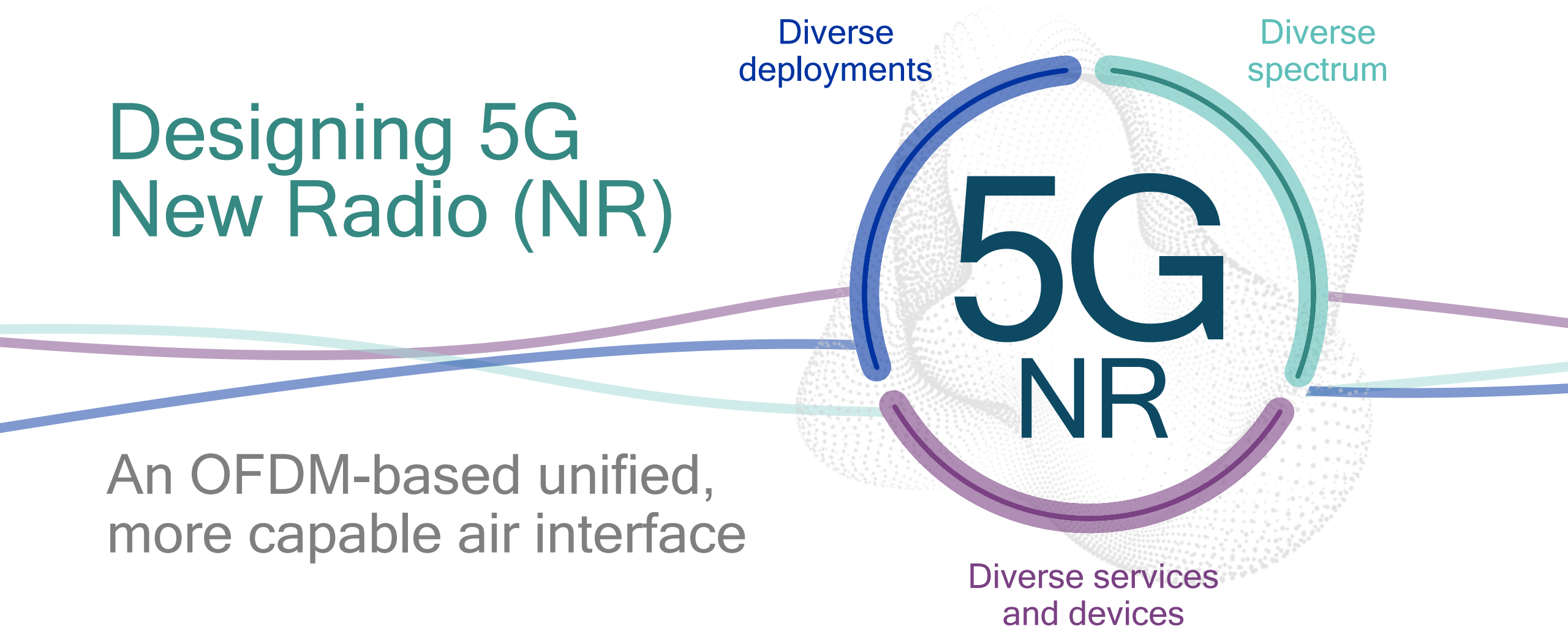






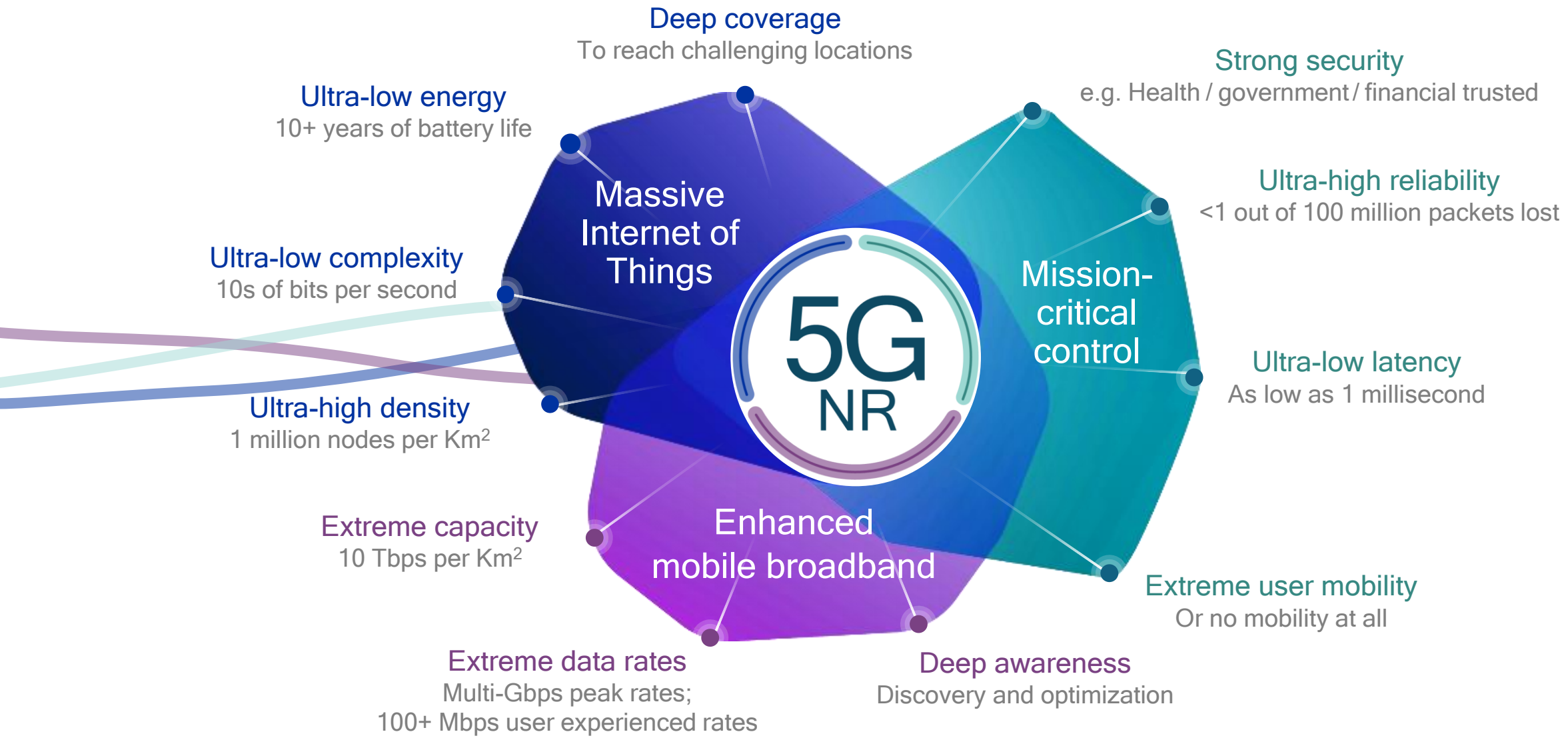


Designing 5G New Radio (NR)



An OFDM-based unified, more capable air interface

Scalability to address diverse service and devices



Based on target requirements for the envisioned 5G use cases

Getting the most out of every bit of diverse spectrum

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

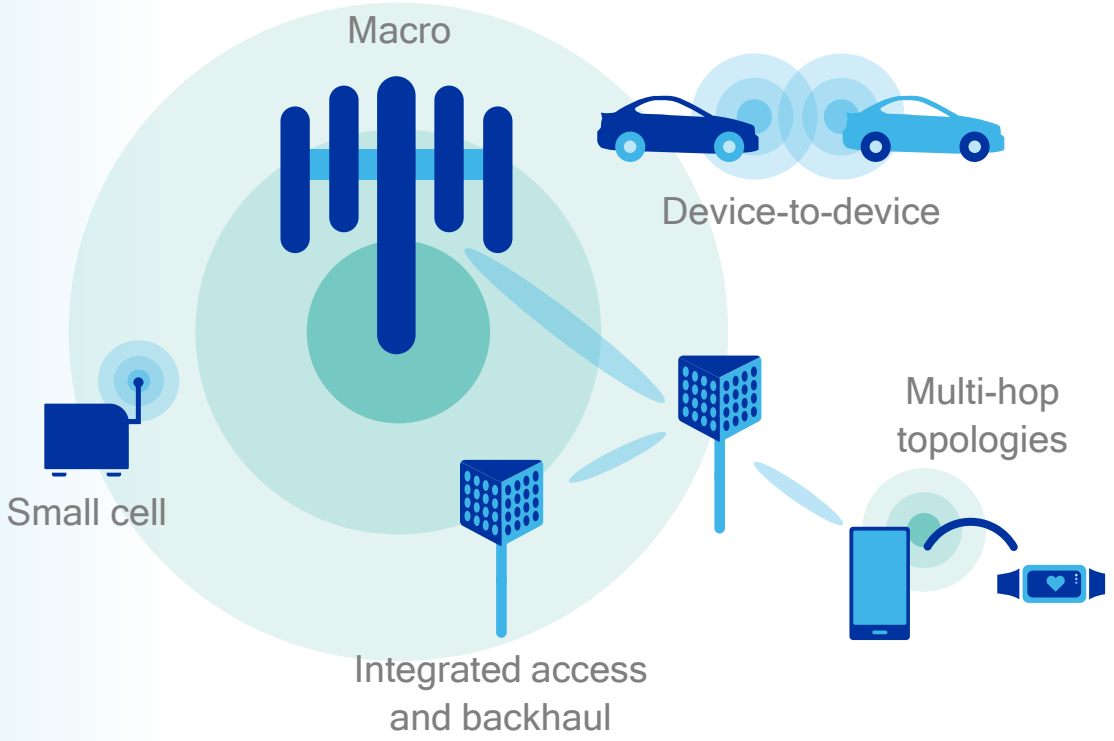
High bands above 24 GHz (mmWave): extreme bandwidths
e.g. 24.25-27.5 GHz, 27.5-29.5, 37-40, 64-71 GHz

Licensed Spectrum
Exclusive use

Shared Spectrum
New shared spectrum paradigms

Unlicensed Spectrum
Shared use

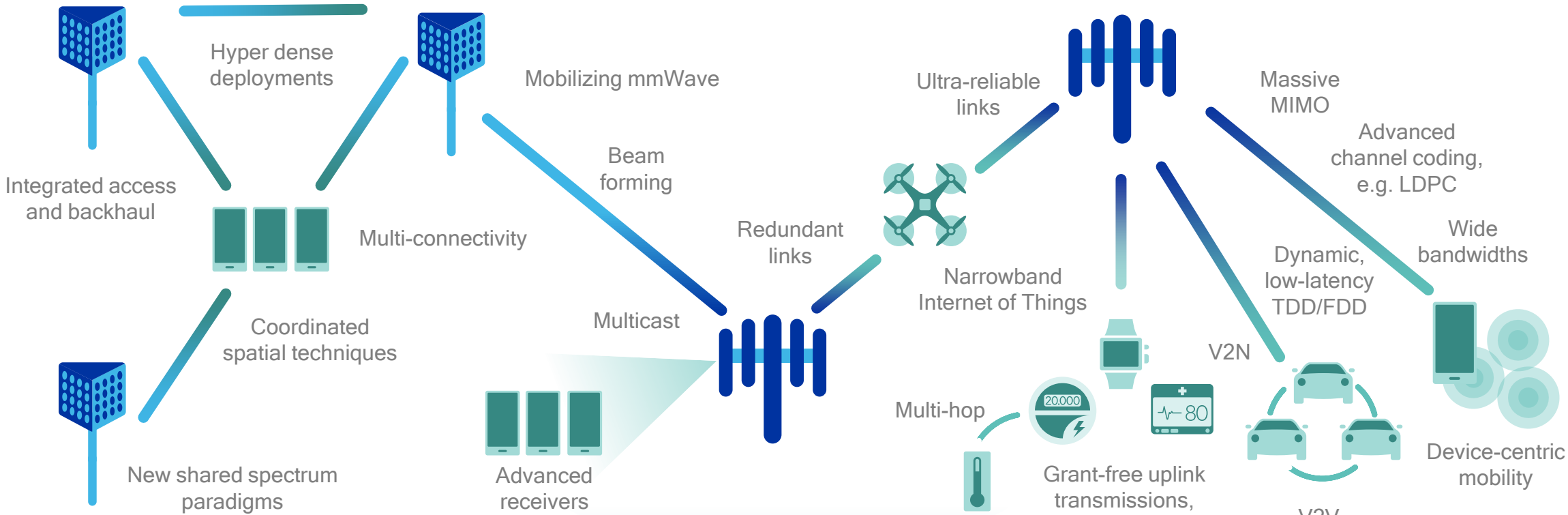
Adaptable to diverse deployments and topologies



