1. Qualcomm Technologies, Inc. September 2016 Making 5G NR a reality Leading the technology innovations for a unified, more capable 5G air interface

[2.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-2-638.jpg?cb=1476298490" \o )Next 30 years Interconnecting their worlds Last 30 years Interconnecting people Utilizing unparalleled systems leadership in connectivity and compute Transforming our world through intelligent connected platforms

[3.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-3-638.jpg?cb=1476298490" \o )1980s Analog voice AMPS, NMT, TACS 1990s Digital voice D-AMPS, GSM, IS-95 (CDMA) 2000s Mobile broadband WCDMA/HSPA+, CDMA2000/EV-DO 2010s Mobile Internet LTE, LTE Advanced Mobile fueled the last 30 years—interconnecting people

[4.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-4-638.jpg?cb=1476298490)Mission-critical services Enhanced mobile broadband Massive Internet of Things Always-available, secure cloud access A unifying connectivity fabric 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

[5.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-5-638.jpg?cb=1476298490) Immersive entertainment and experiences Safer, more autonomous transportation More autonomous manufacturing Reliable access to remote healthcare Improved public safety and security Sustainable cities and infrastructure Digitized logistics and retail More efficient use of energy/utilitiesSmarter agriculture 5G will redefine a wide range of industries A platform for new connected services – existing, emerging and unforeseen

[6.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-6-638.jpg?cb=1476298490" \o ) Diverse deployments Diverse spectrum Diverse services and devices Designing 5G New Radio (NR) An OFDM-based unified, more capable air interface NR

[7.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-7-638.jpg?cb=1476298490" \o )

Scalability to address diverse service and devices

Based on target requirements for the envisioned 5G use cases

Massive Internet of Things

Mission- critical control

Enhanced mobile broadband

Deep coverage To reach challenging locations

Ultra-low energy 10+ years of battery life

Ultra-low complexity 10s of bits per second

Ultra-high density 1 million nodes per Km2

Extreme capacity 10 Tbps per Km2

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

Deep awareness Discovery and optimization

Extreme user mobility Or no mobility at all

Ultra-low latency As low as 1 millisecond

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

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

[8.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-8-638.jpg?cb=1476298490)

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 Getting the most out of every bit of diverse spectrum

Licensed Spectrum Exclusive use

Shared Spectrum New shared spectrum paradigms

Unlicensed Spectrum Shared use

[9.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-9-638.jpg?cb=1476298490)

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 Macro Small cell Integrated access and backhaul Device-to-device Multi-hop topologies

[10.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-10-638.jpg?cb=1476298490)

Pioneering new technologies to meet 5G NR requirements Based on ITU vision for IMT-2020 compared to IMT-advanced 3x spectrum efficiency 10x experienced throughput 10x decrease in end- to-end latency 100x network efficiency 10x connection density 100x traffic capacity New levels of capability and efficiency Coordinated spatial techniques Multi-connectivity Mobilizing mmWave New shared spectrum paradigms Hyper dense deployments Advanced receivers Massive MIMO Ultra-reliable links Beam forming Grant-free uplink transmissions, e.g. RSMA V2V Wide bandwidths Advanced channel coding, e.g. LDPCIntegrated access and backhaul Device-centric mobility Dynamic, low-latency TDD/FDD Redundant links Multi-hop Multicast Narrowband Internet of Things V2N

[11.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-11-638.jpg?cb=1476298490) Simplifying 5G deployments with multi-connectivity Fully leveraging 4G LTE and Wi-Fi investments for a seamless user experience 5G Carrier aggregation 5G / 4G / 3G / Wi-Fi multimode deviceSmall cell Macro 4G LTE 5G below 6GHz 5G below 6GHz 5G above 6GHz 4G LTE, LTE Unlicensed and Wi-Fi Wi-Fi 4G/5G Macro 4G below 6GHz 4G Macro 4G/5G below 6GHz 5G above 6GHz 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)

[12.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-12-638.jpg?cb=1476298490) The path to 5G includes a strong LTE foundation Note: Estimated commercial dates. Not all features commercialized at the same time Rel-10/11/12 LTE Advanced Rel-13 and beyond LTE Advanced Pro Rel-15 and beyond 5G NR5GNR 2015 2020 Advanced MIMO Carrier aggregation Massive MIMO Device-to-device Shared spectrum NB-IoT 256QAM C-V2X Enhanced broadcast Gigabit-class LTE Low Latency Further backwards- compatible enhancement Significantly improve performance, cost and energy efficiency 2010

[13.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-13-638.jpg?cb=1476298490) TM Anyone can talk about 5G. We are creating it.

