Making 5G NR a reality

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

CTIA Super Mobility 2016 - 5G Technical Workshop
Qualcomm Technologies, Inc.
September 8th, 2016
#whywait @Qualcomm

5G Vision & 5G NR Introduction

Durga Malladi
SVP, Engineering
Qualcomm Technologies, Inc.

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

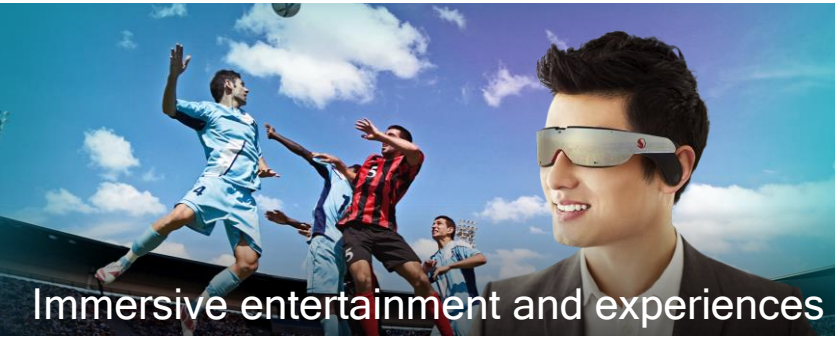
Massive Internet of Things

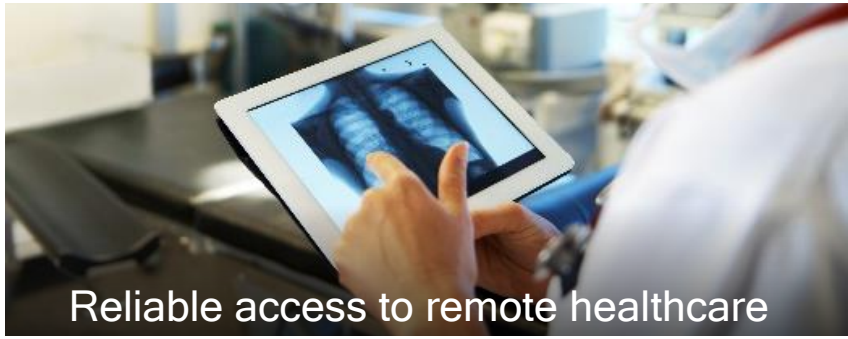
Unifying connectivity platform for future innovation

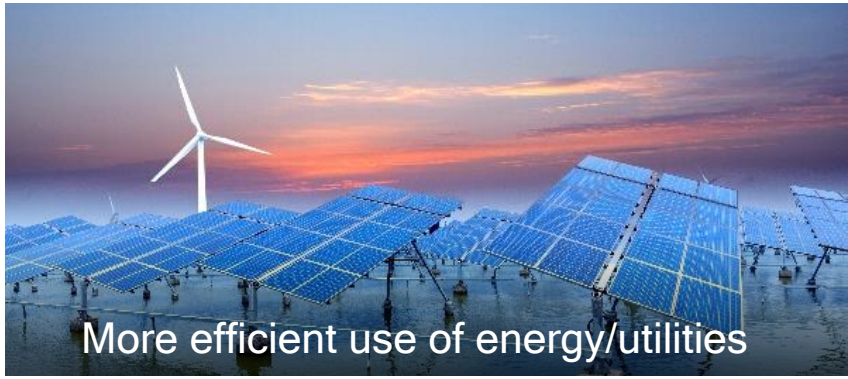
Convergence of spectrum types/bands, diverse services, and deployments, with new technologies to enable a robust, future-proof 5G platform

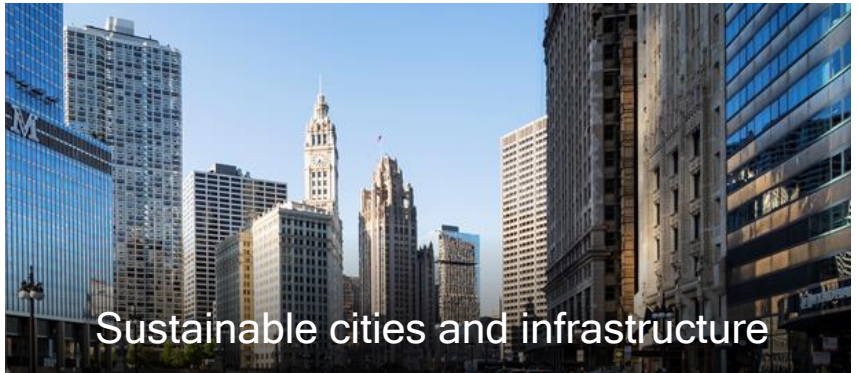
5G will redefine a wide range of industries

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

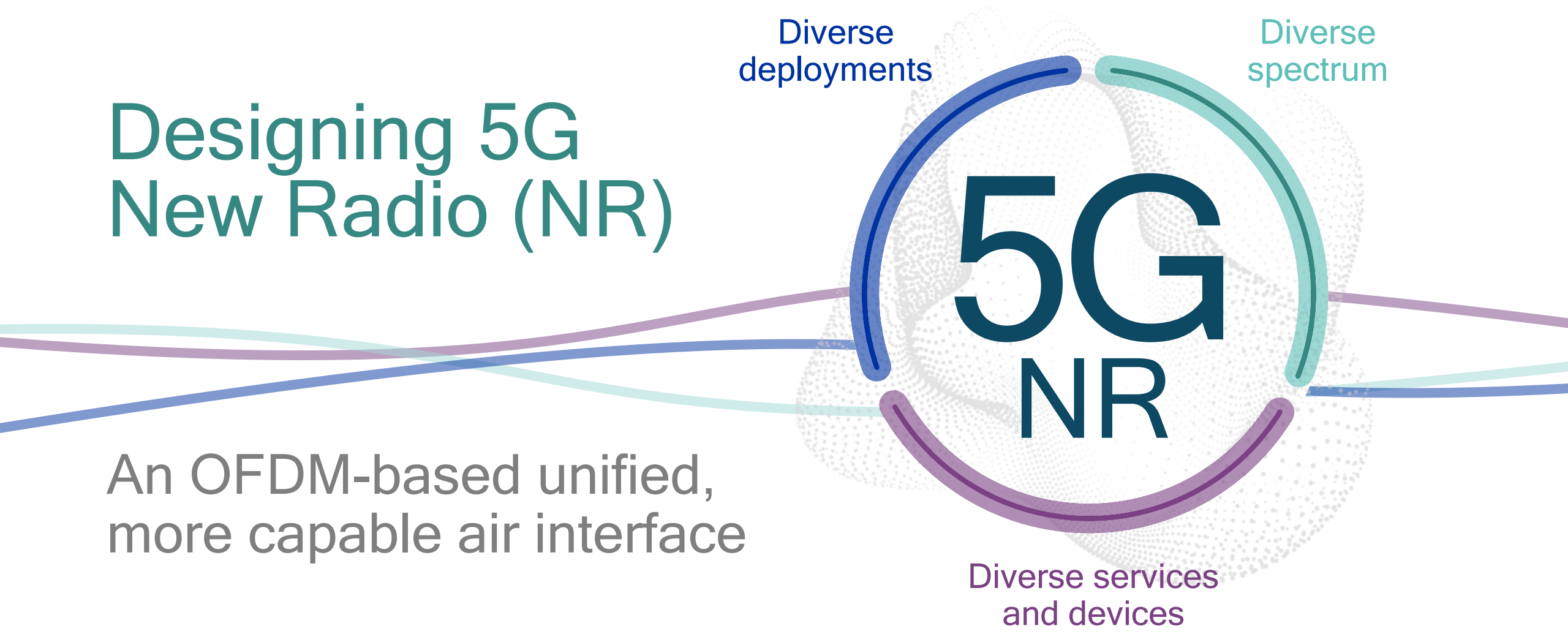






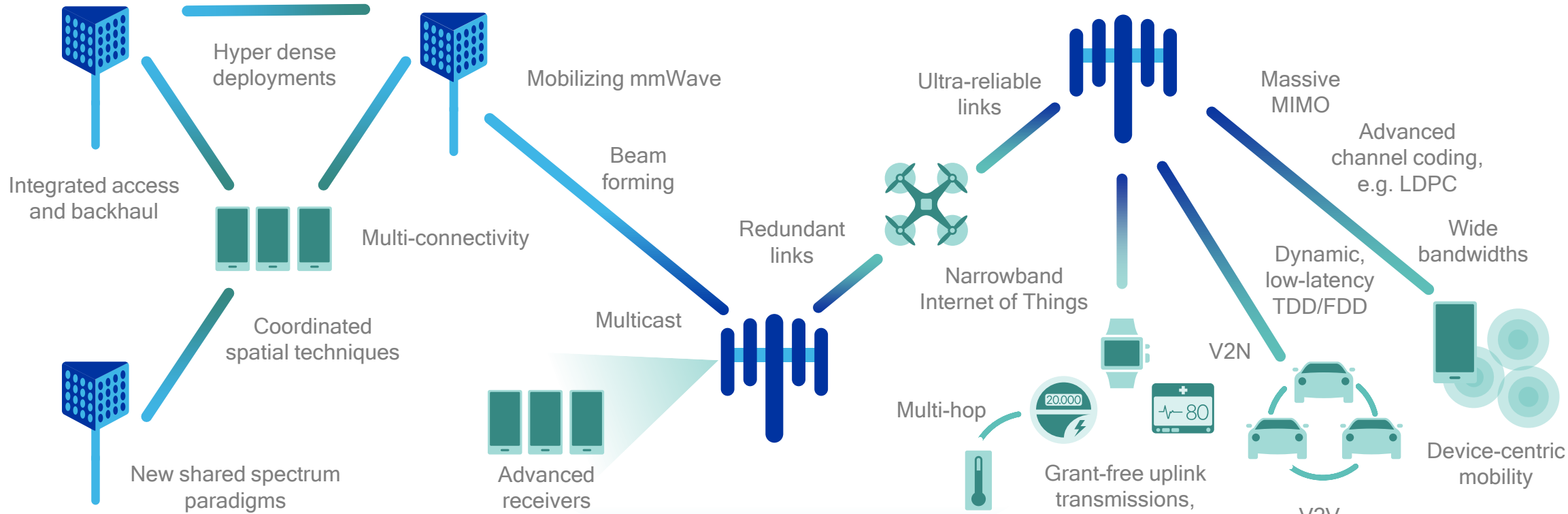


Designing 5G New Radio (NR)



An OFDM-based unified, more capable air interface

Pioneering new technologies to meet 5G NR requirements



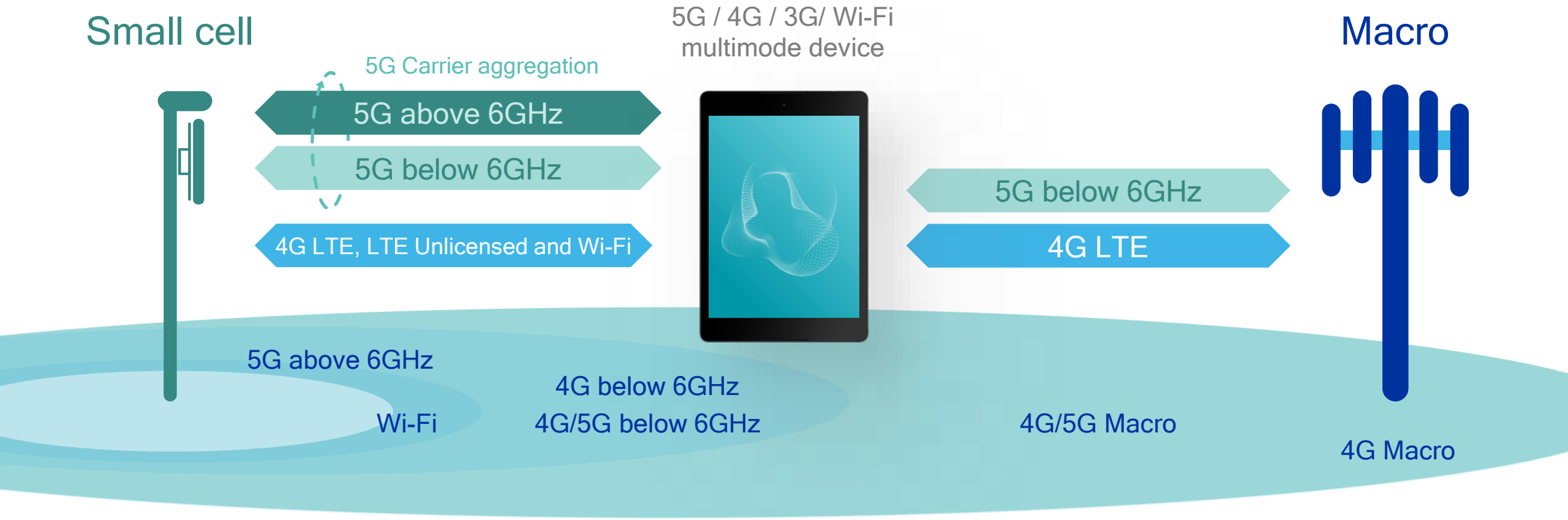
New levels of capability and efficiency

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

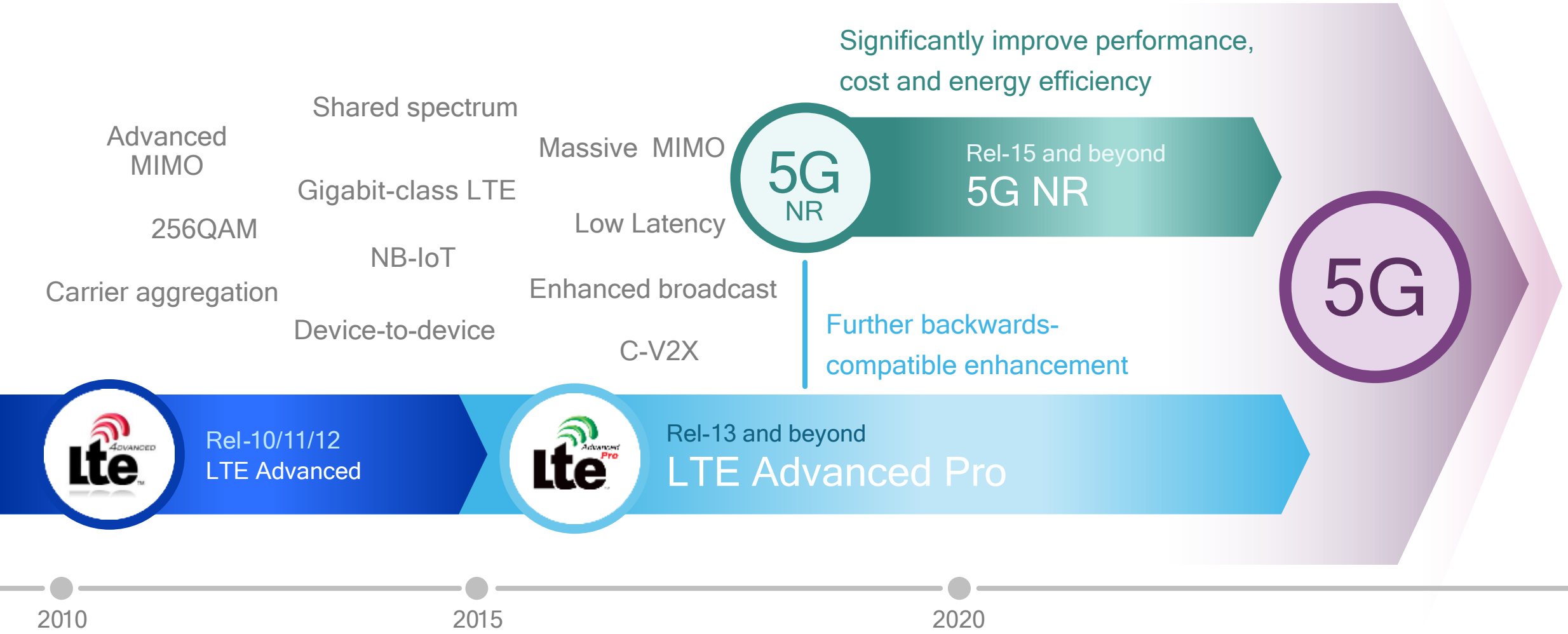
Simplifying 5G deployments with multi-connectivity

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)

