Spectrum for 4G and 5G

Qualcomm Technologies, Inc.

December, 2017

Using all available spectrum types and spectrum bands

Licensed spectrum

Exclusive use

Over 40 bands globally for LTE, remains the industry's top priority

Shared spectrum

New shared spectrum paradigms

Example: 2.3 GHz Europe / 3.5 GHz USA

Unlicensed spectrum

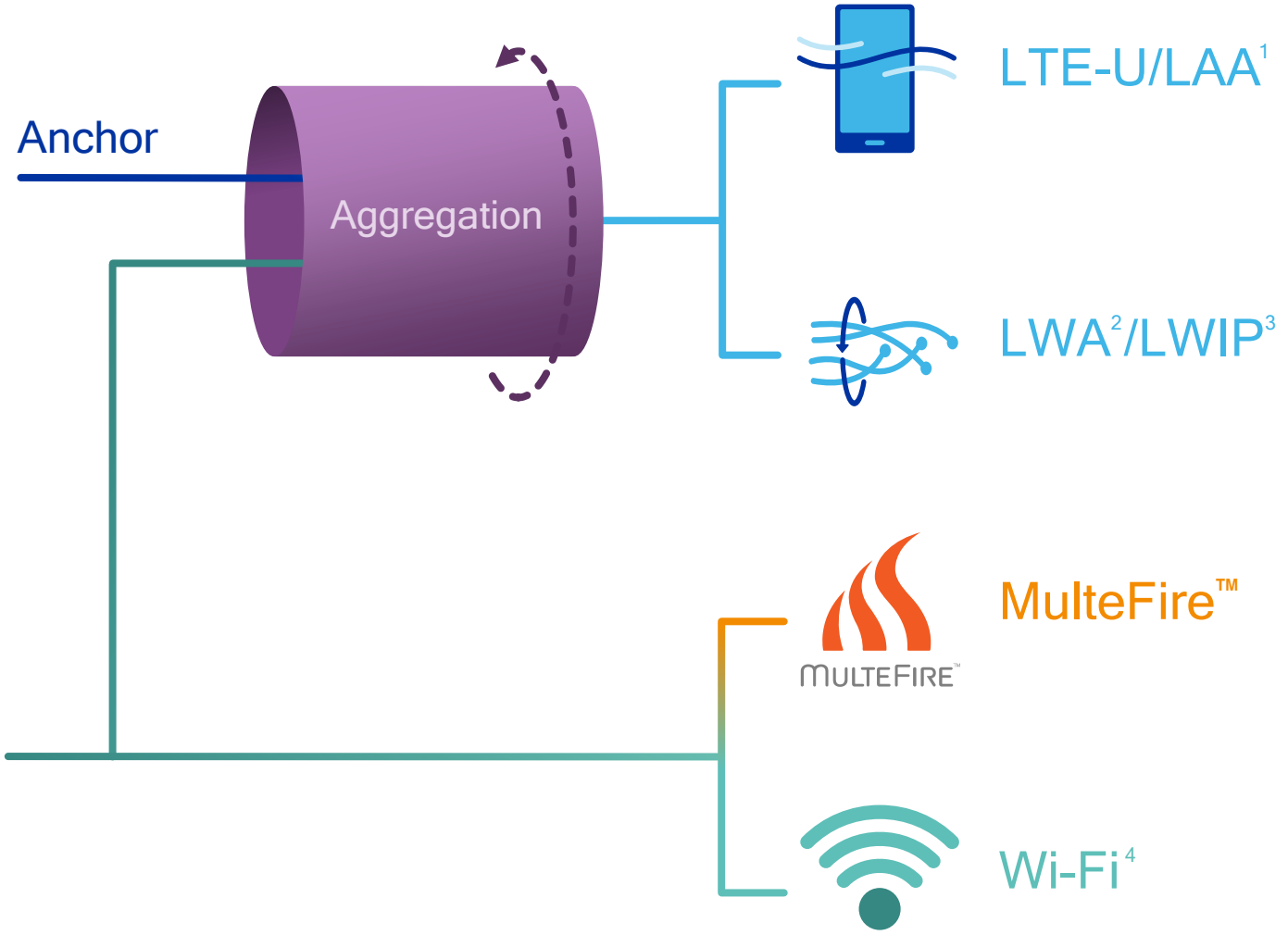
Shared use

Example: 2.4 GHz / 5-7 GHz / 57-71 GHz global

Making best use of shared/unlicensed spectrum

Licensed spectrum
Exclusive use

Unlicensed spectrum
Shared use



LTE-U/LAA[1]
Targeting mobile operators using LTE in unlicensed spectrum for new small cell deployments

LWA[2]**/LWIP**[3]
Targeting mobile operators leveraging existing carrier Wi-Fi deployments

MulteFire™
Broadens LTE ecosystem to enhanced and new deployment opportunities, suitable for neutral host

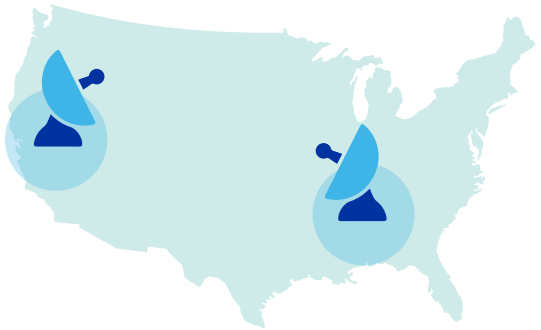
Wi-Fi[4]
Evolving for enhanced performance and expanding to new usage models, used today as neutral host

1. Licensed-Assisted Access (LAA), also includes enhanced LAA (eLAA); 2. LTE WLAN Link Aggregation (LWA); 3. LTE WLAN radio level integration with IPsec tunnel (LWIP); 4. 802.11ac / .11ad / .11ax / .11ay

New opportunities with shared/unlicensed spectrum

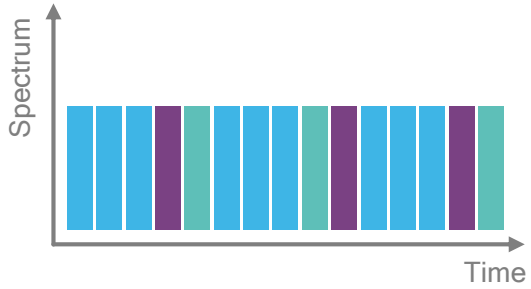
Unlocking more spectrum

Shared spectrum can unlock spectrum that is lightly used by incumbents



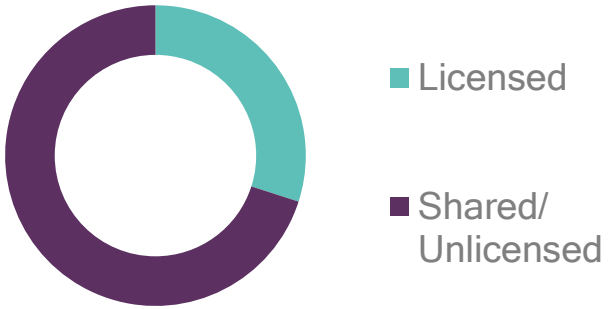
New spectrum sharing innovations

Spectrum sharing has the potential to increase spectrum utilization



A lot of spectrum may be shared/unlicensed

FCC 2016 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 GHz of licensed spectrum and 7.6 GHz of shared/unlicensed spectrum.

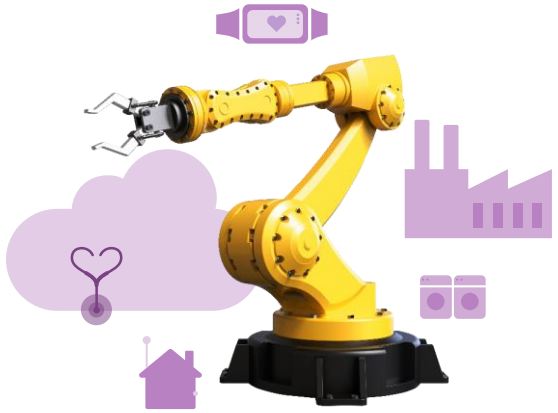
Spectrum sharing valuable for wide range of deployments