[14.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-14-638.jpg?cb=1476298490) We are driving technology innovations to mobilize mmWave Working with operators on trials & early deployments starting late 2017/early 20181 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 28 GHz mmWave RFIC development 802.11ad 60 GHz chipset commercial for mobile devices 5G mmWave prototype system and trial platform 1.79 cm 0.71 cm Qualcomm® VIVE™ 802.11ad 60 GHz technology with a 32-antenna array End-to-end system operating at 28 GHz demonstrating NLOS operation and robust mobility With integrated PA, LNA, phase shifter, power splitters for beamforming

[15.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-15-638.jpg?cb=1476298490) 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 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 Driving standardization on 5G NR OFDM-based designs implemented on the prototype system are being utilized to drive 3GPP standardization Watch the demo video at: <https://www.qualcomm.com/videos/5g-nr-sub-6ghz-prototype-system>

[16.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-16-638.jpg?cb=1476298490)16 We are accelerating the path to 5G NR Best-in-class 5G prototype systems and testbeds 5G standards, technology and research leadership Impactful trials and early deployments with network operators Modem and RFFE leadership to solve 5G complexity Such as advanced channel coding, self-contained subframe, mobilizing mmWave, … Roadmap to 5G significantly more complex and faster moving—builds upon our rich history of industry firsts Test, demonstrate and verify our innovative 5G designs to contribute to and drive standardization Over-the-air interoperability testing leveraging prototype systems and our leading global network experience Qualcomm Snapdragon is a product of Qualcomm Technologies, Inc.

[17.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-17-638.jpg?cb=1476298490) Continue to evolve LTE in parallel to become a critical part of the 5G Platform 5G NR R16 launches R17 + 5G evolutionR16 5G Work Items 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 study items R15 5G Work Items Gigabit LTE & LTE IoT deployments 3GPP 5G NR R14 Study Item 2016 20212017 2019 2020 20222018 5G NR R15 launches2Accelerating 5G NR1 with trials & early deployments

[18.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-18-638.jpg?cb=1476298490) 5G NR R151 will establish the 5G foundation For enhanced mobile broadband and beyond Optimized OFDM-based waveforms A common, flexible framework Advanced wireless technologies With scalable numerology and TTI, plus optimized multiple access for different use cases Such as massive MIMO, robust mmWave, advanced channel coding, and device-centric mobility To efficiently multiplex services and features with a dynamic, low-latency TDD/FDD design Unified design across spectrum types and bands For licensed and shared/unlicensed spectrum bands both below 6 GHz and above 6 GHz2 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

