5G NR – DRIVING WIRELESS EVOLUTION INTO NEW VERTICAL DOMAINS

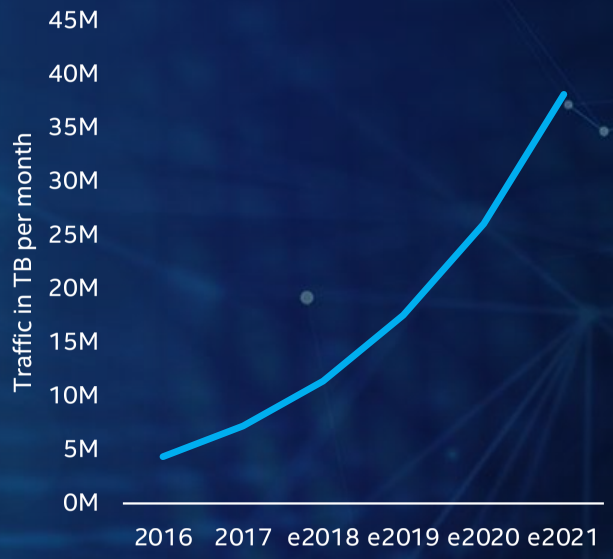
Next Generation and Standards
August 2018

LEGAL DISCLAIMER

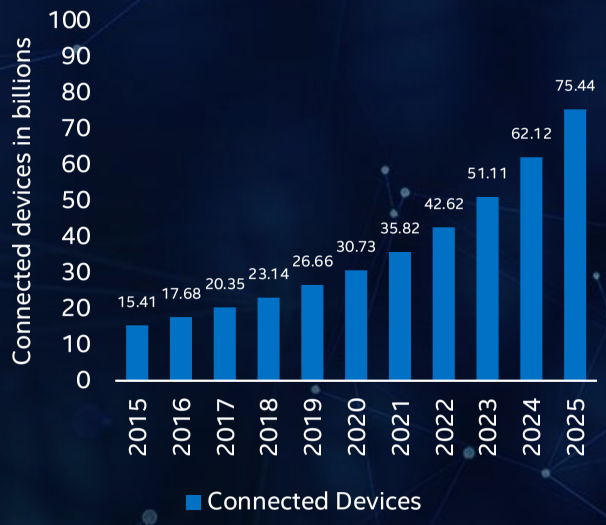
Intel technologies' features and benefits depend on system configuration and may require enabled hardware, software or service activation. Performance varies depending on system configuration. No computer system can be absolutely secure. Check with your system manufacturer or retailer or learn more at [most relevant URL to your product].

MOBILE USAGE CONTINUES TO GROW

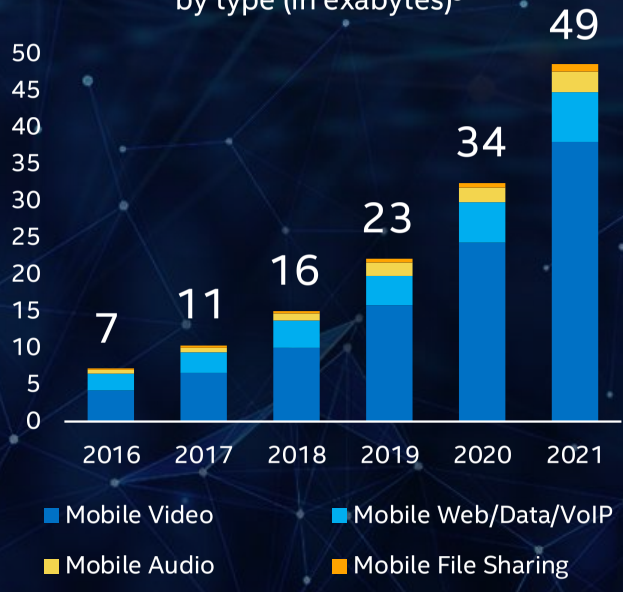
Global mobile video traffic 2016-21[1]
(Terabytes per month)



Internet of Things (IoT) connected devices installed base worldwide from 2015 to 2025 (in billions)[2]



Global monthly mobile data traffic, by type (in exabytes)[3]



IN TERMS OF OVERALL LARGER APP TRAFFIC – VIDEO...

...BY VOLUME OF CONNECTED DEVICES...

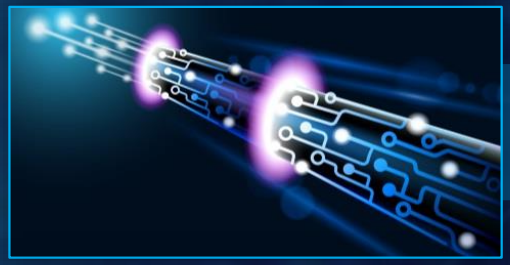
...BY MOBILE DATA CONSUMPTION

1 Source: Cisco Systems © Statistica 2018; Additional Information: Worldwide Cisco Systems, 2016
2 Source: HIS © Statista 2018; Additional information: Worldwide; IHS:; 2015 to 2016
3 Source: Cisco, BI Intelligence calculations, 2017

NEW APPLICATIONS STRESS EXISTING WIRELESS SERVICES

LOW-POWER CONNECTED DEVICE GROWTH VIA IOT

BILLIONS of connected devices by 2020[1]



ENHANCED MOBILE BROADBAND

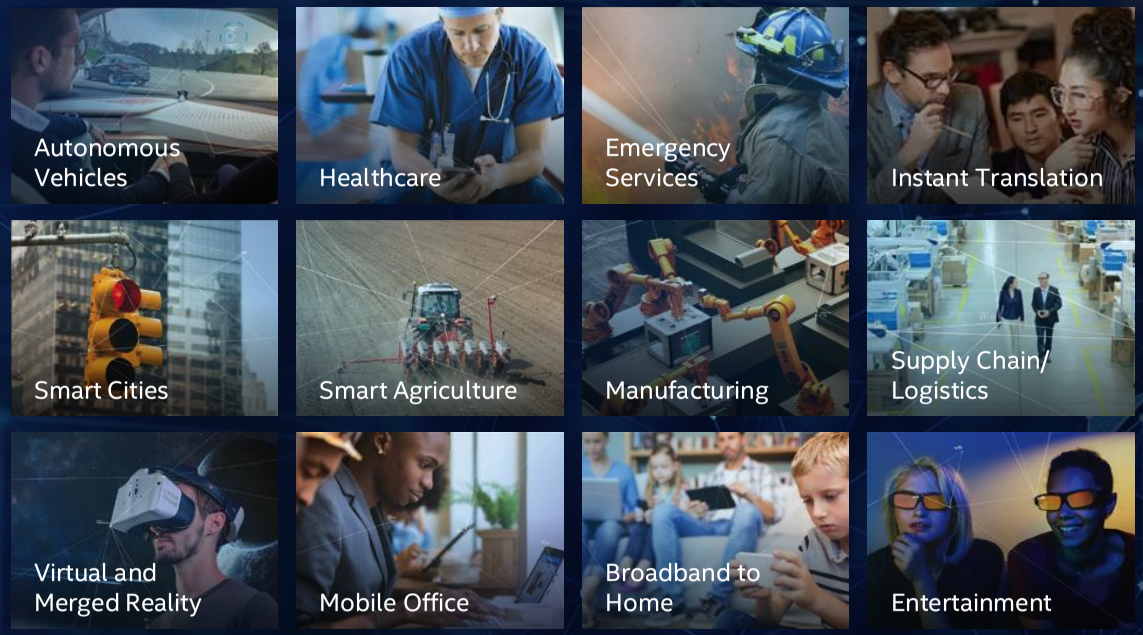
>1B 5G subscriptions of enhanced mobile broadband by 2023[2]