Licensed spectrum aggregation

Better user experience with higher speeds

Enhanced local broadband

Neutral host, neighborhood network



Private 5G networks

Industrial IoT, Enterprise

Enhancing existing deployments,

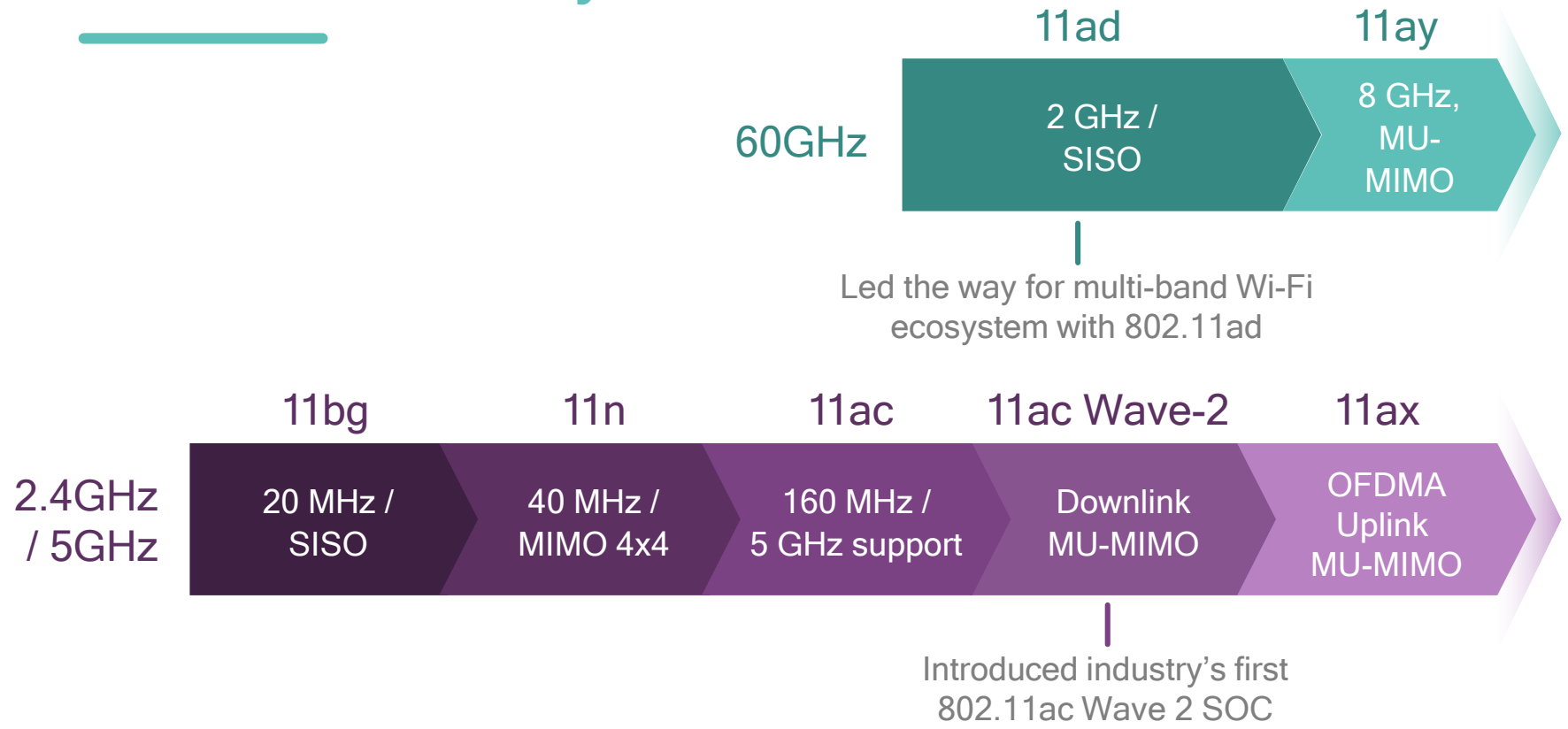
Examples today: Gigabit LTE with LAA[1]

New types of deployments,

Examples today: Private LTE networks

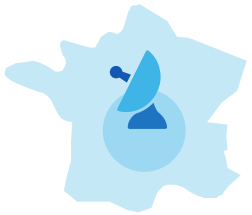
1. Licensed-Assisted Access (LAA);

Qualcomm Technologies, Inc. (QTI) leading the way with Wi-Fi in the mobile industry



Qualcomm Wi-Fi chipsets are products of Qualcomm Technologies, Inc.

Pioneering shared spectrum technologies in LTE



LSA[1]

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

LTE-U

Designed the original technology, commercialized by the LTE-U Forum, deployed in the US

LAA[2]

First over-the-air trials with DT 2015, multiple commercial deployments globally and 2nd gen. Gigabit LTE tested 2017

MULTEFIRE™

A founder of the MulteFire Alliance, first OTA connection Oct. 2016, Release 1.0 specification Jan. 2017

ALLIANCE cbrs

A founder of the CBRS[3] Alliance and a key contributor to coexistence

1) Licensed Shared Access (LSA); 2) Licensed-Assisted Access (LAA), enhanced LAA (eLAA), Deutsche Telekom (DT), SK Telecom (SKT); 3) Citizen Broadband Radio Service (CBRS)

LTE-U and LAA are now a commercial reality

Specifications finalized and published

LTE-U Forum published the LTE-U specs in Q1 2014, 3GPP published Rel. 13 standard with LAA in Q1 2016

FCC authorized devices for US deployments

FCC has granted equipment authorization for both LTE-U[1] and LAA[2]

LAA for global deployments

Listen-before-talk (LBT) is used by both LAA and Wi-Fi globally in the 5 GHz unlicensed band

Supported by Qualcomm® Snapdragon™ LTE modems

LTE-U starting with X12 LTE modem; LAA starting with X16 LTE modem in Snapdragon 835 mobile platform

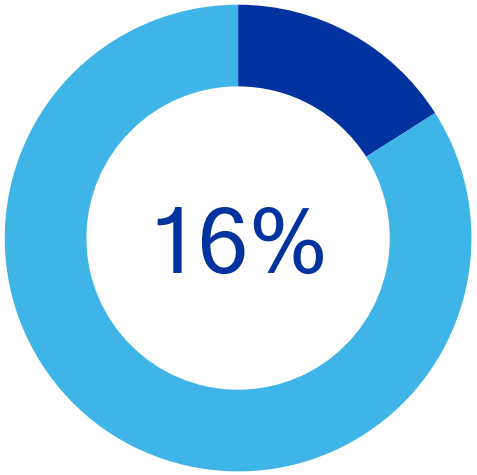
Qualcomm Snapdragon is a product of Qualcomm Technologies, Inc.

1 FCC blog https://www.fcc.gov/news-events/blog/2017/02/22/oet-authorizes-first-lte-u-devices; 2 FCC blog https://www.fcc.gov/news-events/blog/2016/09/23/industry-makes-progress-unlicensed-lte-coexistence

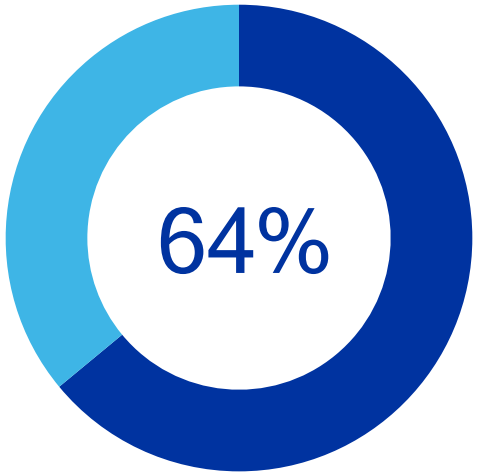
Enabling Gigabit LTE all over the world by using LAA

More operators can deliver Gigabit LTE using LAA in 5 GHz unlicensed spectrum

Share of operators who can deploy Gigabit LTE

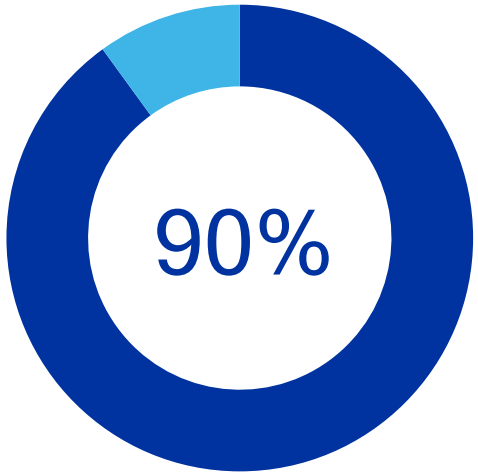


60 MHz licensed[1]



X16 LTE Modem

20 MHz licensed + LAA



X20 LTE Modem

10 MHz licensed + LAA

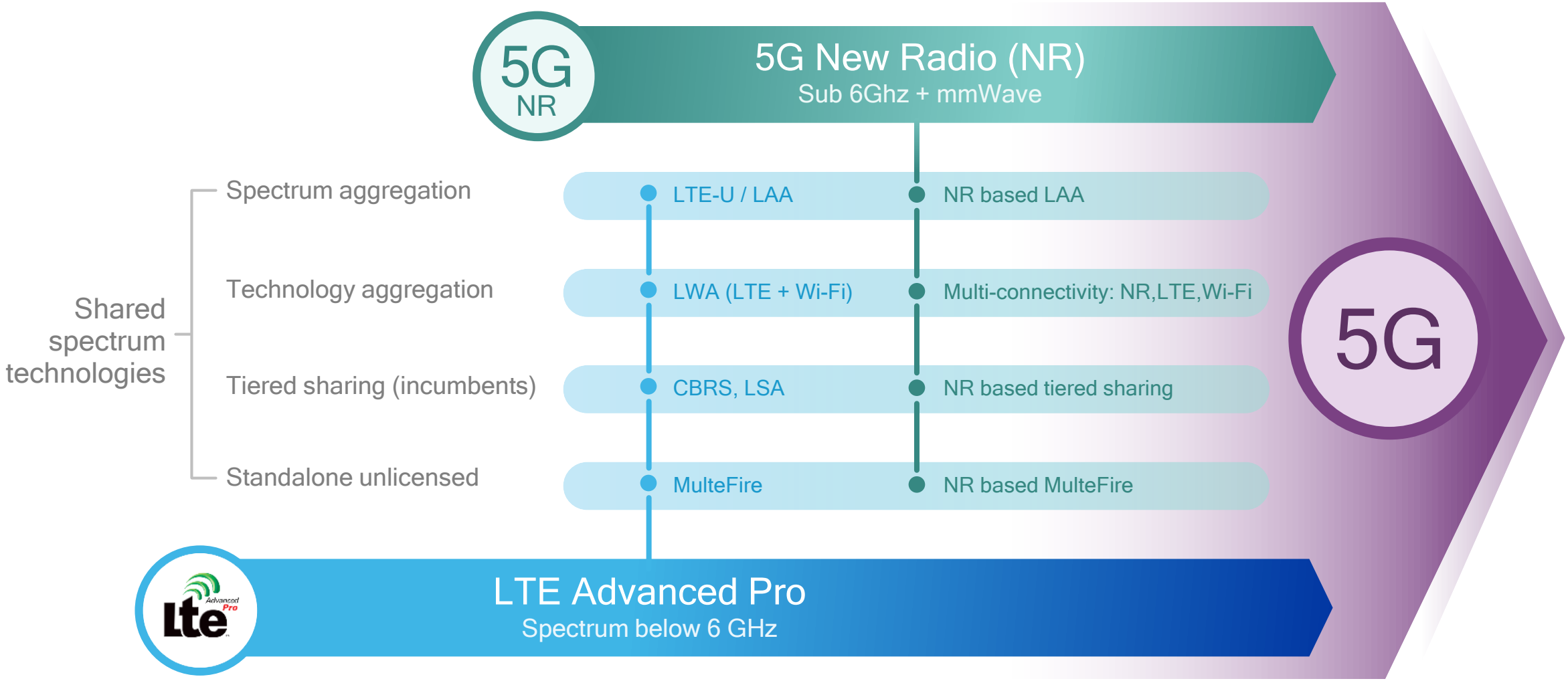
Over 17 commercial devices, including smartphones, always connected PC, mobile broadband devices…