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



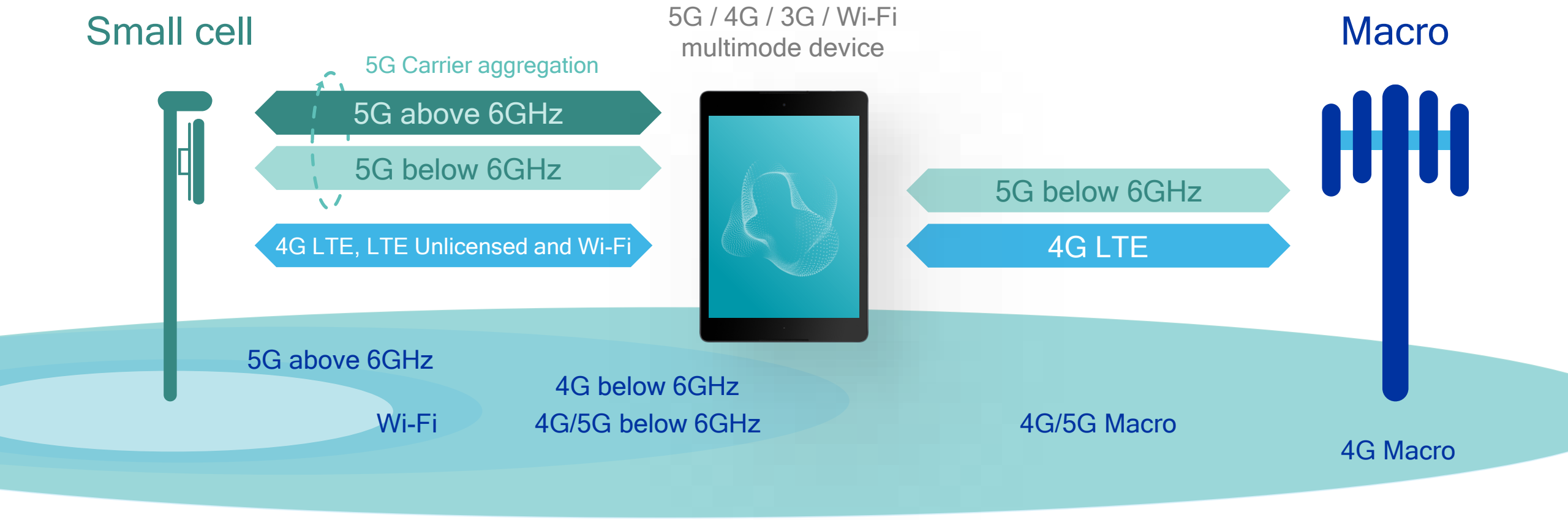
New levels of capability and efficiency

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

Based on ITU vision for IMT-2020 compared to IMT-advanced

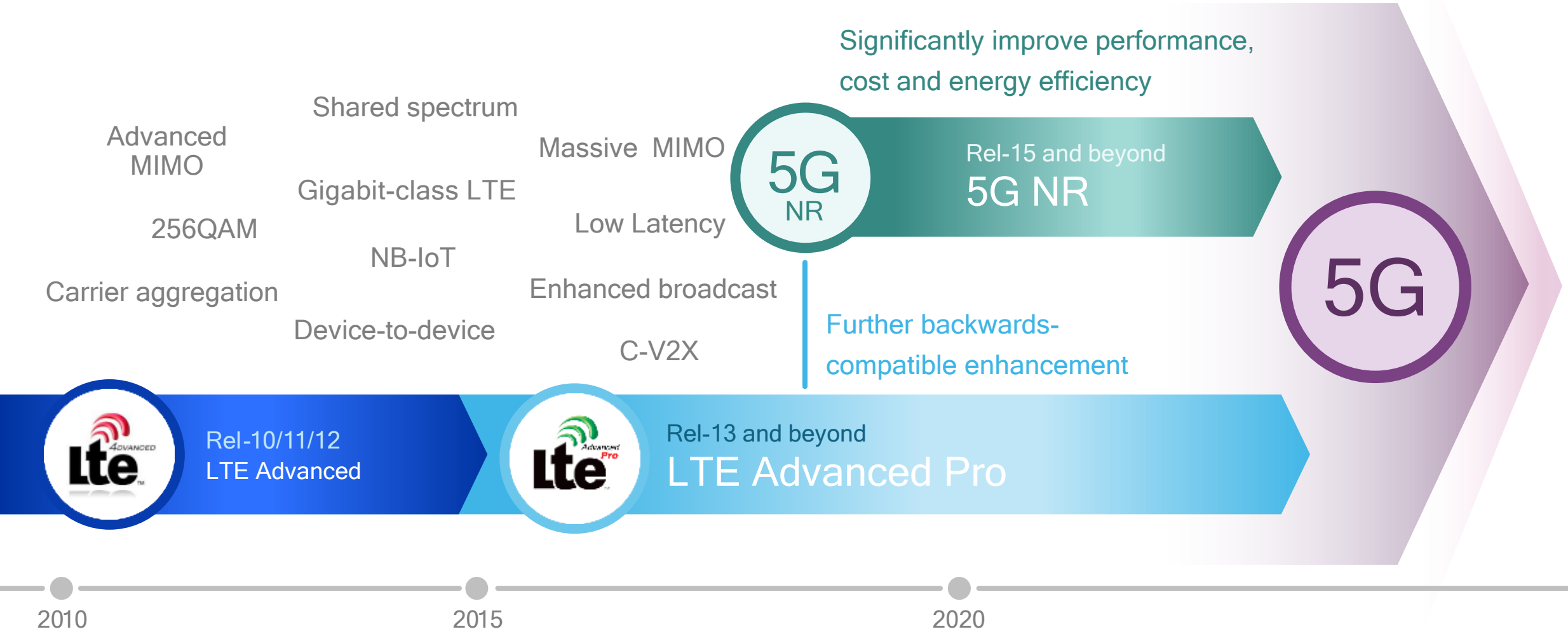
Simplifying 5G deployments with multi-connectivity

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



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



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

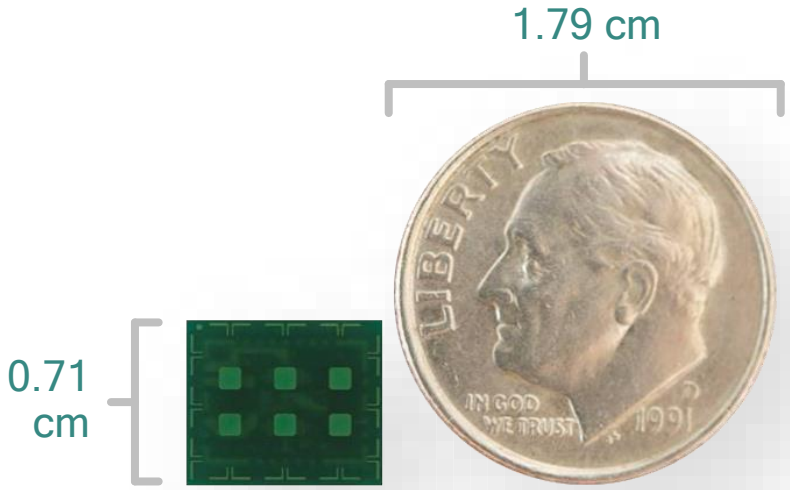
QUALCOMM®
Why Wait™

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

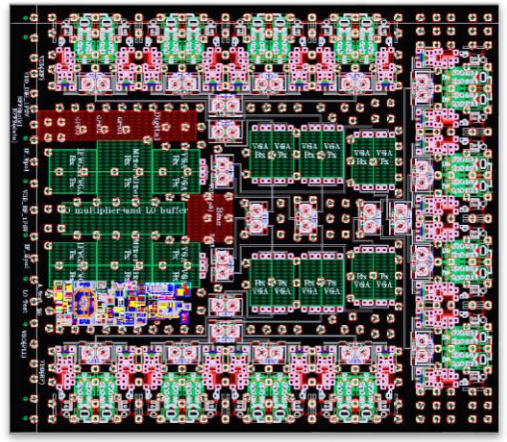


Qualcomm® VIVE™ 802.11ad 60 GHz technology with a 32-antenna array

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



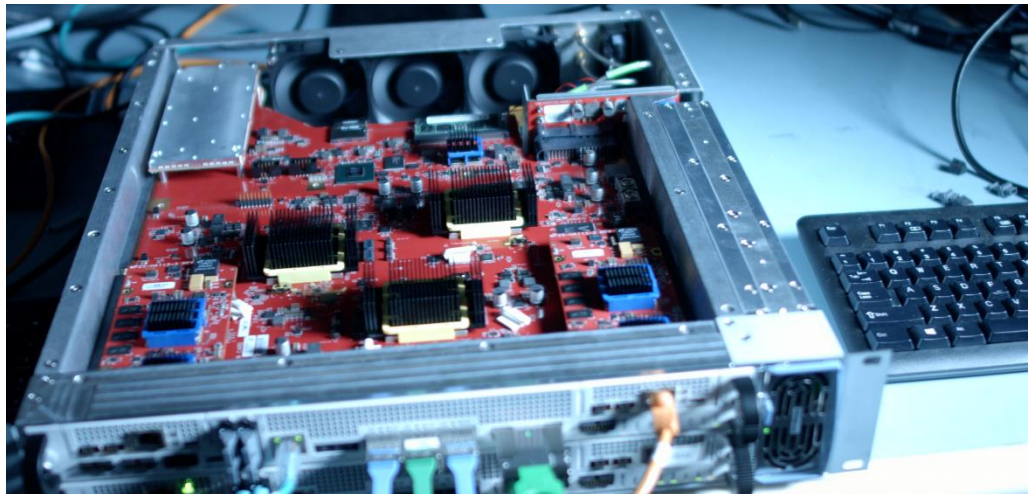
With integrated PA, LNA, phase shifter, power splitters for beamforming

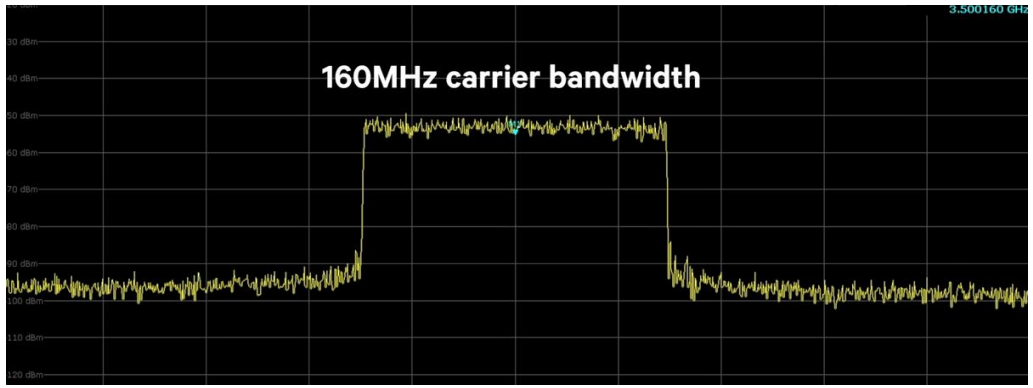
Qualcomm VIVE is a product of Qualcomm Atheros, Inc.

1 For limited regional fixed wireless deployments (e.g. Korea and US) operating at 28 and 39 GHz; also will be utilized for mobile wireless access trials to drive 5G NR standardization

Bringing new level of performance for sub-6 GHz

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





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

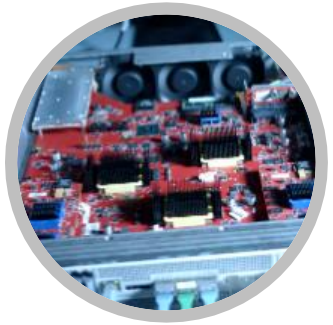
Will enable impactful 5G NR trials

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



Test, demonstrate and verify our innovative 5G designs to contribute to and drive standardization

5G standards, technology and research leadership

3GPP™

A GLOBAL INITIATIVE

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

Impactful trials and early deployments with network operators

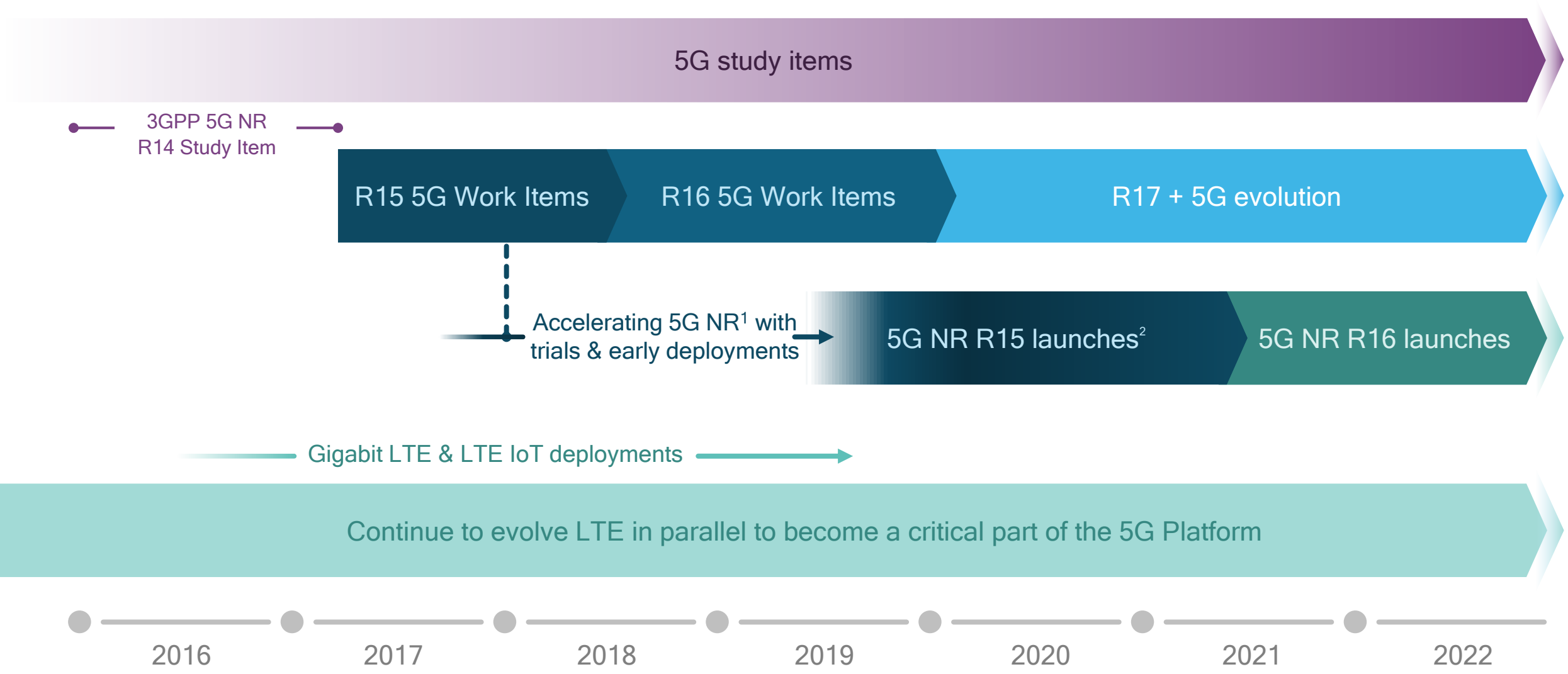
Over-the-air interoperability testing leveraging prototype systems and our leading global network experience

Modem and RFFE leadership to solve 5G complexity

Qualcomm snapdragon™

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

5G NR standardization progressing for 2019 launches



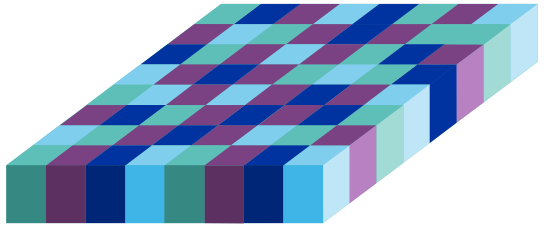
Note: Estimated commercial dates. 1 The latest plenary meeting of the 3GPP Technical Specifications Groups (TSG#72) has agreed on a detailed workplan for Release-15; 2 Forward compatibility with R16 and beyond

