This presentation addresses potential use cases and views on characteristics of 5G technology and is not intended to reflect a commitment to the characteristics or commercialization of any product or service of Qualcomm Technologies, Inc. or its affiliates.
5G will enhance existing and expand to new use cases

- **Enhanced Mobile Broadband**: Faster, more uniform user experiences
- **Wide Area Internet of Things**: More efficient, lower cost communications with deeper coverage
- **Higher-Reliability Control**: Lower latency and higher reliability

- Smart homes/buildings/cities
- Autonomous vehicles, object tracking
- Infrastructure monitoring & control, e.g. Smart Grid
- Remote control & process automation, e.g. aviation, robotics
- New form factors, e.g. wearables and sensors
- Mobile broadband, e.g. UHD virtual reality
- Demanding indoor/outdoor conditions, e.g. venues
- Smart homes/buildings/cities
- Autonomous vehicles, object tracking
- Infrastructure monitoring & control, e.g. Smart Grid
- Remote control & process automation, e.g. aviation, robotics
- New form factors, e.g. wearables and sensors
- Mobile broadband, e.g. UHD virtual reality
- Demanding indoor/outdoor conditions, e.g. venues
Scalable across a broad variation of requirements

- **Lower energy**
  - 10+ years of battery life

- **Lower complexity**
  - 10s of bits per second

- **Higher density**
  - 1 million nodes per Km²

- **Enhanced capacity**
  - 10 Tbps per Km²

- **Enhanced data rates**
  - Multi-Gigabits per second

- **Frequent user mobility**
  - Or no mobility at all

- **Higher reliability**
  - As low as 1 millisecond

- **Higher reliability control**
  - <1 out of 100 million packets lost

- **Stronger security**
  - e.g. Health / government / financial trusted

- **Better awareness**
  - Discovery and optimization

- **Wide area Internet of Things**

- **Deeper coverage**
  - To reach challenging locations

Based on target requirements for the envisioned 5G use cases
Current 3GPP timeline delivers 5G spec for 2020 launch*

Anticipated 5G commercialization timeline – our view

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<td>4G evolution - LTE will evolve in parallel with 5G</td>
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* For information on 3GPP’s 5G timeline, see: http://www.3gpp.org/news-events/3gpp-news/1734-ran_5g
Multi-connectivity across bands & technologies

4G+5G multi-connectivity improves coverage and mobility

Leverage 4G investments to enable phased 5G rollout
A new 5G unified air interface is the foundation

Diverse spectrum
- Licensed, shared licensed, and unlicensed spectrum
- Spectrum bands below 1 GHz, 1 GHz to 6 GHz, & above 6 GHz (incl. mmWave)
- FDD, TDD, half duplex
- Device-to-device, mesh, relay network topologies

Diverse services and devices
- From wideband multi-Gbps to narrowband 10s of bits per second
- Multiplexing of lower latency and more-reliable traffic and nominal traffic
- From high user mobility to no mobility at all
- From wide area macro to indoor / outdoor hotspots

Diverse deployments

Optimized OFDM-based waveforms
- With scalable numerology and TTI, plus optimized multiple access for different use cases

A common, more flexible framework
- To more efficiently multiplex services and features—designed for forward compatibility

Advanced wireless technologies
- Such as massive MIMO, more robust mmWave and a self-contained TDD design
Natively incorporate advanced wireless technologies
Key 5G design elements across services

**Enhanced Mobile Broadband**
Faster, more uniform user experiences
- Scalable to wider bandwidths
- Designed for diverse spectrum types
- Massive MIMO
- More robust mmWave design
- Improved network/signaling efficiency
- Native HetNets & multicast support
- Opportunistic carrier/link aggregation

**Wide-Area Internet of Things**
More efficient, lower cost communications
- Lower complexity, narrower bandwidth
- Lower energy waveform
- Optimized link budget
- Decreased overheads
- Managed multi-hop mesh

**Higher-Reliability Control**
Lower latency and more reliable links
- Lower latency bounded delay
- Optimized PHY/pilot/HARQ
- Multiplexing with nominal
- Simultaneous, redundant links
- Grant-free transmissions
Optimized waveforms and multiple access
With heavy reliance on the OFDM family adapted to new extremes

OFDM family the right choice for mobile broadband and beyond
- Scalable waveform with lower complexity receivers
- More efficient framework for MIMO spatial multiplexing – higher spectral efficiency
- Allows enhancements such as windowing/filtering for enhanced localization
- SC-OFDM well suited for uplink transmissions in macro deployments

Resource Spread Multiple Access (RSMA) for target use cases
- Enable asynchronous, non-orthogonal, contention-based access that is well suited for sporadic uplink transmissions of small data bursts (e.g. IoT)