43 Operators in 25 countries with Gigabit LTE planned or trialed

Qualcomm Snapdragon is a product of Qualcomm Technologies, Inc.; 1) Assuming using 4x4 MIMO and 256-QAM

Ushering in new spectrum sharing paradigms with 5G

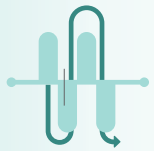
Pioneering spectrum sharing technologies with LTE today



Learn more at: http://www.qualcomm.com/spectrum-sharing

5G NR will natively support all different spectrum types

5G NR



Licensed Spectrum
Exclusive use

Shared Spectrum
New shared spectrum paradigms

Unlicensed Spectrum
Shared use

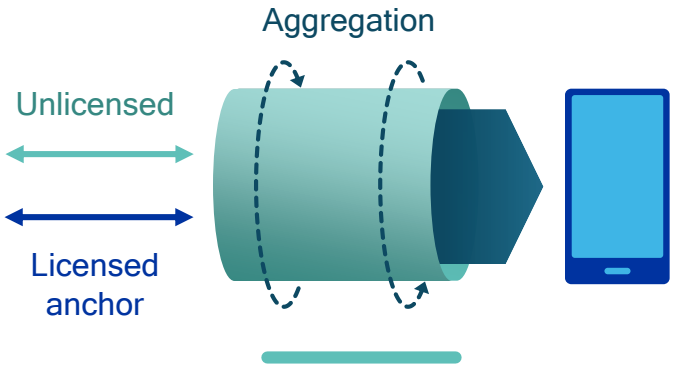
High bands (mmWave) above 24 GHz
Extreme bandwidths

Mid bands between 1-6 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

3GPP study on 5G NR operation in unlicensed spectrum

First time 3GPP studies cellular technology operating stand-alone in unlicensed[1]

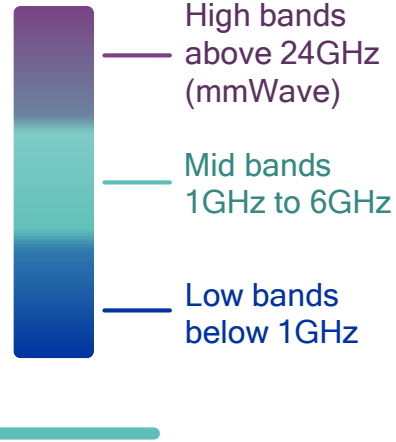


NR-based LAA

NR in unlicensed aggregated with LTE (dual-connectivity) or NR (carrier-aggregation) in licensed spectrum

Stand-alone unlicensed

NR operating standalone in unlicensed spectrum. This will become the MulteFire™ evolution path to 5G



Across spectrum bands

Both below and above 6 GHz, e.g., 5GHz, 37GHz, 60GHz* (*assuming no change to waveform)

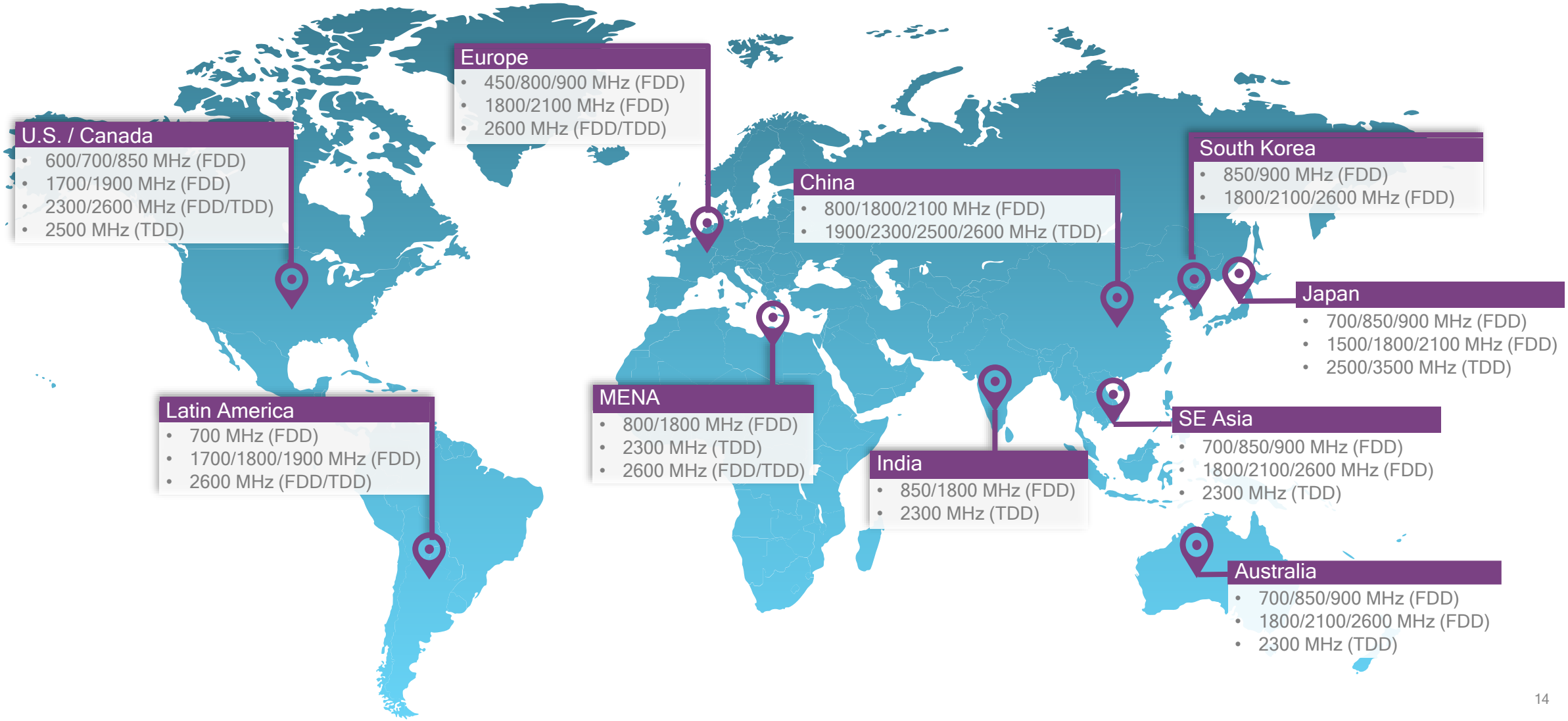
Fair co-existence in any unlicensed spectrum: NR/NR, NR/LTE, NR/Wi-Fi