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

For enhanced mobile broadband and beyond

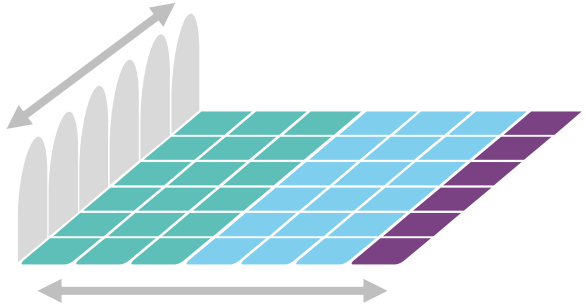
Optimized OFDM-based waveforms

With scalable numerology and TTI, plus optimized multiple access for different use cases



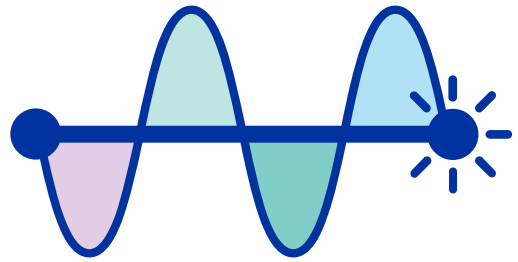
A common, flexible framework

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



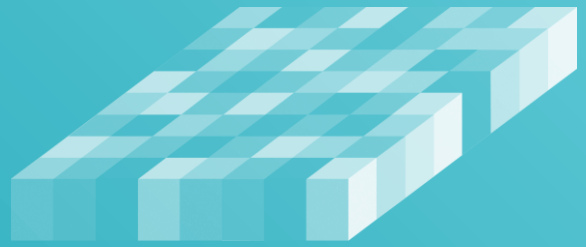
Unified design across spectrum types and bands

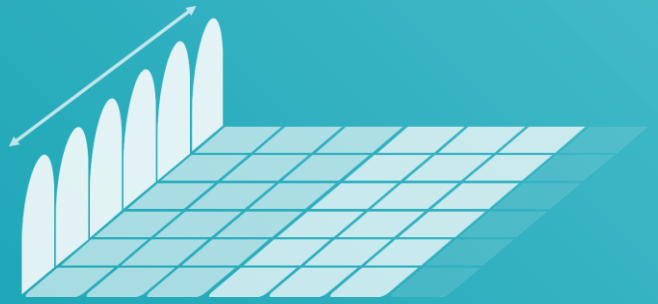
For licensed and shared/unlicensed spectrum bands both below 6 GHz and above 6 GHz[2]

[1] 3GPP R16+ will bring continued eMBB evolution, plus new features for massive IoT and mission-critical; [2] 3GPP R15 focused on spectrum bands up to ~40 GHz; R16+ will bring support for bands up to ~100 GHz

Designing 5G NR

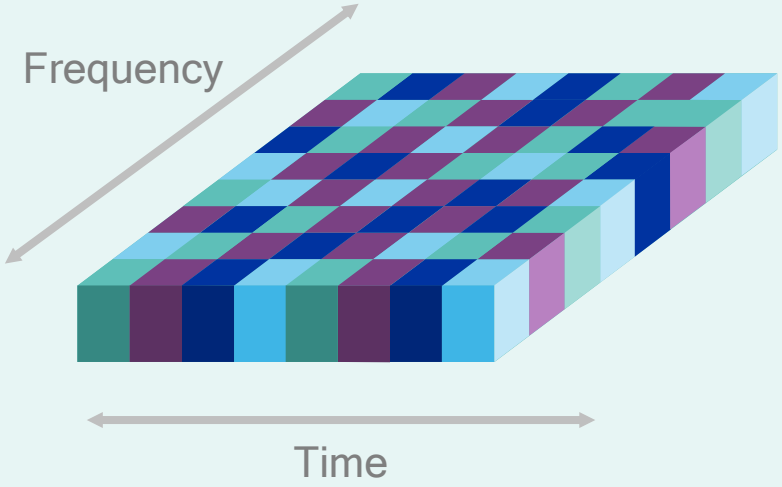
Leading the technology innovations for a unified, more capable 5G air interface





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

Adapted for scaling to an extreme variations of 5G requirements



Spectral efficiency

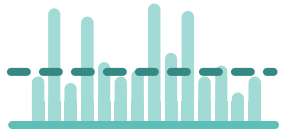
Efficient framework for MIMO spatial multiplexing

Low complexity

Low complexity receivers even when scaling to wide bandwidths

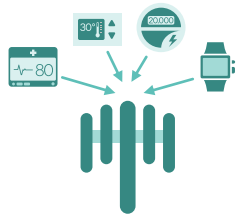
Frequency localization

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

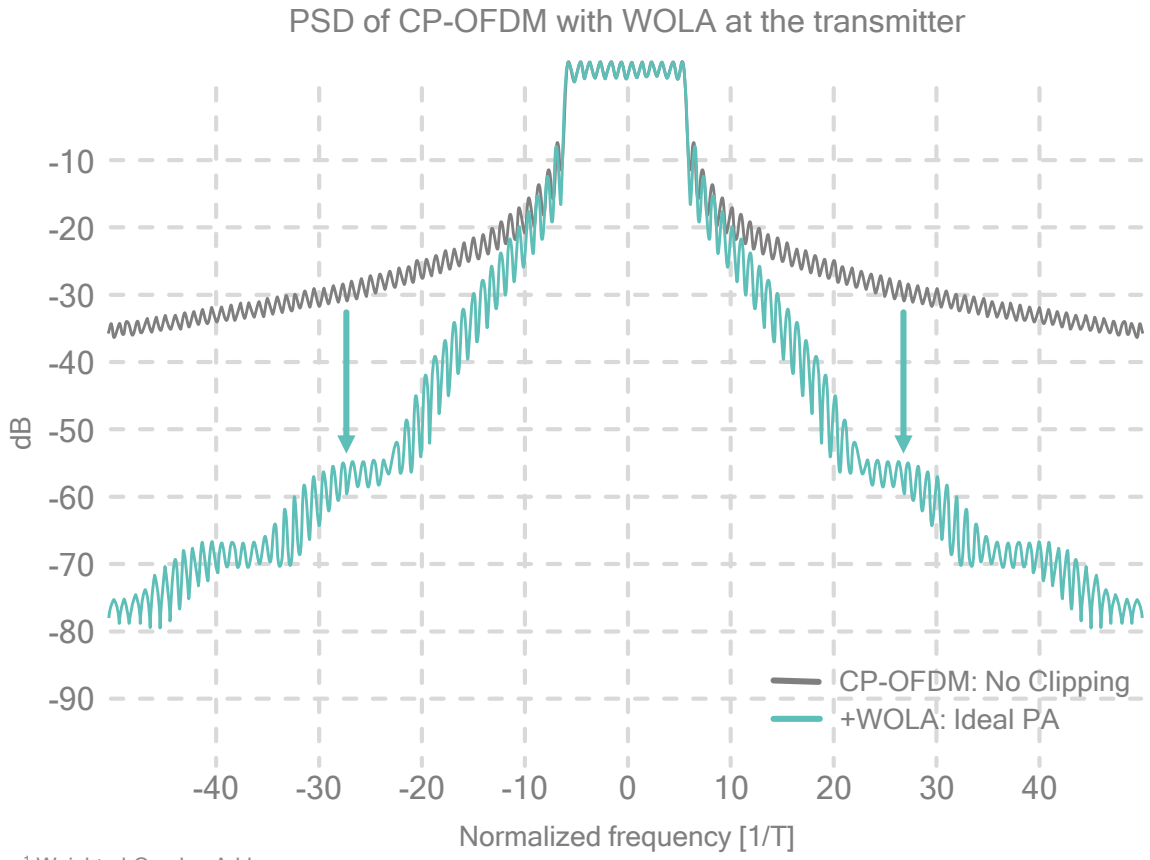
Co-exist with optimized waveforms and multiple access for wide area IoT

[1] Weighted Overlap Add; [2] Such as Resource Spread Multiple Access (RSMA) - more details later in presentation

Efficient service multiplexing with windowed OFDM

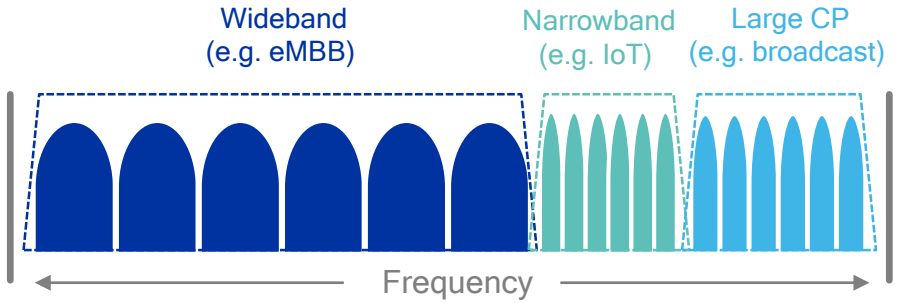
OFDM with WOLA[1] windowing

Substantially increases frequency localization



Key for 5G service multiplexing

Mitigate interference between flexible sub-carriers



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

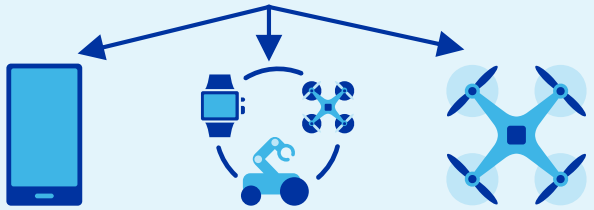
[1] Weighted Overlap Add

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

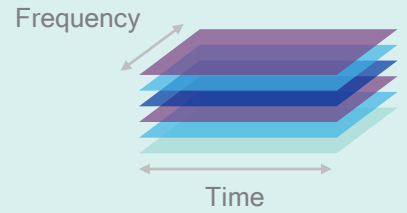
Massive IoT

Low energy single-carrier[2]

Mission-critical

CP-OFDM / SC-OFDM[1]

+



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

Forward compatibility

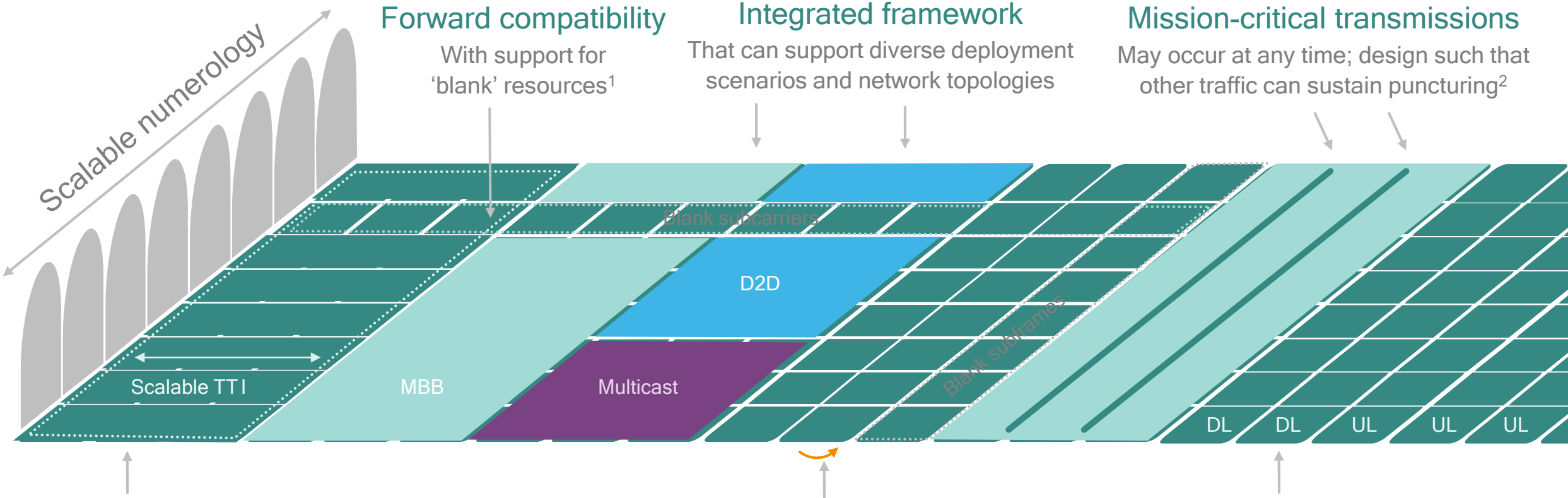
With support for 'blank' resources[1]

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]



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

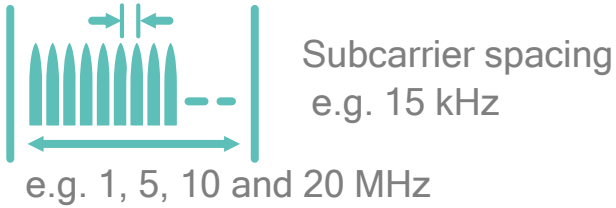
Faster switching for more flexible capacity based on traffic conditions

[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

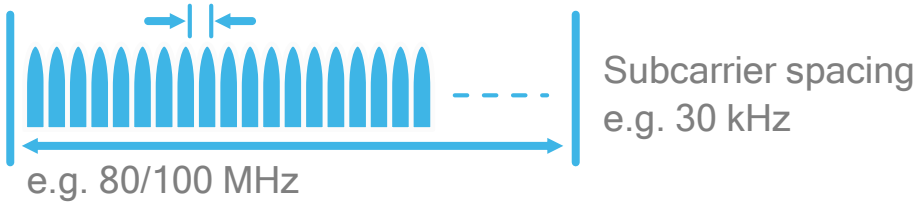
Scalable numerology with scaling of subcarrier spacing

Efficiently address diverse spectrum, deployments and services

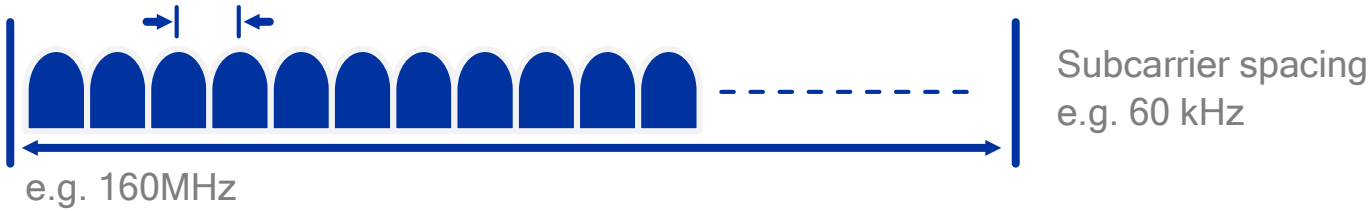
Outdoor and macro coverage
FDD/TDD <3 GHz