1. [19.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-19-638.jpg?cb=1476298490)Designing 5G NR Leading the technology innovations for a unified, more capable 5G air interface
2. [20.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-20-638.jpg?cb=1476298490)201 Weighted Overlap Add; 2 Such as Resource Spread Multiple Access (RSMA) – more details later in presentation Co-exist with optimized waveforms and multiple access for wide area IoT Efficient framework for MIMO spatial multiplexing Single-carrier OFDM well suited for efficient uplink transmissions Windowing can effectively minimizes in-band and out-of-band emissions Low complexity receivers even when scaling to wide bandwidths Spectral efficiency Low complexity Frequency localization Lower power consumption Asynchronous multiplexing MIMO Time Frequency OFDM family is the right choice for 5G mobile broadband and beyond Adapted for scaling to an extreme variations of 5G requirements
3. [21.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-21-638.jpg?cb=1476298490)21 Efficient service multiplexing with windowed OFDM OFDM with WOLA1 windowing Substantially increases frequency localization PSD of CP-OFDM with WOLA at the transmitter -10 -20 -30 -40 -50 -60 -70 -80 -90 -40 -30 -20 -10 0 10 20 30 40 CP-OFDM: No Clipping +WOLA: Ideal PA 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 Key for 5G service multiplexing Mitigate interference between flexible sub-carriers Wideband (e.g. eMBB) Narrowband (e.g. IoT) Large CP (e.g. broadcast) Frequency 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. dB Normalized frequency [1/T]
4. [22.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-22-638.jpg?cb=1476298490)22 Download Qualcomm Research whitepaper for detailed analysis: https://www.qualcomm.com/documents/5g-research-waveform-and-multiple-access-techniques Optimizing for diverse services and deployments 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 Optimized for different services Macro cell SC-OFDM 1 + SC-FDMA To maximize device energy efficiency Small cell CP-OFDM 1 + OFDMA To maximize spectral efficiency Low energy single-carrier 2 Massive IoT CP-OFDM / SC-OFDM 1 Mission-critical 5G NR Uplink Optimized for different deployments 5G NR Downlink Unified downlink design Time Frequency Resource Spread Multiple Access (RSMA) 3 Grant-free transmissions efficient for sporadic transfer of small data bursts with asynchronous, non-orthogonal, contention-based access Massive IoT Mission- critical Mobile Broadband CP-OFDM 1 + OFDMA Also recommended for D2D and inter-cell communications to maximize Tx/Rx design reuse +
5. [23.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-23-638.jpg?cb=1476298490)23 A flexible framework with forward compatibility Efficiently multiplex envisioned and future 5G services on the same frequency 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 Integrated framework That can support diverse deployment scenarios and network topologies Scalable transmission time interval (TTI) For diverse latency requirements—capable of latencies an order of magnitude lower than LTE Mission-critical transmissions May occur at any time; design such that other traffic can sustain puncturing2 Forward compatibility With support for ‘blank’ resources1 Blank subcarriers Scalable TTI MBB D2D Multicast 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 DL ULDL UL UL
6. [24.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-24-638.jpg?cb=1476298490)24 Scalable numerology with scaling of subcarrier spacing Efficiently address diverse spectrum, deployments and services Subcarrier spacing e.g. 15 kHz Outdoor and macro coverage FDD/TDD <3 GHz e.g. 1, 5, 10 and 20 MHz Indoor wideband TDD e.g. 5 GHz (Unlicensed) e.g. 160MHz mmWave TDD e.g. 28 GHz Outdoor and small cell TDD > 3 GHz e.g. 80/100 MHz e.g. 500MHz Subcarrier spacing e.g. 30 kHz Subcarrier spacing e.g. 60 kHz Subcarrier spacing, e.g. 120 kHz Example usage models and channel bandwidths
7. [25.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-25-638.jpg?cb=1476298490)25 Scalable Transmission Time Interval (TTI) Scalable TTI for diverse latency and QoS requirements Longer TTI for higher spectral efficiency Shorter TTI for low latency and high reliability Scalable number of TTIs per subframe1 1 Further bundling of TTIs possible; 2 Symbols across numerologies align at symbol boundaries; 3 TTI spans integer number of symbols; 4 Subcarrier spacing Efficient multiplexing of long & short TTIs to allow transmissions to start on symbol boundaries2,3 1 ms subframe with 14 symbols of SCS4 = 15 kHz 0 1 2 11 12 13… Short TTI with 2 symbols of SCS = 15 kHz0 1 0 1 2 3 4 5 6 7 Short TTI with 8 symbols of SCS = 60 kHz 500 us TTI with 14 symbols of SCS = 30 kHz0 1 2 11 12 13…