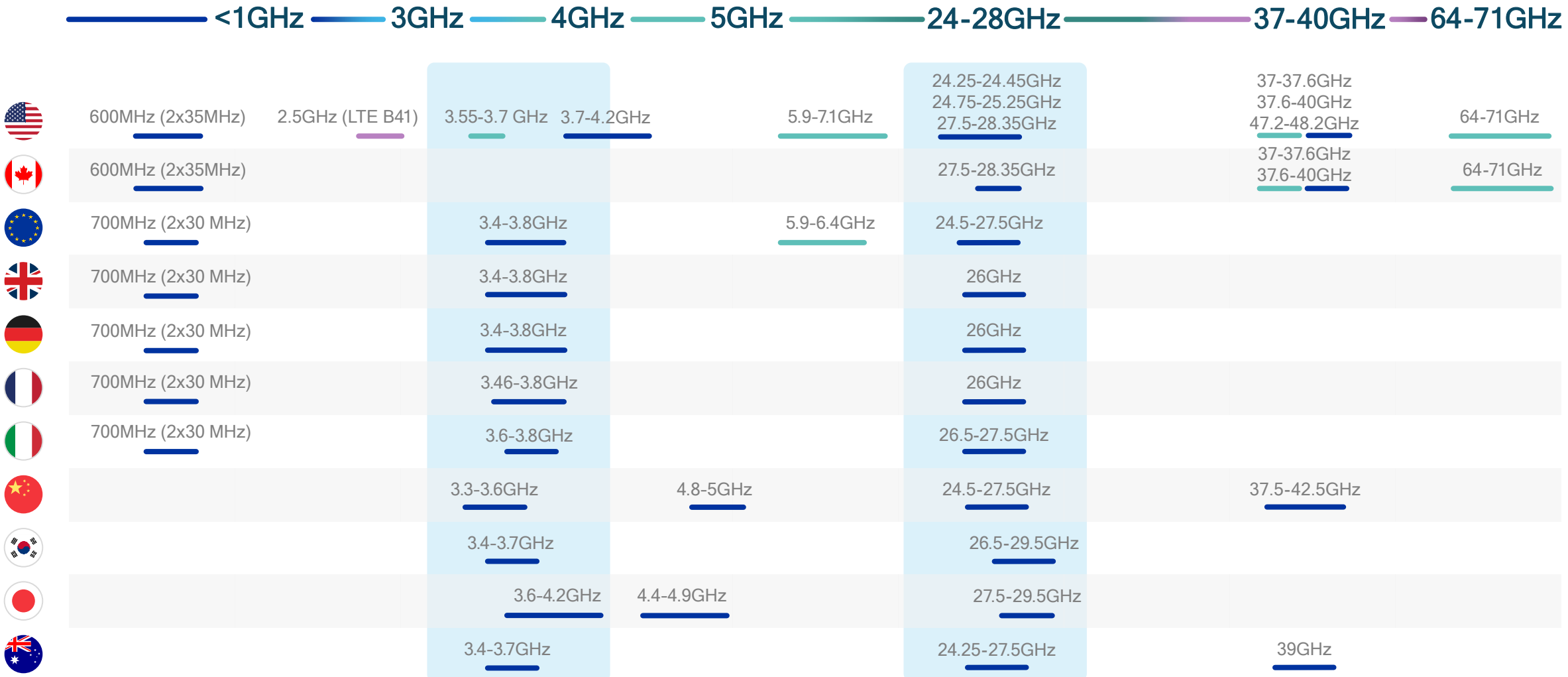
1.Study item in Rel.15 (RP-170828), which could be followed by a work item that is completed in Rel. 16.

Global 4G & 5G spectrum update

Global 4G LTE spectrum landscape

Over 1,000 band combinations now supported for LTE





Global snapshot of 5G spectrum

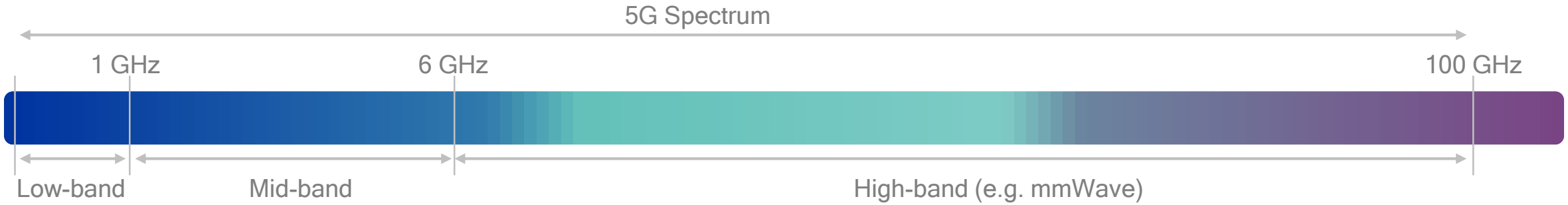
Around the world, these bands have been allocated or targeted

New 5G band

- Licensed
- Unlicensed / shared
- Existing band

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

- Successfully auctioned a portion of the 600 MHz band that generated $19.8B in proceeds after assignment phase
- Includes 70 MHz (2 x 35 MHz) of licensed spectrum and 14 MHz for unlicensed use
- Spectrum availability timing aligns with 5G

Mid-band
Citizens Broadband Radio Service

- Opening up 150 MHz in 3.5 GHz band with 3-tier sharing with incumbents, PAL[1], GAA[2]
- FCC to improve PAL rules in 2017 to make them suitable for 5G
- CBRS Alliance formally launched to drive an LTE-based ecosystem
- FCC Notice of Inquiry on 3.7-4.2 GHz and 5.9-7.1 GHz

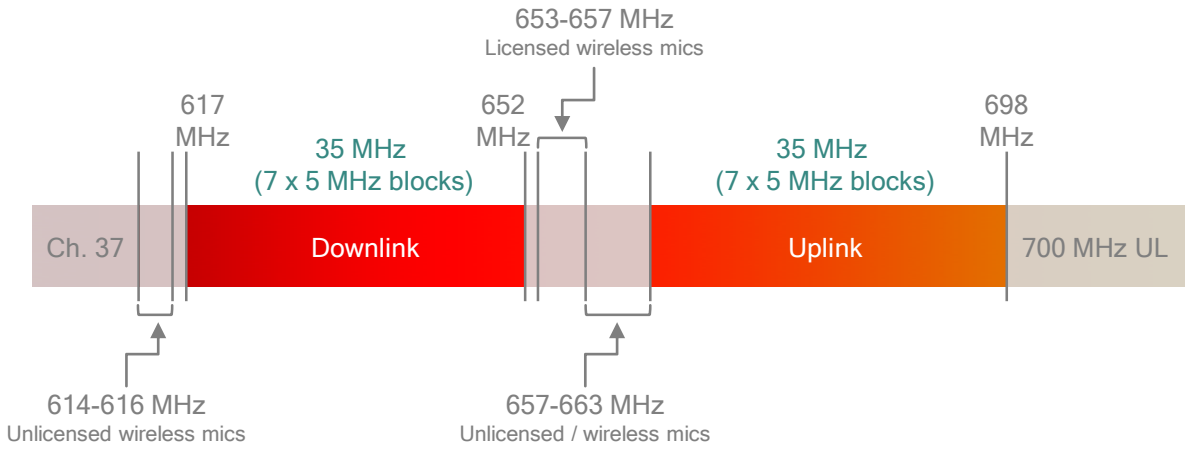
High-band
2016 Spectrum Frontiers Ruling[3] and second mmWave ruling in 2017

- In 2016, FCC announced opening up of 11 GHz in multiple mmWave bands, 70% of newly opened spectrum is shared or unlicensed
- Unanimously approved. FCC also asked for comment on other candidate bands identified for IMT-2020
- In Nov. 2017, FCC adopted second order allocating 24.25-24.45, 24.75-25.25 GHz, and 47.2-48.2 GHz

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

Low-band: 600 MHz getting ready for 5G NR and LTE

Initially LTE in areas w/ cleared spectrum; 5G when spectrum is cleared of TV stations



600 MHz Spectrum

Meeting 5G timeline

Process of clearing the spectrum & repacking TV stations will take 39 months

Greater capacity and wider coverage

Low-band spectrum is optimized for long-range macro deployments - optimal for connecting the wide-area IoT and more

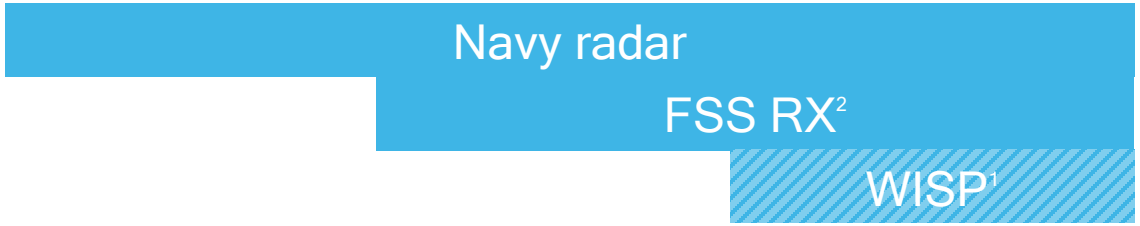
Broad industry support

QTI is working closely with operators & OEMs to enable early launches, incorporating our industry-leading modem, transceiver, and RFFE

Mid-band: CBRS introduces a 3-tiered shared spectrum

FCC to optimize PAL rules in 2017 for 5G deployments

Tier 1
Incumbents

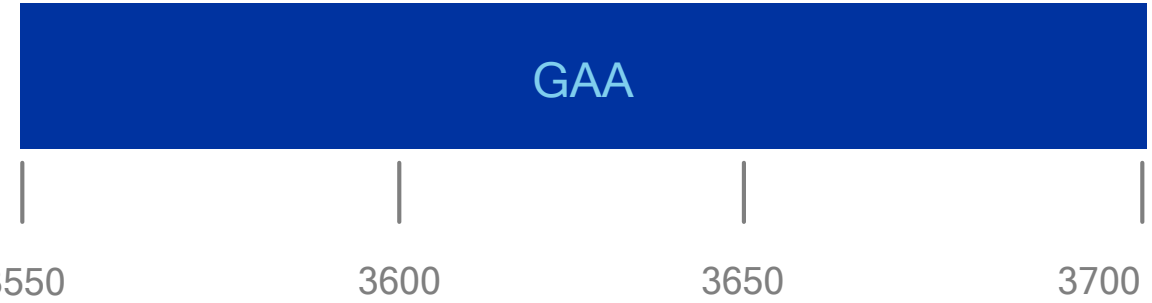


Incumbents are protected from interference from PAL and GAA

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)

High-band: 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 ruling expected in 2017 for additional candidate bands

Including 24.25-24.45, 24.75-25.25, as well as 42-42.5

European Commission driving a Gigabit Society[1]

Deploying 5G across Europe by 2020 with pre-commercial trials starting in 2018

EC 5G Action Plan – published in Sept. 2016

- Early trials in 2017, pre-commercial trials from 2018
- Full commercial 5G services (one major city per country) in 2020
- All urban areas and major terrestrial transport paths with 5G coverage by 2025