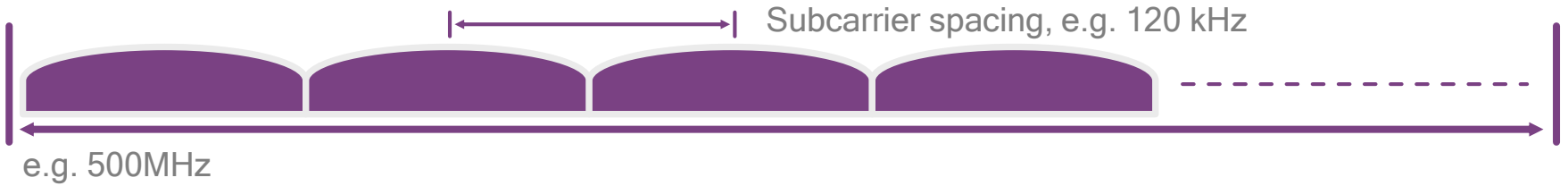
Outdoor and small cell
TDD > 3 GHz



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



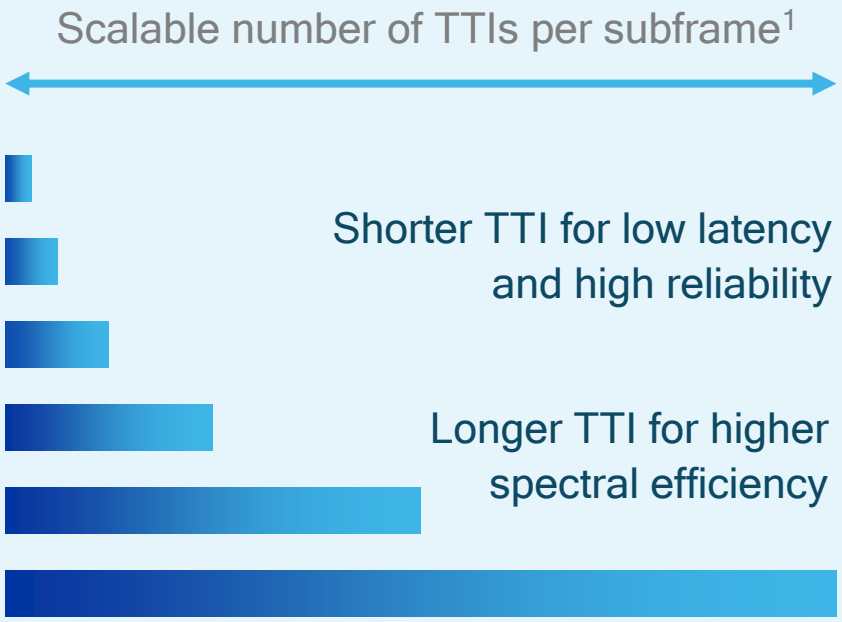
mmWave
TDD e.g. 28 GHz



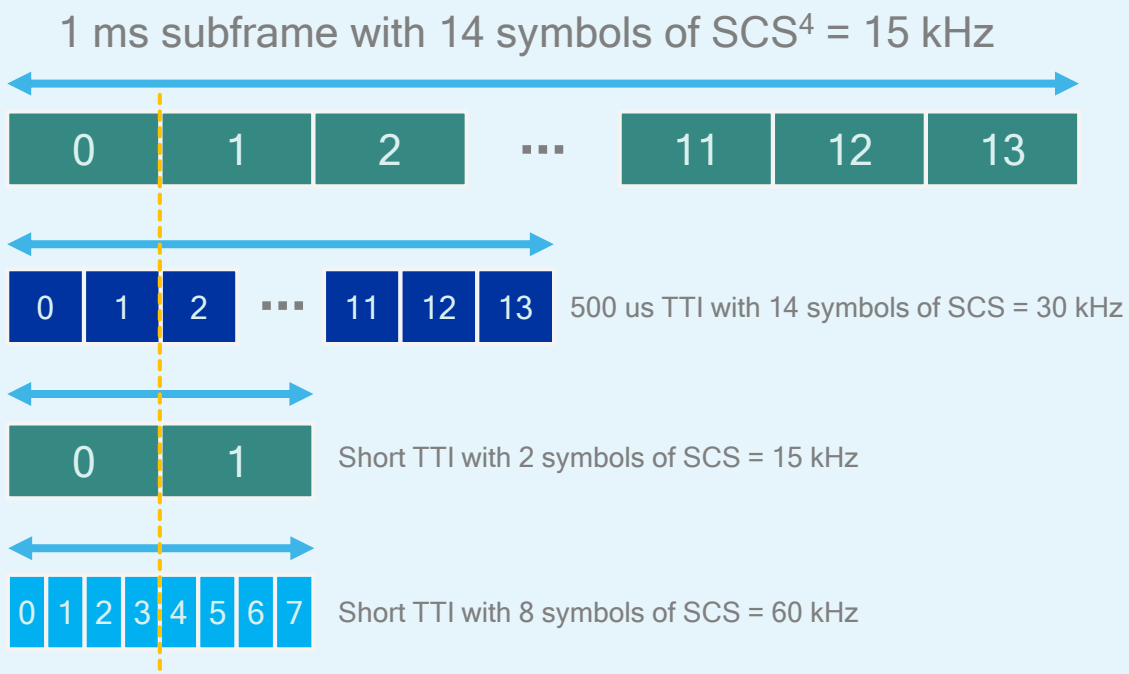
Example usage models and channel bandwidths

Scalable Transmission Time Interval (TTI)

Scalable TTI for diverse latency and QoS requirements



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



[1] Further bundling of TTIs possible; 2 Symbols across numerologies align at symbol boundaries; 3 TTI spans integer number of symbols; 4 Subcarrier spacing

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

Example: TDD downlink

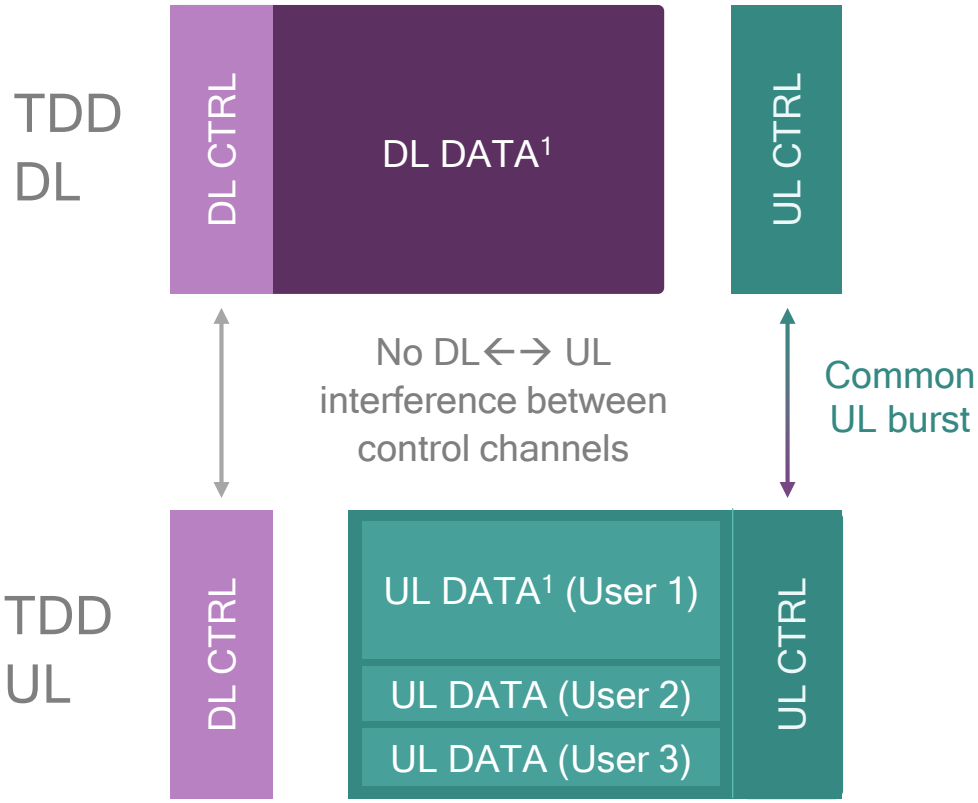
D2D, mesh and relay
Headers for e.g. direction of the link for dynamic distributed scheduling

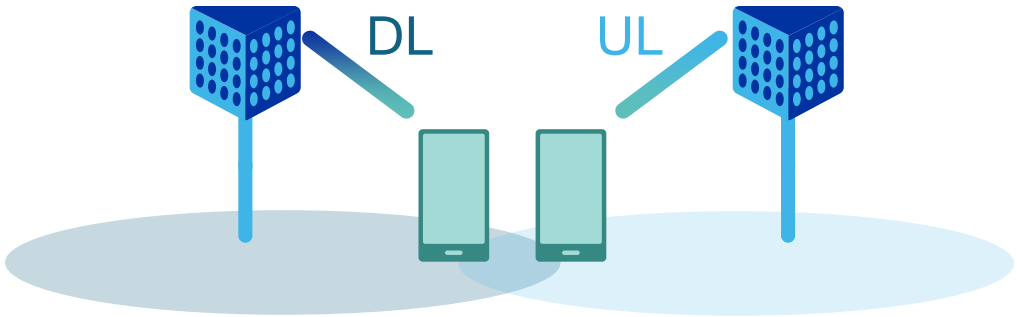
Massive MIMO
Leveraging channel reciprocity in UL transmission for DL beamforming training

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





- Allows for robust, dynamic DL/UL switching driven by different loading and traffic types
- Enables integrated access and backhaul co-channel deployments for mmWave

[1] Can also be control information

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

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

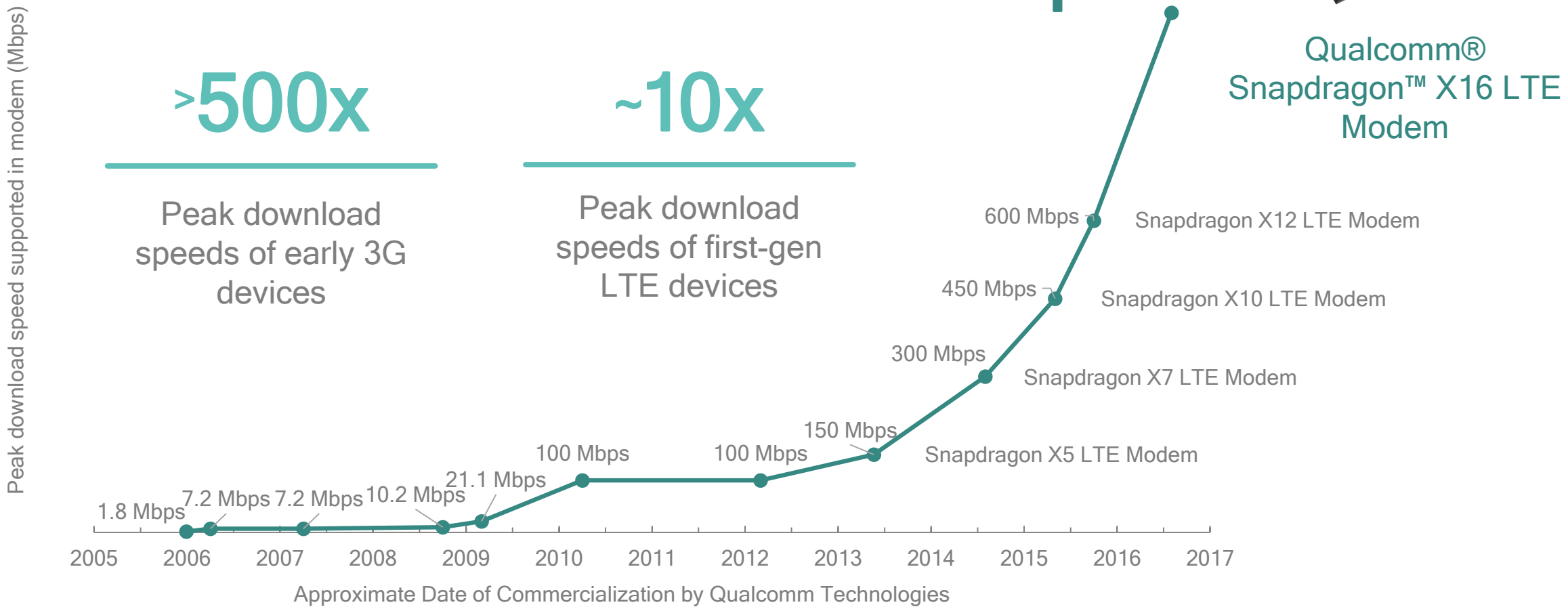
Qualcomm® Snapdragon™ X16 LTE Modem

>500x

Peak download speeds of early 3G devices

~10x

Peak download speeds of first-gen LTE devices

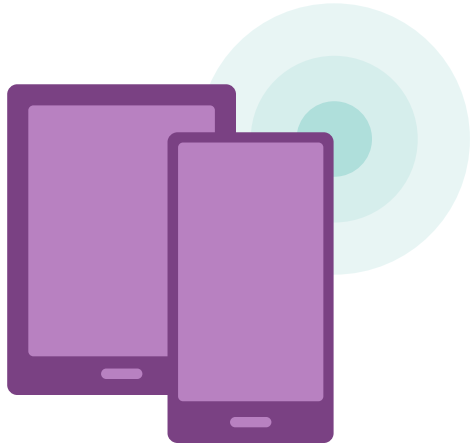


Qualcomm Snapdragon is a product of Qualcomm Technologies, Inc.