8. [26.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-26-638.jpg?cb=1476298490)26 Unlicensed spectrum Listen-before-talk headers e.g. Clear Channel Assessment (CCA) and hidden node discovery Self-contained integrated subframe design UL/DL scheduling info, data and acknowledgement in the same sub-frame D2D, mesh and relay Headers for e.g. direction of the link for dynamic distributed scheduling Adaptive UL/DL Flexible configuration for capacity allocation; also dynamic on a per-cell basis Massive MIMO Leveraging channel reciprocity in UL transmission for DL beamforming training Example: TDD downlink Guard Period Add’l headers ACK (Rx) Ctrl (Tx) Data (Tx) Faster, more flexible TDD switching and turn around, plus support for new deployment scenarios and forward compatibility
9. [27.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-27-638.jpg?cb=1476298490)27 New self-contained TDD design enables new use cases Eliminates control channel interference to allow for robust, dynamic DL/UL switching No DL⇓◊ UL interference between control channels TDD DL TDD UL DLCTRL UL DATA1 (User 1) UL DATA (User 2) UL DATA (User 3) ULCTRL DLCTRL • Allows for robust, dynamic DL/UL switching driven by different loading and traffic types • Enables integrated access and backhaul co-channel deployments for mmWave DL DATA1 ULCTRL Common UL burst DL UL 1 Can also be control information
10. [28.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-28-638.jpg?cb=1476298490)28 5G NR design innovations across diverse services Enhanced Mobile Broadband • Mobilizing mmWave • Advanced channel coding• Shared spectrum • Massive MIMO • Wider bandwidths • Dynamic, low-latency TDD/FDD • Native HetNet and multicast support• Device-centric mobility Massive IoT • Low complexity narrowband • Optimized link budget • Managed multi-hop mesh • Low power modes for deep sleep • Grant-free uplink transmissions Mission-Critical Control • Low-latency with bounded delay • Simultaneous redundant links • Efficient multiplexing with nominal traffic • Grant-free uplink transmissions • Optimized PHY/pilot/HARQ • Reliable device-to-device links • Efficient signaling
11. [29.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-29-638.jpg?cb=1476298490)29 Enhancing mobile broadband Extreme throughput Ultra-low latency Uniform experience
12. [30.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-30-638.jpg?cb=1476298490)30 Breaking the Gigabit barrier in LTE today The first real glimpse of our 5G future Qualcomm Snapdragon is a product of Qualcomm Technologies, Inc. Subject to network availability 1.8 Mbps 7.2 Mbps 7.2 Mbps10.2 Mbps 21.1 Mbps 100 Mbps 100 Mbps 150 Mbps 300 Mbps 450 Mbps 600 Mbps 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 Peakdownloadspeedsupportedinmodem(Mbps) Approximate Date of Commercialization by Qualcomm Technologies Qualcomm® Snapdragon™ X16 LTE Modem 1Gbps Peak download speeds of first-gen LTE devices Peak download speeds of early 3G devices Snapdragon X12 LTE Modem Snapdragon X10 LTE Modem Snapdragon X7 LTE Modem Snapdragon X5 LTE Modem ~10x>500x
13. [31.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-31-638.jpg?cb=1476298490)31 Continuing to evolve LTE for enhanced mobile broadband Pioneering 5G technologies and ensuring a consistent user experience as 5G rolls out 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 Gbps+ peak rates More uniform experience Better coverage Significantly lower latencies
14. [32.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-32-638.jpg?cb=1476298490)32 Designing 5G NR for significantly lower latency 10x lower latency than today’s LTE networks 1 Compared to LTE’s 8 HARQ interlaces FDD Fewer (variable) interlaces for HARQ1 0 1 0 1 ACK0 Data ACK ACK1 ACK0 HARQ RTT TDD Self-contained design reduces RTT Scalable TTI Ex: TDD downlink Guard Period ACK (Rx) Ctrl (Tx) Data (Tx) Data and acknowledgement in the same subframe TTI 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
15. [33.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-33-638.jpg?cb=1476298490)33 Delivering advanced 5G NR channel coding ME-LDPC 1 codes more efficient than today’s LTE Turbo codes at higher data rates 1 Multi-Edge Low-Density Parity-Check; 2 such as Polar or TBCC Also exploring alternative channel coding for mission-critical and massive IoT traffic 2 Easily parallelizable decoder scales to achieve high throughput at low complexity Significant gains over LTE Turbo – particularly for large block sizes suitable for MBB Efficient encoding/decoding enables shorter TTI High Efficiency Low Complexity Low Latency Example ME-LDPC Basegraph
16. [34.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-34-638.jpg?cb=1476298490)34 Many more antennas to increase coverage and capacity Evolving towards Massive MIMO 5G NR Rel. 15 (Massive MIMO) Support even larger # of antenna elements (up to 256) with new features, e.g. hybrid beamforming, distributed MIMO Exploit 3D beamforming utilizing a 2D antenna array Azimuth beamforming Elevation beamforming 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