Pioneer spectrum bands for 5G

- Low-band (700 MHz), mid-band (3.4-3.8 GHz), high-band (24.25-27.5 GHz)
- EC Mandate to CEPT focusing on 3.5 GHz and 26 GHz pioneering bands – target completion June 2018
- Additional EC Mandate to CEPT on extended L band (1427 – 1518 MHz) – target completion by end of 2017
- CEPT harmonization of the 26 GHz band ahead of WRC-19 (June 2018 target)
- 5G commercial services to use both 3.4-3.8 GHz and 26 GHz in Europe by 2020

Full set of 5G spectrum bands – agree on by end of 2017

- Works towards a recommended approach for the authorization of the specific 5G spectrum bands above 6 GHz – focus on the bands for WRC-19 (e.g., 31.8 – 33.4 GHz, 40.5 – 43.5 GHz in addition to 24.25 – 27.5 GHz)
- Maximizes spectrum sharing opportunities – sharing as regulatory tool central to European Electronic Communications Code

1 http://www.vodafone.com/content/dam/group/policy/downloads/Vodafone_Group_Call_for_the_Gigabit_SocietyFV.pdf

5G spectrum in Europe

Focus on mid-band (3.4–3.8 GHz) and 26 GHz (24.25-27.5 GHz) for 2017+

EC RSC, CEPT, key European Member States are driving regulatory activities to accelerate 5G rollout in EU
Intense regulatory activities for 3.4-3.8 GHz and 26 GHz with auctions expected in 2018-2019 timeframe

- Government 5G strategy for UK published in March 2017 – DCMS and HM Treasury
- Ofcom planning to auction 150 MHz in 3.4-3.6 GHz in 2018/ 2019 – more spectrum (116MHz) in 3.6 – 3.8 GHz in 2019
- Legal Challenges might delay 3.4-3.6GHz auction to 2018 at the earliest, likelihood of a multiband auction scenario in 2019 including (700MHz, 3.4-3.8GHz and 26GHz)
- For mmWave, Ofcom has initiated a work program on 26 GHz band availability for early 5G deployment

- BenetzA planning to award 3.4-3.8 GHz in the forthcoming awarding process – expected in 2018
- For mmWave, 26.5 – 27.5GHz could be included in 2018 award

- ARCEP to award 340 MHz (3.46-3.8GHz) of spectrum in 2018; ARCEP spectrum consultation included 26 GHz

- Italian government will award 700MHz, 3.6-3.8GHz and 26.5-27.5GHz in 2018
- Multiband auction included in the country budget plan for 2018
- Major 5G trials gov't program on 100 MHz of spectrum in 3.7-3.8 GHz; discussions on re-farming 3.4-3.6 GHz between MoD, MiSE, AGCOM

- Ireland successful auction of 350 MHz of spectrum for 5G – 26GHz auction in 2018

- In Spain, the 3.6-3.8 GHz band could be tendered according to market and operators needs from 2018
- Consultation ongoing on 5G Plan of Ministry for Digital Agenda; CNMC proposal to free up spectrum in the 3.4 – 3.8 GHz range
- Spain consulting on 26 GHz band – at least 1.4 GHz available for release in 2018

- Ficora is looking at "large-scale 5G tests" in 26 GHz, decided to make available up to 1 GHz for it in 2017

- PTS is looking at "large-scale 5G tests" in 26 GHz, decided to make available up to 1 GHz for it in 2017
- Commitment to make available pioneering bands by 2020 – spectrum plan expected to be announced in Q1 2018

Other countries:

Belgium, Austria, Switzerland planning to release spectrum in 2018/2019 timeframe

5G Spectrum in Europe

Focus on mid-band (3.4-3.8 GHz) and 26 GHz (24.25-27.5 GHz) for 2018+

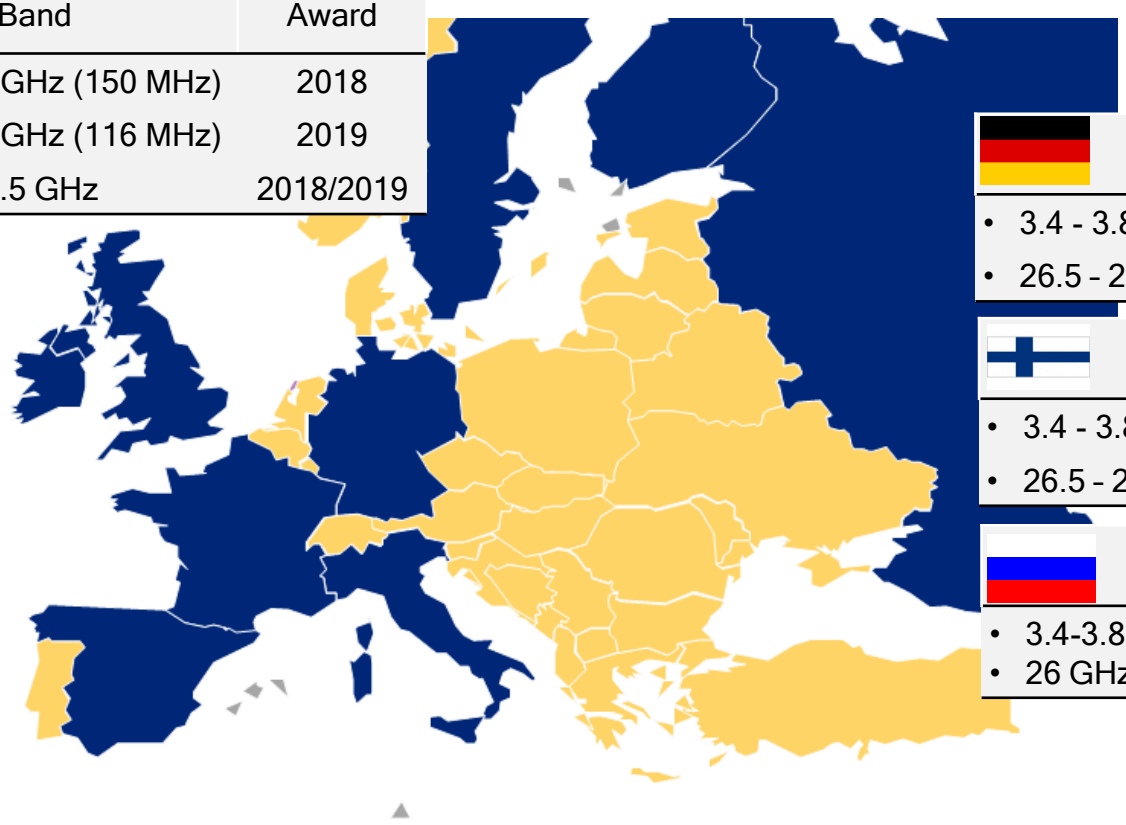
Band	Award
• 3.4 - 3.8 GHz (350 Mhz)	2017
• 26 GHz	2018

Band	Award
• 3.46 - 3.8 GHz	2018
• 26 GHz	2019

Band	Award
• 3.4-3.8 GHz	2019/2020
• 26.5 - 27.5 GHz	2019/2020

Band	Award
• 3.6 - 3.8 GHz	2018
• 26.5 - 27.5 GHz	2018

Band	Award
• 3.4 - 3.6 GHz (150 MHz)	2018
• 3.6 - 3.8 GHz (116 MHz)	2019
• 26.5 - 27.5 GHz	2018/2019



Band	Award
• 3.4 - 3.8 GHz	2018
• 26.5 - 27.5 GHz	2018?

Band	Award
• 3.4 - 3.8 GHz	2018
• 26.5 - 27.5 GHz	2020

	Award
• 3.4-3.8 GHz	2019/20*
• 26 GHz	2020+*

eMBMS[1] delivers terrestrial Digital TV more efficiently

A strong candidate to deliver next-gen digital TV in Europe–opportunity elsewhere

Single cellular broadcast network

Broadcast also for digital TV content and unicast for on-demand and interactivity

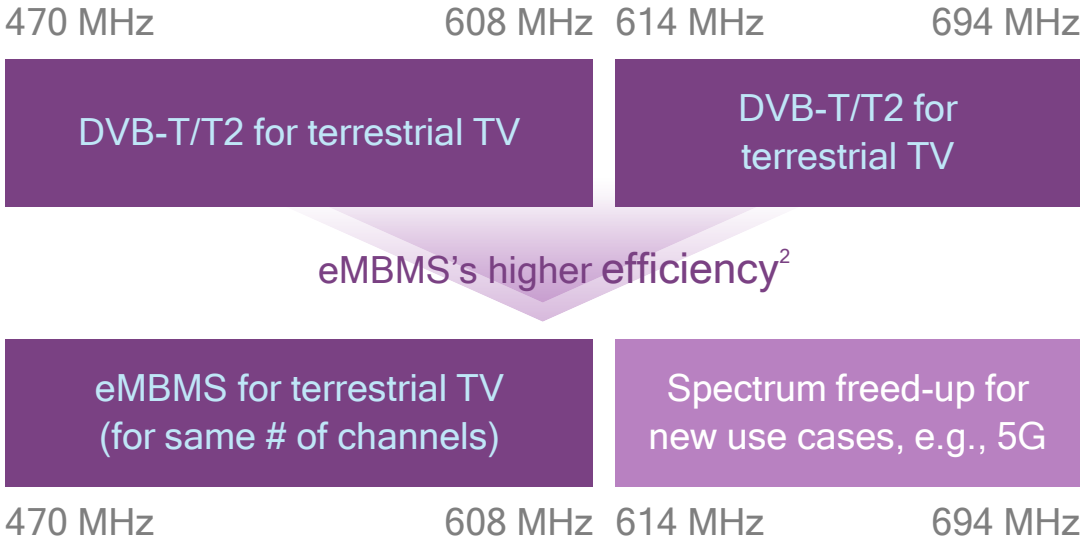
Addresses existing/new devices

Content to new device types (e.g., receive-only fixed devices like a TV) and mobile devices