Subject to network availability

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

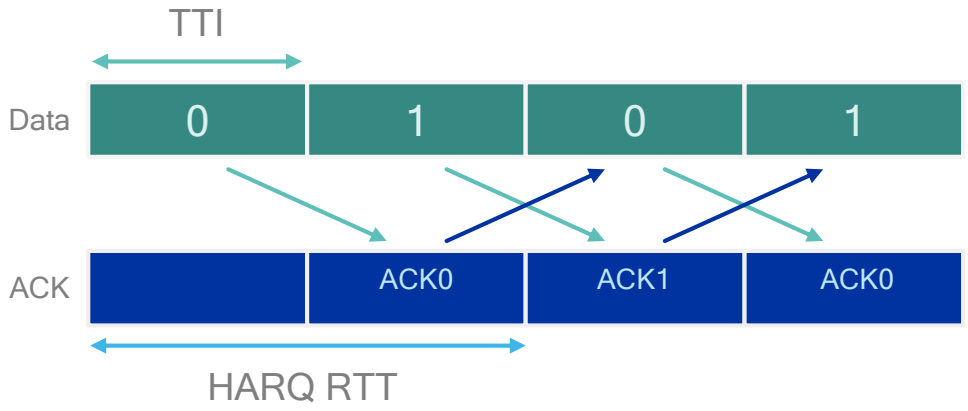
Exploit 3D beamforming (FD-MIMO) to increase capacity and coverage

Designing 5G NR for significantly lower latency

10x lower latency than today's LTE networks

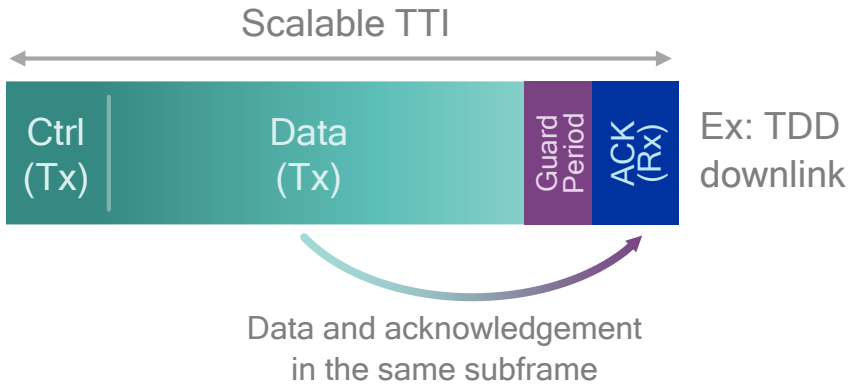
FDD

Fewer (variable) interlaces for HARQ[1]



TDD

Self-contained design reduces RTT



Improved performance by addressing TCP/UDP throughput limitations

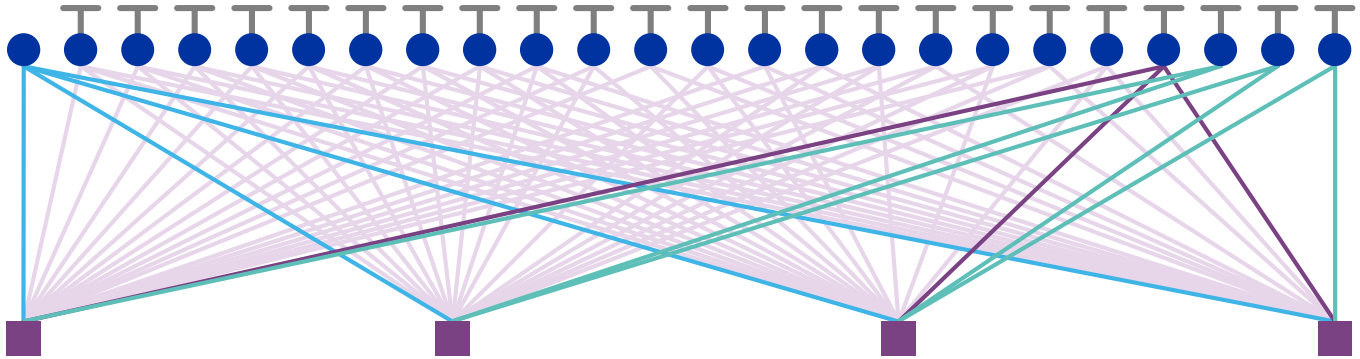
Better user experience for real-time applications such as Video-over-IP applications

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

1 Compared to LTE's 8 HARQ interlaces

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

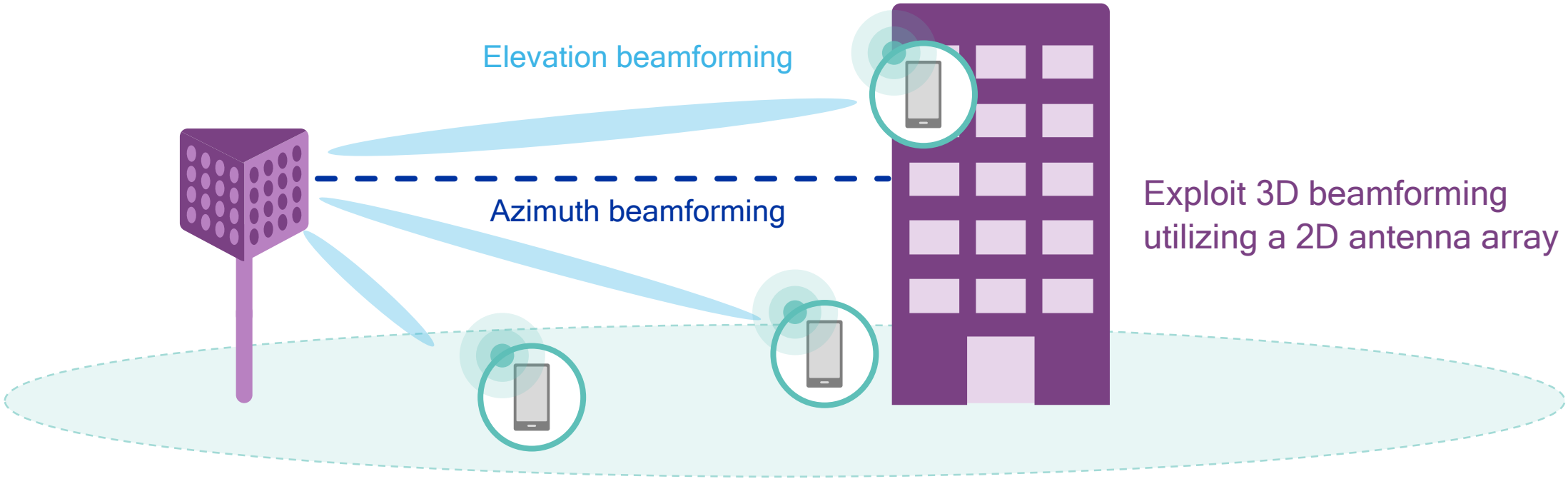
Efficient encoding/decoding enables shorter TTI

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



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

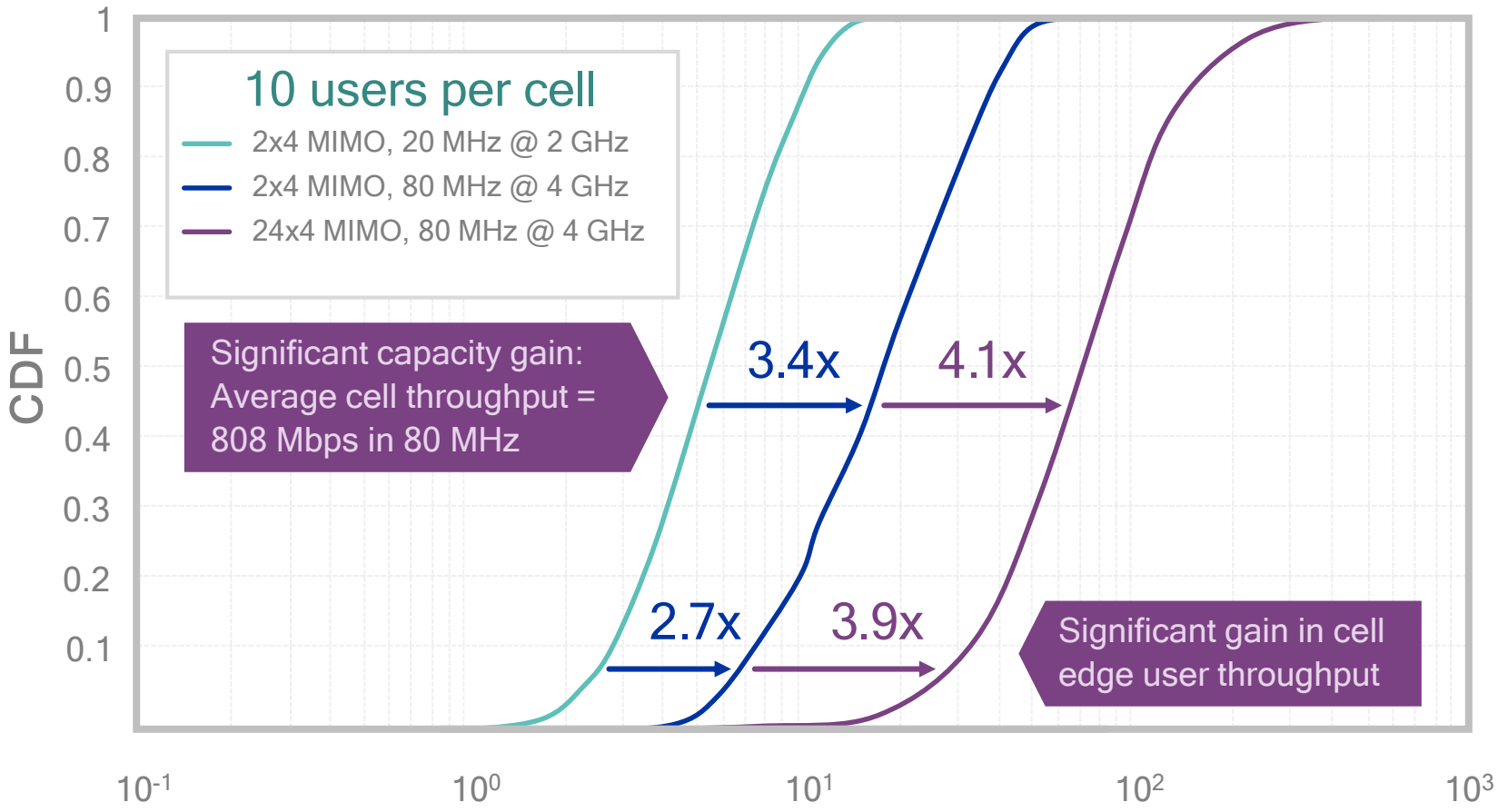
LTE Rel. 13 (FD-MIMO)
2D codebook support for 8-, 12- and 16-antenna elements with Reference Signal enhancements for beamforming

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

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

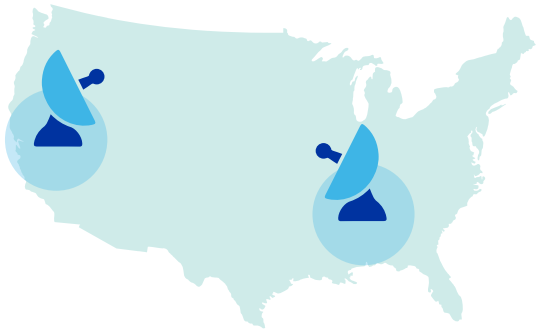


Source: Qualcomm Technologies, Inc. simulations; Macro-cell with 1.7km inter-site distance, 10 users per cell, 46 dBm Tx power at base station, 20MHz@2GHz and 80MHz@4GHz BW TDD, 2.4x Massive MIMO

Shared/unlicensed spectrum is important for 5G

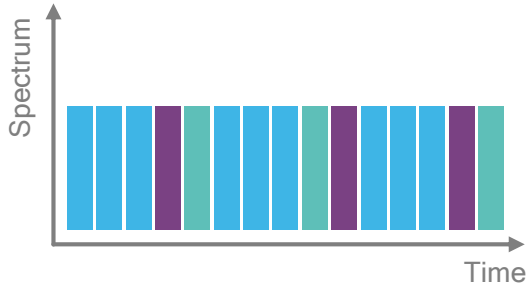
Unlocking more spectrum

Shared spectrum can unlock spectrum that is lightly used by incumbents



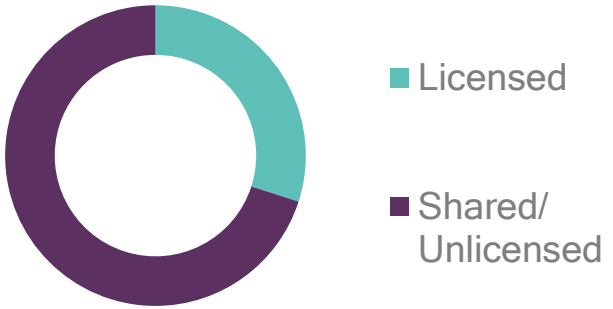
High spectrum utilization

Spectrum sharing has the potential to increase spectrum utilization



A lot of spectrum may be shared/unlicensed

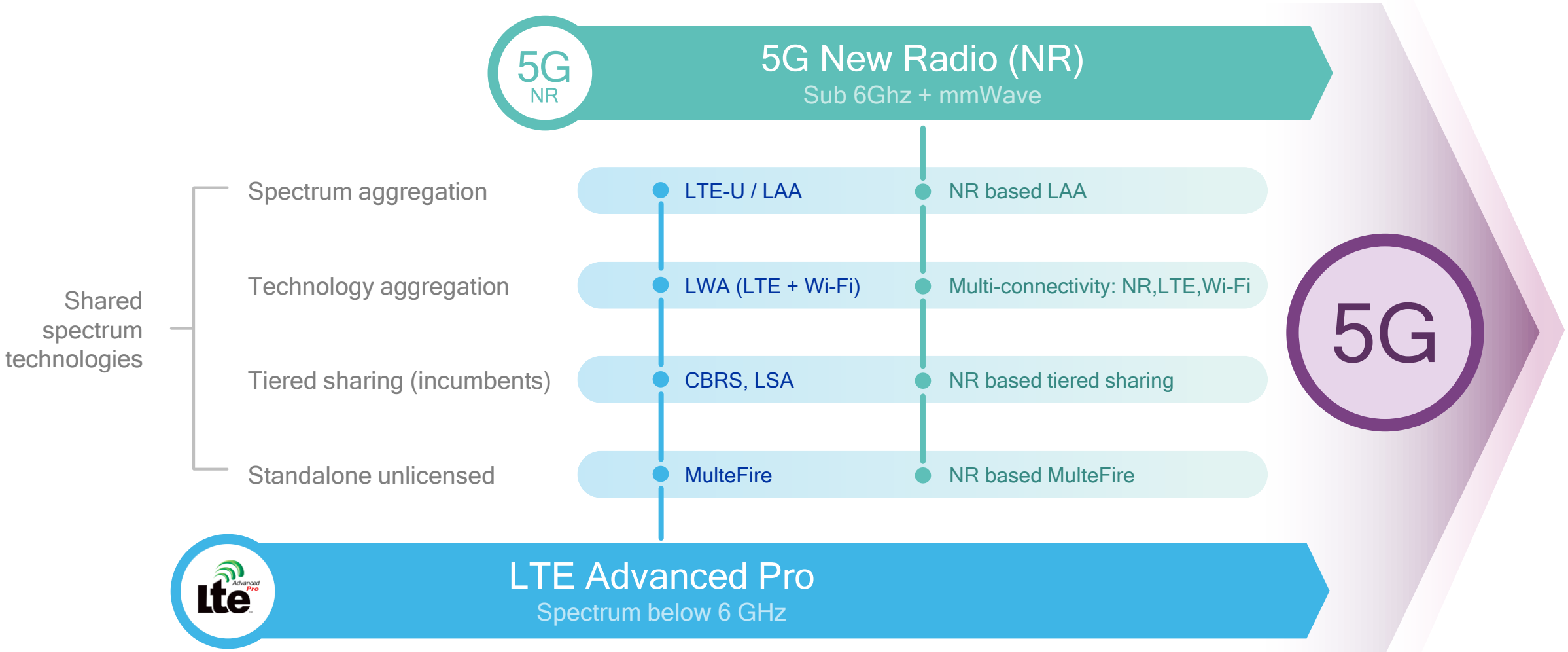
FCC recent decision on high-band spectrum included a significant portion of shared/unlicensed[1]



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.