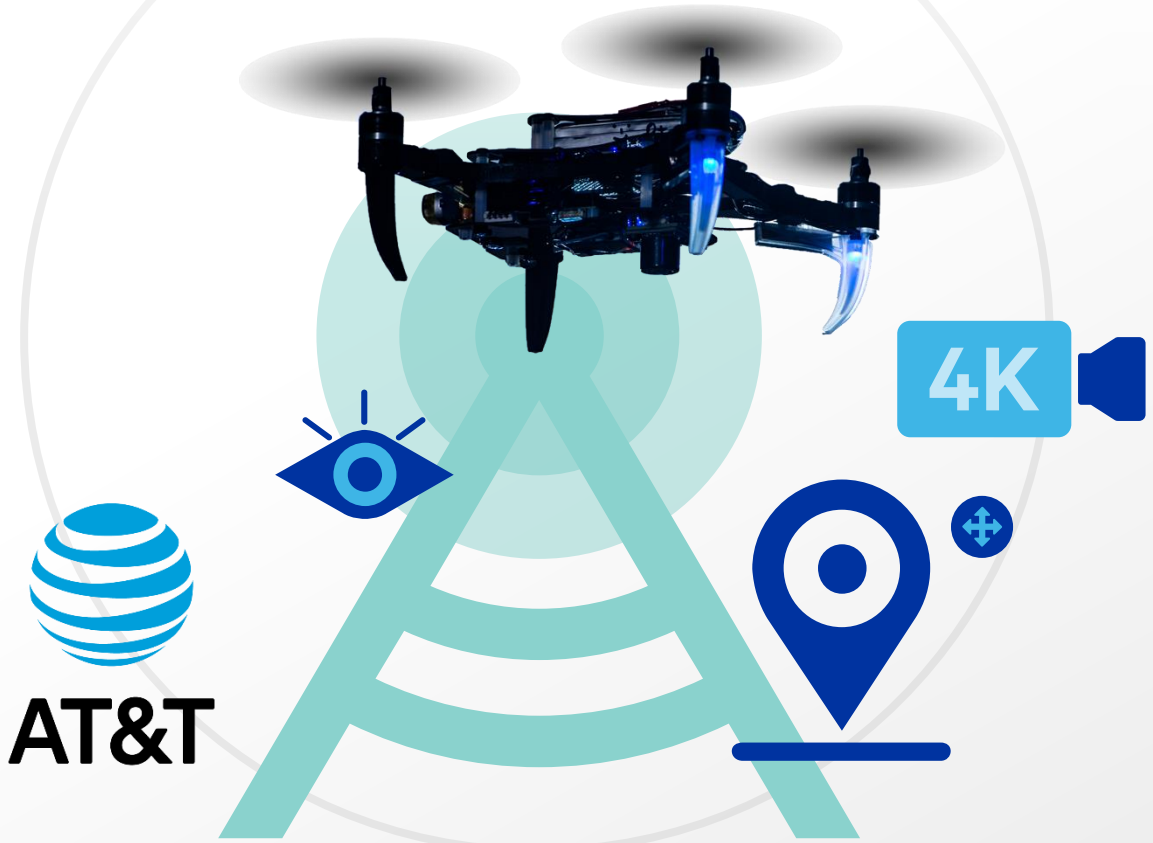
The path to 5G includes a strong LTE foundation



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

Qualcomm and AT&T announce UAS trial

Preparing for wide-scale deployment of 5G mission critical services



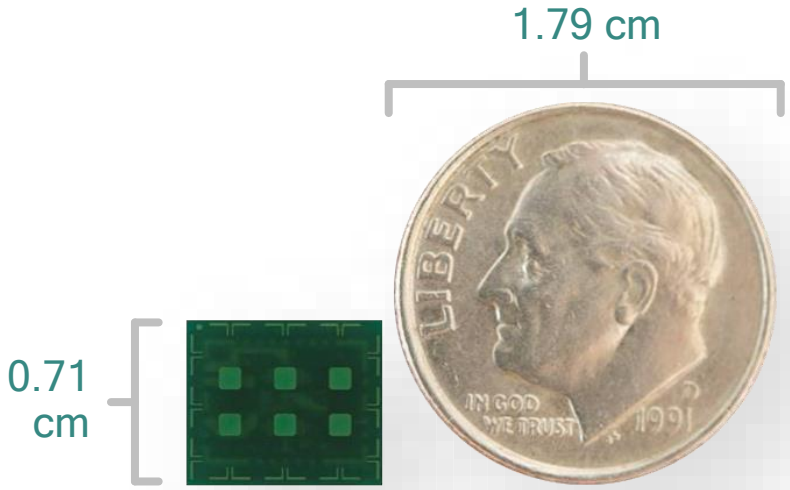
1. Optimize LTE Networks
2. Inform Regulations
3. Drive 5G Specifications

Advancing safe and secure UAS operations

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

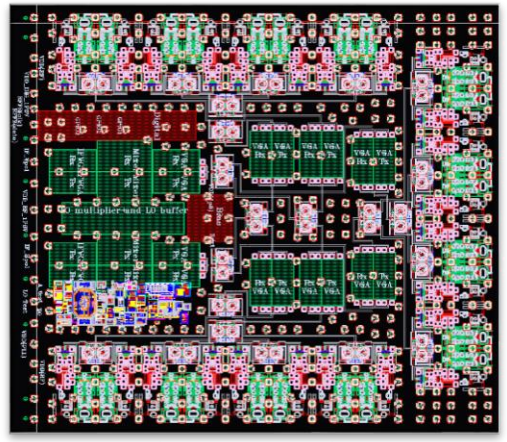


Qualcomm® VIVE™ 802.11ad 60 GHz technology with a 32-antenna array

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



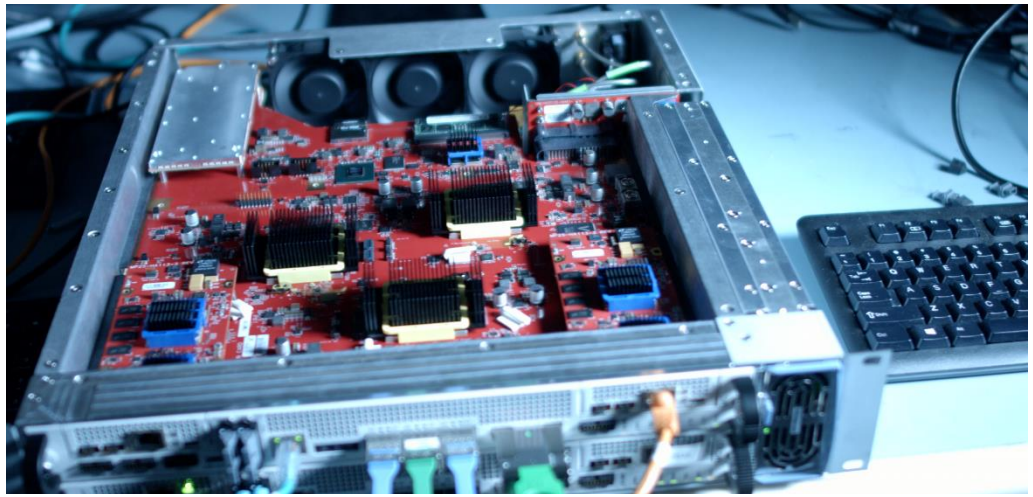
With integrated PA, LNA, phase shifter, power splitters for beamforming

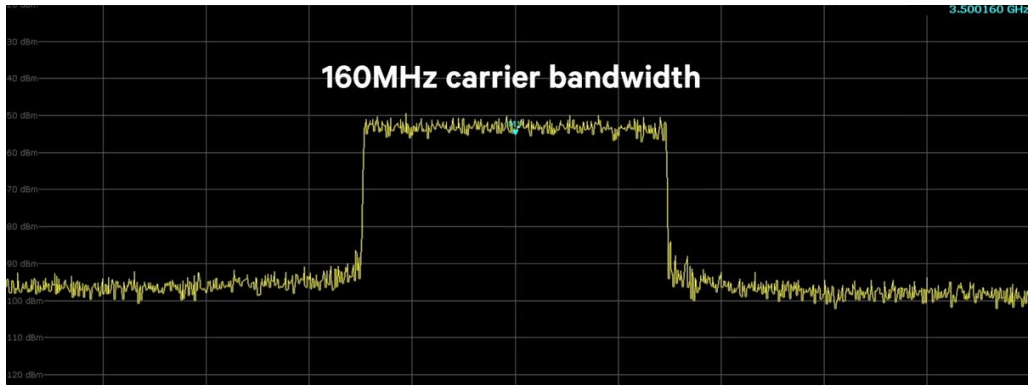
Qualcomm VIVE is a product of Qualcomm Atheros, Inc.

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

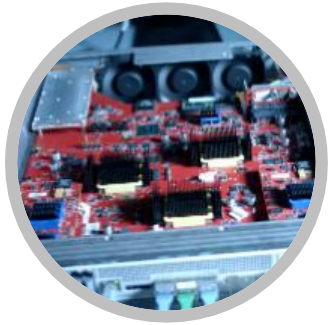
Will enable impactful 5G NR trials

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

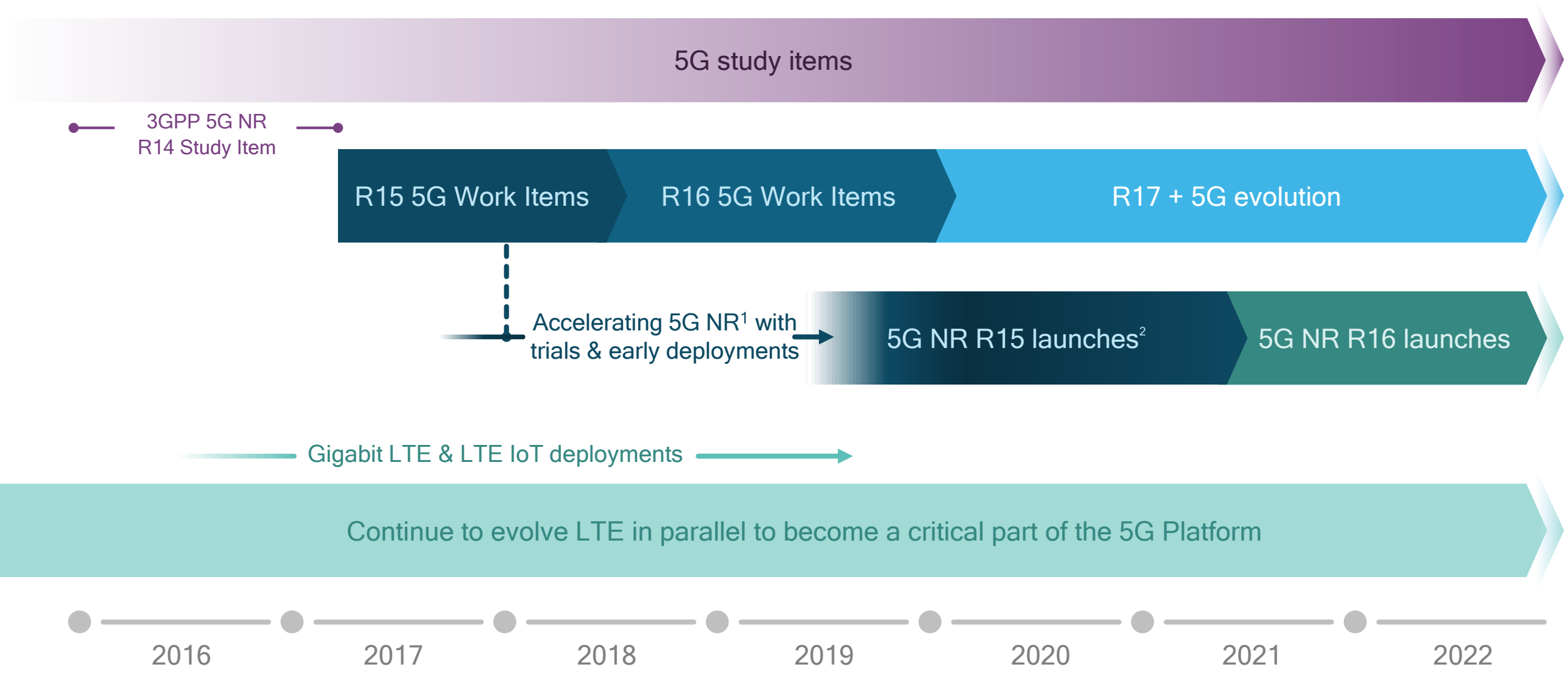
Over-the-air interoperability testing leveraging prototype systems and our leading global network experience