ULTRA-LOW LATENCY AND RELIABILITY

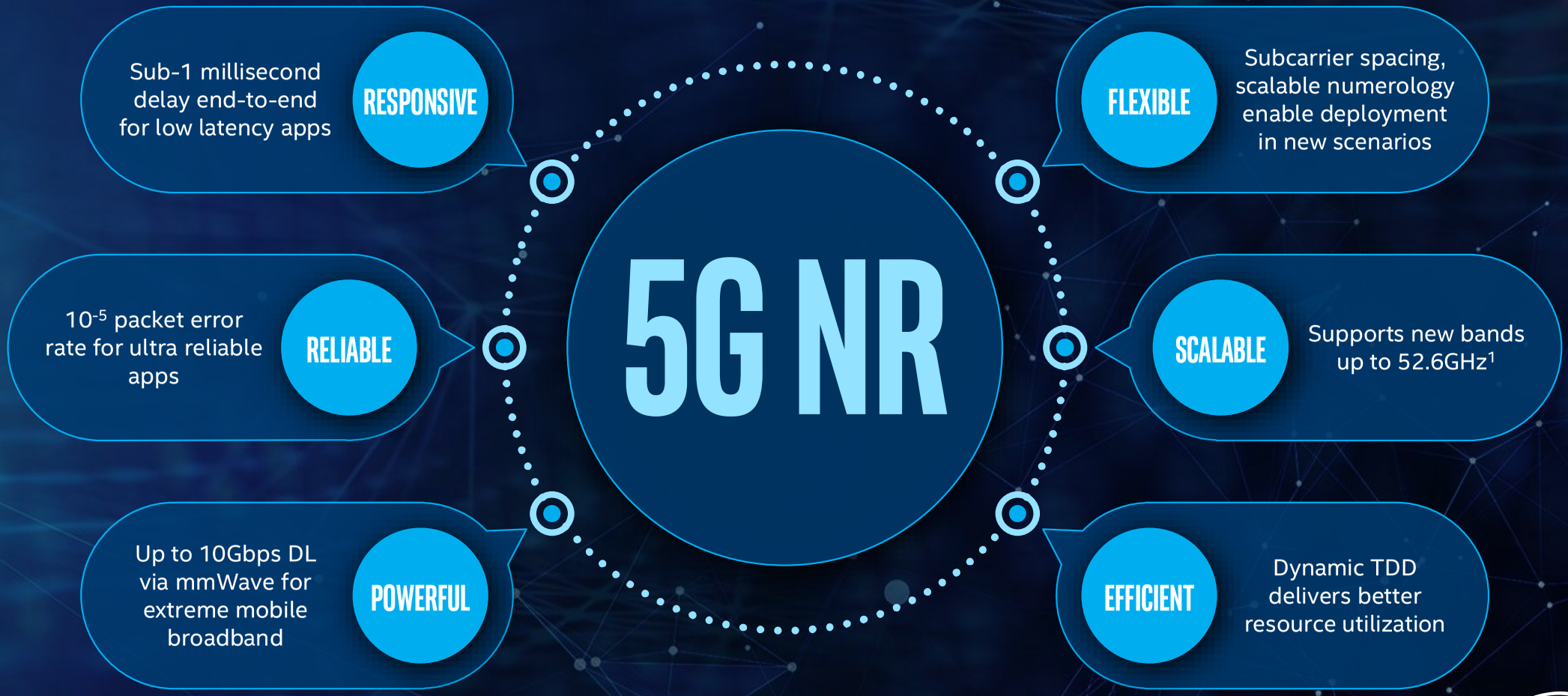
1M autonomous cars on the road by 2025; Internet apps with sub-10 millisecond latency[3]