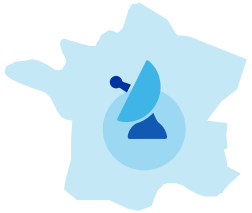
We are pioneering 5G shared spectrum today

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



1) Licensed-Assisted Access (LAA), LTE Wi-Fi Link Aggregation (LWA), Citizen Broadband Radio Service (CBRS), Licensed Shared Access (LSA)

Pioneered shared/unlicensed spectrum in 4G LTE



LSA[1]

Technically extensive pilot in France with Ericsson and Red in Jan 2016

LTE-U

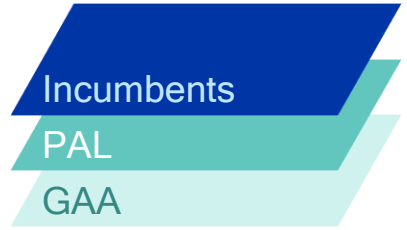
We designed the original proposal, commercialized by the LTE-U forum

LAA[2]

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

MULTEFIRE™

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



CBRS[3]

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

1) Licensed Shared Access (LSA); 2) Licensed-Assisted Access (LAA); 3) Citizen Broadband Radio Service (CBRS), Priority Access Licenses (PAL), General Authorized Access (GAA)

Realizing the mmWave opportunity for mobile broadband

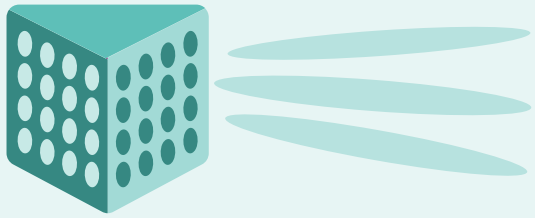
Extreme bandwidth opportunity

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

Mobilizing mmWave challenge

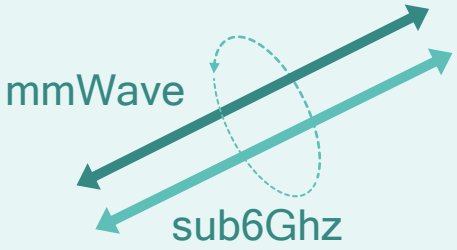
- Robustness due to high path loss and susceptibility to blockage
- Device cost/power and RF challenges at mmWave frequencies

5G NR



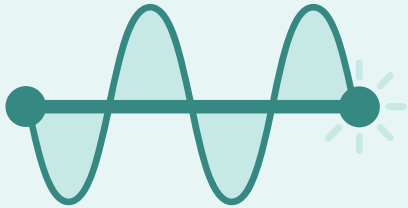
Smart beamforming and beam tracking

Increase coverage and minimize interference



Tight interworking with sub 6 GHz

Increase robustness, faster system acquisition



Optimized mmWave design for mobile

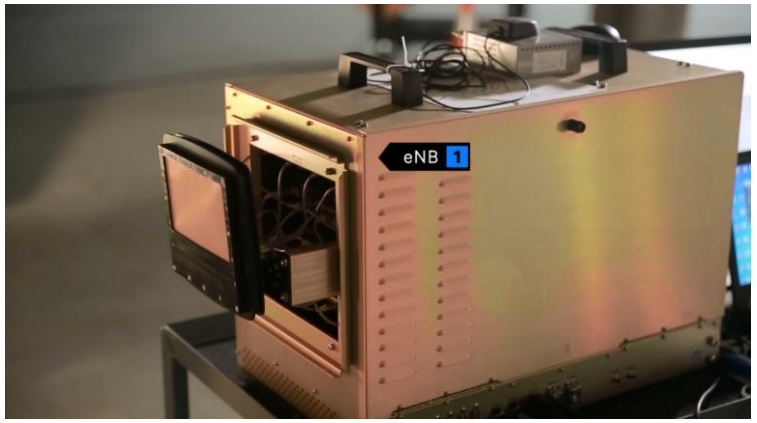
To meet cost, power and thermal constraints

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

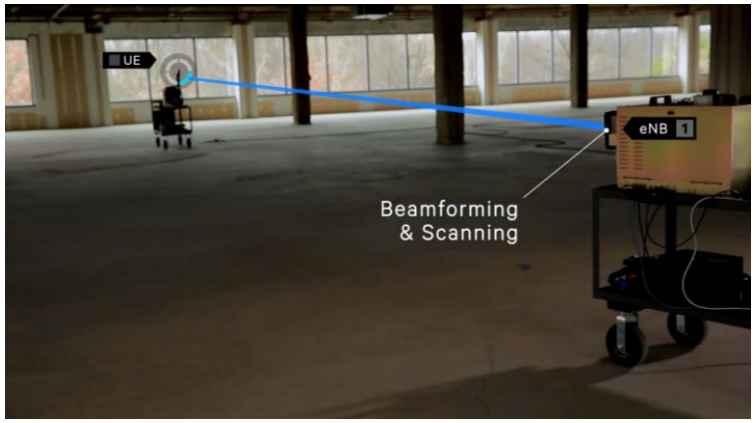
Mobilizing mmWave–live demonstration of our prototype

Millimeter Wave UE

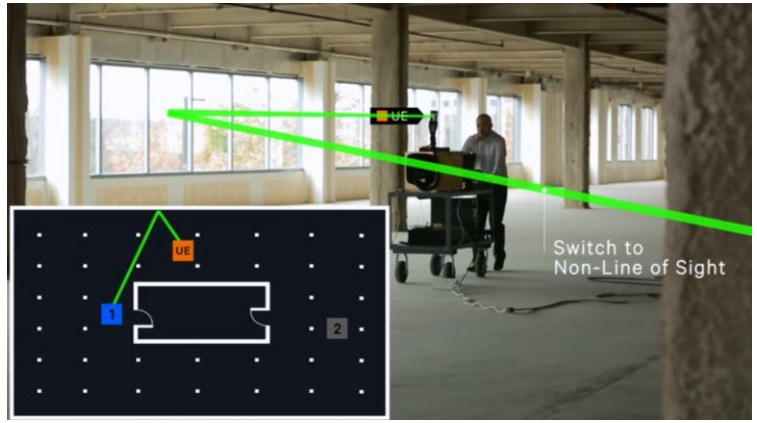
Millimeter wave base station



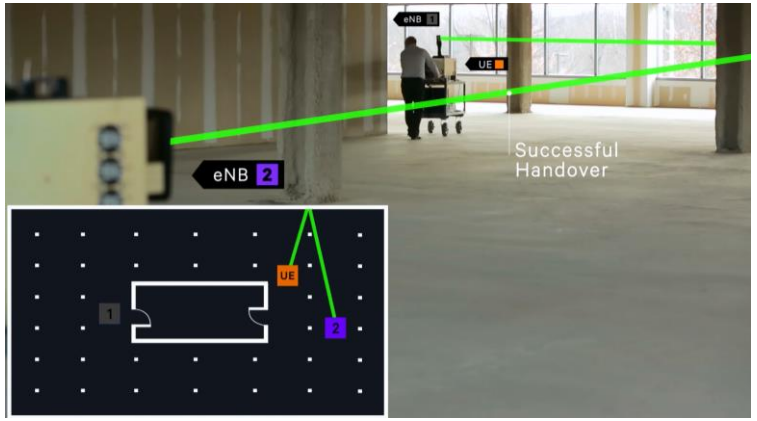
Beamforming and scanning



Non-line-of-sight through reflection



Handover



Outdoor

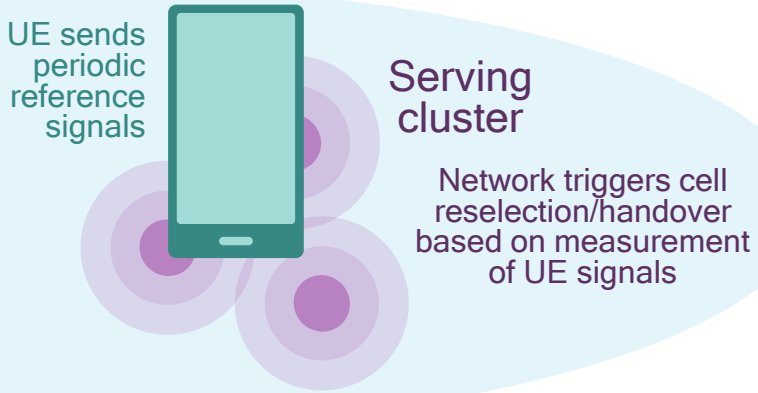
Learn more at: www.qualcomm.com/videos/mobilizing-mmwave-5g

Device-centric mobility management in 5G NR

Control plane improvements to improve energy and overhead efficiency

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]

1 Coordinated MultiPoint is an LTE Advanced feature to send and receive data to and from a UE from several access nodes to ensure the optimum performance is achieved even at cell edges;

2 Minimum system information is broadcast periodically, other system information available on demand; may dynamically revert to broadcast system info when needed, e.g. system info changes

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

[1] Including Cellular & LPWA M2M connections, Machina Research, June, 2016

We are evolving LTE for the Internet of Things

Paving the path to Narrowband 5G for massive IoT

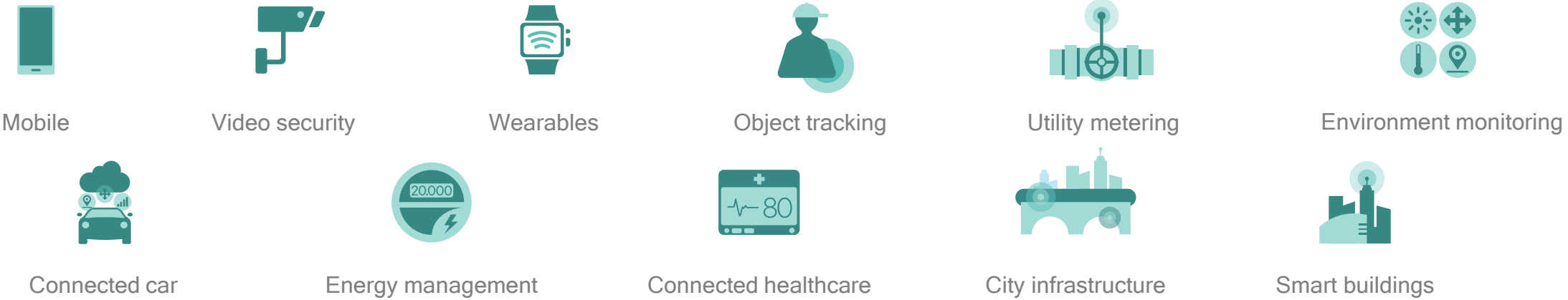
Scaling up in performance and mobility

Scaling down in complexity and power

Today

New narrowband IoT technologies (3GPP Release 13+)

LTE Cat-4 and above	LTE Cat-1	LTE Cat-M1 (eMTC)	Cat-NB1 (NB-IoT)
>10 Mbps	Up to 10 Mbps	Variable rate up to 1 Mbps	10s of kbps
n x 20 MHz	20 MHz	1.4 MHz narrowband	200 kHz narrowband



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

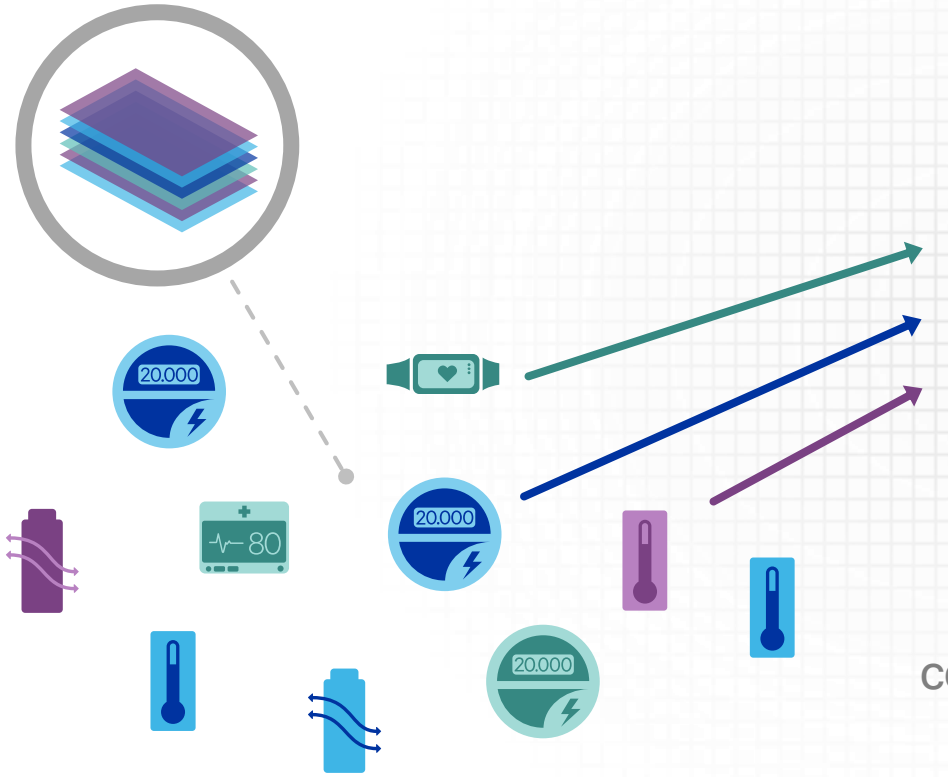
[1] Resource Spread Multiple Access

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



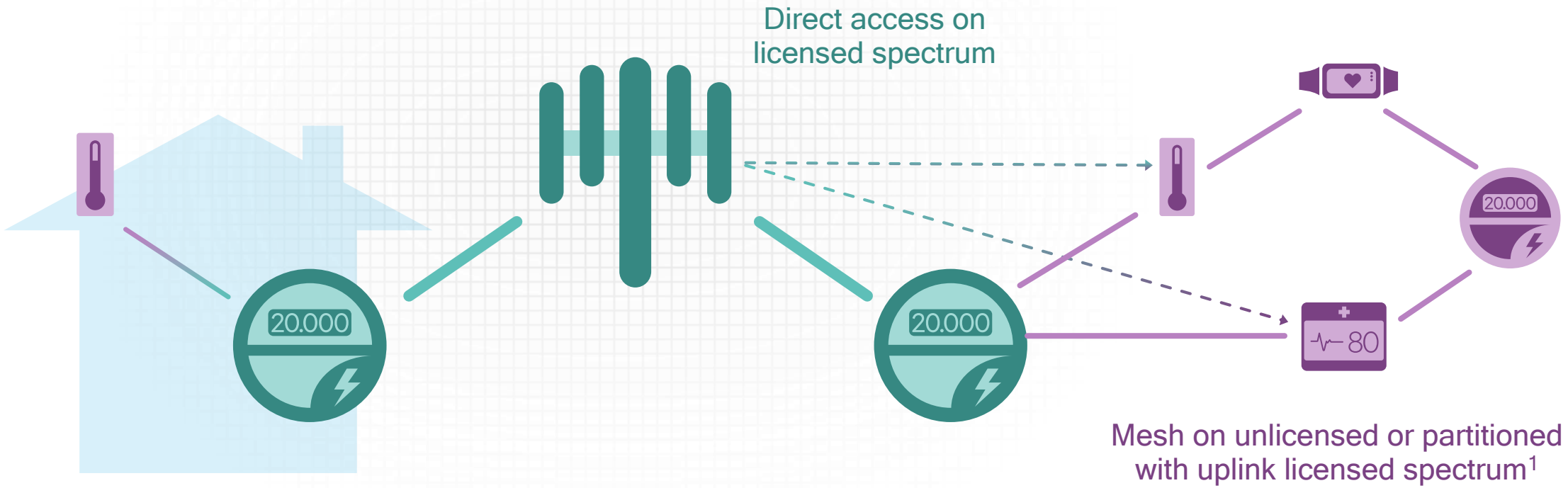
Downlink remains OFDM-based for coexistence with other services

Increased battery life

Scalability to massive # of things

Better link budget

Support for multi-hop mesh with WAN management



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.