17. [35.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-35-638.jpg?cb=1476298490)35 Massive MIMO is a key enabler for higher spectrum bands Allows reuse of existing sites and same transmit power at e.g. 4 GHz 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 • 1.7 km inter-site distance • 46 dBm transmit power Macro site 1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 10-1 100 101 102 103 CDF 3.4x 4.1x 3.9x2.7x Significant gain in cell edge user throughput 10 users per cell 2x4 MIMO, 20 MHz @ 2 GHz 2x4 MIMO, 80 MHz @ 4 GHz 24x4 MIMO, 80 MHz @ 4 GHz Significant capacity gain: Average cell throughput = 808 Mbps in 80 MHz
18. [36.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-36-638.jpg?cb=1476298490)36 Shared/unlicensed spectrum is important for 5G 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. Shared spectrum can unlock spectrum that is lightly used by incumbents Unlocking more spectrum High spectrum utilization A lot of spectrum may be shared/unlicensed Spectrum sharing has the potential to increase spectrum utilization FCC recent decision on high-band spectrum included a significant portion of shared/unlicensed1 Licensed Shared/ Unlicensed Time Spectrum
19. [37.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-37-638.jpg?cb=1476298490)37 We are pioneering 5G shared spectrum today Building on LTE-U/LAA, LWA, CBRS/LSA and MulteFire1 1) Licensed-Assisted Access (LAA), LTE Wi-Fi Link Aggregation (LWA), Citizen Broadband Radio Service (CBRS), Licensed Shared Access (LSA) Tiered sharing (incumbents) Spectrum aggregation Technology aggregation Standalone unlicensed MulteFire LTE-U / LAA LWA (LTE + Wi-Fi) CBRS, LSA NR based MulteFire NR based LAA Multi-connectivity: NR,LTE,Wi-Fi NR based tiered sharing 5G New Radio (NR) Sub 6Ghz + mmWave LTE Advanced Pro Spectrum below 6 GHz Shared spectrum technologies
20. [38.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-38-638.jpg?cb=1476298490)38 Pioneered shared/unlicensed spectrum in 4G LTE 1) Licensed Shared Access (LSA); 2) Licensed-Assisted Access (LAA); 3) Citizen Broadband Radio Service (CBRS), Priority Access Licenses (PAL), General Authorized Access (GAA) Technically extensive pilot in France with Ericsson and Red in Jan 2016 LSA1 We designed the original proposal, commercialized by the LTE-U forum LTE-U Performed world’s first over-the-air LAA trial with Deutsche Telekom Nov 2015 LAA2 A founder of the MulteFire Alliance and a key contributor to its specification A founder of the CBRS Alliance and a key contributor to coexistence CBRS3 Incumbents PAL GAA
21. [39.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-39-638.jpg?cb=1476298490)39 Realizing the mmWave opportunity for mobile broadband • Robustness due to high path loss and susceptibility to blockage • Device cost/power and RF challenges at mmWave frequencies Mobilizing mmWave challenge 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 mmWave sub6Ghz • Extreme bandwidths capable of Multi-Gbps data rates • Flexible deployments (integrated access/backhaul) • High capacity with dense spatial reuse Extreme bandwidth opportunity NR Learn more at: www.qualcomm.com/documents/promise-5g-mmwave-how-do-we-make-it-mobile
22. [40.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-40-638.jpg?cb=1476298490)40 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
23. [41.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-41-638.jpg?cb=1476298490)41 Device-centric mobility management in 5G NR Control plane improvements to improve energy and overhead efficiency 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 Serving clusterEdgeless mobility zone (area of tightly coordinated cells) Periodic sync SIB request Transmit SIB No SIB request No SIB transmission Lightweight mobility for device energy savings • Apply COMP-like1 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 present2 UE sends periodic reference signals Network triggers cell reselection/handover based on measurement of UE signals
24. [42.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-42-638.jpg?cb=1476298490)42 Connecting massive Internet of Things Power efficient Low complexity Long range
25. [43.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-43-638.jpg?cb=1476298490)43 Cellular technologies enable a wide range of IoT services 1 Including Cellular & LPWA M2M connections, Machina Research, June, 2016 >5B IoT connections by 20251 Smart cities Lighting, traffic sensors, smart parking,… Mobile health Wearables, gateways, remote patient,… Environmental monitoring Agriculture, forecast fire/ air pollution sensors,… Smart utilities Smart grid, gas/water/ electric meters Ubiquitous coverage Reliable and secure Global ecosystem Always-on connectivity Connected building Security, video surveillance, smoke detectors,… Connected industrial Process/equipment monitoring, HVAC, … Asset tracking Fleet management, pet/kid trackers, shipping,… Connected retail Vending machines, ATM, digital ads,…