1. Cisco
2. Ericsson Mobile Report 2018
3. 1M autonomous cars by 2025 via HIS Markit; Ericsson and Huawei news releases

5G USE CASES, SPECTRUM AND DEPLOYMENTS

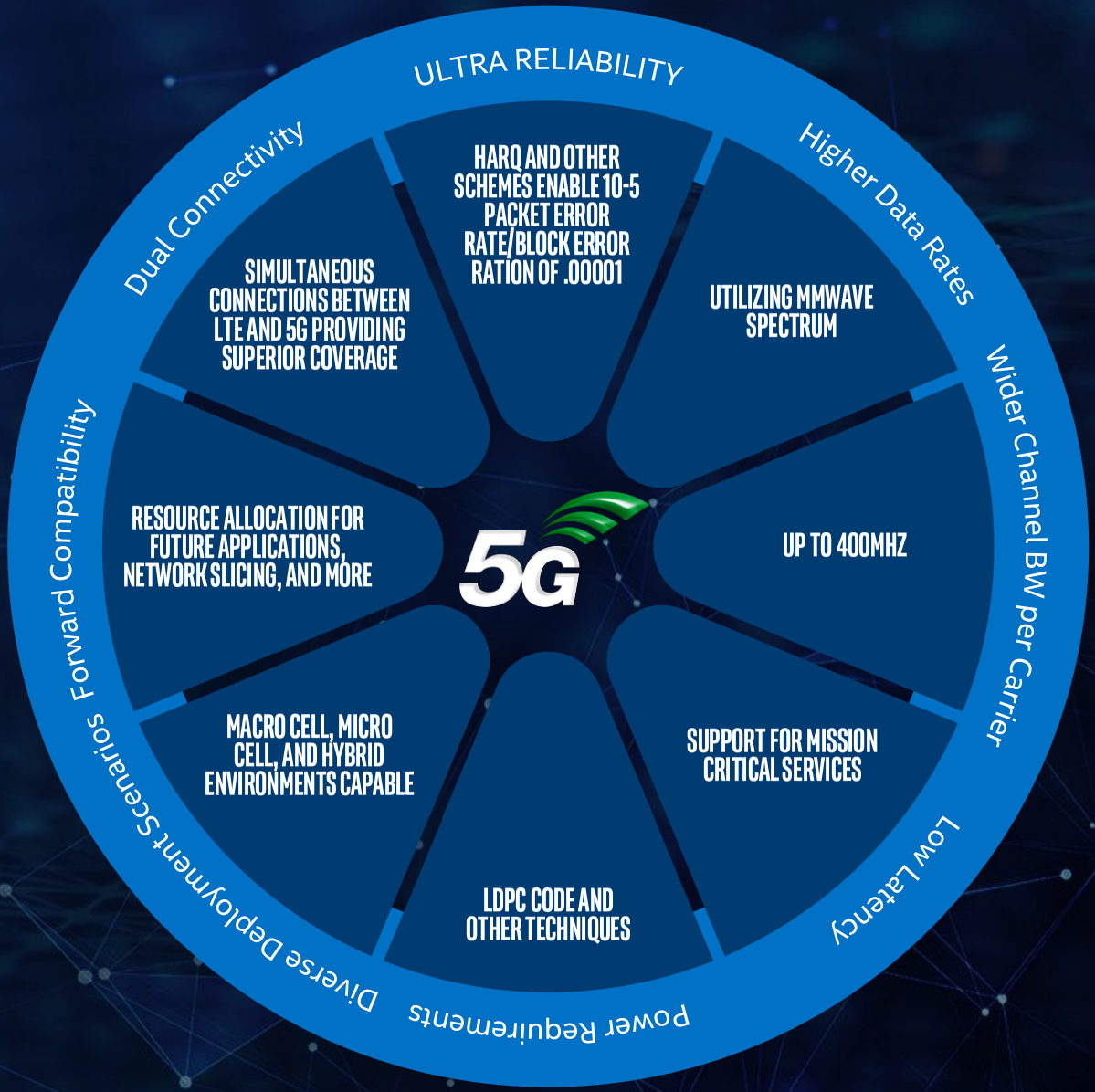


ENTER 5G NR – A TRULY UNIFIED AIR INTERFACE

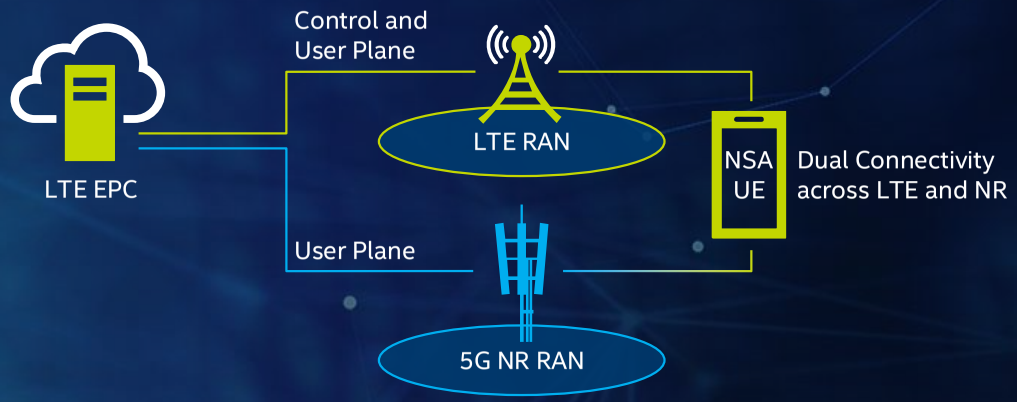


1 5G-NR in Rel-17 is expected to support up to 100 GHz

DIFFERENTIATING 5G NR FROM LTE



5G ARCHITECTURE OPTIONS



NON-STANDALONE (NSA)

First wave of 5G service deployments

Uses 5G frequencies for improved data throughput

Leverages existing 4G deployments; Smoother migration to 5G

STANDALONE (SA)

Standard approved in June 2018

Simplified network infrastructure

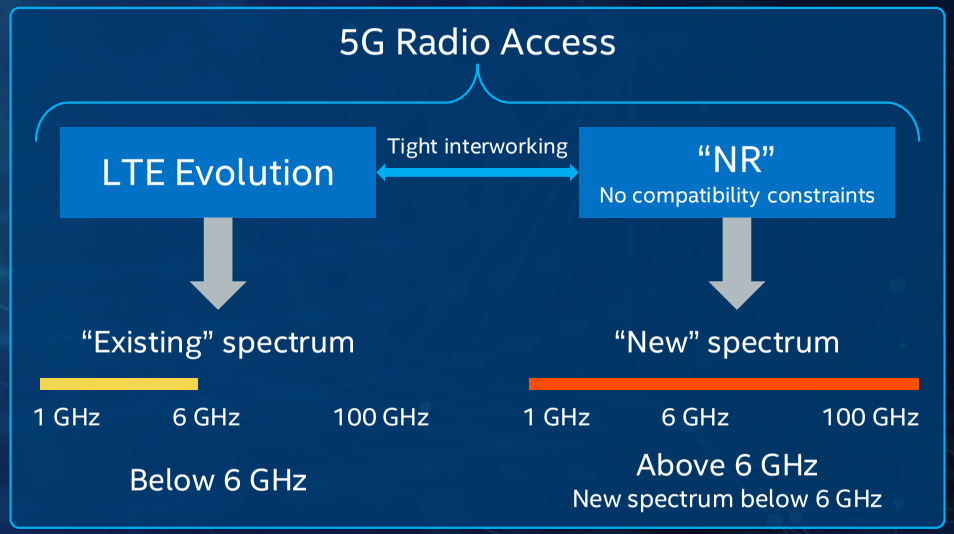
Lower cost

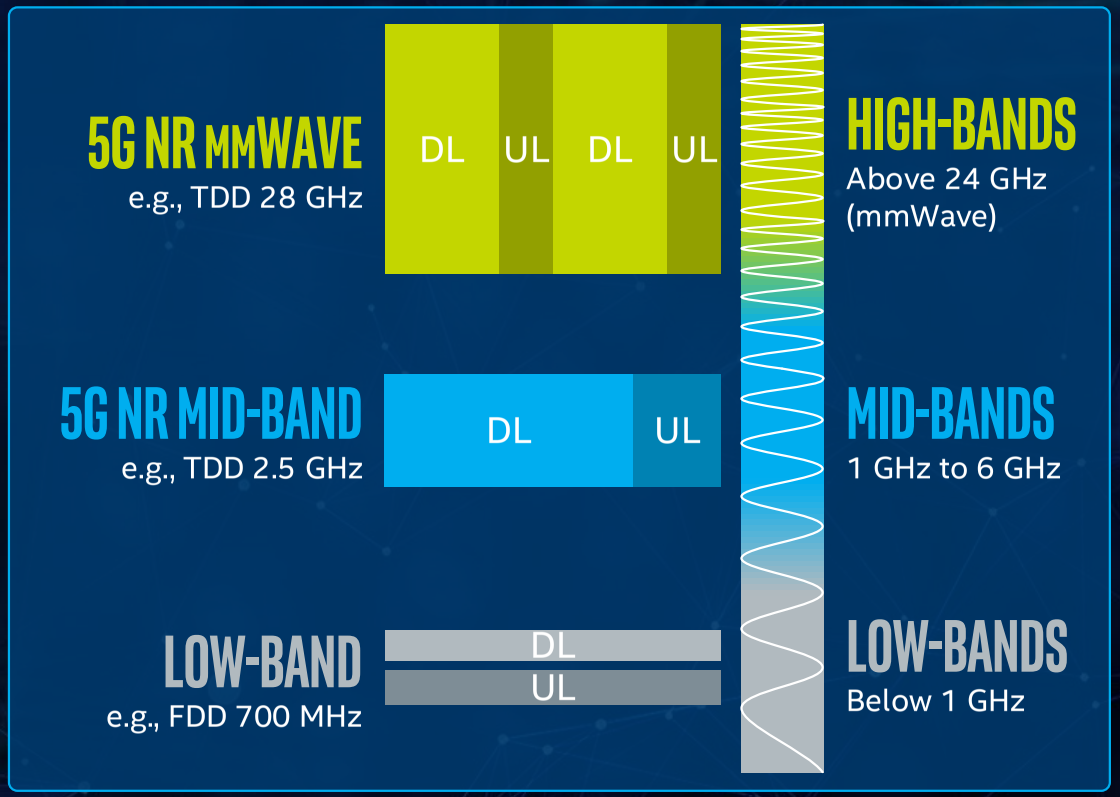
Ideal for use cases such as URLLC

5G NR SUPPORTS HIGHER AND DIVERSE FREQUENCY BANDS WITH FAR GREATER BANDWIDTH

20 times wider bandwidth per component carrier (400MHz for 5G NR vs. 20MHz for LTE)