Shared broadcast delivery

To serve users from multiple providers and operators–enabling new media delivery

EU decision to harmonize 700 MHz by June 30th, 2020 for mobile broadband networks[5]



1. Evolved Multimedia Broadcast Multicast Service; 2. ~2x more efficient than DVB-T/ATSC and provides longer range up to 15km (with further extended CP of 200 us and features such as 2x2 MIMO, 256 QAM, increased subframe limit); Assumptions: current broadcast technology operates in MFN mode with a frequency reuse of at least 4 with a spectrum efficiency of up to 4 bps/Hz inside each cell. This corresponds to an overall spectrum efficiency of approx. 1bps/Hz. Whereas eMBMS operates in SFN over the entire coverage area with a spectrum efficiency of up to 2bps/Hz 5. Introducing technology neutrality in 470-694 MHz, with priority for broadcasting services until 2030

Opening more spectrum for 5G is a global effort

5G spectrum status in key Asian markets and Australia

- MIIT officially allocated 3.3-3.6 GHz & 4.8-5.0 GHz as official 5G bands
- MmWave in longer term. Chinese gov't solicited public opinion for candidate bands of 24.75-27.5 GHz & 37-42.5 GHz non-exclusively in Jun'17
- Chinese government approved small scale trial frequencies usage in 24.75-27.5 GHz & 37-42.5 GHz mmWave ranges in Jul'17

- Phase 1 (2018+): 27.5-28.5 GHz & 3.4-3.7 GHz, also 26.5-29.5 GHz if 3GPP assigns it to 5G, auction expected in 2018
- Phase 2 (2018-2021): 2 GHz BW in 26.5-27.5 GHz, 28.5-29.5 GHz, or WRC-19 bands
- Phase 3 (2021-2026): Looking at another 1 GHz allocation

- Trials have started at 4.4-4.9 GHz & also looking at 3.6-4.2 GHz; mmWave: 27.5-29.5 GHz
- Official 5G bands: 3.7 GHz, 4.5 GHz (max 500 MHz in sub-6 GHz), and 28 GHz (max 2 GHz)
- Actual band(s) allocation and technical rules are expected in 2018

- Regulator issued a public consultation on 5G spectrum, including bands below 1 GHz, between 1 and 6 GHz, and above 6 GHz.

- Regulator announced plan to allocate low-band, mid-band (3.4-3.7 GHz) and mmWave (24.25-28.35 GHz) spectrum

- Demonstrated 5G operating in 28 GHz mmWave band

- Planning for 3.4 to 3.7 GHz and also investigating mmWave bands
- Telstra has already announced trials in 2018 at the Commonwealth Games, using 28 and 39 GHz
- Many other governments in the region initiating 5G stakeholder consultations this year

Asia Pacific Telecommunity also driving 4G & 5G spectrum

Working on regional spectrum allocation, harmonization, and innovation

- Established in 1979, headquartered in Bangkok, Thailand
- Founded on joint initiative of the UNESCAP[1] and ITU
- 38 member countries and 130+ associate/affiliate members

- We are working within APG[2] with our ecosystem partners and regulators on planning for the next World Radio Conference (WRC-19) to develop regional proposals.
- Also actively working within AWG[3] to help drive regional spectrum harmonization, spectrum sharing studies, and to encourage innovation.

1 United Nations Economic and Social Commission for Asia and the Pacific; 2 APT Conference Preparatory Group; 3 APT Wireless Group

Opening more spectrum for 5G is a global effort

5G spectrum status in Latin America

Latin America

- Studying bands identified at WRC-15 for IMT, including L-Band and 3.4 – 3.6 GHz
- Targeting millimeter waves to be identified at WRC-19
- Supporting regulatory efforts in CITEL & ITU

Anyone can talk about 5G.
We are making it a reality.

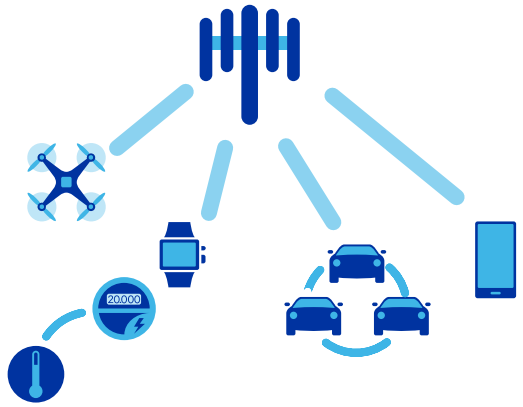
QUALCOMM®

Learn more at www.qualcomm.com/5G

Qualcomm Research 5G NR end-to-end prototype systems

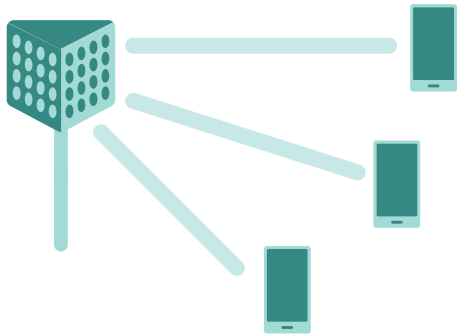
Sub-6 GHz

Ubiquitous coverage and capacity for a wide-range of 5G use cases



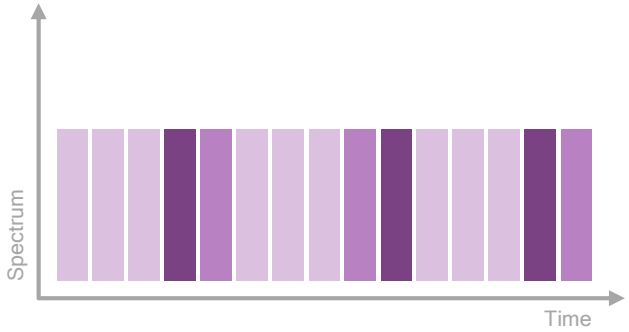
Mobilizing mmWave

Large bandwidths for extreme throughput and capacity



Spectrum sharing

More efficient utilization of, and access to, scarce resources

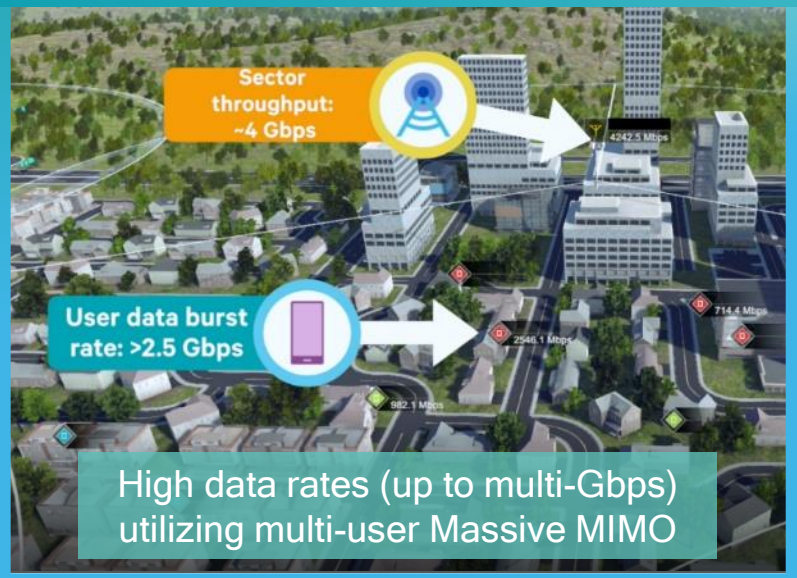


Accelerating 5G NR commercialization

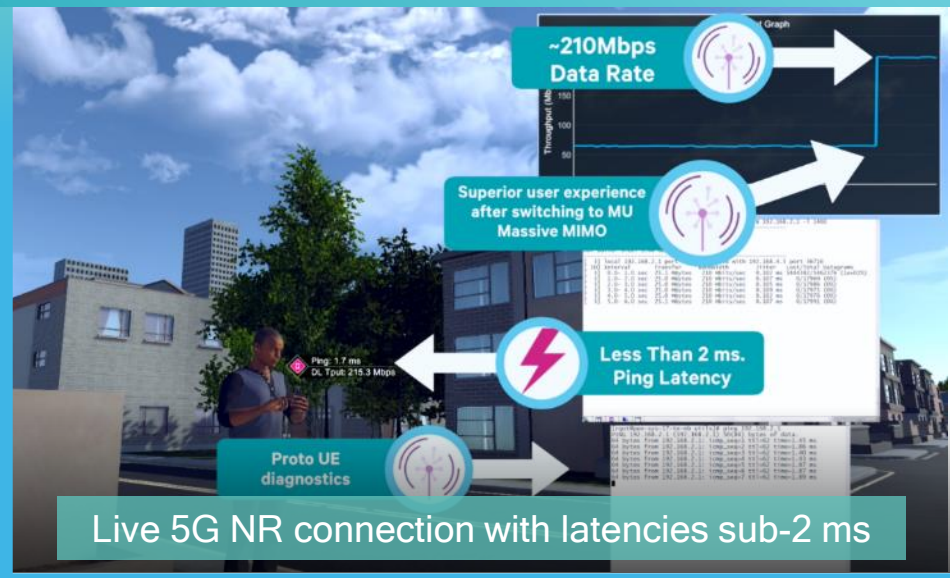
Test, demonstrate and verify our 5G designs | Drive and track 3GPP 5G NR standardization | Achieve impactful trials with network operators | Drive timely commercialization