26. [44.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-44-638.jpg?cb=1476298490)44 We are evolving LTE for the Internet of Things Paving the path to Narrowband 5G for massive IoT Mobile Video security Wearables Object tracking Energy managementConnected car Connected healthcare City infrastructure Smart buildings Environment monitoringUtility metering Today New narrowband IoT technologies (3GPP Release 13+) LTE Cat-4 and above >10 Mbps n x 20 MHz LTE Cat-1 Up to 10 Mbps 20 MHz LTE Cat-M1 (eMTC) Variable rate up to 1 Mbps 1.4 MHz narrowband Cat-NB1 (NB-IoT) 10s of kbps 200 kHz narrowband Scaling up in performance and mobility Scaling down in complexity and power
27. [45.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-45-638.jpg?cb=1476298490)45 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 RSMA1 & multi-hop mesh 5G NR will bring new capabilities for the massive IoT NB-IoT continuing to evolve beyond Release 13—foundation of Narrowband 5G 1 Resource Spread Multiple Access
28. [46.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-46-638.jpg?cb=1476298490)46 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 Increased battery life Scalability to massive # of things Better link budget Downlink remains OFDM-based for coexistence with other services
29. [47.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-47-638.jpg?cb=1476298490)47 Support for multi-hop mesh with WAN management 1 Greater range and efficiency when using licensed spectrum, e.g. protected reference signals . Network time synchronization improves peer-to-peer efficiency 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. Direct access on licensed spectrum Mesh on unlicensed or partitioned with uplink licensed spectrum1
30. [48.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-48-638.jpg?cb=1476298490)48 Enabling mission-critical services High reliability Ultra-low latency High availability
31. [49.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-49-638.jpg?cb=1476298490)49 We are pioneering mission-critical services with LTE today Actively driving C-V2X 3GPP Release 14 Work Item and beyond, building upon our leadership in LTE Direct and LTE Broadcast Testing drone operation on commercial 4G LTE networks at FAA-authorized UAS Flight Center, representing “real world” conditions Cellular Vehicle-to-Everything (C-V2X) Cellular drone communications
32. [50.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-50-638.jpg?cb=1476298490)50 Pioneering C-V2X with rich roadmap to 5G C-V2X increases reaction time over 802.11p/DSRC for improved safety use cases Based on link level curves and the 3GPP LOS path loss model @ 10% Packet Error – Actual performance varies significantly with vehicle density and environment 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 Braking distance ~2.5secReaction time ~9.2sec C-V2X range >450m 802.11p range ~225m Reaction time ~3.3sec LTE ~8dB higher link budget due to single carrier waveform, coding gain, longer transmission time and higher Tx power 140km/h 140km/h 0km/h
33. [51.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-51-638.jpg?cb=1476298490)51 To optimize LTE networks and advance 5G for mission critical services Testing drone operation over commercial LTE networks 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
34. [52.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-52-638.jpg?cb=1476298490)52 5G NR will enable new mission-critical control services A platform for tomorrow’s more autonomous world Industrial automation Robotics Aviation Autonomous vehicles Energy/ Smart grid Medical Strong e2e security Security enhancements to air interface, core network, & service layer across verticals1 1ms e2e latency Faster, more flexible frame structure; also new non-orthogonal uplink access Ultra-high availability Simultaneous links to both 5G and LTE for failure tolerance and extreme mobility Ultra-high reliability Ultra-reliable transmissions that can be time multiplexed with nominal traffic through puncturing 1 Also exploring alternative roots of trust beyond the SIM card
35. [53.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-53-638.jpg?cb=1476298490)53 Efficient mission-critical multiplexing with other services A more flexible design as compared to dedicated mission-critical resources (e.g. FDM) 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 Nominal traffic (with new FEC and HARQ design) Time Frequency One TTI 1st transmission 2st transmission Opportunity for uplink RSMA non-orthogonal access using OFDM waveforms
36. [54.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-54-638.jpg?cb=1476298490)54 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 Mission-critical capacity Mission-critical capacity Mission-critical capacity Latency Latency Latency e.g. 1e-4 BLER1 e.g. 1e-2 BLER Example:2X bandwidth for 3x capacity gain2 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.
37. [55.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-55-638.jpg?cb=1476298490)As we did in 3G and 4G, Qualcomm is leading the world to 5G Making 5G NR a reality 3G 4G