1. Reduce overhead to support wide band operation
2. Facilitates efficient implementation

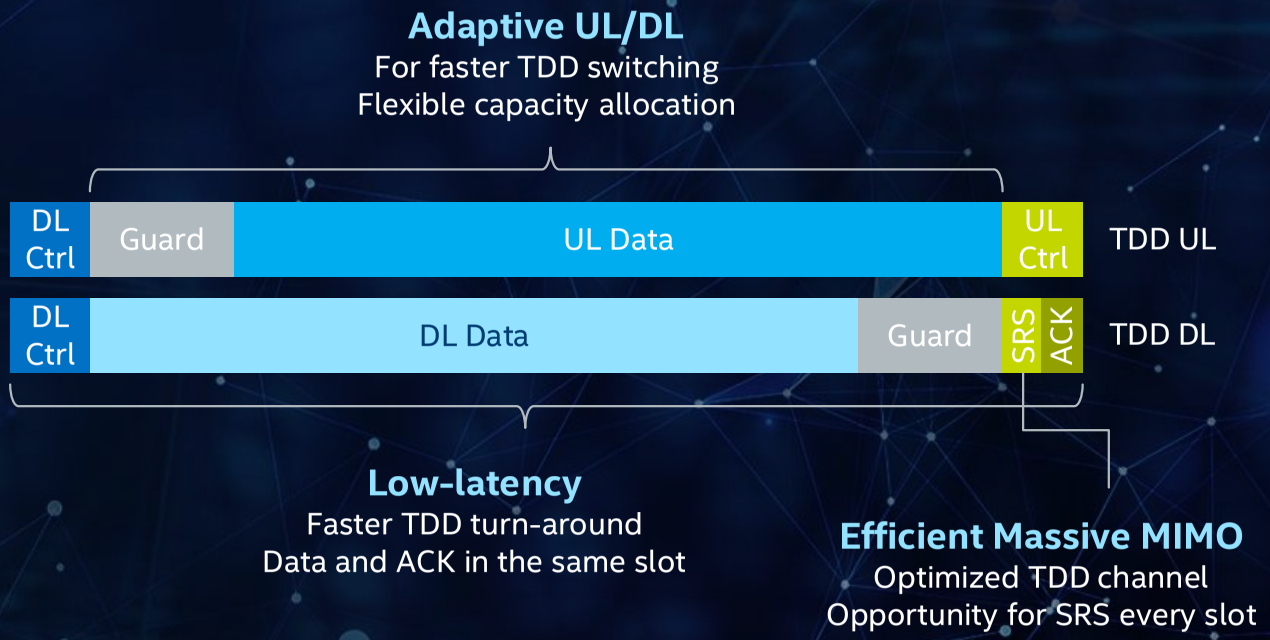




EFFICIENT 5G NR TDD SELF-CONTAINED SLOT STRUCTURE

MODULAR SLOT STRUCTURE WITH NO STATIC TIMING RELATIONSHIPS ACROSS SLOTS

- Faster TDD switching enabling adaptive UL/DL capacity allocation
- Significantly low latency with fast TDD turnaround
  - e.g., 125 to 1 ms slot duration
- Opportunity for better UL/UL scheduling
- Data and ACK in the same slot
- Advanced reciprocity-based massive antenna techniques
  - With SRS every slot for an optimal TDD channel reciprocity
- Channel reservation using additional headers



5G NR PHYSICAL LAYER: SCALABLE NUMEROLOGY

5G NR Modulations Schemes

- Supports QPSK, 16 QAM, 64 QAM similar to LTE
- UL includes $\pi/2$-BPSK
  - For reduced PAPR & high power efficiency at lower data rates
- 5G NR Waveform
- Waveform (for eMMB/URLLC and < 52.6 GHz)
  - DL Waveform: CP-OFDM
  - UL Waveform: CP-OFDM + DFT-s-OFDM
    - CP-OFDM targeted at high throughput scenarios
    - DFT-s-OFDM targeted at power limited scenarios
- Bandwidth
  - Maximum CC bandwidth is 400 MHz
  - Maximum number of subcarriers is 3300
    - 4096-FFT is needed
  - Maximum number of CCs is 16

Subcarrier spacing	15kHz	30kHz (2 x 15 kHz)	60kHz (4 x 15 kHz)	15 x 2^nkHz, (n = 3, 4, ...)
OFDM symbol duration	66.67 µs	33.33 µs	16.67 µs	66.67/2^n µs
Cyclic prefix duration	4.69 µs	2.34 µs	1.17 µs	4.69/2^n µs
OFDM symbol including CP	71.35 µs	35.68 µs	17.84 µs	71.35/2^n µs
Number of OFDM symbols per slot	14	14	12 or 14	14
Slot duration	1000 µs	500 µs	250 µs	1000/2^n µs

FRAME STRUCTURE

Frame: 10 ms

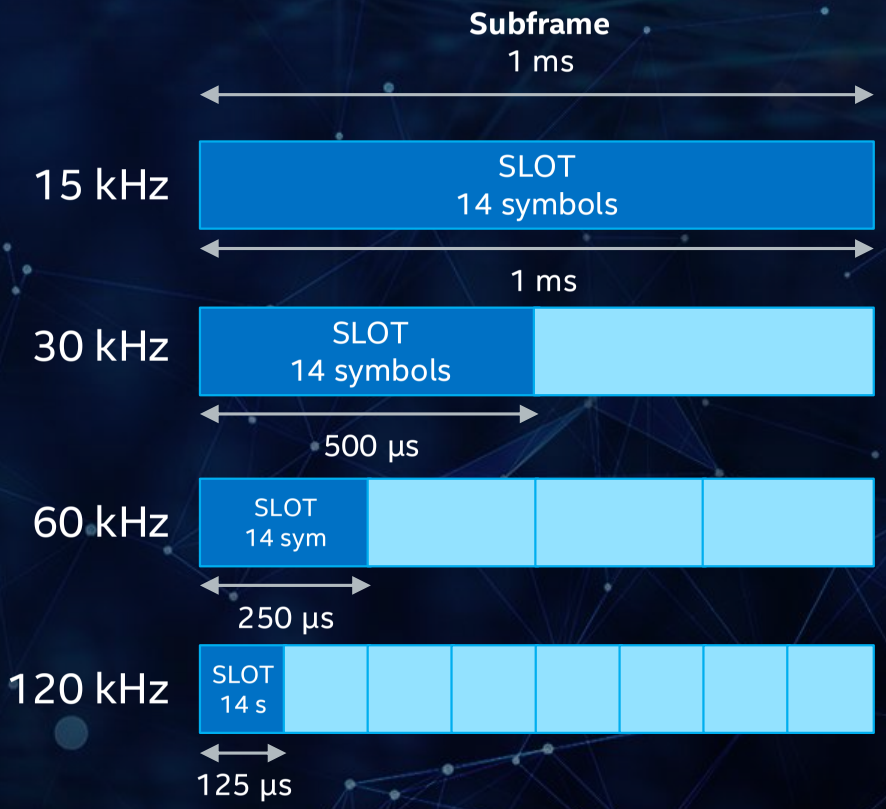
Subframe: Reference period of 1 ms

Slot (slot based scheduling)

- **14 OFDM symbols**
- One possible scheduling unit
  - Slot aggregation allowed
- Slot length scales with the subcarrier spacing
  - Slot length = $^{1ms}/_{2^{\mu}}$

Mini Slot (non slot based scheduling)