Bringing new capabilities and efficiency to sub-6 GHz

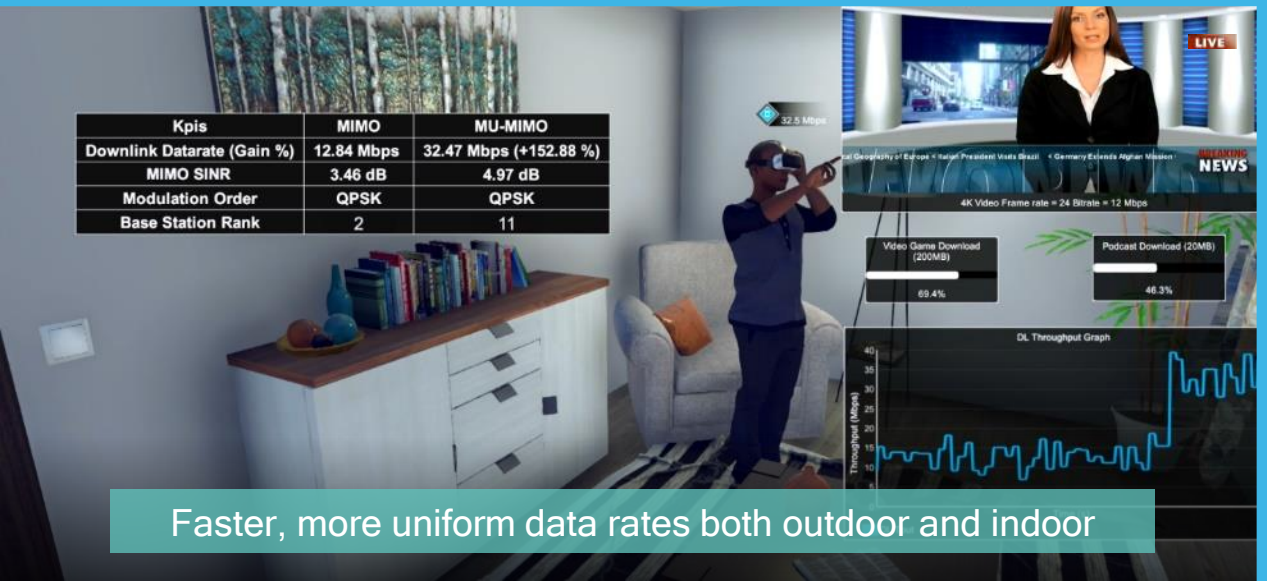
Wide area coverage at 3.3-3.8 GHz band with multiple simultaneous users



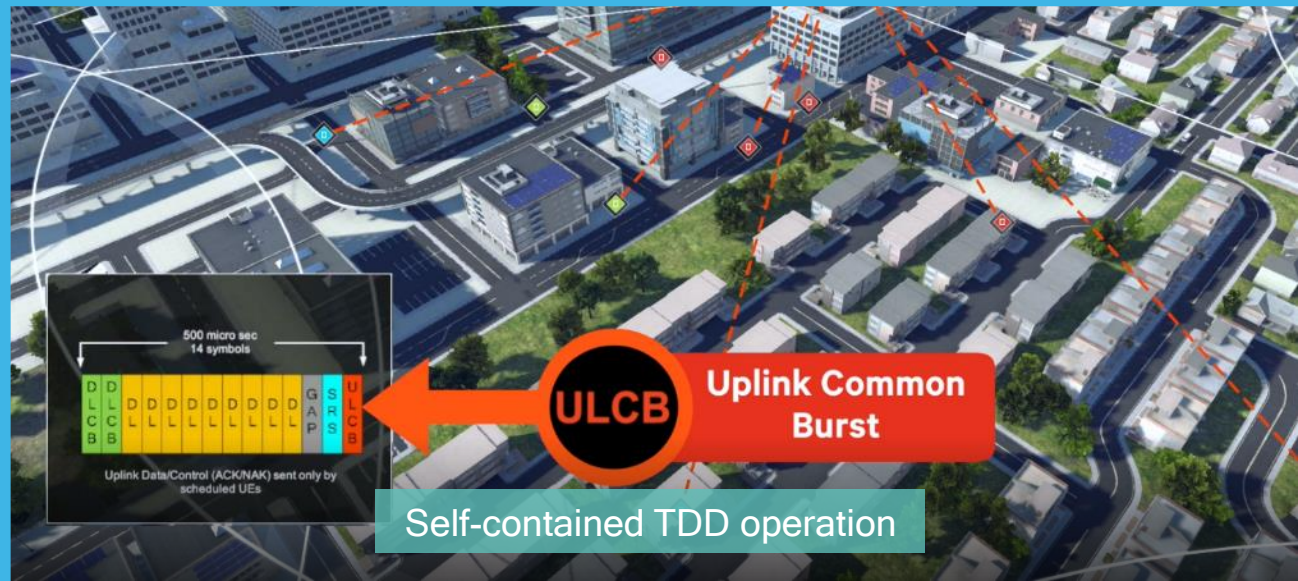
High data rates (up to multi-Gbps) utilizing multi-user Massive MIMO



Live 5G NR connection with latencies sub-2 ms



Faster, more uniform data rates both outdoor and indoor



Self-contained TDD operation

Leading the way on 5G NR trials to accelerate deployments

Starting 2nd half of 2017 in collaboration with operators and infrastructure vendors