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

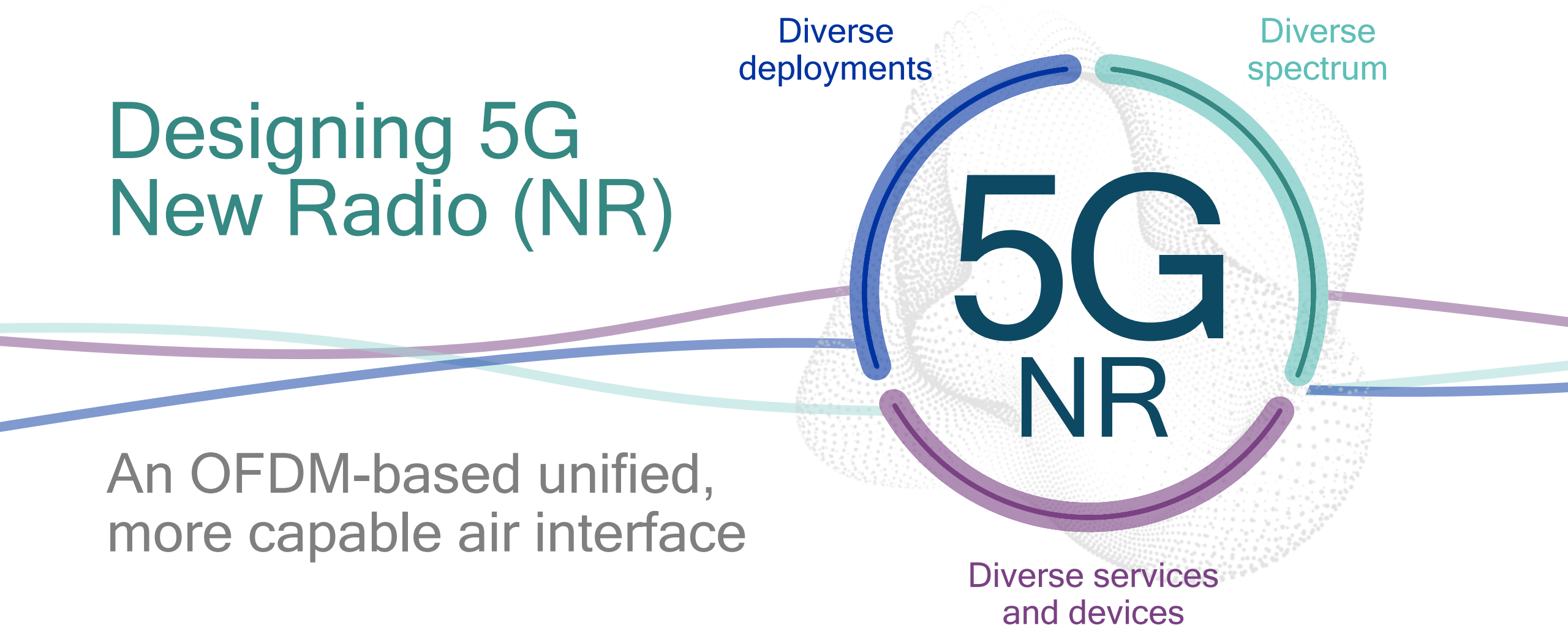
QUALCOMM®
Why Wait™

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

5G NR Design & Technology Innovation

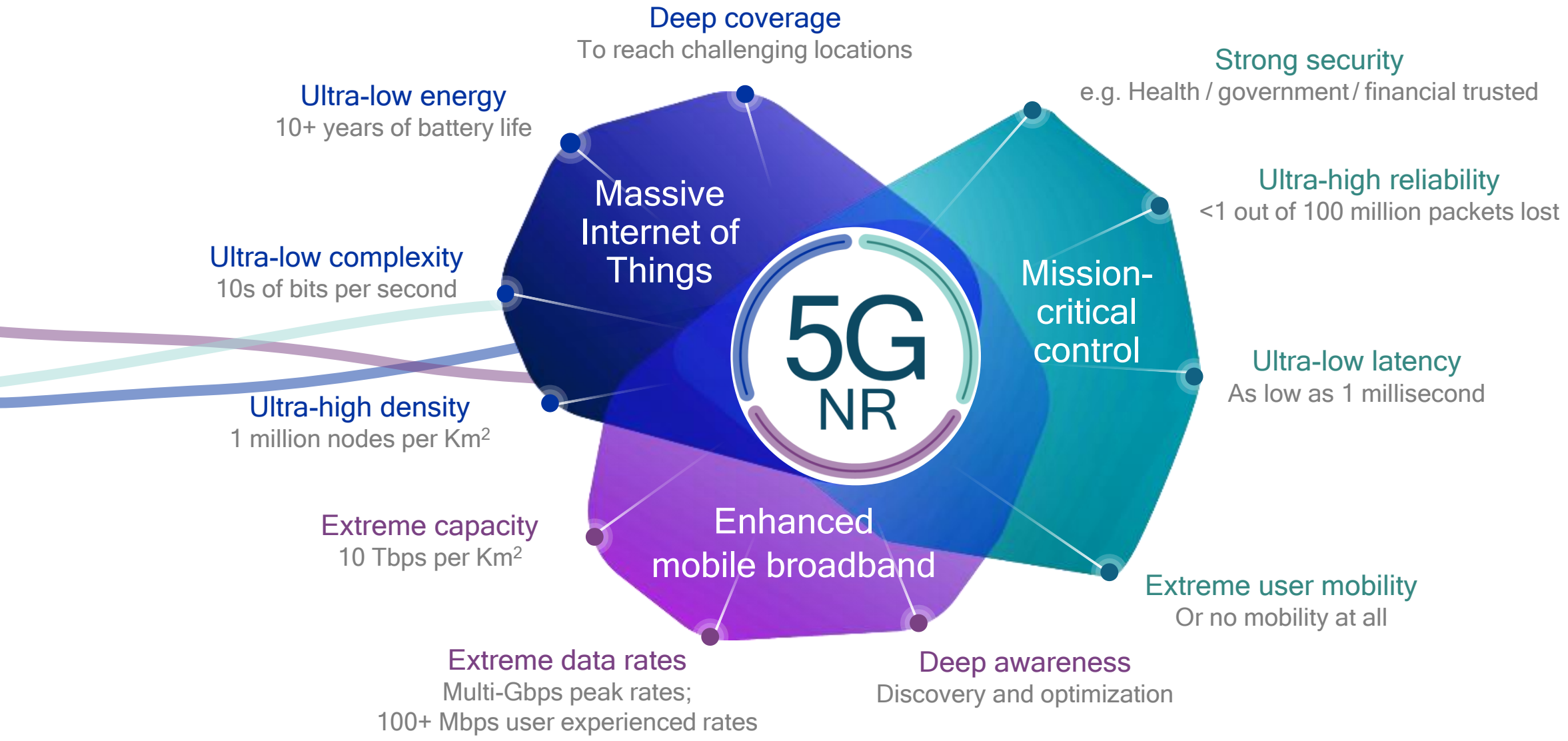
John Smee
VP, Engineering
Qualcomm Technologies, Inc.

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

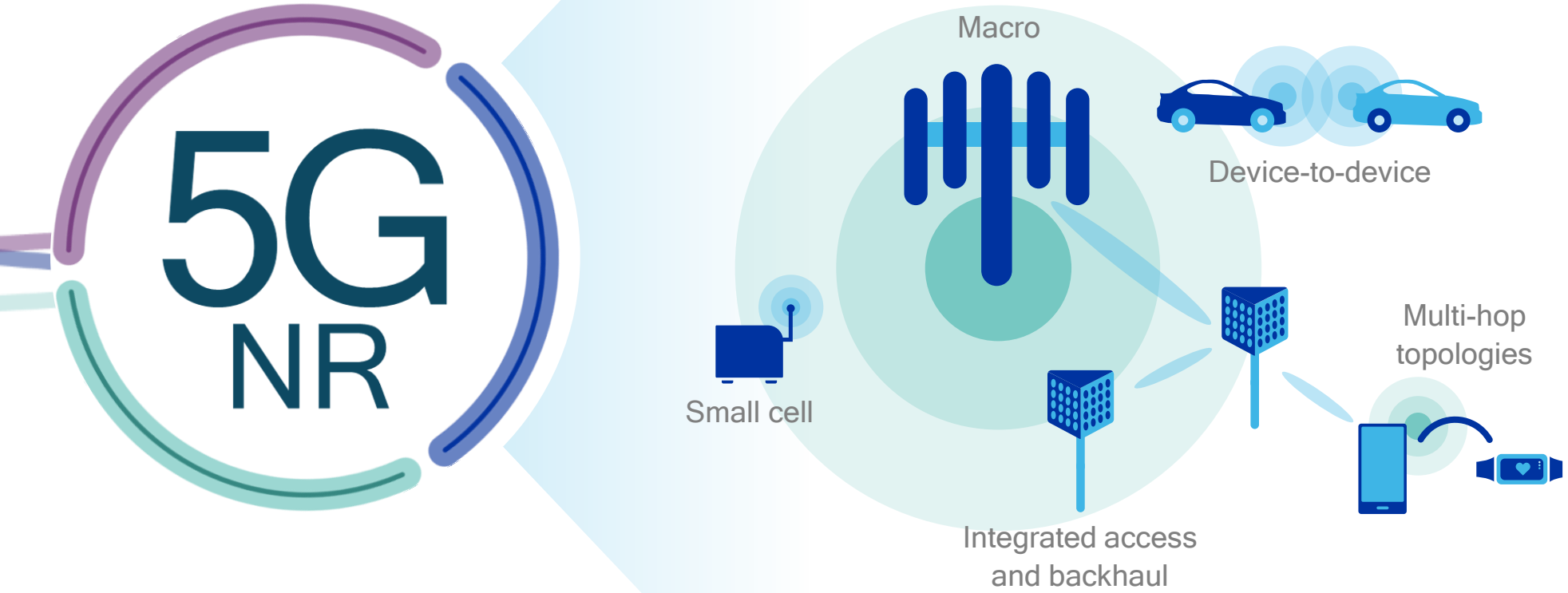
High bands above 24 GHz (mmWave): extreme bandwidths
e.g. 24.25-27.5 GHz, 27.5-29.5, 37-40, 64-71 GHz

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

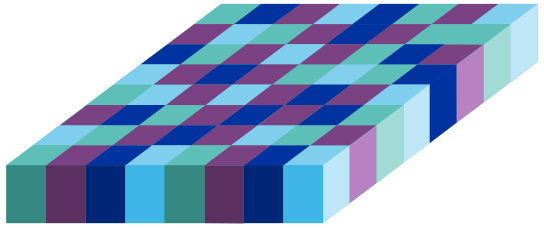
Mobile operator networks provide ubiquitous coverage–the backbone of 5G

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

For enhanced mobile broadband and beyond

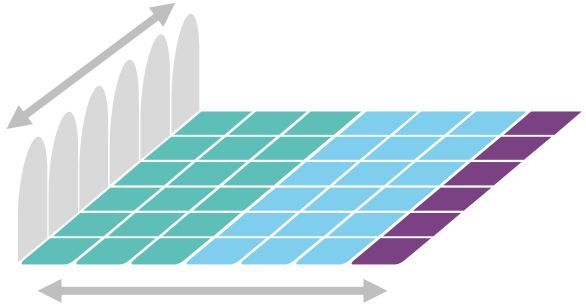
Optimized OFDM-based waveforms

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



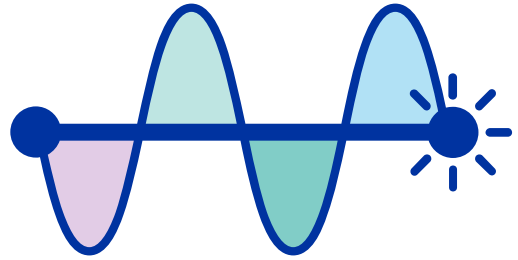
A common, flexible framework

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



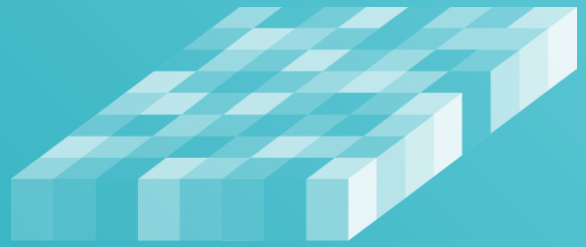
Unified design across spectrum types and bands

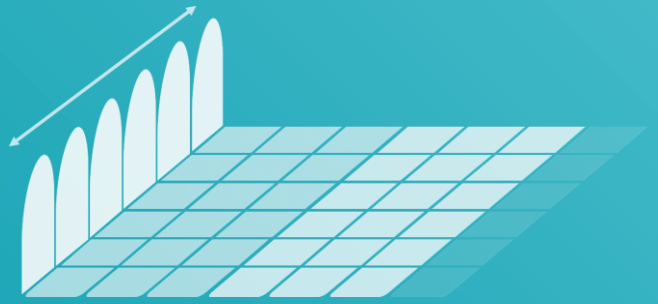
For licensed and shared/unlicensed spectrum bands both below 6 GHz and above 6 GHz[2]

[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

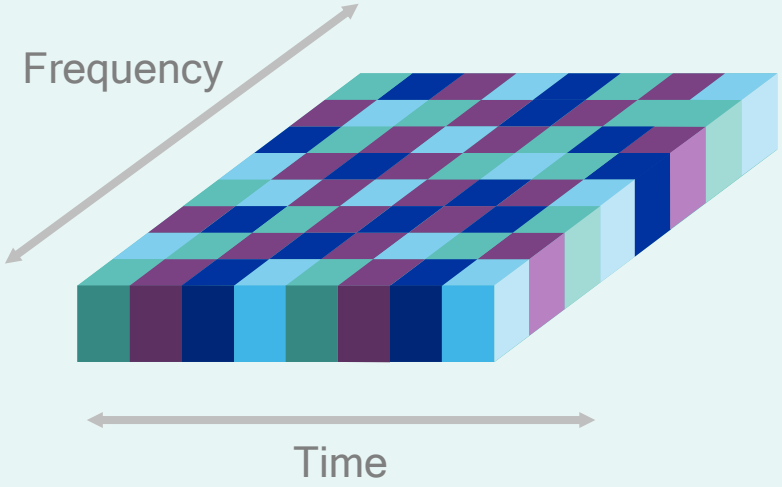
Leading the technology innovations for a unified, more capable 5G air interface





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

Adapted for scaling to an extreme variations of 5G requirements



Spectral efficiency

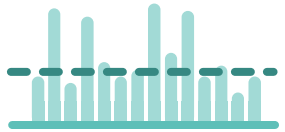
Efficient framework for MIMO spatial multiplexing

Low complexity

Low complexity receivers even when scaling to wide bandwidths

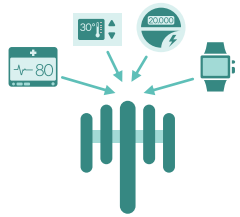
Frequency localization

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

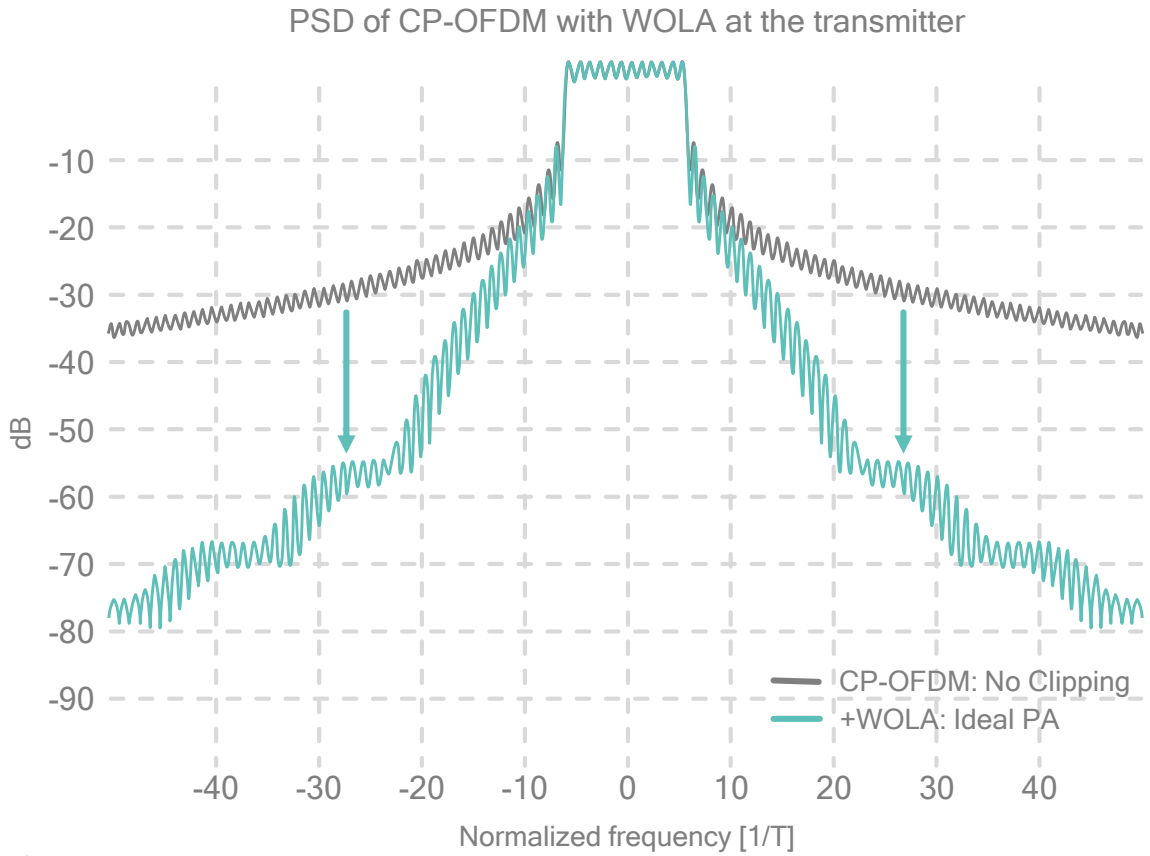
Co-exist with optimized waveforms and multiple access for wide area IoT

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

Efficient service multiplexing with windowed OFDM

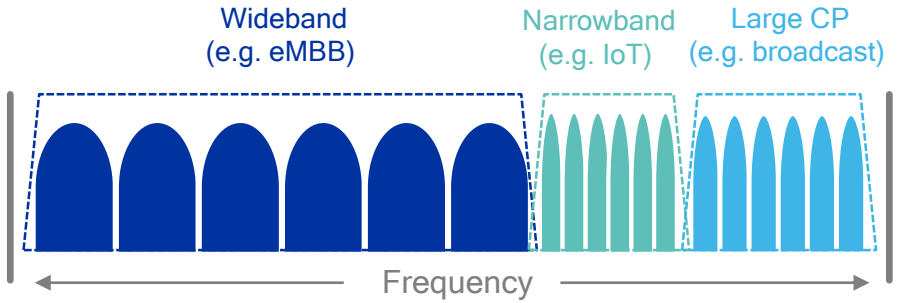
OFDM with WOLA[1] windowing

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

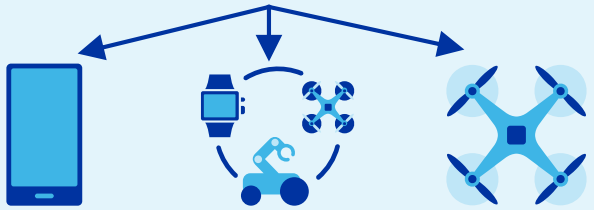
[1] Weighted Overlap Add

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

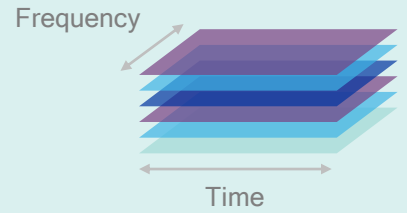
Massive IoT

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

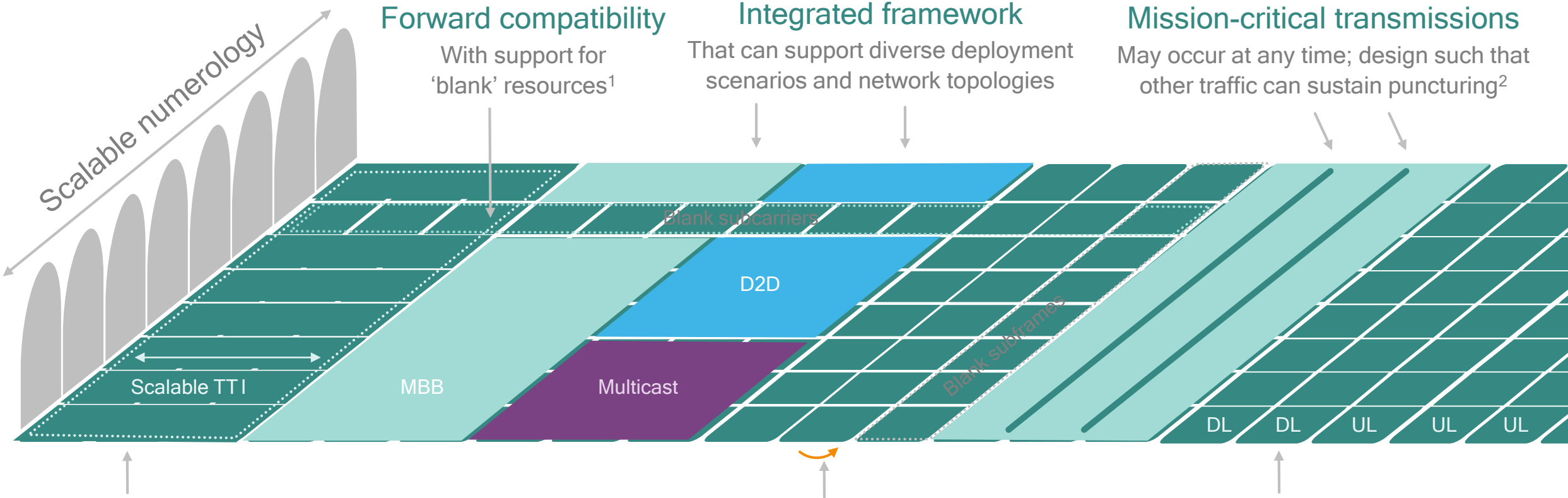
With support for 'blank' resources[1]