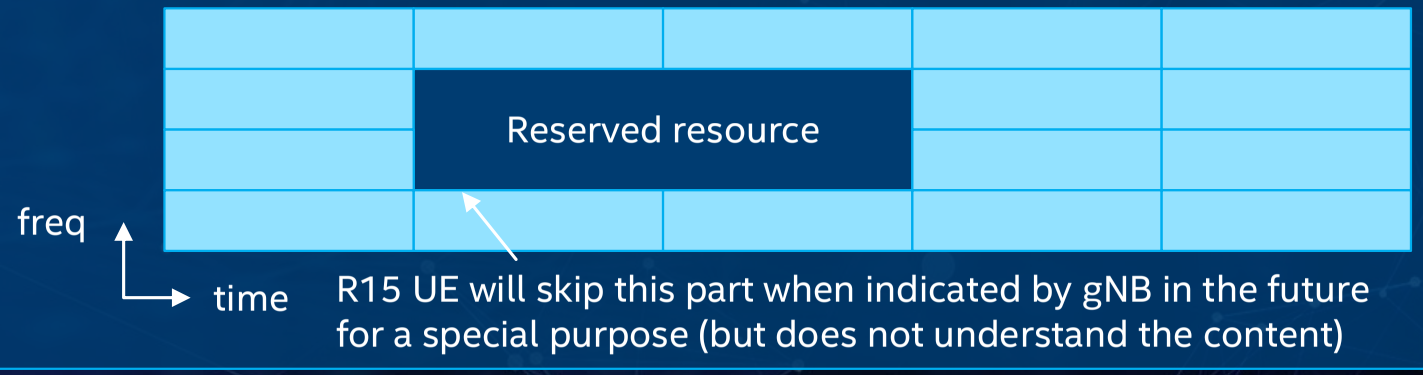
- **These are Type B PDSCH/PUSCH Slots**
- **7, 4 or 2 OFDM symbols**
- Minimum scheduling unit



5G NR CAN EVOLVE TO MEET FUTURE MARKET NEEDS
WITHOUT SACRIFICING EFFICIENCY

- Allow future evolution while minimally sacrificing efficiency
- Support of reserved resources
- Built-in forward compatibility allows for future support
- Resource allocation for a variety of uses
- Allows network slicing

CAPABILITIES PER INTERFACE



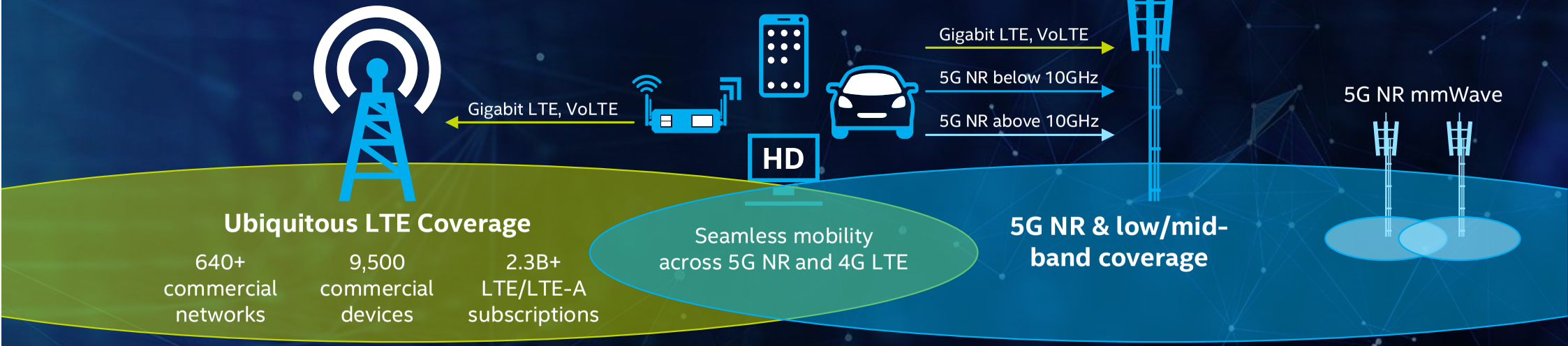
SUMMARY OF LTE VS. NR COMPARISON

	LTE	5G-NR
Maximum Bandwidth (per CC)	20 MHz	50 MHz (@ 15 kHz), 100 MHz (@ 30 kHz), 200 MHz (@ 60 kHz), 400 MHz (@ 120 kHz)
Subcarrier Spacing	15 kHz	2^n • 15 kHz TDM and FDM multiplexing
Waveform	CP-OFDM for DL; SC-FDMA for UL	CP-OFDM for DL; CP-OFDM and DFT-s-OFDM for UL
Maximum Number of Subcarriers	1200	3300
Subframe Length	1 ms (moving to 0.5 ms)	1 ms
Latency (Air Interface)	0.5 ms	0.5 ms
Slot Length	7 symbols in 500 µs	14 symbols (duration depends on subcarrier spacing) 2, 4 and 7 symbols for mini-slots
Channel Coding[2]	Turbo Code (data); TBCC (control)	Polar Codes (control); LDPC (data)
Initial Access	PVS[1] Beamforming in Digital Domain	Beamforming
MIMO	8x8	8x8
Reference Signals	UE Specific DMRS and Cell Specific RS	Front-loaded DMRS (UE-specific)
Duplexing	FDD, Semi-Static TDD, Half-Duplex FDD, Dynamic TDD	FDD, Semi-Static TDD, Half-Duplex FDD, Dynamic TDD

1. Precoding Vector Switching
2. LTE: Turbo coding for PDSCH/PUSCH, TBCC for PDCCH/PBCH, simplex coding for PHICH, RM/dual-RM for PUCCH
   NR: Polar coding for PDCCH UL UCI (DL; CA Polar, UL; PC Polar), LDPC for PDSCH/PUSCH, RM for small size of data for PUCCH

DUAL CONNECTIVITY LEVERAGES EXISTING LTE DEPLOYMENTS

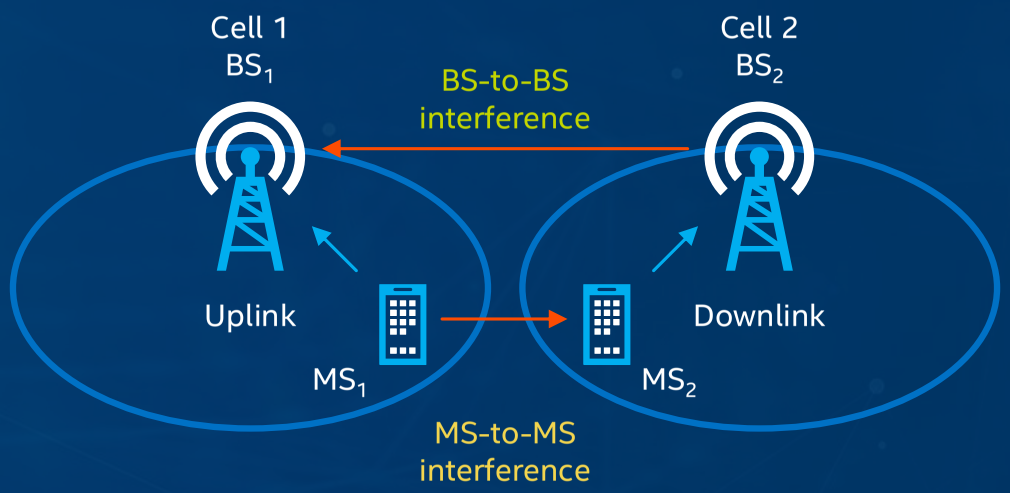
5G NR MAKES USE OF LTE COVERAGE FOUNDATION VIA DUAL CONNECTIVITY



Simultaneously connected to LTE & NR base stations
Quick fallback to LTE if blockage in NR link or if UE moves out of NR range