3GPP-compliant trials
and interoperability testing
at sub-6 GHz & mmWave

5G
NR

In collaboration with…

at&t

中国移动 China Mobile

NTT docomo

SK telecom

Sprint

vodafone

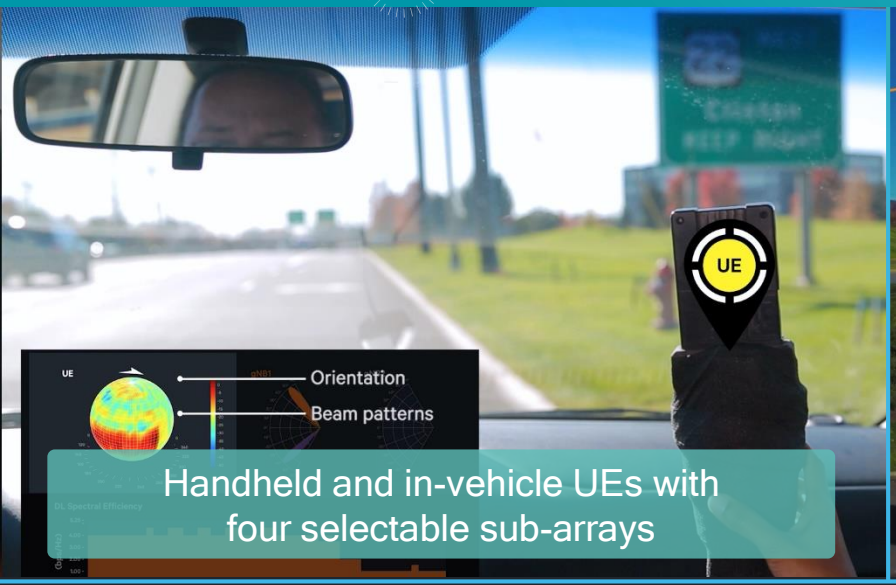
ERICSSON

NOKIA

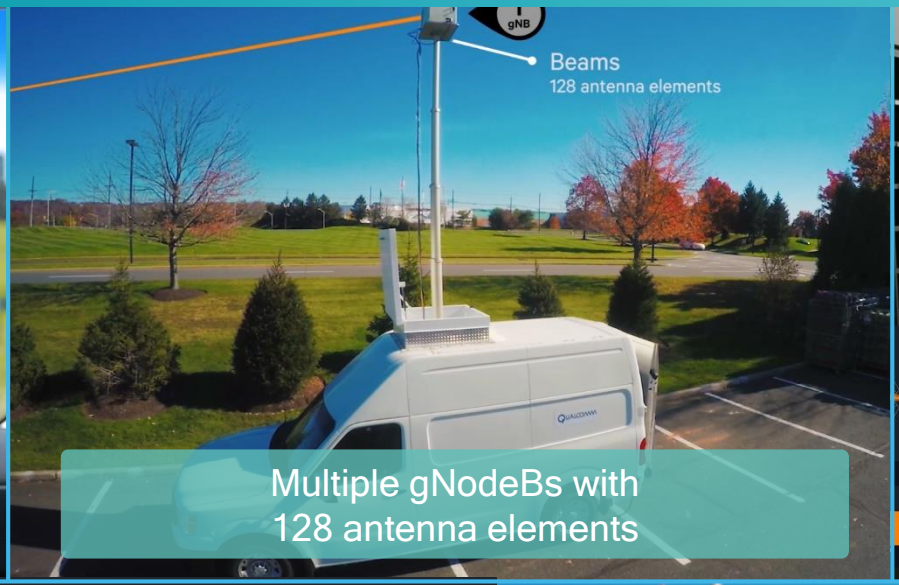
ZTE中兴

…and more to come

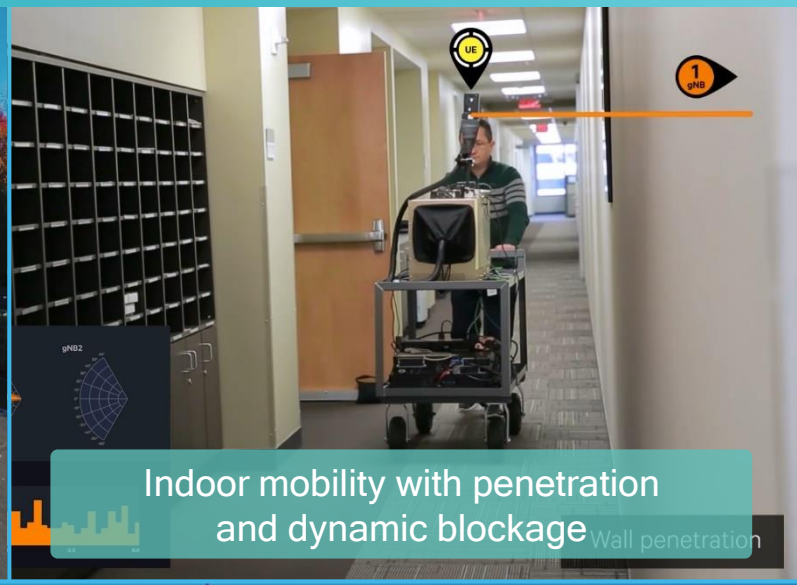
Mobilizing 5G mmWave in real-world environments



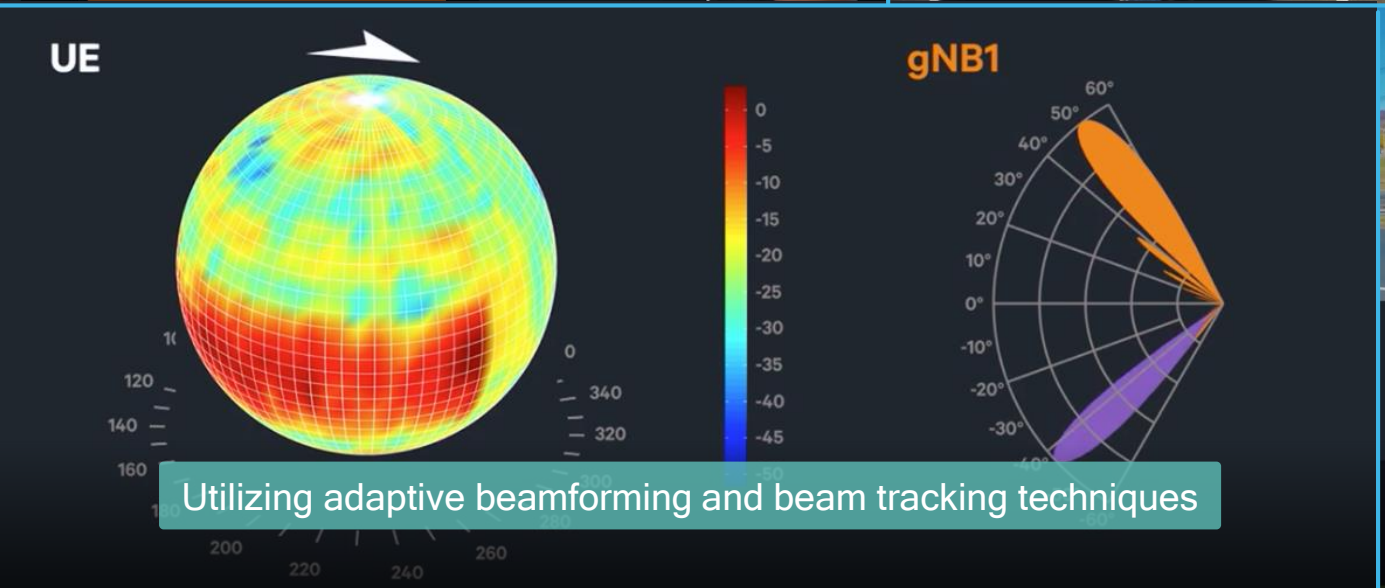
Handheld and in-vehicle UEs with four selectable sub-arrays



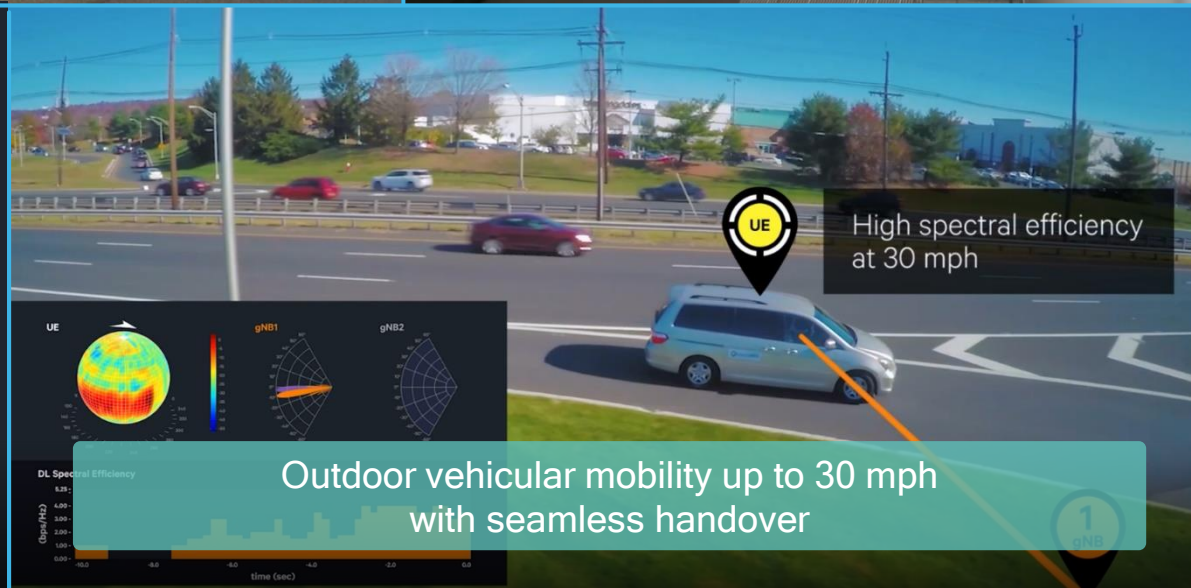
Multiple gNodeBs with 128 antenna elements



Indoor mobility with penetration and dynamic blockage



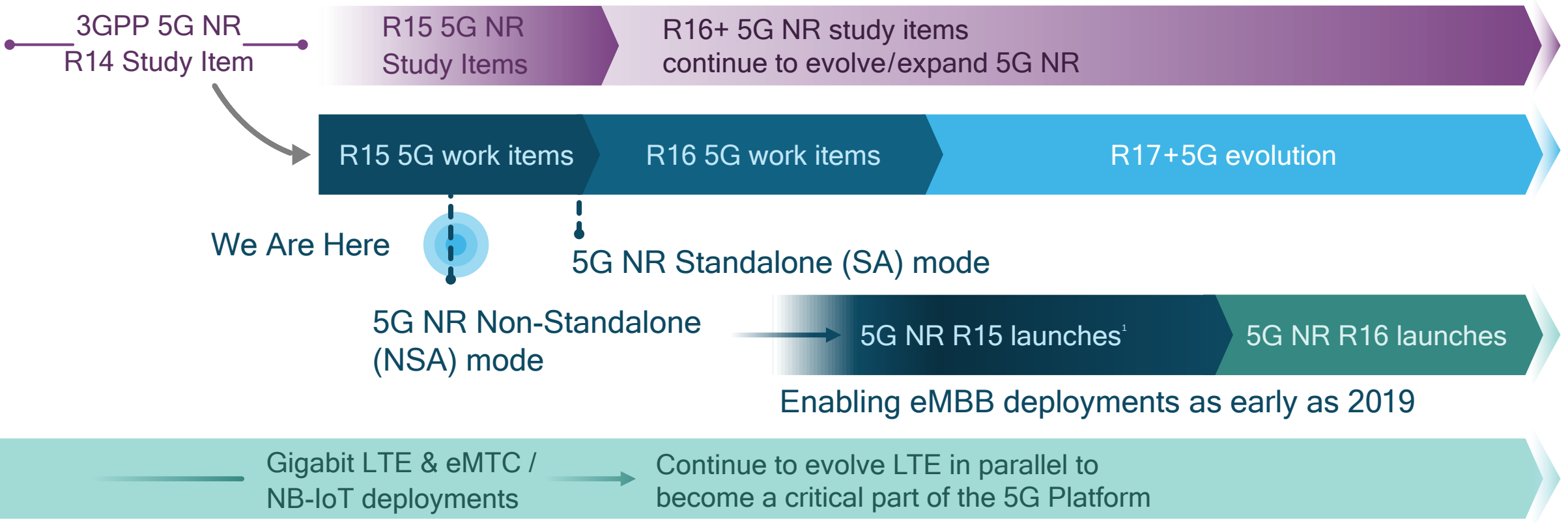
Utilizing adaptive beamforming and beam tracking techniques



Outdoor vehicular mobility up to 30 mph with seamless handover

Accelerating 5G NR – the global 5G standard

To meet the global demand for enhanced mobile broadband



1. Forward compatibility with R16 and beyond

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

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

Snapdragon X50
5G Modem Family

Announced the world's first 5G NR multimode modems for premium smartphones in 2019

Learn more at www.qualcomm.com/5G

Thank you

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