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

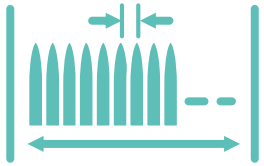
Faster switching for more flexible capacity based on traffic conditions

[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

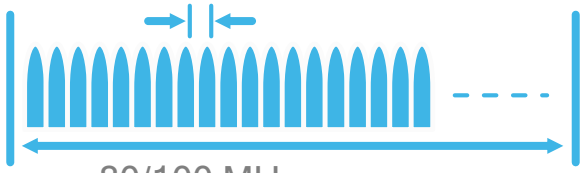
Outdoor and macro coverage
FDD/TDD <3 GHz



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

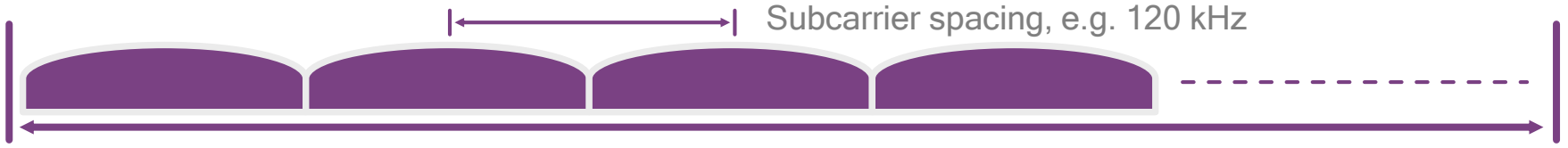
e.g. 80/100 MHz

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

Subcarrier spacing
e.g. 60 kHz

e.g. 160MHz

mmWave
TDD e.g. 28 GHz



e.g. 500MHz

Example usage models and channel bandwidths

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

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

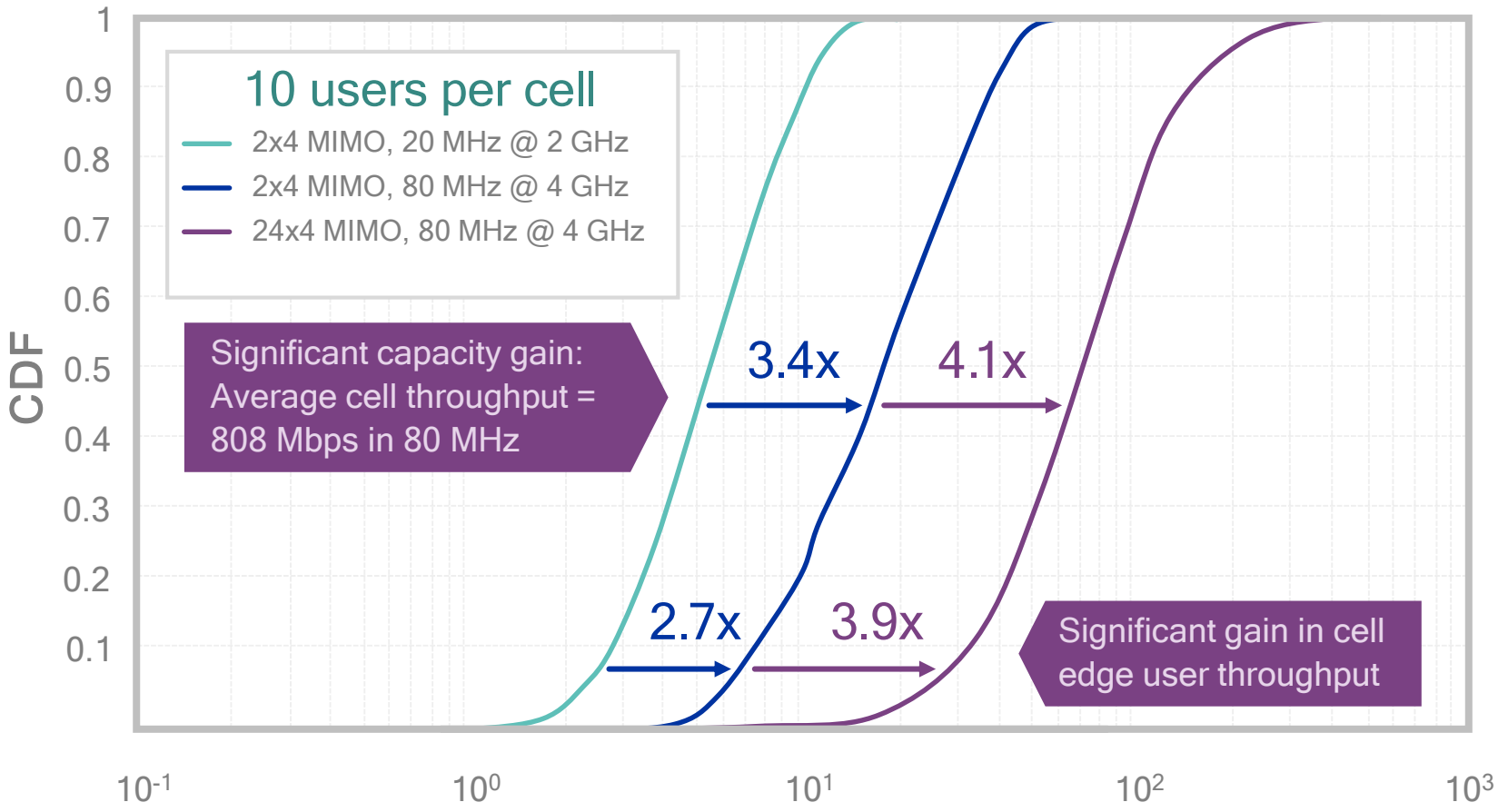
Ultra-low latency

Uniform experience

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

Realizing the mmWave opportunity for mobile broadband

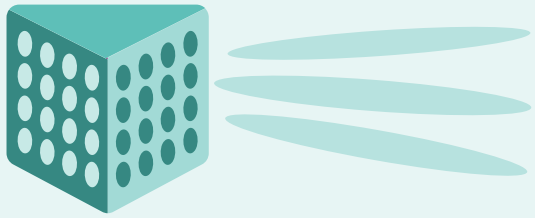
Extreme bandwidth opportunity

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

Mobilizing mmWave challenge

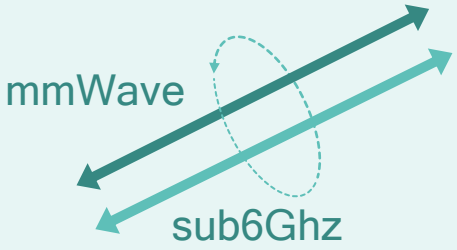
- Robustness due to high path loss and susceptibility to blockage
- Device cost/power and RF challenges at mmWave frequencies

5G NR



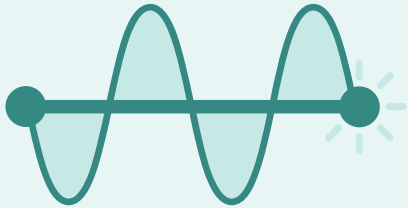
Smart beamforming and beam tracking

Increase coverage and minimize interference



Tight interworking with sub 6 GHz

Increase robustness, faster system acquisition



Optimized mmWave design for mobile

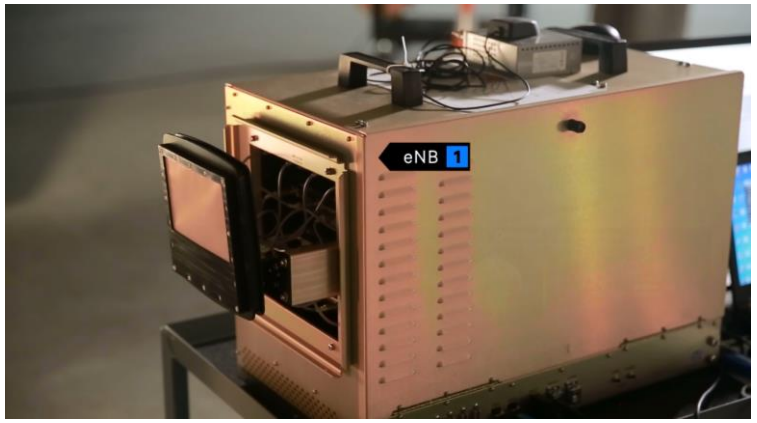
To meet cost, power and thermal constraints

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

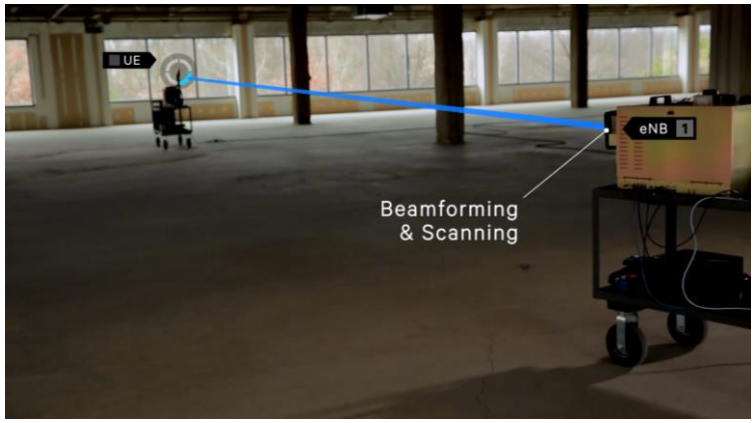
Mobilizing mmWave–live demonstration of our prototype

Millimeter Wave UE

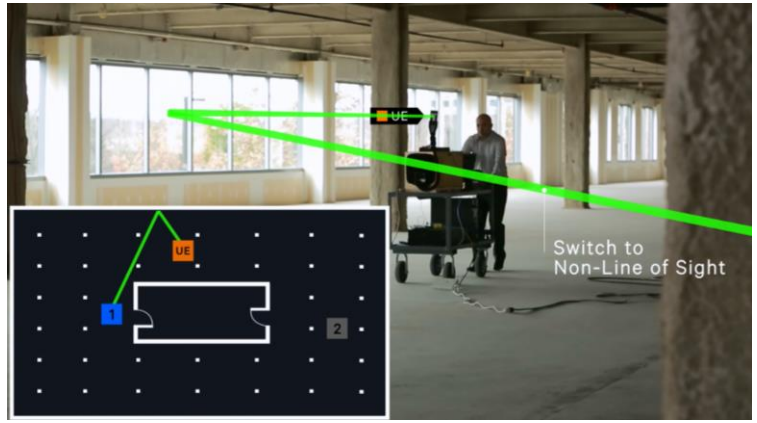
Millimeter wave base station



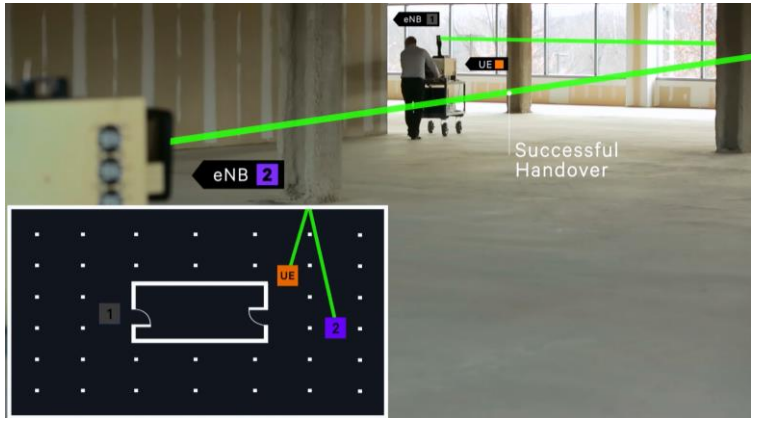
Beamforming and scanning



Non-line-of-sight through reflection



Handover

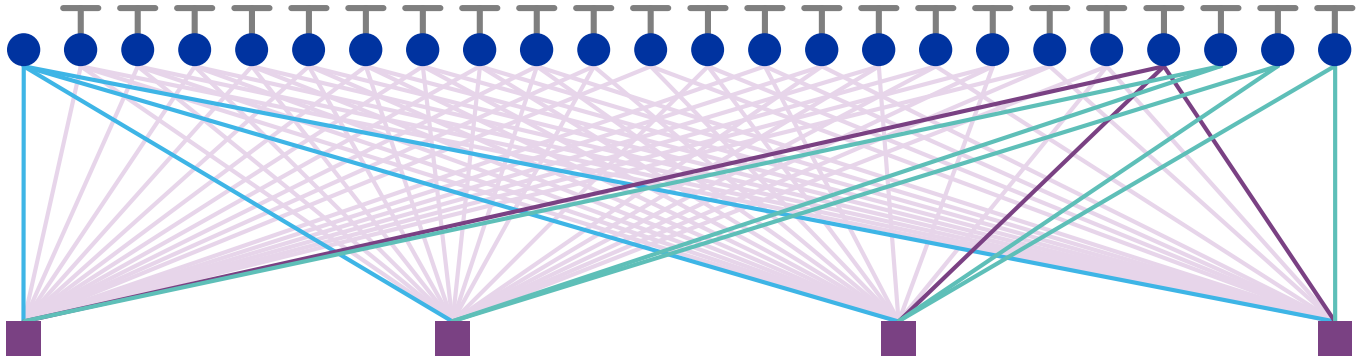


Outdoor

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

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]

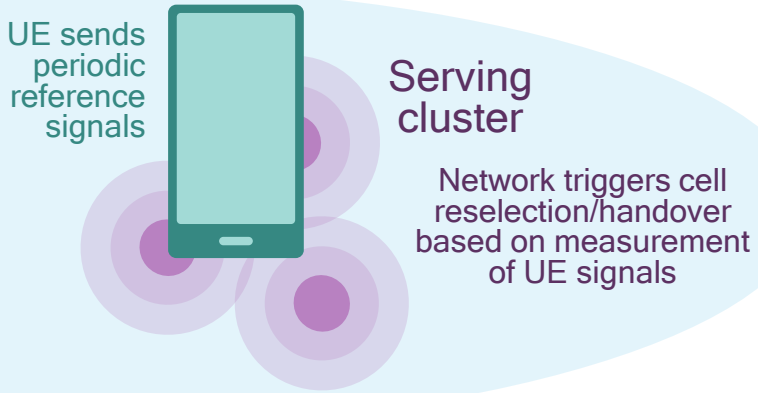
[1] Multi-Edge Low-Density Parity-Check; [2] such as Polar or TBCC