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

5G

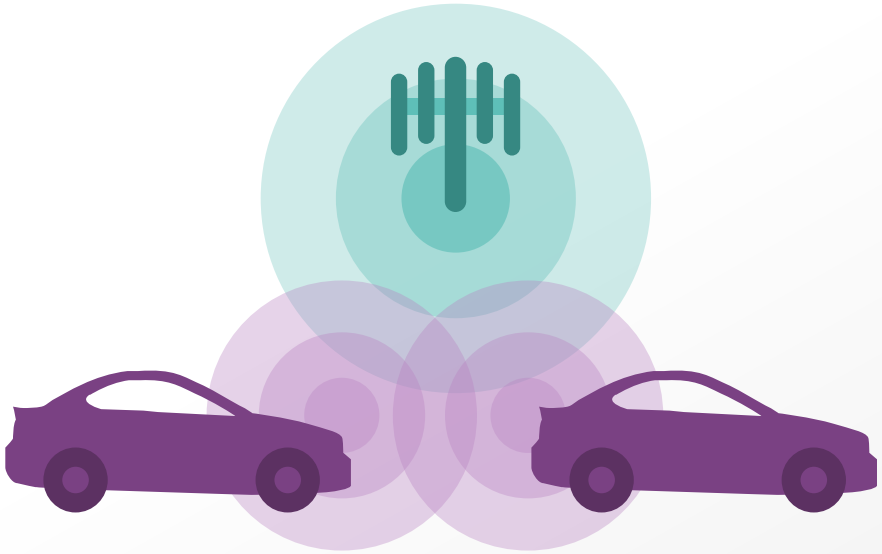
Enabling mission-critical services

High reliability

Ultra-low latency

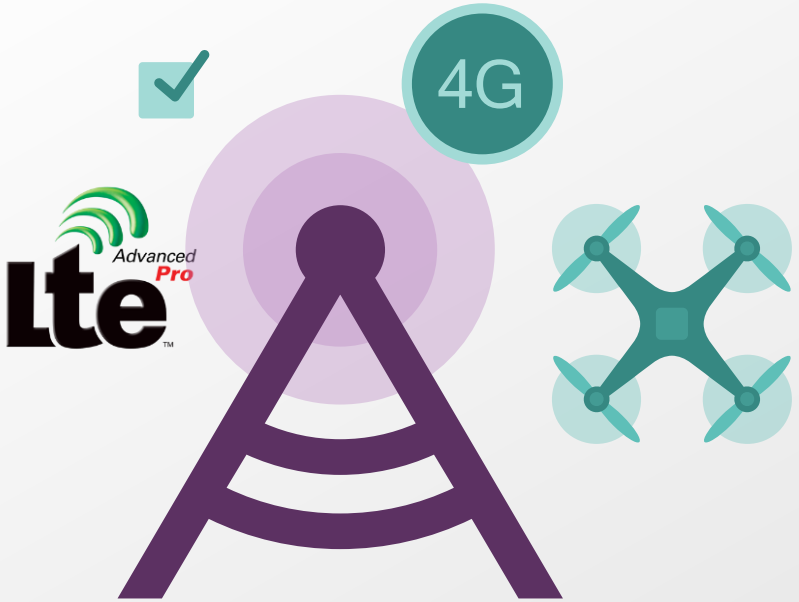
High availability

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

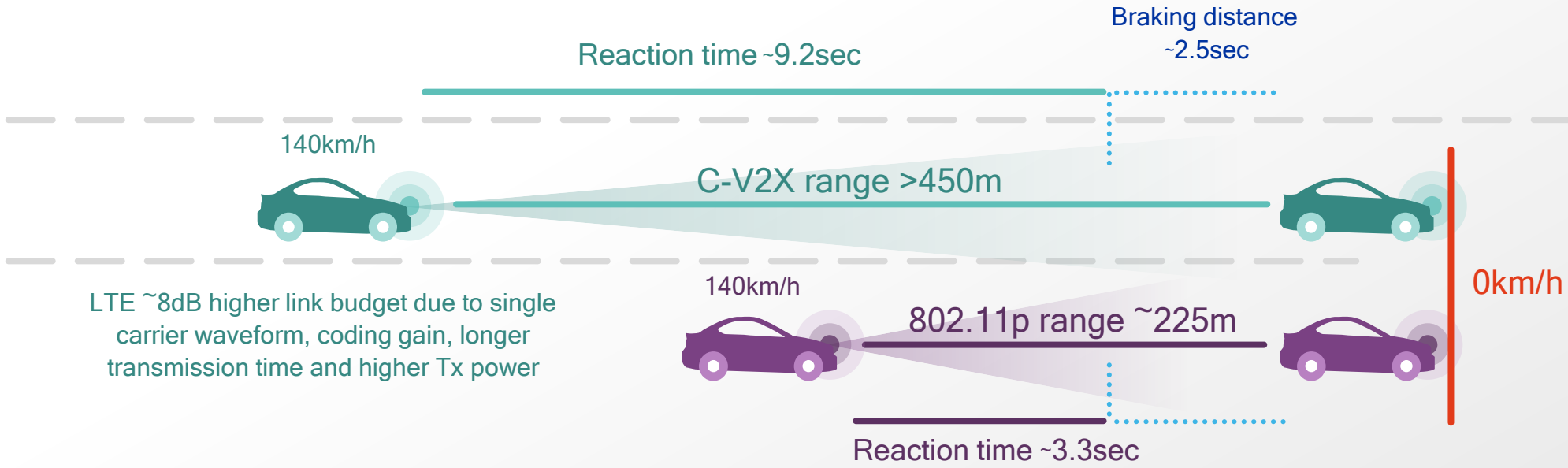


Cellular drone communications

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



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

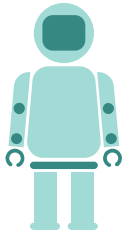
Opportunities for optimization

- Interference management
- Handover optimization
- LTE Drone Specific Requirements

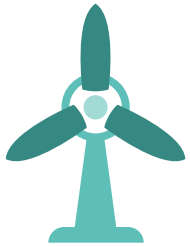
5G NR will enable new mission-critical control services

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

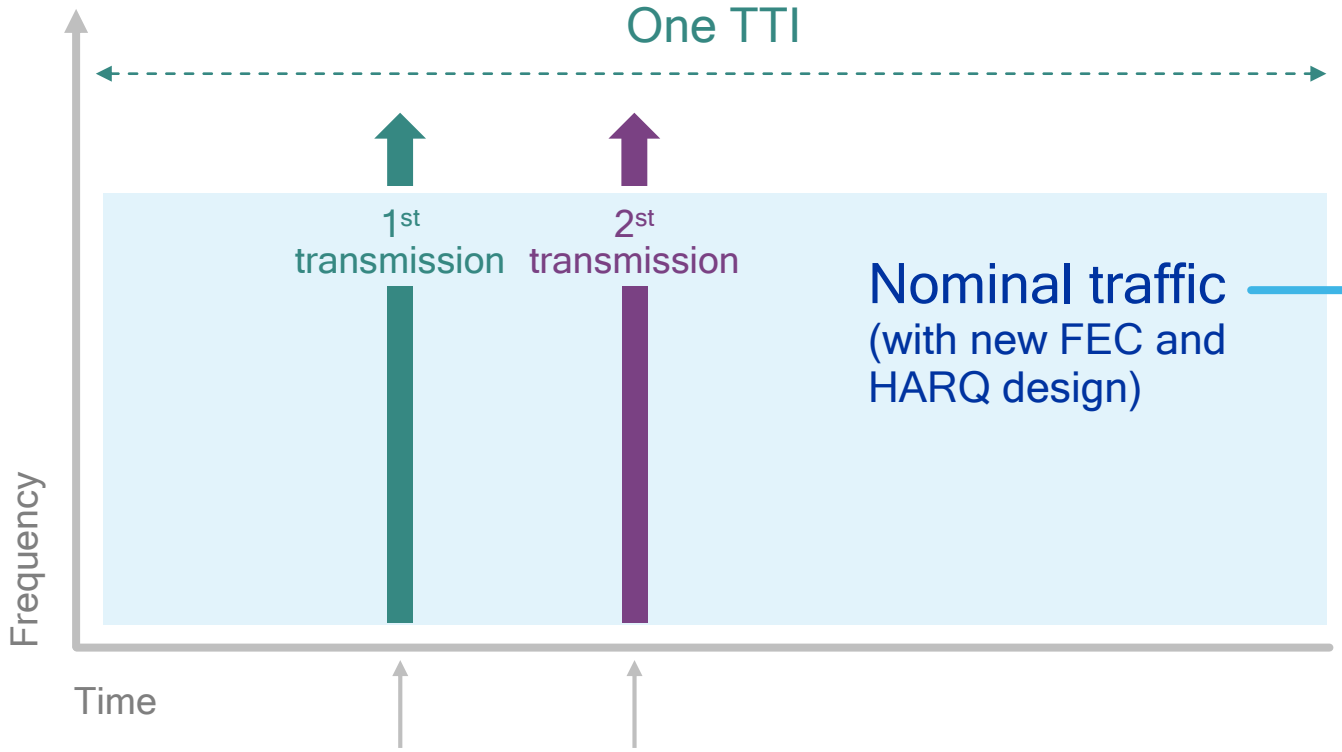
Strong e2e security

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)



Nominal traffic
(with new FEC and HARQ design)

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

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

Opportunity for uplink RSMA non-orthogonal access using OFDM waveforms

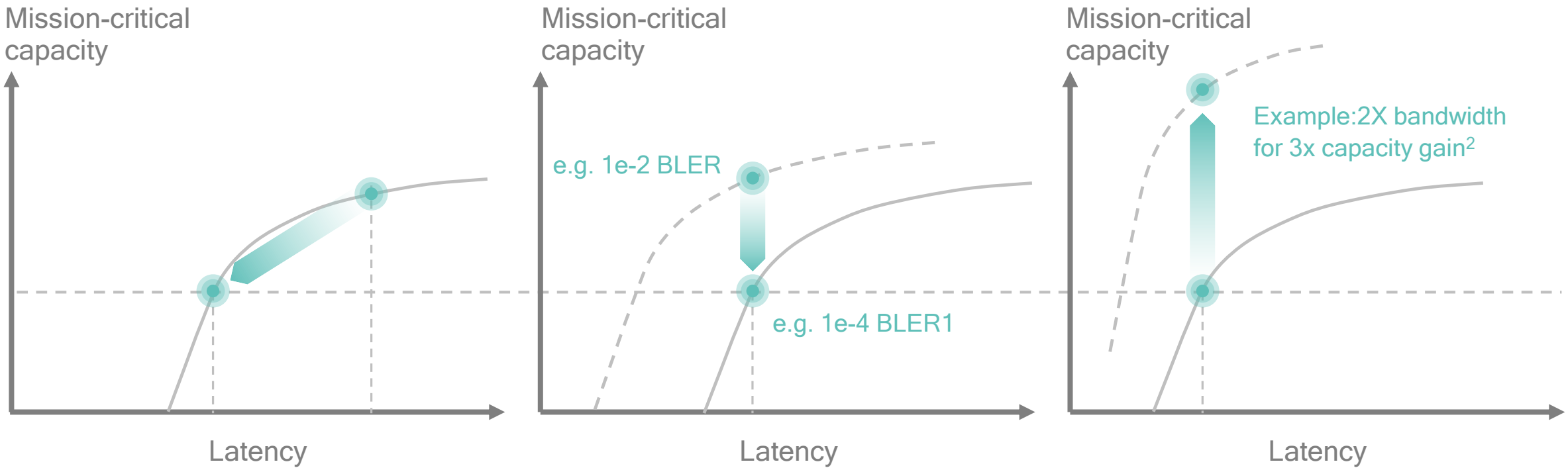
New 5G design allows for optimal trade-offs