5G NR SUPPORT FOR DYNAMIC TDD
IMPROVES PERFORMANCE IN SMALL CELL DEPLOYMENTS

CROSS LINK INTERFERENCE IN DYNAMIC TDD[1]



- Support for dynamic change of DL/UL direction
- Flexible and efficient usage of time & frequency resources
- Cross-link interference handling between DL and UL is critical
- Allows adjustments of DL/UL under instantaneous loads
  - DL/UL direction can change every slot (e.g., 0.5 ms or 1 ms)

1. Cross Link Interference (CLI) is not specified in Rel-15 but can be enabled by network implementation; specification is planned to be introduced n Rel-16

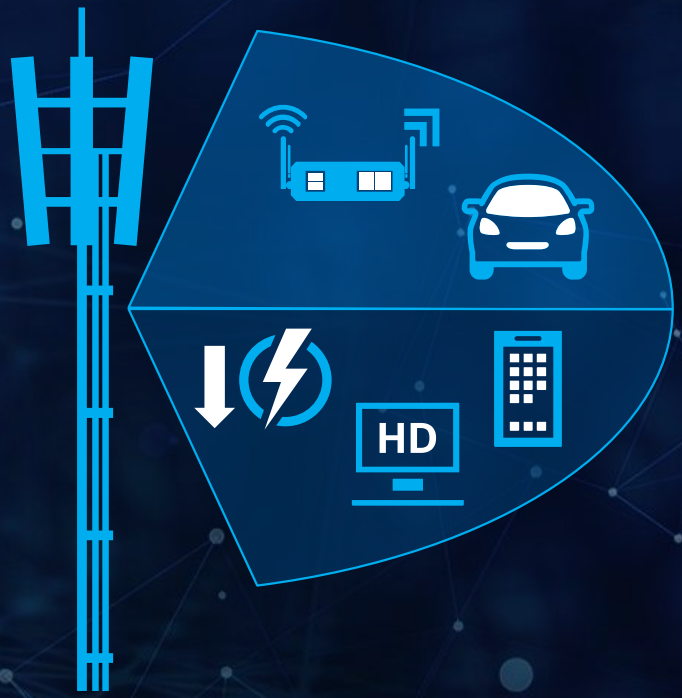
5G NR REDUCES POWER CONSUMPTION
VARIOUS TECHNIQUES ARE USED FOR POWER SAVINGS

For Base Stations

Base stations will remove always-on reference signal

5G-NR uses a new BW Part (BWP) concept to let UE monitor PDCCH only a narrow BW of CC

3GPP Rel-16 working on new concepts for power savings



For UEs

5G NR–based end points deliver smaller BW for control than data

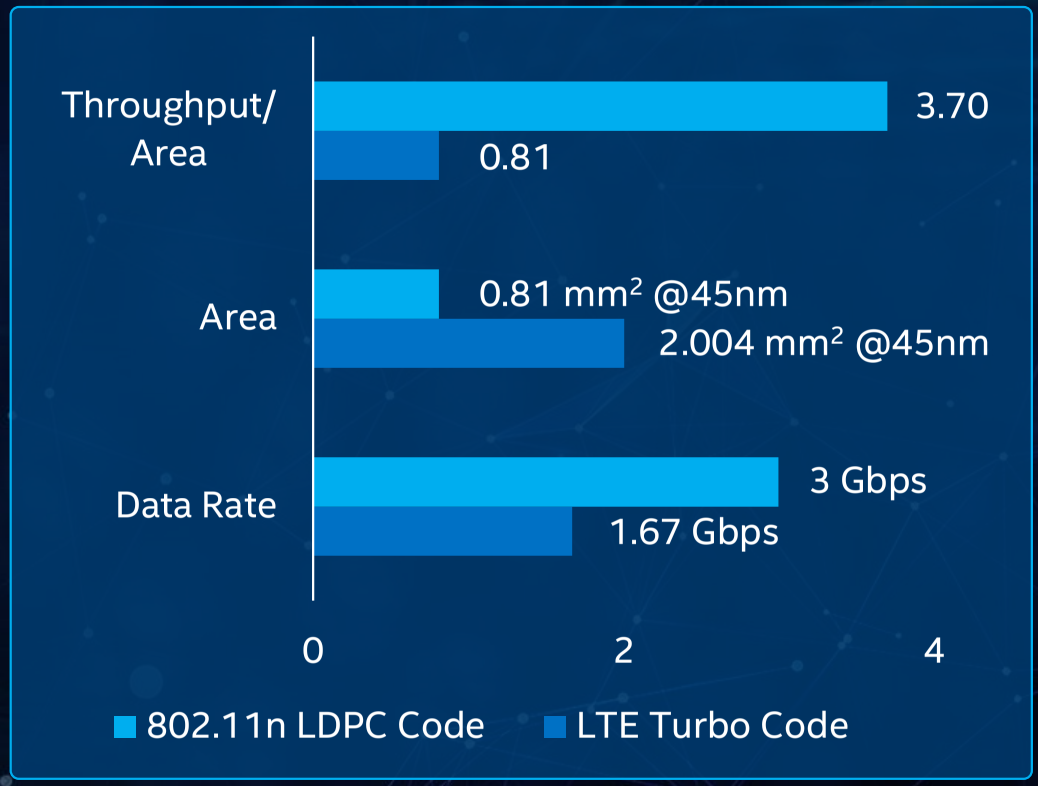
5-NR design allows reduced configurable search space for increased UE power savings

UE will feature reduced control channel decoding attempts
- (In LTE, UE monitors control every slot)