Device-centric mobility management in 5G NR

Control plane improvements to improve energy and overhead efficiency

Edgeless mobility zone

(area of tightly coordinated cells)

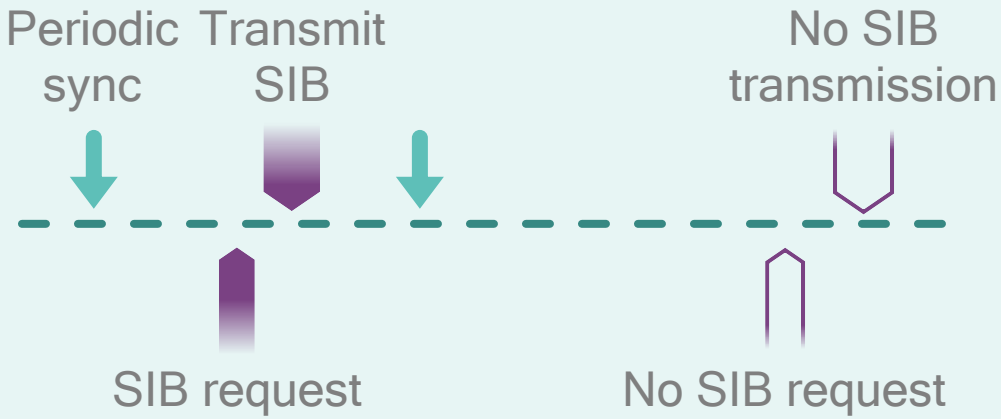


Lightweight mobility for device energy savings

- 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

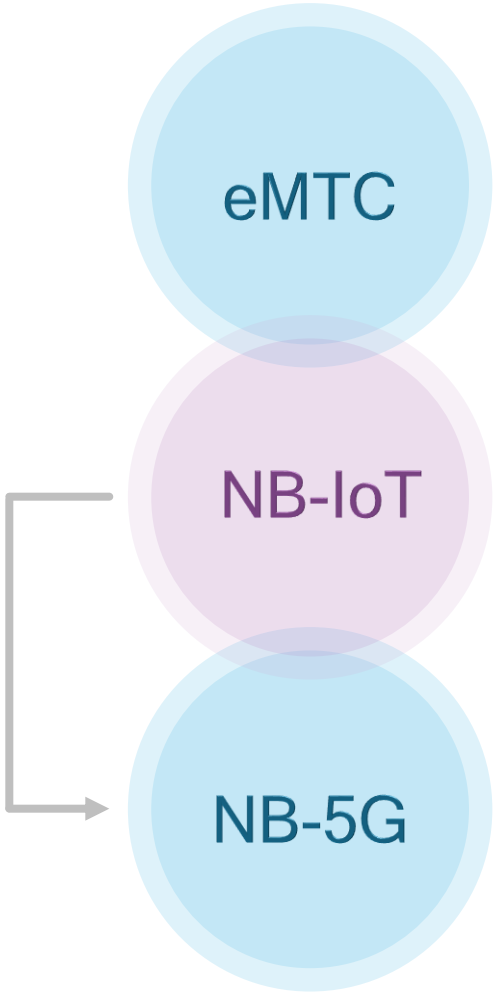
Power efficient

Low complexity

Long range

5G NR will bring new capabilities for the massive IoT

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



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

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

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

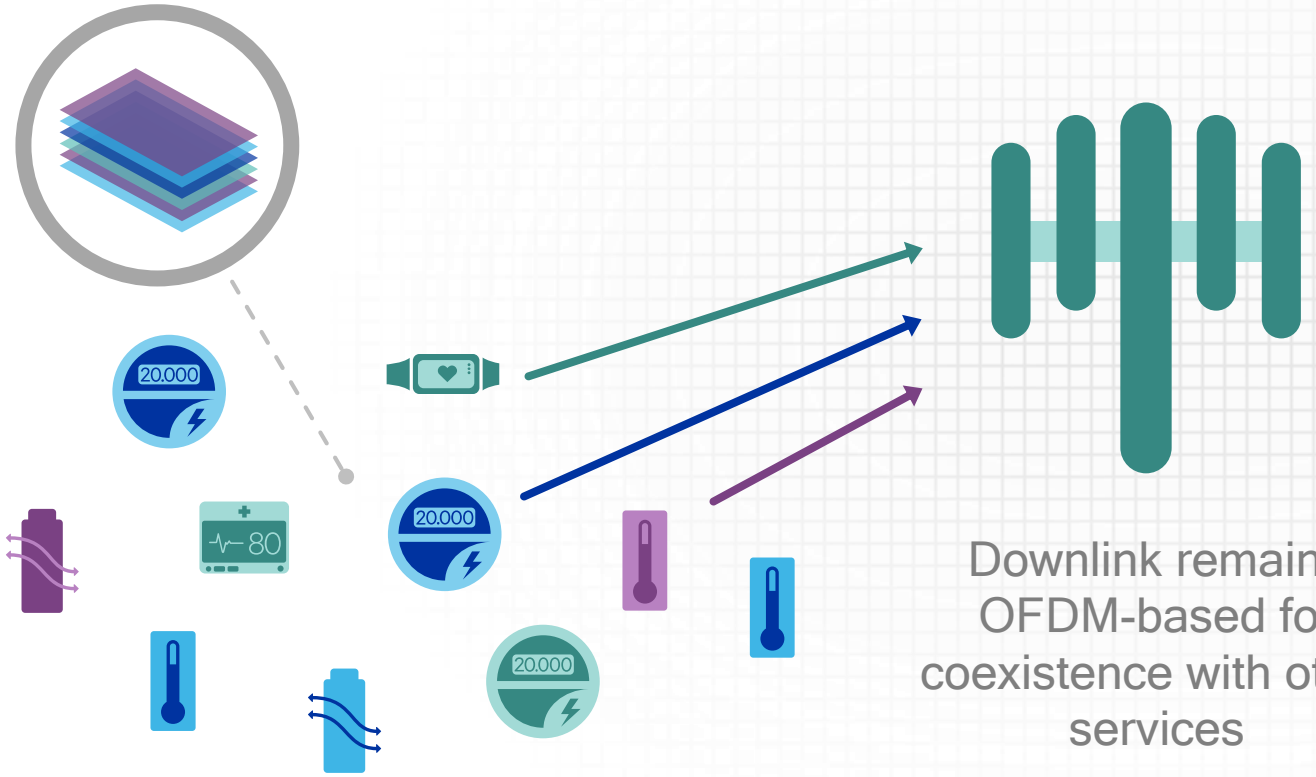
[1] Resource Spread Multiple Access

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



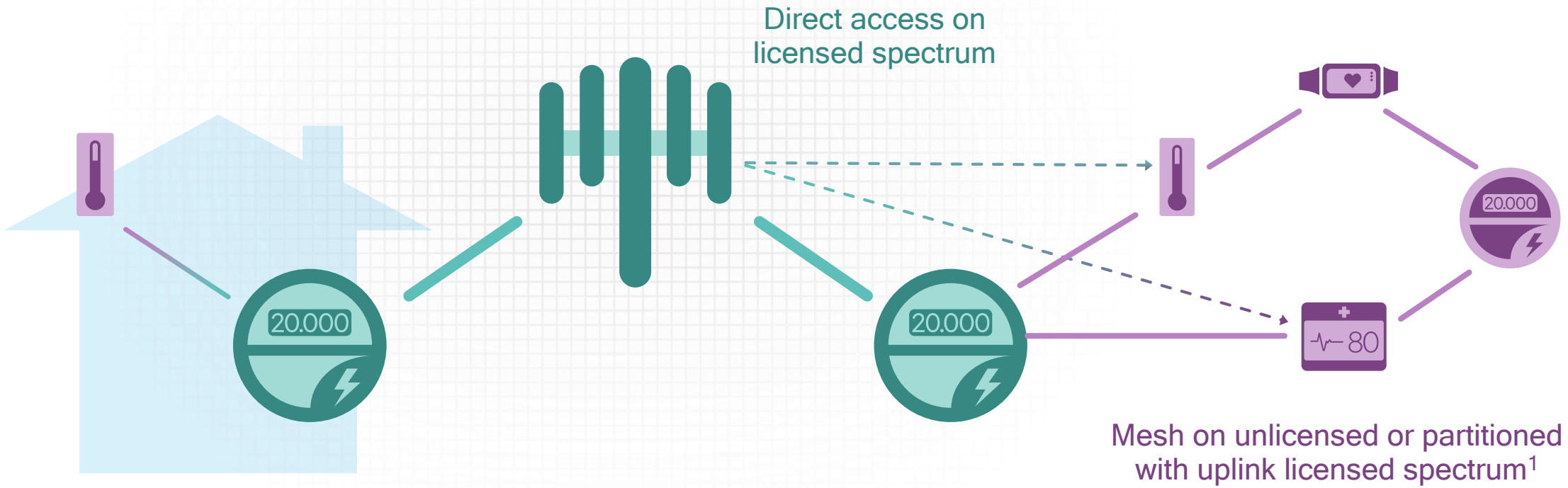
Downlink remains OFDM-based for coexistence with other services

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

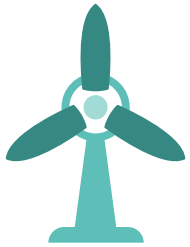
High availability

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

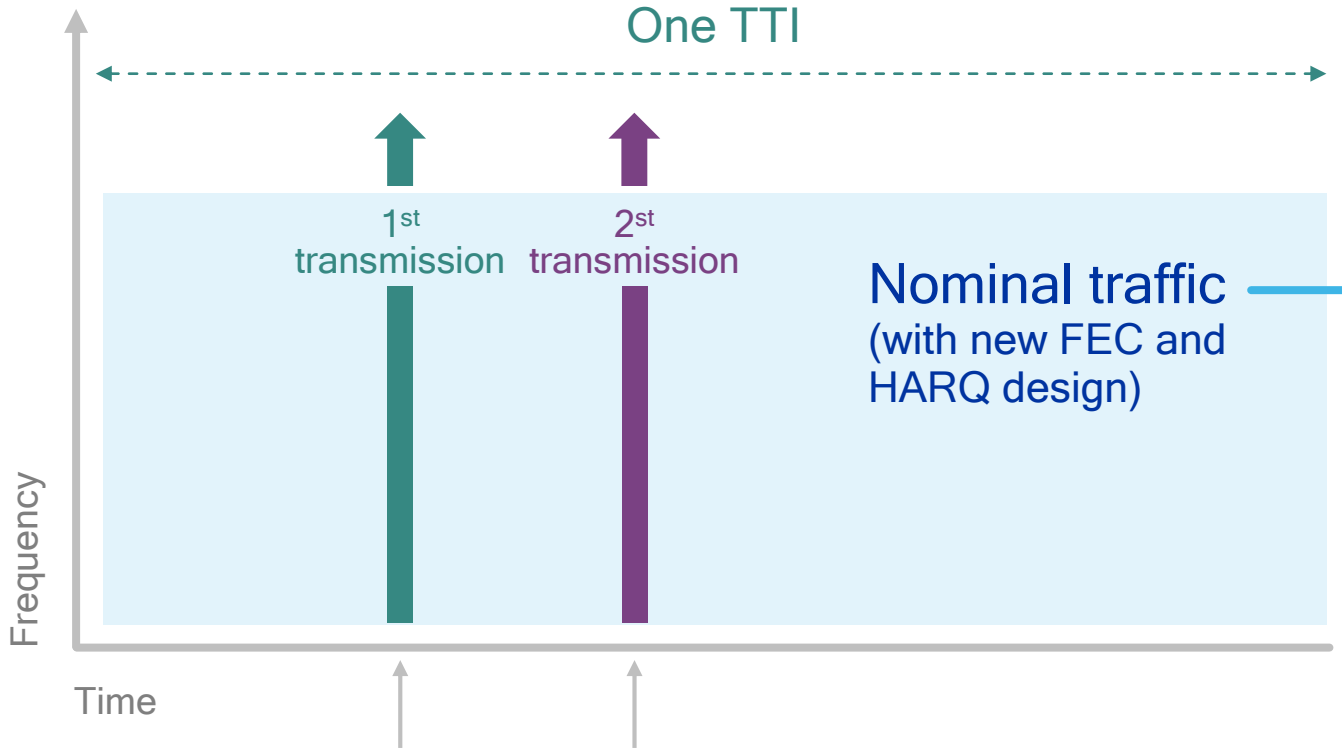
Strong e2e security

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

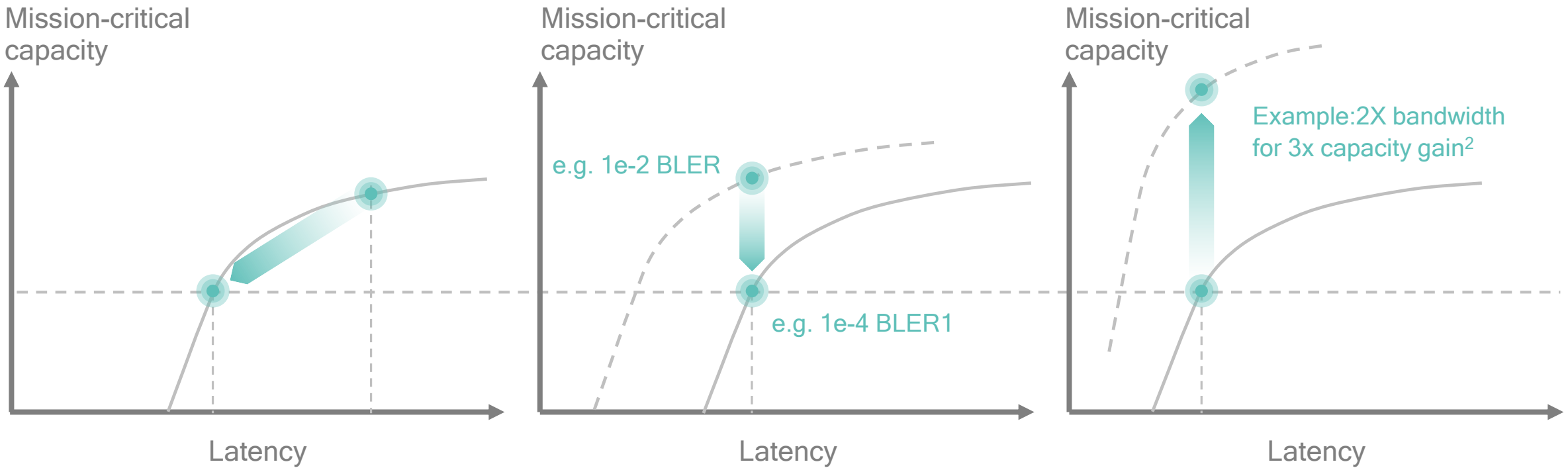
New 5G design allows for optimal trade-offs

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

Latency vs. capacity…

Reliability vs. capacity…

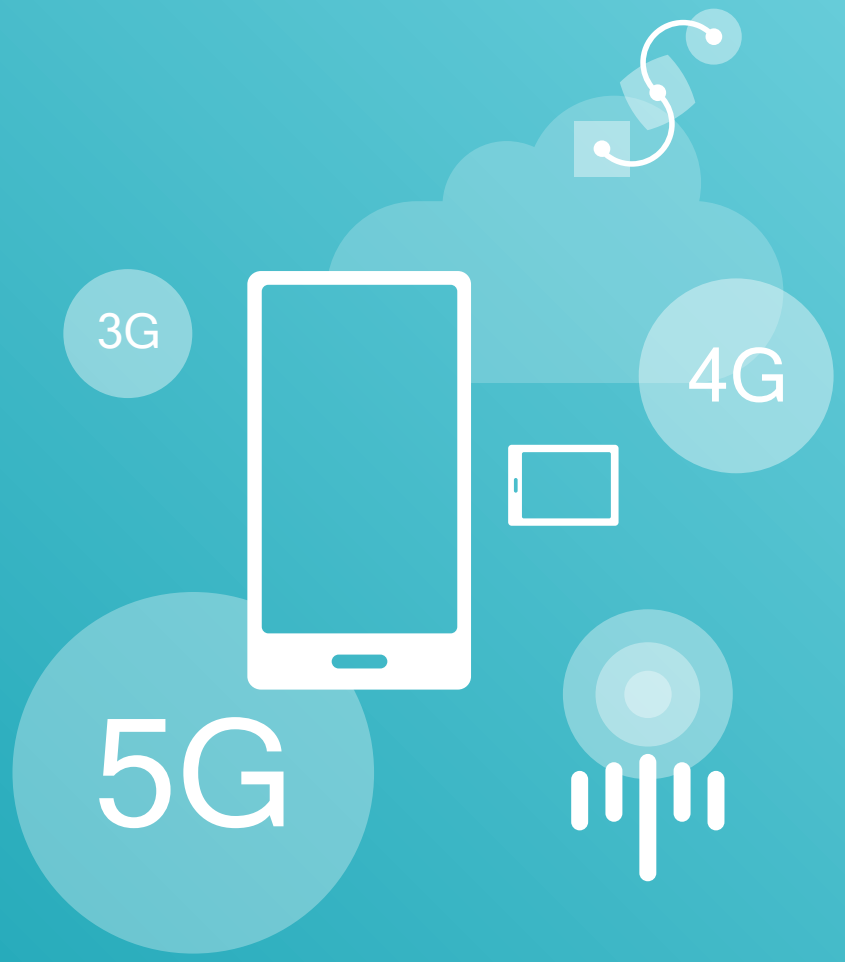
But wider bandwidth can offset reductions