38. [56.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-56-638.jpg?cb=1476298490)56 We are designing a unified, more capable 5G air interface FDD, TDD, half duplex Licensed, shared licensed, and unlicensed spectrum Spectrum bands below 1 GHz,1 GHz to 6 GHz, and above 6 GHz (incl. mmWave) Device-to-device, mesh, relay network topologies 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 spectrum Diverse services and devices Diverse deployments
39. [57.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-57-638.jpg?cb=1476298490)57 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 Mobile broadband Internet of Things Mission-critical control
40. [58.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-58-638.jpg?cb=1476298490)58 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
41. [59.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-59-638.jpg?cb=1476298490)59 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 Qualcomm® Snapdragon™ X16 LTE modem industry’s first Gigabit Class LTE modem (4x CA, LAA, 4x4 MIMO, 256-QAM) Technologies for hyper-densification, e.g. Qualcomm UltraSON™ self-organization and converged LTE / Wi-Fi solutions New technologies such as LSA for sharing with incumbents, LTE-U, LWA, LAA, MulteFire™ for over-the-air sharing Qualcomm® VIVE 802.11ad 60 GHz chipset commercial for mobile devices with a 32-antenna array element LTE Direct and LTE Broadcast (including digital TV), and new standard for Cellular V2X (C-V2X) communications New LTE IoT technologies (eMTC, NB-IoT), and optimizing technologies for cellular drone communications 5G NR
42. [60.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-60-638.jpg?cb=1476298490)60 Our modem and RF leadership is critical to 5G Roadmap to 5G is significantly more complex and faster moving Source: Qualcomm Technologies Inc. 2,000+modem features to-date and counting 50+ spectrum bands 450 MHz–5.8 GHz (licensed and unlicensed) ~200 Carrier Aggregation combinations New LTE services, e.g. LTE Broadcast, VoLTE Wi-Fi, 3G, 2G technologies 4G LTE OFDM-based waveforms, transmission modes, and UE categories LTE multi-mode today
43. [61.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-61-638.jpg?cb=1476298490)61 More diverse deployment scenarios Many more spectrum bands/types A much wider variation of use cases Advanced wireless technologies FDD, TDD, half duplex Licensed, shared and unlicensed From below 1 GHz to mmWave OFDM adapted to extremes Massive MIMO Robust mmWave Mission-critical and nominal traffic High to no mobility Device-to-device, mesh, relay Wide area to hotspots Wideband to narrowband Roadmap to 5G Our modem and RF leadership is critical to 5G Roadmap to 5G is significantly more complex and faster moving
44. [62.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-62-638.jpg?cb=1476298490)62 Qualcomm Research 5G NR prototype systems Testbed for 5G designs to drive standardization and timely commercialization Qualcomm Research is a division of Qualcomm Technologies, Inc. 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
45. [63.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-63-638.jpg?cb=1476298490)63 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 Anyone can talk about 5G. We are creating it. Investing in 5G for many years—building upon our leadership foundation Learn more at www.qualcomm.com/5G
46. [64.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-64-638.jpg?cb=1476298490)Questions? - Connect with Us @Qualcomm\_tech http://www.slideshare.net/qualcommwirelessevolution http://www.youtube.com/playlist?list=PL8AD95E4F585237C1&feature=plcp www.qualcomm.com/wireless BLOG www.qualcomm.com/news/onq
47. [65.](https://image.slidesharecdn.com/making-5g-nr-a-reality4-161012185305/95/making-5g-nr-a-reality-65-638.jpg?cb=1476298490)Follow us on: For more information, visit us at: www.qualcomm.com & www.qualcomm.com/blog Nothing in these materials is an offer to sell any of the components or devices referenced herein. ©2016 Qualcomm Technologies, Inc. and/or its affiliated companies. All Rights Reserved. Qualcomm, Snapdragon, VIVE, and UltraSON are trademarks of Qualcomm Incorporated, registered in the United States and other countries. Other products and brand names may be trademarks or registered trademarks of their respective owners. References in this presentation to “Qualcomm” may mean Qualcomm Incorporated, Qualcomm Technologies, Inc., and/or other subsidiaries or business units within the Qualcomm corporate structure, as applicable. Qualcomm Incorporated includes Qualcomm’s licensing business, QTL, and the vast majority of its patent portfolio. Qualcomm Technologies, Inc., a wholly-owned subsidiary of Qualcomm Incorporated, operates, along with its subsidiaries, substantially all of Qualcomm’s engineering, research and development functions, and substantially all of its product and services businesses, including its semiconductor business, QCT. Thank you