5G NR DELIVERS ADVANCED CHANNEL CODING SCHEMES FOR GREATER BANDWIDTH

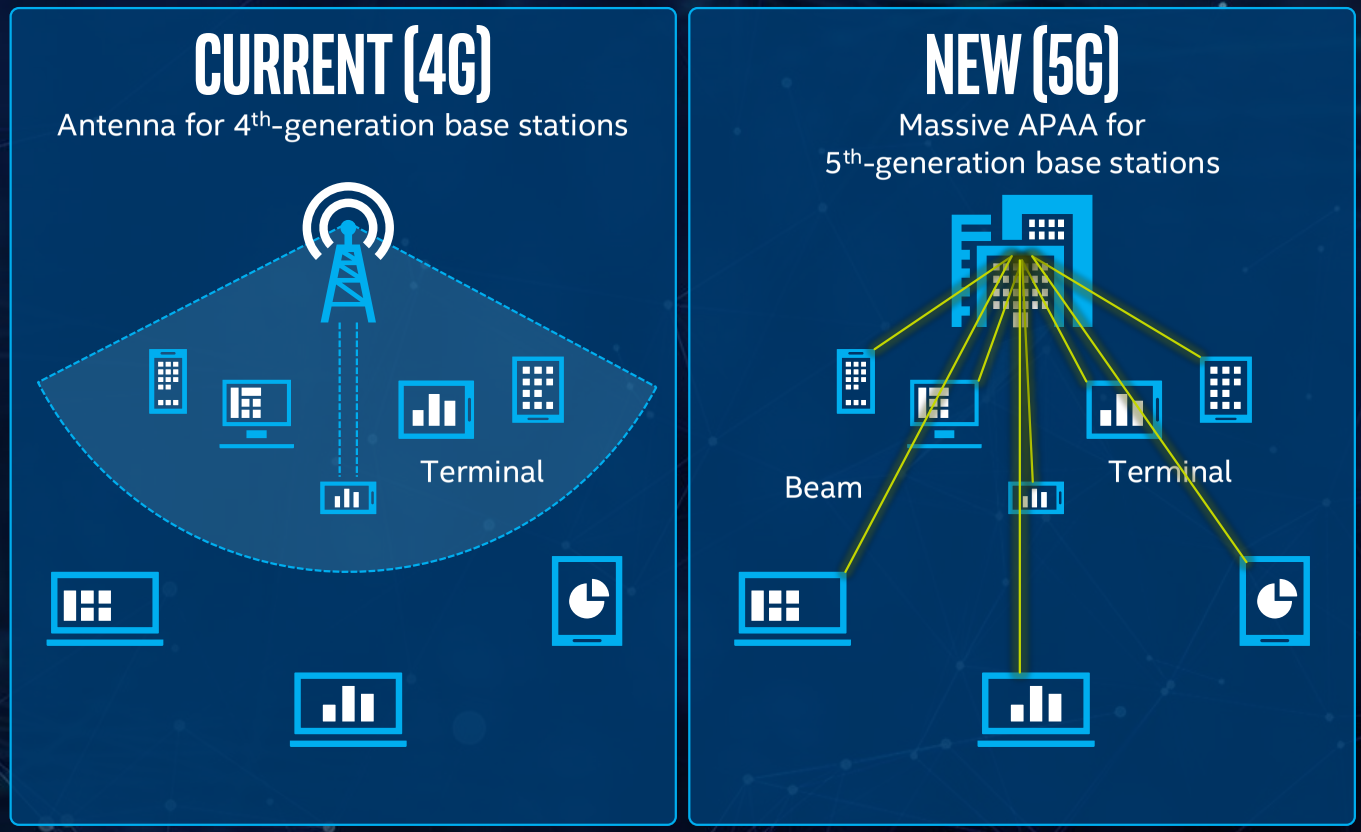
Turbo code is suitable for LTE speeds but not effective for 5G demands

- LDPC for data plane and Polar code schemes for control provide …
- Support for very high peak rates and lower latency
- Better performance in small packet transmissions



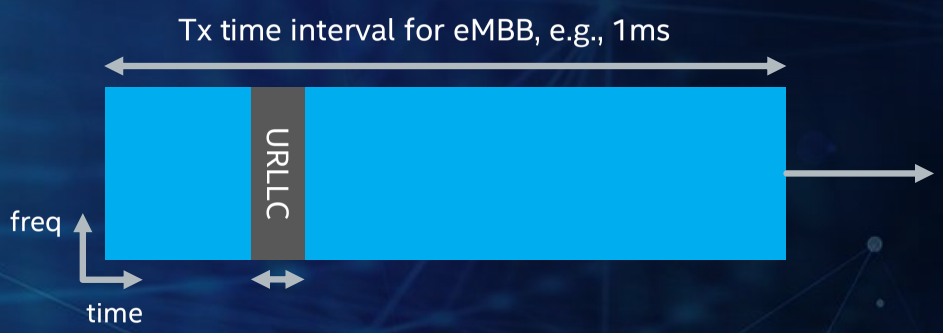
5G NR USES MASSIVE MIMO & MULTI-ANTENNA TECHNIQUES
FOR ENHANCED NETWORK CAPACITY AND COVERAGE

- For lower frequencies, moderate number of active antennas are used (around 32 Tx chains)
  - Robust CSI-RS transmission DL and UL CSI reporting are critical
- For high frequencies, 5G NR uses a large number of antennas capable of beamforming with
- More spatial data streams for very high spectral efficiency
- Timely & enhanced channel status feedback, MIMO layer precoding
- Innovative New beam management\tracking, decoupled DL & UL antenna techniques



5G NR DELIVERS LOW LATENCY AND HIGH RELIABILITY

- Support 1ms end-to-end delay, e.g., via 1-symbol Tx time interval
- Support for ultra-reliable transmission, e.g., 10^{-5} packet error rate via packet duplication from multiple transmission points



Remote Surgery image source: ©[2016] Intuitive Surgical, Inc.

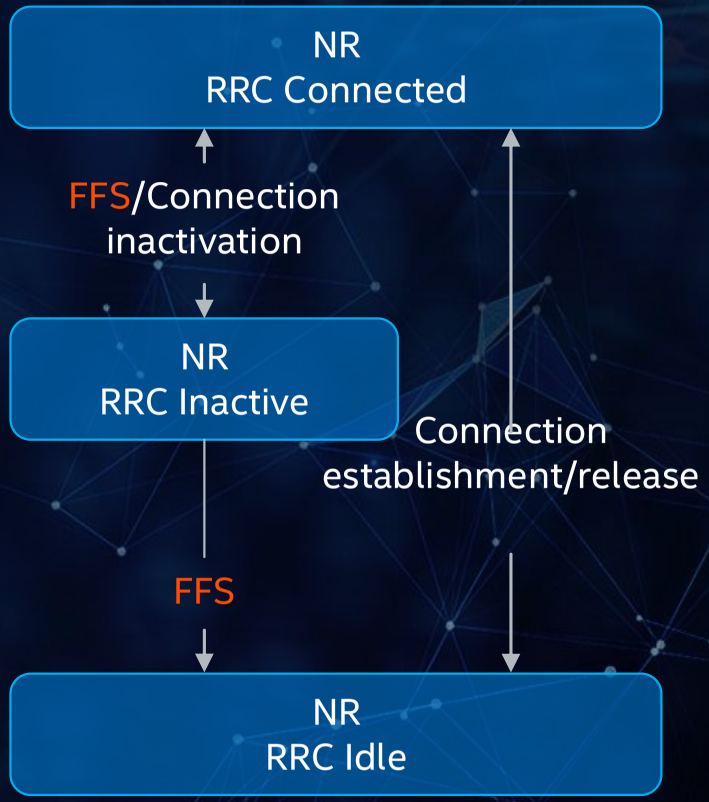
5G NR AN ULTRA LEAN DESIGN WITH ENHANCED ENERGY EFFICIENCY

5G NR Minimizes Always-on Transmissions

- NR Reference signals are transmitted only when necessary

RRC Inactive State Conserves Network Resources

- New UE power-efficient RRC state, “RRC Inactive” that is a RAN controlled “Idle” state
- Fast transition between Inactive and Connected with far less signaling
- “Paging” controlled by RAN-based notification area managed by NR RAN



OTHER ENHANCED FEATURES

ENHANCED INITIAL ACCESS

Sharp time/freq detection of PSS, Improved cross-correlation for SSS

Configurable sync signal periodicity

FLEXIBLE SCHEDULING AND HARQ

Flexible timing between PDCCH and PDSCH, between PDCCH and PUSCH, between PDSCH and ACK

SUPPORT DIFFERENT QoS PER PACKET (NOT FEASIBLE IN LTE)

5G Core Network splits data into QoS flows with a QoS flow marking (QFI) based on QoS needed for the packet

VARIOUS UL PROTOCOL ENHANCEMENTS FOR LOW LATENCY & COMPLEXITY

ON DEMAND SYSTEM INFORMATION (SIB)