[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



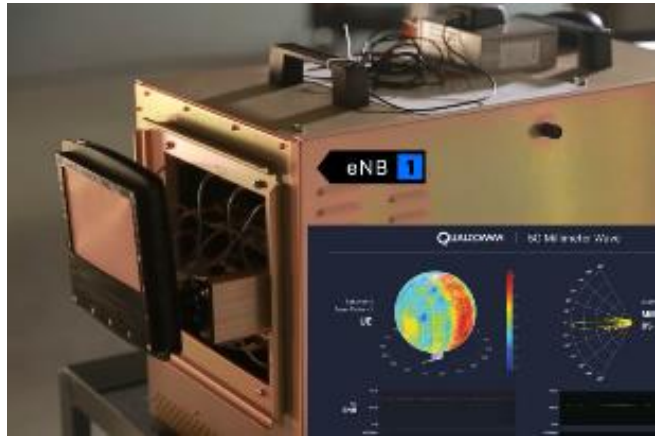
Qualcomm Research 5G NR prototype systems

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



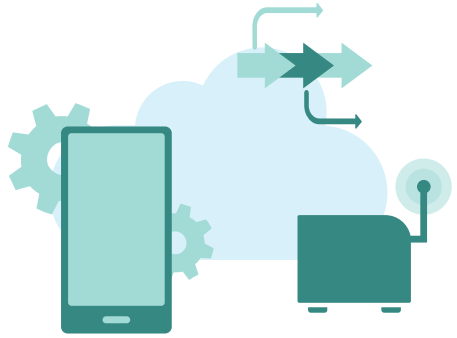
End-to-end system operating at 28 GHz, demonstrating beam forming and scanning to address non-line-of-sight scenarios, improve indoor/outdoor range, and provide robust mobility

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

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

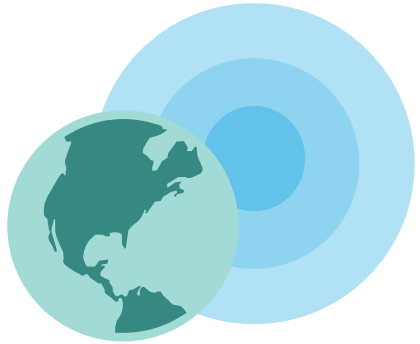
Wireless/OFDM technology and chipset leadership

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

5G Shared Spectrum

Mingxi Fan
VP, Engineering
Qualcomm Technologies, Inc.

New spectrum sharing paradigms–opportunity to innovate

Can enable more efficient utilization of, and access to, scarce resources

Licensed spectrum

Exclusive use

Example: 2.1 GHz

Shared spectrum

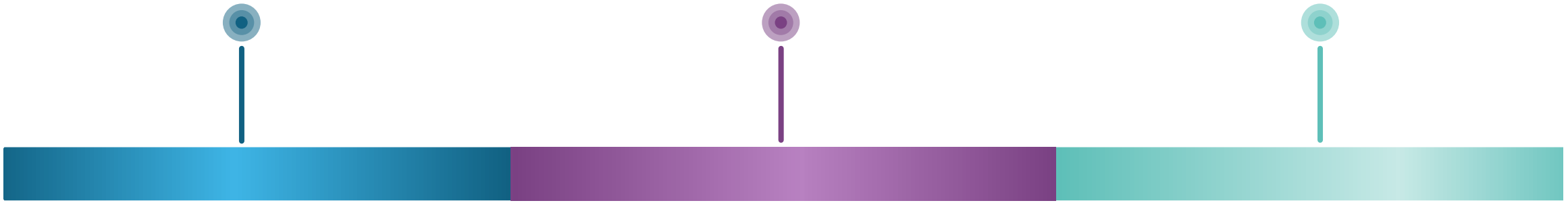
New shared spectrum paradigms

Example: 2.3 GHz Europe / 3.5 GHz USA

Unlicensed spectrum

Shared use

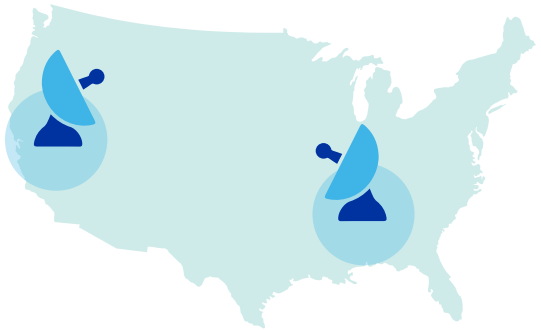
Example: 2.4 GHz global / 5 GHz global



Shared/unlicensed spectrum is important for 5G

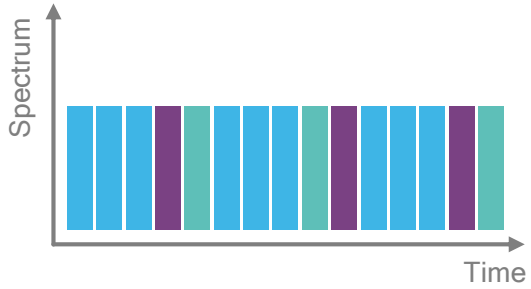
Unlocking more spectrum

Shared spectrum can unlock spectrum that is lightly used by incumbents



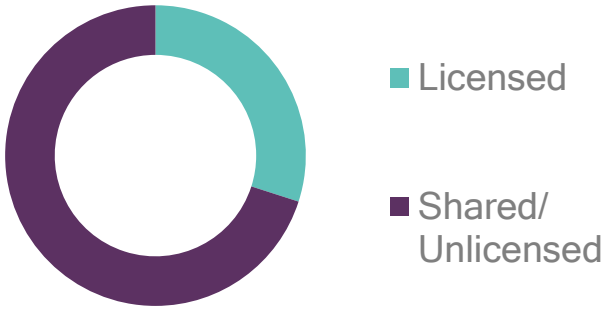
High spectrum utilization

Spectrum sharing has the potential to increase spectrum utilization



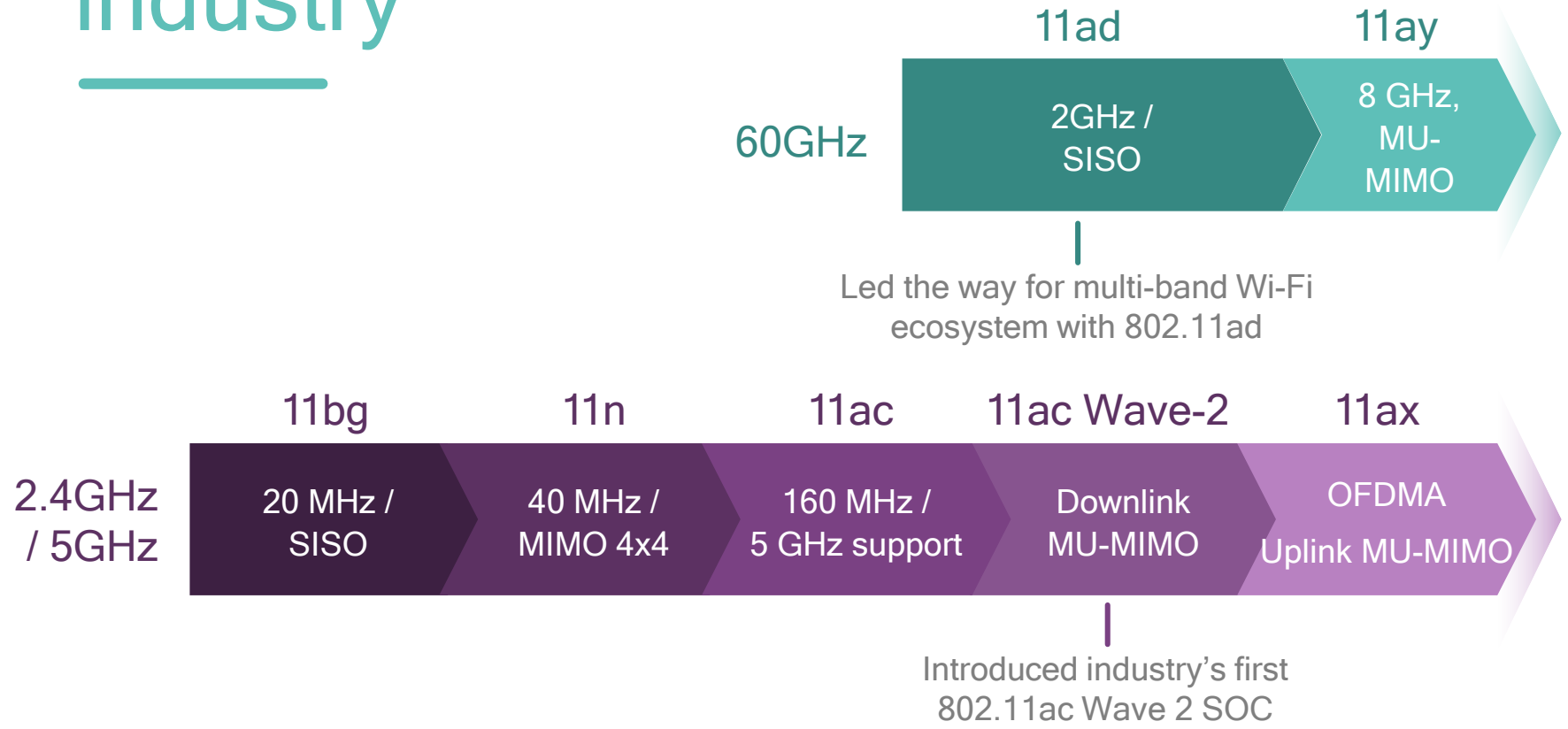
A lot of spectrum may be shared/unlicensed

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

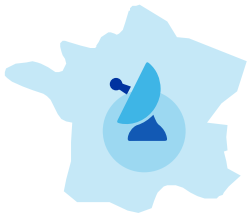


1) FCC ruling FCC 16-89 on 7/14/2016 allocated 3.25 MHz of licensed spectrum and 7.6 MHz of shared/unlicensed spectrum.

Leading the way with Wi-Fi in the mobile industry



Pioneered shared/unlicensed spectrum in 4G LTE



LSA[1]

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

LTE-U

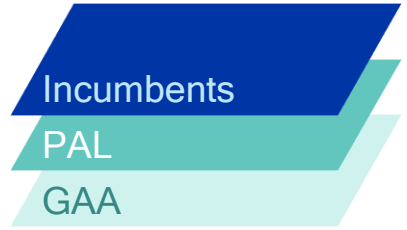
We designed the original proposal, commercialized by the LTE-U forum

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]

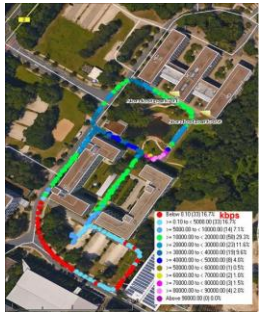
A founder of the CBRS Alliance and a key contributor to coexistence

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

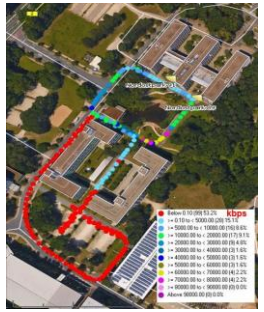
LTE is the high performance option in unlicensed spectrum

LAA ~2X coverage outdoors compared to Wi-Fi[1]

LAA



LWA (Wi-Fi)

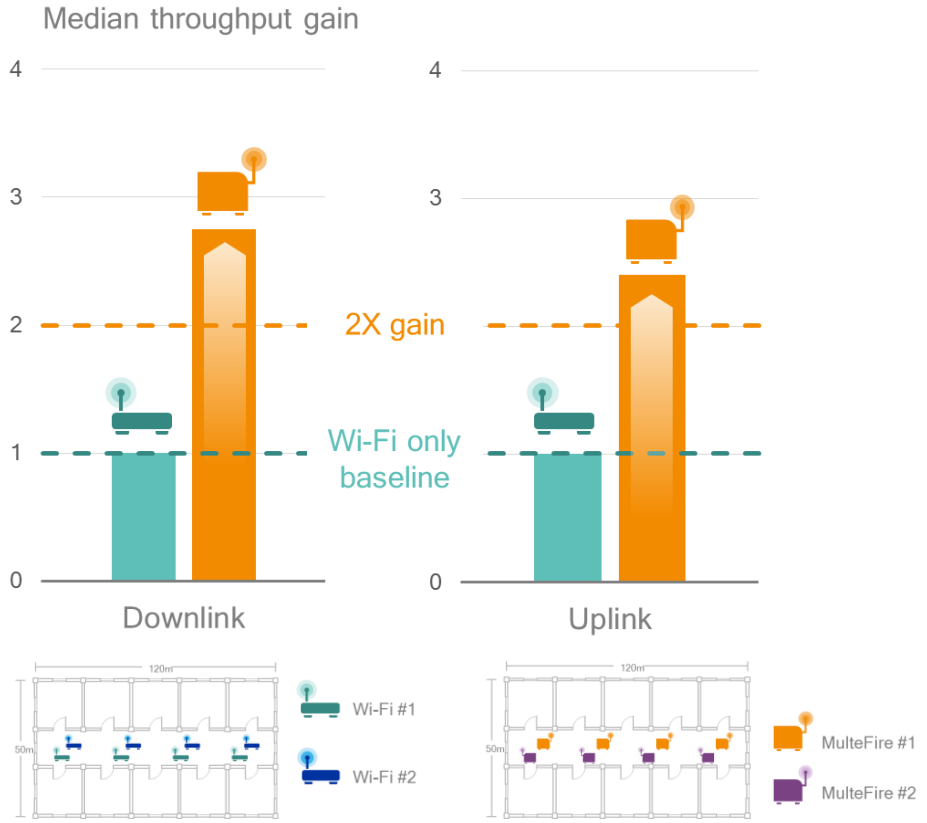


Downlink coverage in unlicensed

Mbps	Wi-Fi	LAA
		x2.5
>10	24% of route	60% of route
		x1.8
>1	39% of route	71% of route
		X1.7
>0	47% of route	82% of route

World's first over-the-air LAA trial in Nov. 2015 together with Deutsche Telekom

MulteFire by itself offers >2X capacity over Wi-Fi[2]

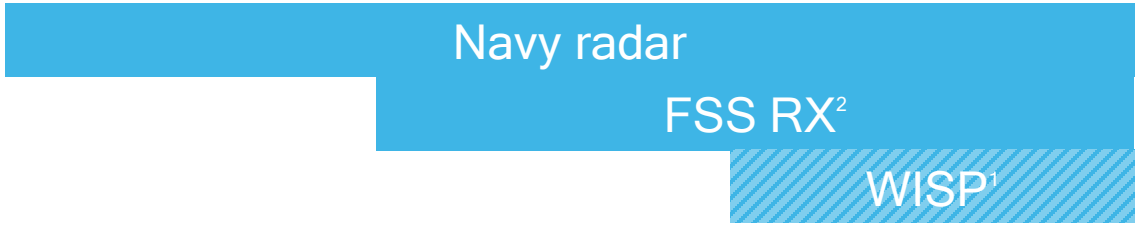


1) Single small cell, LAA based on 3GPP release 13; LWA using 802.11ac; LTE on 10 MHz channel in 2600 MHz licensed spectrum with 4W transmit power; the following conditions are identical for LAA and Wi-Fi: 2x2 downlink MIMO, same 20 MHz channel in 5 GHz unlicensed spectrum with 1W transmit power. terminal transmit power 0.2W, mobility speed 6-8 mph; 2 Based on geo-binned measurements over test route; 2) Indoor, single 20 MHz channel in 5 GHz, 80%-20% traffic split between down- and uplink, bursty traffic generated with 4 Mb files arriving with exponential inter arrival times, high traffic load with buffer occupancy at 50% in downlink and 20% in uplink for Wi-Fi only baseline, 4 APs per operator, 2 operators, office building size 120m x 50m, propagation model 3GPP indoor hotspot (InH), Wi-Fi is 802.11ac, MIMO 2x2, no MU-MIMO

