5G NR – DRIVING WIRELESS EVOLUTION INTO NEW VERTICAL DOMAINS
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].

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MOBILE USAGE CONTINUES TO GROW

Global mobile video traffic 2016-211 (Terabytes per month)

In terms of overall larger app traffic – video...

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

...by volume of connected devices...

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

...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

Intel 5G – Next Generation and Standards
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
   *Other names and brands may be claimed as the property of others.
5G USE CASES, SPECTRUM AND DEPLOYMENTS

Ultra Reliability and Low Latency
- Autonomous Vehicles
- Healthcare
- Emergency Services
- Instant Translation

Massive M2M Connectivity
- Smart Cities
- Smart Agriculture
- Manufacturing
- Supply Chain/Logistics

Enhanced Mobile Broadband
- Virtual and Merged Reality
- Mobile Office
- Broadband to Home
- Entertainment

Spectrum and Deployments:
- 1GHz
- 3GHz
- 10GHz
- 30GHz
- 100GHz

Pico sites

Macro / Micro sites
ENTER 5G NR – A TRULY UNIFIED AIR INTERFACE

**Responsive**
Sub-1 millisecond delay end-to-end for low latency apps

**Reliable**
10^{-5} packet error rate for ultra reliable apps

**Powerful**
Up to 10Gbps DL via mmWave for extreme mobile broadband

**Flexible**
Subcarrier spacing, scalable numerology enable deployment in new scenarios

**Scalable**
Supports new bands up to 52.6GHz

**Efficient**
Dynamic TDD delivers better resource utilization

---

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

Intel 5G – Next Generation and Standards
Differentiating 5G NR from LTE

- **Ultra Reliability**
  - HARQ and other schemes enable 10^{-5} packet error rate/block error ratio of 0.00001

- **Resource Allocation**
  - Simultaneous connections between LTE and 5G providing superior coverage

- **Superior Coverage**
  - Providing coverage

- **Up to 400MHz**
  - Utilizing mmWave spectrum

- **400MHz**
  - Up to 400MHz

- **Support for Mission Critical Services**
  - Macro cell, micro cell, and hybrid environments capable

- **LDPC Code and Other Techniques**
  - LDPC code and other techniques

- **Diverse Deployment Scenarios**
  - Forward compatibility

- **Power Requirements**
  - Low latency

- **Higher Data Rates**
  - Wider channel BW per carrier

Intel 5G – Next Generation and Standards
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

Intel 5G – Next Generation and Standards
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

Adaptive UL/DL
For faster TDD switching
Flexible capacity allocation

Low-latency
Faster TDD turn-around
Data and ACK in the same slot

Efficient Massive MIMO
Optimized TDD channel
Opportunity for SRS every slot
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 eMBB/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

<table>
<thead>
<tr>
<th>Subcarrier spacing</th>
<th>15kHz</th>
<th>30kHz (2 x 15 kHz)</th>
<th>60kHz (4 x 15 kHz)</th>
<th>$15 \times 2^n$kHz, $(n = 3, 4, ...)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFDM symbol duration</td>
<td>66.67 µs</td>
<td>33.33 µs</td>
<td>16.67 µs</td>
<td>66.67/$2^n$ µs</td>
</tr>
<tr>
<td>Cyclic prefix duration</td>
<td>4.69 µs</td>
<td>2.34 µs</td>
<td>1.17 µs</td>
<td>4.69/$2^n$ µs</td>
</tr>
<tr>
<td>OFDM symbol including CP</td>
<td>71.35 µs</td>
<td>35.68 µs</td>
<td>17.84 µs</td>
<td>71.35/$2^n$ µs</td>
</tr>
<tr>
<td>Number of OFDM symbols per slot</td>
<td>14</td>
<td>14</td>
<td>12 or 14</td>
<td>14</td>
</tr>
<tr>
<td>Slot duration</td>
<td>1000 µs</td>
<td>500 µs</td>
<td>250 µs</td>
<td>1000/$2^n$ µs</td>
</tr>
</tbody>
</table>
**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 = \( \frac{1\text{ms}}{2^\mu} \)

**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**

Reserved resource

freq

time

R15 UE will skip this part when indicated by gNB in the future for a special purpose (but does not understand the content)
# SUMMARY OF LTE VS. NR COMPARISON

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

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

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

EXISTING DEPLOYMENTS

Ubiquitous LTE Coverage
- 640+ commercial networks
- 9,500 commercial devices
- 2.3B+ LTE/LTE-A subscriptions

5G AUGMENTED DEPLOYMENTS

Gigabit LTE, VoLTE
- 5G NR below 10GHz
- 5G NR above 10GHz

Ubiquitous LTE Coverage

Seamless mobility across 5G NR and 4G LTE

5G NR & low/mid-band coverage

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

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 in 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

![Graph showing Throughput/Area, Area, and Data Rate for 802.11n LDPC Code and LTE Turbo Code]
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
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

**VARIABLE UL PROTOCOL ENHANCEMENTS FOR LOW LATENCY & COMPLEXITY**

**ON DEMAND SYSTEM INFORMATION (SIB)**
- Flexible scheduling and HARQ
- Various UL protocol enhancements for low latency & complexity
- On demand system information (SIB)
- Support different QoS per packet (not feasible in LTE)
### 5G NR Standards and Features

<table>
<thead>
<tr>
<th>Year</th>
<th>Rel</th>
<th>NR Access Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>Rel-15</td>
<td>eMBB &amp; URLLC, Scalable numerology, Enhanced MIMO, Advanced coding schemes, Support for dynamic TDD</td>
</tr>
<tr>
<td>2019</td>
<td>Rel-16</td>
<td>eMBB &amp; URLLC enhancements, NR-Unlicensed, NOMA (Non-Orthogonal Multiple Access), NR-V2X, Industrial IoT Enhancement, SON/MDT, Positioning, Reduced power consumption</td>
</tr>
<tr>
<td>2020</td>
<td>Rel-17</td>
<td>eMBB &amp; URLLC enhancement, NR V2X Enhancements, NR Beyond 52.6 GHz (up to 100 GHz), NR-UNlicensed Enhancements (in 60 GHz), Non-3GPP integration</td>
</tr>
</tbody>
</table>

**Rel 15 Deployment – 2019:**
- **Rel 16 Deployment - 2020:**
- **Broad Commercial Launch:**
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 5G NR 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

verizon
ERICSSON
China Mobile
AT&T
SK telecom
kt
TATA
DOCOMO
Telia
Telstra
NOKIA
T-Mobile

Intel 5G – Next Generation and Standards
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
- 3GPP NR early interoperability
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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