5G NR STANDARDS AND FEATURES

2018	2019	2020
Rel-15	Rel-16	Rel-17
NR Access Technology	eMBB & URLLC enhancements	eMBB & URLLC enh
eMBB & URLLC	NR-Unlicensed	NR V2X Enhancements
Scalable numerology	NOMA (Non-Orthogonal Multiple Access)	NR Beyond 52.6 GHz (up to 100 GHz)
Enhanced MIMO	NR-V2X	NR-Unlicensed Enhancements (in 60 GHz)
Advanced coding schemes	Industrial IoT Enhancement	Non-3GPP integration
Support for dynamic TDD	SON/MDT	
	Positioning	
	Reduced power consumption	

Rel 15 Deployment – 2019 | Rel 16 Deployment - 2020 | Broad Commercial Launch

INTEL'S INNOVATIONS ARE A MAJOR DRIVER TO 5G NR

Intel Continues to Lead the Ecosystem in Creating New Standards

Providing valuable contributions in proprietary research, reference designs, and insights from a myriad of trials

Intel Made Significant Contributions to 3GPP Rel-15 Specifications

Intel delivered contributions to the entire 5GNR specification, including those related to coding, error correction, modulation, spatial sub-channelization, beamforming, radio link adaptation, and more

Intel's Prototypes Set the Stage for Early 5G Deployments

Intel® 5G MTP Intel® ATP contributed key guidance on the power of 5G in dozens of early field trials

Intel's Years of R&D Leadership Will Help Guide the 5G Ecosystem

Interoperability testing and real-world tests with industry leaders help guide deployments around the globe

INTEL'S 5G PROJECTS AROUND THE WORLD

50+ TRIALS WORLDWIDE

INTEL® 5G MOBILE TRIAL PLATFORM (MTP)
COMPLETE 5G FUNCTIONALITY IN A SMALL FORM FACTOR

MTP-NR is Intel's 5G CPE prototype for pre-commercial field trial testing & research

MTP-NR Features

- Ultra-high performance 5G architecture
- Up to 10Gbps throughput
- 2x processing capability vs. 2nd-Gen 5G MTP
- 28GHz and 39GHz bands
- 28GHz IF and RF for sub-6GHz
- Band support: 600-900Mhz, 3.3-4.2GHz, 4.4-4.9GHz, 5.1-5.9GHz
- 4x4 MIMO
- 16 antenna elements
- +11dBm power output
- 36 dBmi EIRP
- Based on state-of-the art Intel® Stratix® 10 FPGAs
- 3GPP NR early interoperability
- 200 MHz & 400MHz BW and up to 2Gbps Peak

INTEL® AUTOMOTIVE TRIAL PLATFORM (ATP): TESTING 5G ON THE GO

Multiple Successful Trials w/ Global Leaders

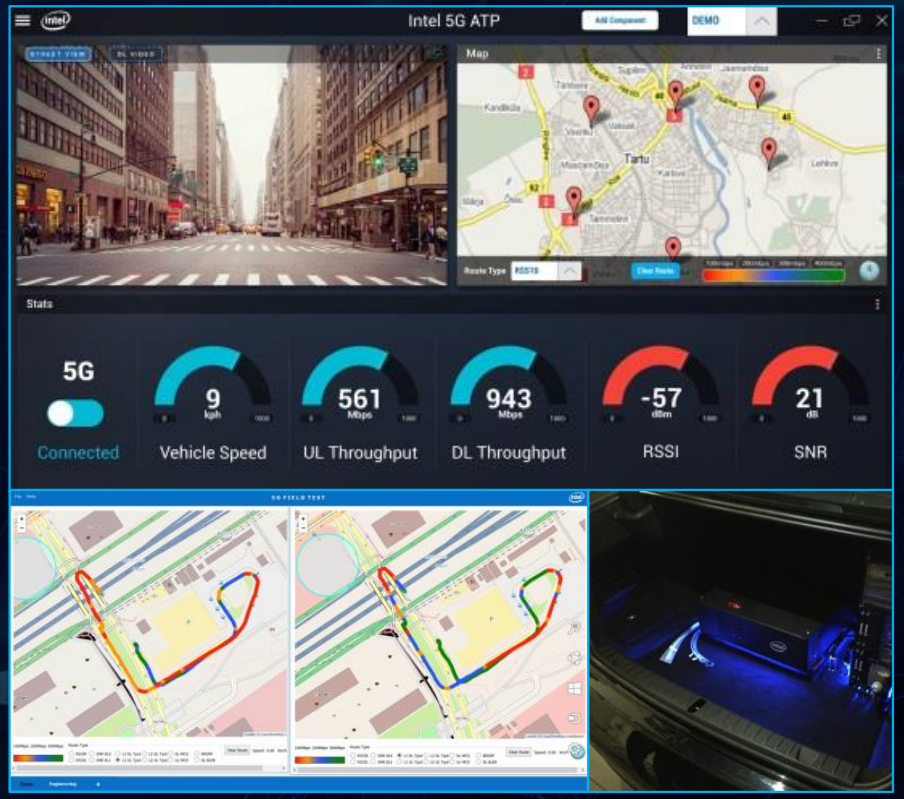
- Multiple trials w/ NTT DoCoMo*, China Telecom*, BMW*, Ferrari*, and others
- Applications range from remote bulldozer operation to windsurfing to autonomous driving

Automotive Trial Platform (ATP) Details

- 28GHz mmWave
- Intel® Core™ i7 Processor
- Powered by 5 Intel® Arria® 10 FPGAs
- ATP baseband is same as MTP 2nd gen

Technical Trial Results

- 5G at 28GHz mmWave operation using Intel 5G RFIC
- Integrated sub-6GHz and 28GHz RFFE operation w/ multi-panel antenna
- DL throughput of over 1Gbps; UL of 600 Mbps



*Other names and brands may be claimed as the property of others.

SUMMARY

A revolutionary aspect of 5G NR is the operation range extended from sub 1GHz to 100 GHz

5G NR brings in new innovations like beamforming to overcome higher path losses at high frequency of operations

5G NR aims high data capacity and ultra low latencies at both sub-6GHz and mmWave frequencies

5G NR physical layer is based on a flexible and scalable design to support diverse use cases in widely different requirements

Thank You!

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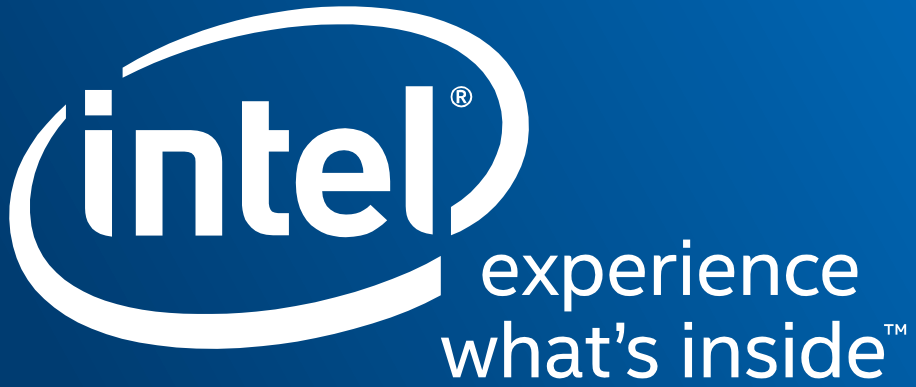
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