CBRS introduces a 3-tiered shared spectrum

Enables to open up 150 MHz spectrum while incumbents are still using it

Tier 1
Incumbents

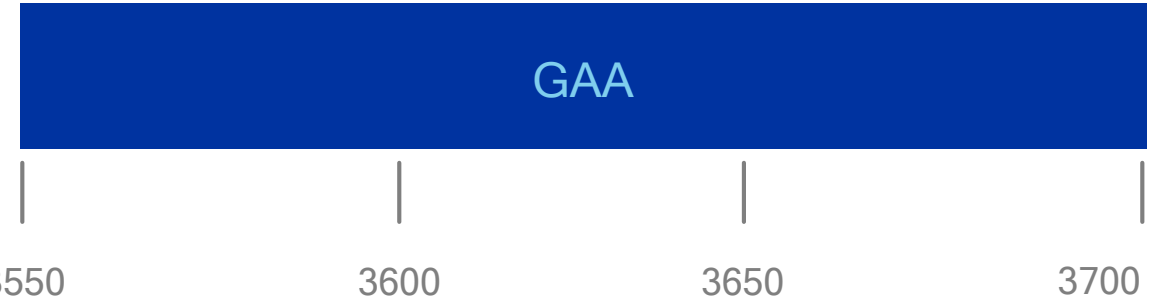


Incumbents are protected from interference from PAL and GAA

Tier 2
Priority Access Licenses (PAL)

PAL has priority over GAA, licensed via auction, 10 MHz blocks, up to 7 licenses

Tier 3
General Authorized Access (GAA)

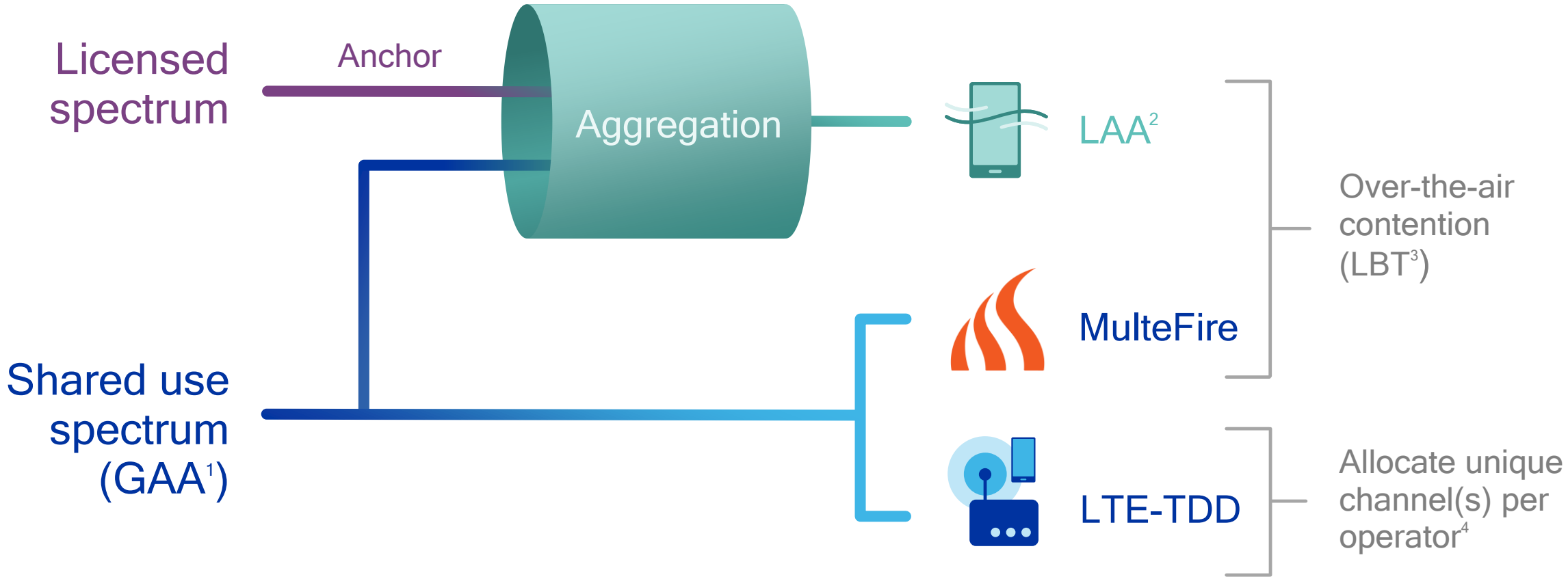


GAA can use any spectrum not used, yields to PAL and incumbents

1) Wireless ISP transitioning from incumbent to PAL/GAA after 5 years; 2) Fixed satellite service - receiving only; 3) Citizen Broadband Radio Service (CBRS)

Multiple high performance LTE options can coexist in GAA[1]

Possible to launch with LTE-TDD and introduce LBT later

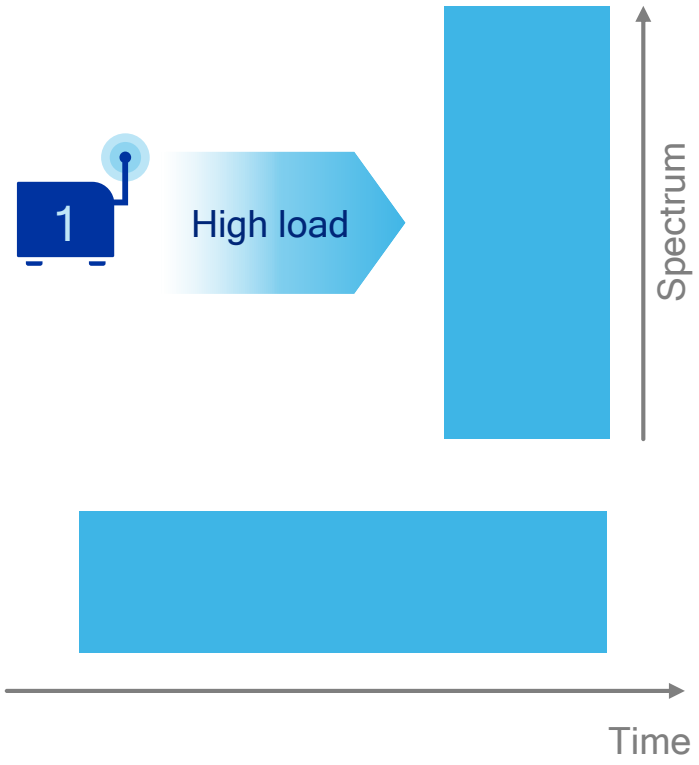


1. General Authorized Access (GAA) is tier 3 in the CBRS 3-tier licensing model for shared 3.5 GHz in USA; 2. Licensed-Assisted Access, also includes enhanced LAA (eLAA); 3. Listen before talk; 4. Channels can be reused with sufficient RF isolation

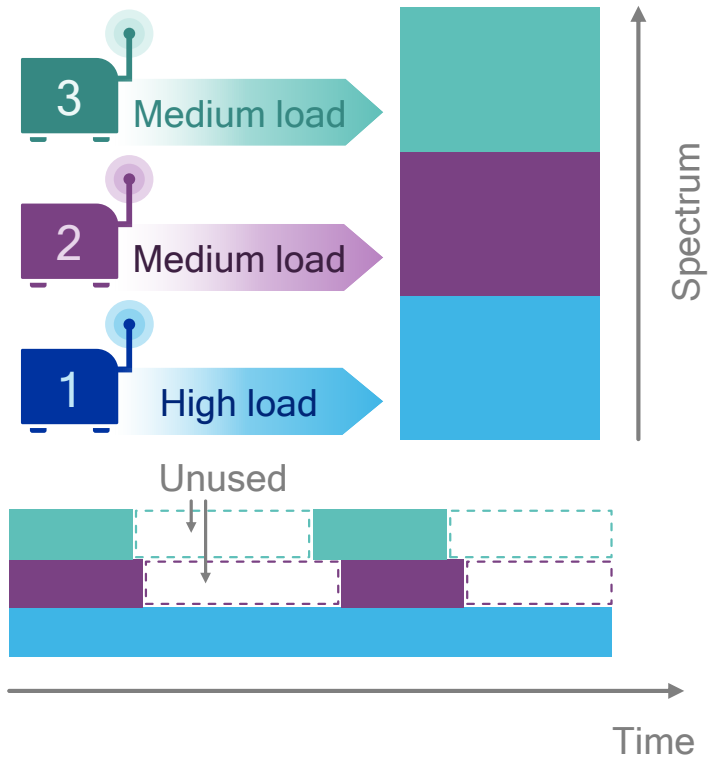
MulteFire helps GAA scale to multiple deployments

Multiple deployments share a wide channel–better spectrum utilization & peak-rate

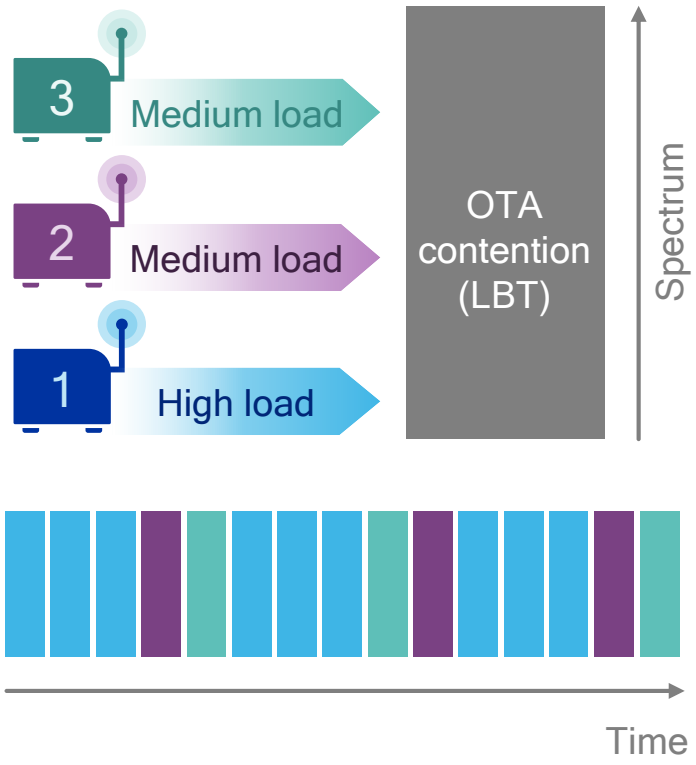
Highest spectrum efficiency with one LTE-TDD deployment



Multiple LTE-TDD deployments with reduced channel size, spectrum may become underutilized[1, 2]

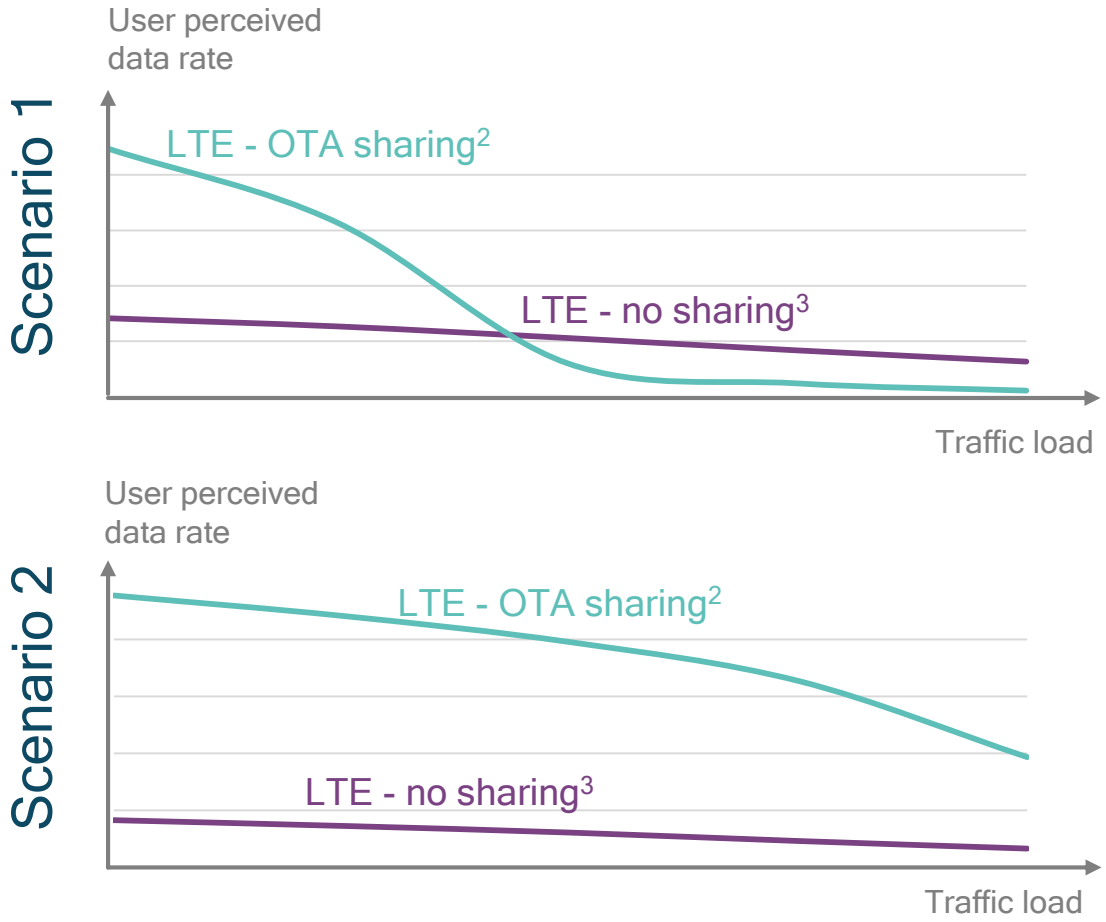


MulteFire brings trunking efficiency from sharing a wide channel to improve spectrum utilization[1,3]



1) Example with one deployment (#1) with a high traffic load and two deployments (#2 and #3) with medium traffic loads; 2) Spectrum cannot always be evenly split; 3) Trunking benefits depend on relative traffic loads.

Potential of high gains from spectrum sharing[1]

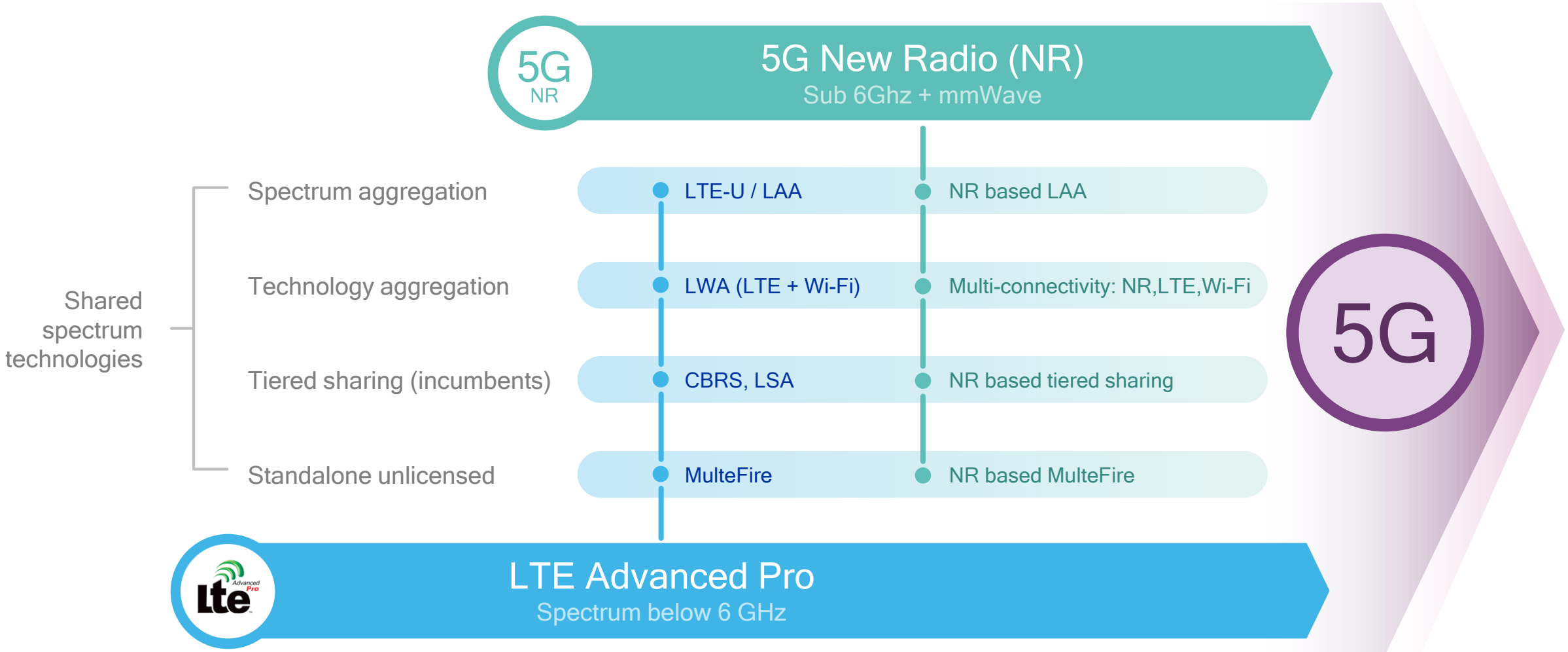


- LTE over-the-air (OTA) sharing performs better at low to moderate loads
- Gains mainly from trunking efficiency with bursty traffic and more flexible TDD
- Room for improvement in the future, e.g., OTA sharing at higher loads

1) These are examples, the gains from LTE OTA sharing is dependent on scenario; 2) Two operators use OTA sharing over the available spectrum; 3) Two operators divide the available spectrum between themselves.