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

Latency vs. capacity…

Reliability vs. capacity…

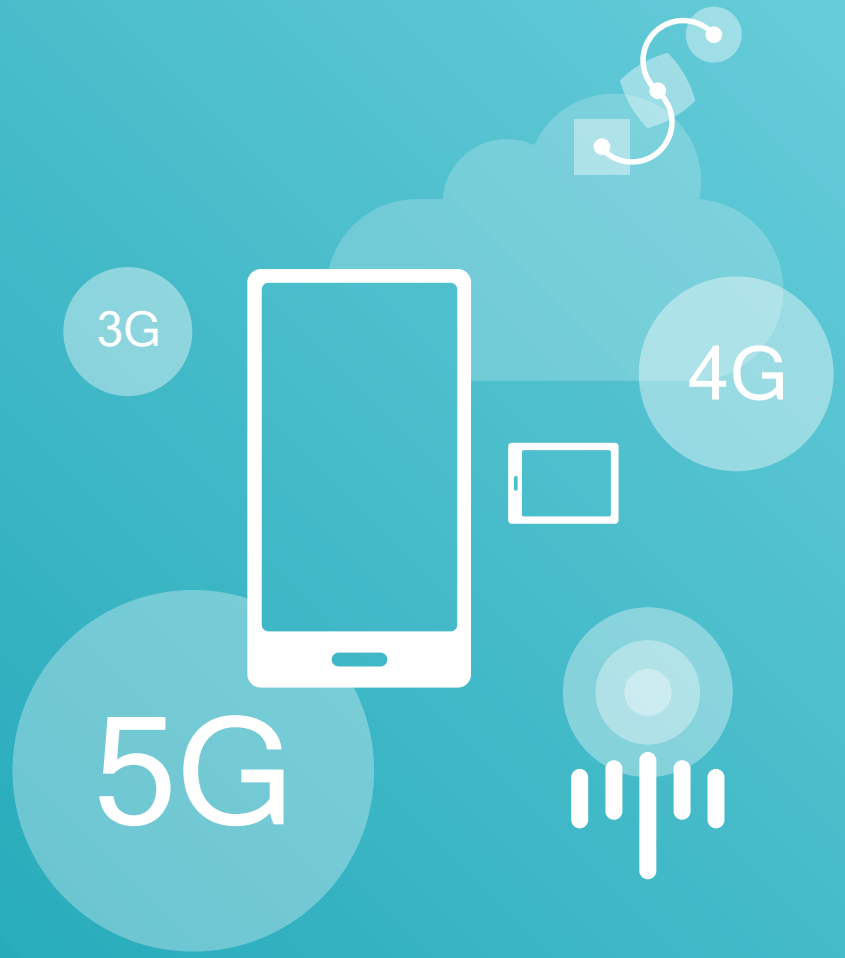
But wider bandwidth can offset reductions



[1] Low BLER Block Error Rate, required to achieve high-reliability with a hard delay bound 2 All data based on Qualcomm simulations with approximate graphs and linear scales. 3x gain when increasing from 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



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

Diverse services and devices

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

Efficient multiplexing of higher-reliability and nominal traffic

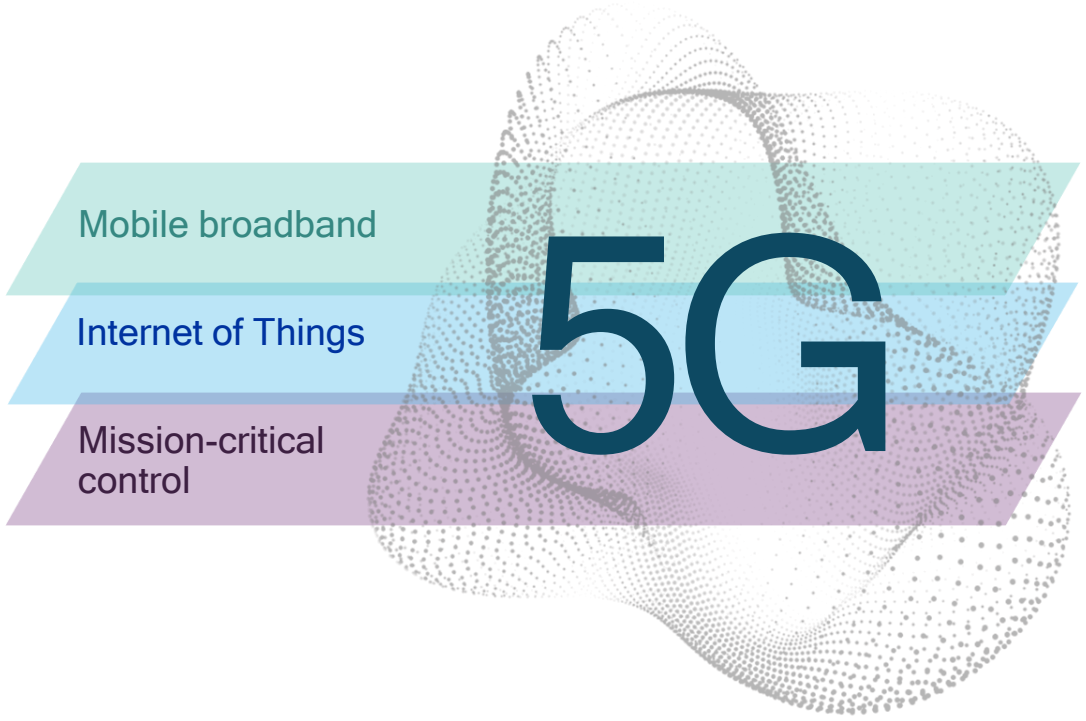
From high user mobility to no mobility at all

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



- 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)

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

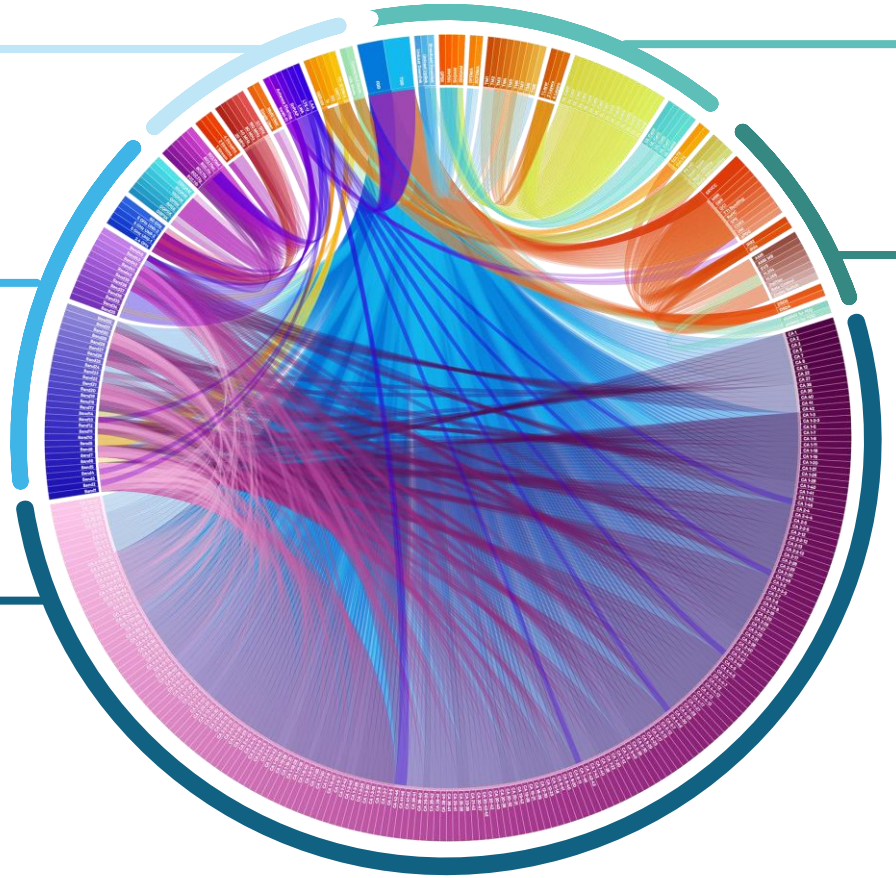
Our modem and RF leadership is critical to 5G

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

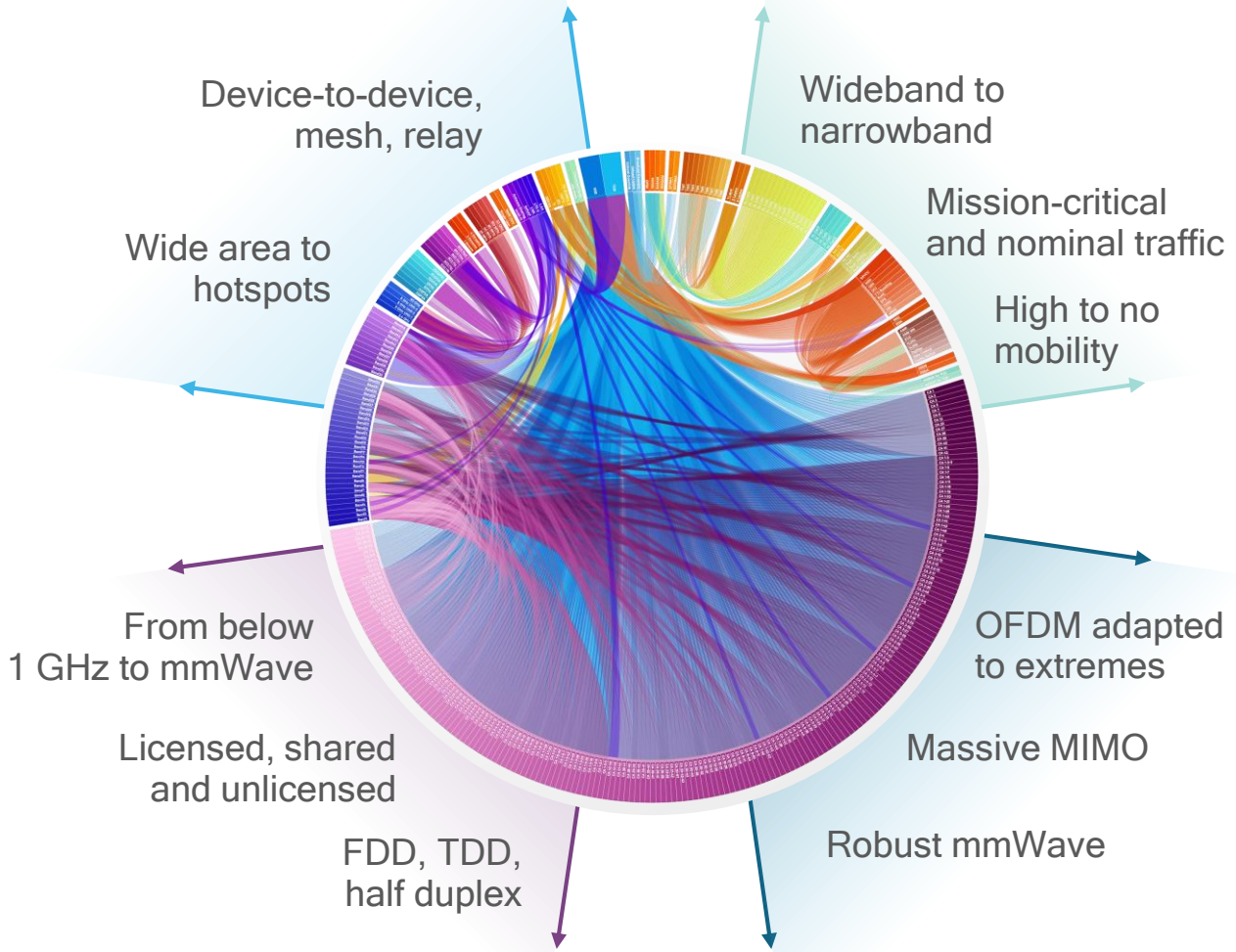
Source: Qualcomm Technologies Inc.

Our modem and RF leadership is critical to 5G

Roadmap to 5G is significantly more complex and faster moving

More diverse deployment scenarios

A much wider variation of use cases



Many more spectrum bands/types

Advanced wireless technologies

Roadmap to 5G

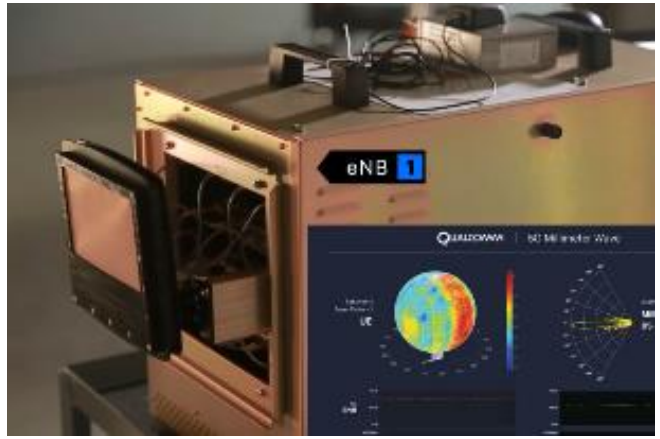
Qualcomm Research 5G NR prototype systems

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



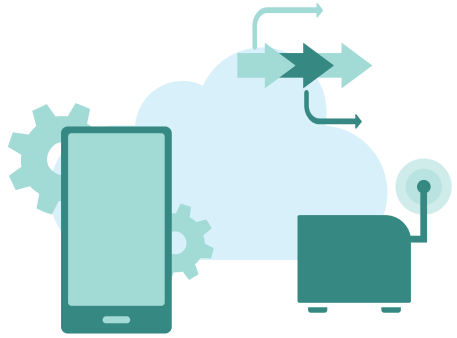
End-to-end system operating at 28 GHz, demonstrating beam forming and scanning to address non-line-of-sight scenarios, improve indoor/outdoor range, and provide robust mobility

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

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

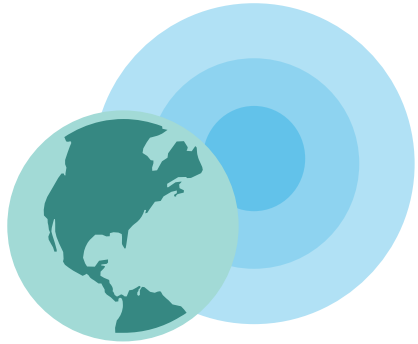
Wireless/OFDM technology and chipset leadership

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

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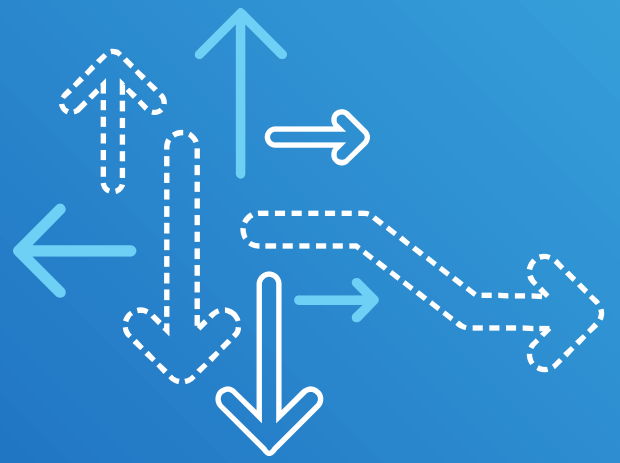

Thank you

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