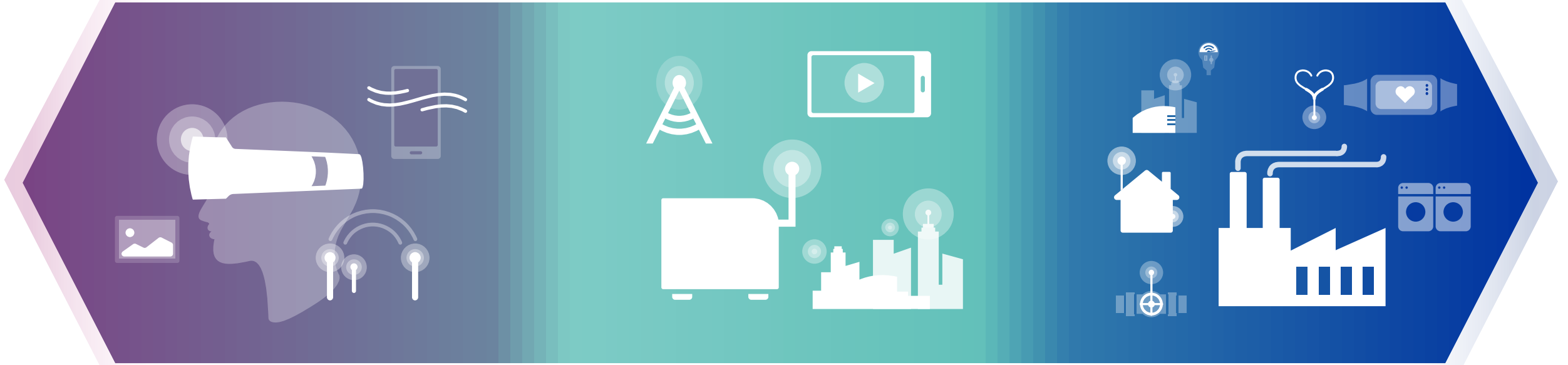
We are pioneering 5G shared spectrum today

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)

Shared spectrum–valuable for wide range of deployments



Extreme bandwidth by aggregating spectrum

Mobile operators provide extreme bandwidths by aggregating shared/unlicensed spectrum with licensed spectrum

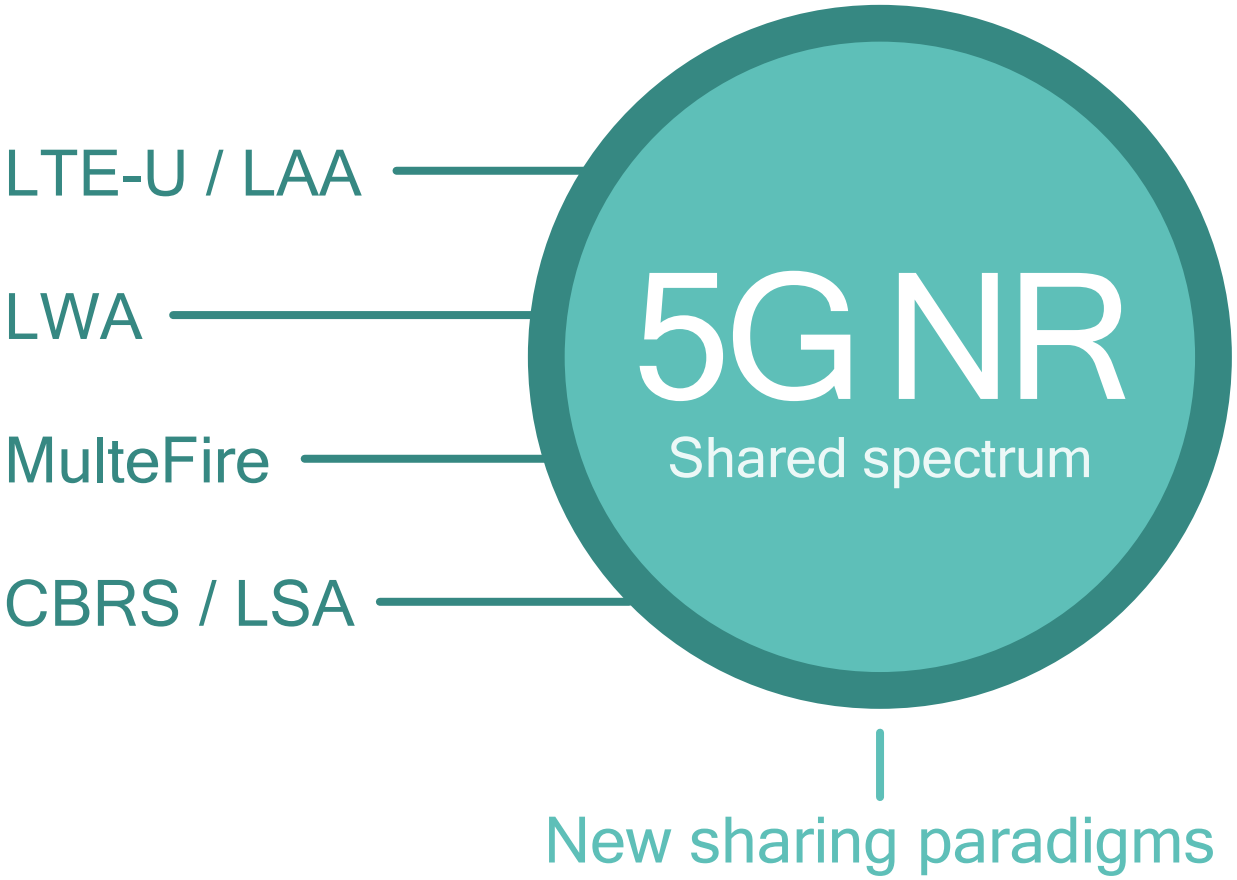
Enhanced local broadband

Shared/unlicensed spectrum enables entities without licensed spectrum to offer enhanced mobile broadband

Internet of Things verticals

Shared/unlicensed spectrum opens up opportunity to service different IoT verticals, e.g., a private IoT network

Designed to take advantage of new sharing paradigms



Flexible radio

- Scalable numerology: narrow-to-wideband
- Spectrum from sub-6GHz to mmWave
- Self-contained integrated sub-frames

Flexible unlicensed operation

- Unlicensed aggregation with licensed anchor
- Multi-connectivity: NR, LTE and/or Wi-Fi
- Stand-alone in unlicensed

Flexible spectrum sharing

- Dynamic sharing between deployments, technologies, priority tiers, etc.
- Enhanced spatial separation with mmWave
- Solutions for new spectrum sharing paradigms

Designed for sharing: Self-contained integrated sub-frame

Faster, more flexible TDD switching, plus support for new deployment scenarios

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

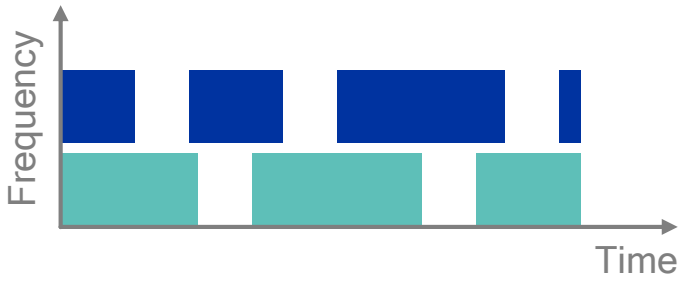
Opportunity to enhance spectrum sharing further

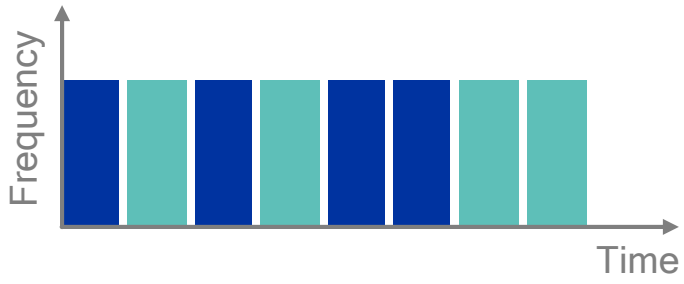
Leveraging 4G leadership to provide new solutions for NR shared spectrum

Licensed spectrum
Full control, partially loaded

LAA/MulteFire
Higher peak rate and utilization

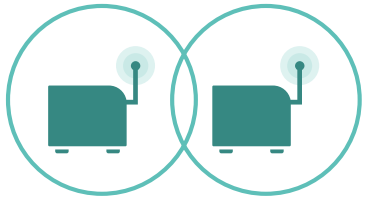
Synchronized access
Increased spectral efficiency

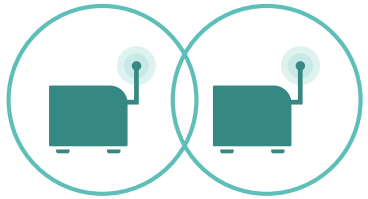


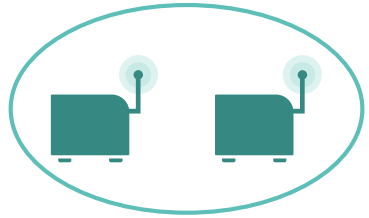


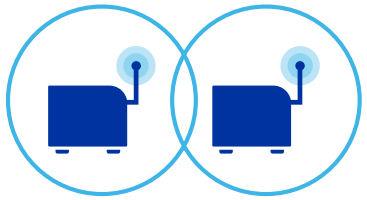
Operator 1

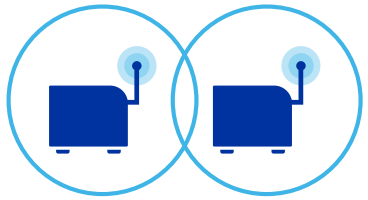
Operator 2

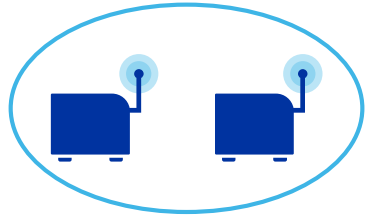








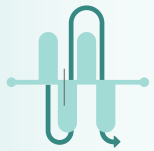




5G NR will natively support all different spectrum types

NR shared spectrum will support new shared spectrum paradigms

5G NR



Licensed Spectrum

Exclusive use

Shared Spectrum

New shared spectrum paradigms

Unlicensed Spectrum

Shared use

High bands above 24 GHz (mmWave)
Extreme bandwidths

Mid bands 1GHz to 6 GHz
Wider bandwidths for e.g. eMBB and mission-critical

Low bands below 1 GHz
Longer range for e.g. mobile broadband and massive IOT

5G Spectrum for US

Dean Brenner
SVP, Government Affairs
Qualcomm Incorporated

5G will support low, mid, and high band spectrum and all regulatory paradigms

Licensed Spectrum
EXCLUSIVE USE

Shared Spectrum
NEW SHARED SPECTRUM PARADIGMS

Unlicensed Spectrum
SHARED USE

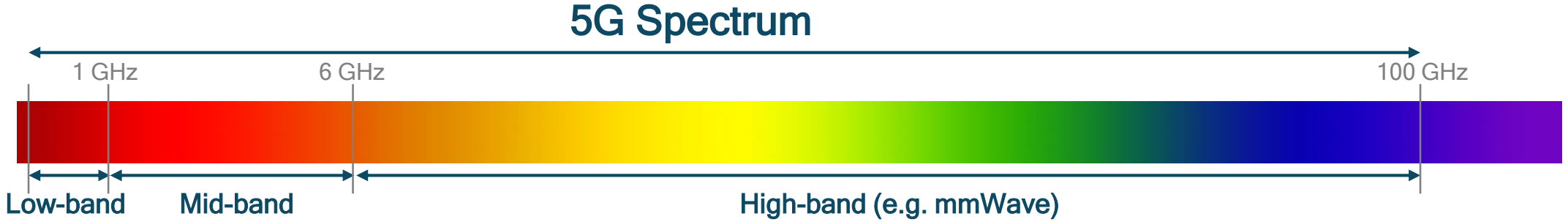
Low bands below 1 GHz: longer range for e.g. mobile broadband and massive Internet of Things

Mid bands 1 GHz to 6 GHz: wider bandwidths for e.g. enhanced mobile broadband and mission critical

High bands above 6 GHz, e.g. mmWave: extreme bandwidths

The FCC is driving key spectrum initiatives to enable 5G

Across low-band, mid-band, and high-band including mmWave



Low-band
Broadcast Incentive Auction

- First stage auction opened up 126 MHz in 600 MHz band, auction failed to close with clearing cost set at $88.4B
- Second stage auction opens up 114 MHz, auction will begin on 9/13
- Spectrum availability timing aligns with 5G

Mid-band
Citizens Broadband Radio Service

- Opening up 150 MHz in 3.5 GHz band
- 3-tier spectrum sharing with incumbents, PAL[1], and GAA[2]
- CBRS Alliance formally launched to drive an LTE-based ecosystem

High-band
Spectrum Frontiers Ruling[3]

- Opening up 11 GHz in multiple mmWave bands
- 70% of newly opened spectrum is shared or unlicensed
- Unanimously approved by FCC with additional candidate bands identified for IMT-2020

1 Priority Access Licenses to be auctioned; 2 General Authorized Access; 3 FCC ruling FCC 16-89 on 7/14/2016 allocated 3.25 MHz of licensed spectrum and 7.6 MHz of shared/unlicensed spectrum.

Spectrum Frontiers ruling for 5G mmWave

Shared and unlicensed spectrum is key for more bandwidths

Licensed access

- 27.5 - 28.35 GHz: 850 MHz (2x425 MHz)
- 37.6 - 38.6 GHz: 1 GHz (5x200 MHz)
- 38.6 - 40 GHz: 1.4 GHz (7x200 MHz)

Shared and unlicensed access

- 37 - 37.6 GHz: 600 MHz (3x200 MHz)
- 64 - 71 GHz: 7 GHz expansion of existing 60 GHz band

Total spectrum = ~11 GHz

FCC also identified additional candidate bands for IMT-2020

Including 24.25-24.35, 24.75-25.25, 31.8-33.4, 42-42.5, 47.2-50.2, 50.4-52.6, 71-76 GHz

The FCC's July 14th Spectrum Frontiers ruling is

" the final piece in the spectrum trifecta of low-band, mid-band, and high-band airwaves that will open up unprecedented amounts of spectrum, speed the rollout of next-generation wireless networks and re-define network connectivity for years to come."

- FCC Chairman Tom Wheeler, June 20, 2016

QUALCOMM®
Why Wait™

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

Thank you

Follow us on:

For more information, visit us at:

www.qualcomm.com & www.qualcomm.com/blog