A more detailed analysis of 5G optimized waveforms and multiple access is available in the appendix of this presentation.
Scalability to much lower latency

Scalable TTI for diverse latency & QoS requirements

- Shorter TTI for lower latency
- Longer TTI for higher spectral efficiency

Order of magnitude lower Round-Trip Time (RTT) than LTE today

FDD
- Fewer (variable) interlaces for HARQ

TDD
- Self-contained design reduces RTT

Example: TDD downlink

Data and acknowledgement in the same subframe
Self-contained TDD subframe design
Faster, more flexible TDD switching & turn around, plus support for new deployment scenarios

Unlicensed spectrum
Listen-before-talk headers e.g. clear Channel Assessment (CCA) and hidden node discovery

Massive MIMO
Leveraging channel reciprocity in UL transmission for DL beamforming training

D2D, mesh and relay
Headers for e.g. direction of the link for dynamic distributed scheduling

Adaptive UL/DL configuration
More flexible capacity allocation; also dynamic on a per-cell basis

Example: TDD downlink
Self-contained TDD sub-frame: UL/DL scheduling info, data and acknowledgement in the same sub-frame
Designing Forward Compatibility into 5G

Flexibly phase-in future features and services

Blank resources

Enable future features/service to be deployed in the same frequency in a synchronous and asynchronous manner

Service multiplexing

E.g. nominal traffic designed to sustain puncturing from higher-reliability transmissions or bursty interference

Common frame structure

Enable future features to be deployed on a different frequency in a tightly integrated manner, e.g. 5G sub 6 GHz control for mmWave

1 'Blank' resources may still be utilized, but designed in a way to not limit future feature introductions
A more flexible framework with forward compatibility

Designed to multiplex envisioned & unforeseen 5G services on the same frequency

Integrated framework
That can support diverse deployment scenarios and network topologies

Higher-reliability transmissions
May occur at any time; design such that other traffic can sustain puncturing\(^1\)

Blank subcarriers
Scalable TTI
For diverse latency requirements — capable of latencies an order of magnitude lower than LTE

Blank subframes
D2D
Multicast
Scalable transmission time interval (TTI)
For diverse latency requirements — capable of latencies an order of magnitude lower than LTE

Forward compatibility
With support for blank subframes and frequency resources for future services/features

\(^1\) Nominal 5G access to be designed such that it is capable to sustain puncturing from higher-reliability transmission or bursty interference
Scalable OFDM numerologies
To meet diverse spectrum bands/types and deployment models

Example usage models and channel bandwidths
Massive MIMO at 4 GHz allows reuse of existing sites

Leverage higher spectrum band using same sites and same transmit power

![CDF and User Throughputs](image)

**Significant average and cell-edge through gain from Massive MIMO**

<table>
<thead>
<tr>
<th>Antenna configuration</th>
<th>2x4, 20 MHz 2 GHz</th>
<th>2x4, 80 MHz 4 GHz</th>
<th>24x4, 80 MHz 4 GHz</th>
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<tbody>
<tr>
<td>Bandwidth</td>
<td>20 MHz</td>
<td>80 MHz</td>
<td>80 MHz</td>
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<tr>
<td>Spectrum band</td>
<td>2 GHz</td>
<td>4 GHz</td>
<td>4 GHz</td>
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<tr>
<td>Cell Edge UE</td>
<td></td>
<td></td>
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<tr>
<td>Throughputs (Mbps)</td>
<td>2.1</td>
<td>5.7</td>
<td>22.1</td>
</tr>
<tr>
<td>Average Cell</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Throughputs (Mbps)</td>
<td>58</td>
<td>197</td>
<td>808</td>
</tr>
<tr>
<td>Average Cell Spectral Efficiency (bps/Hz)</td>
<td>2.9</td>
<td>2.5</td>
<td>10.1</td>
</tr>
</tbody>
</table>

Source: Qualcomm simulations; Macro-cell with 1.7km inter-site distance, 46 dBm Tx power at base station, 20MHz@2GHz and 80MHz@4GHz BW TDD, 24x Massive MIMO. Using 5-quantile throughput for cell edge throughput.
Realizing the mmWave opportunity for mobile broadband

The enhanced mobile broadband opportunity
- Large bandwidths, e.g. 100s of MHz
- Multi-Gbps data rates
- Flex deployments (integrated access/backhaul)
- Higher capacity with dense spatial reuse

The challenge—‘mobilizing’ mmWave
- Robustness results from high path loss and susceptibility to blockage
- Device cost/power and RF challenges at mmWave frequencies

5G Solutions

- Smart beamforming & beam tracking
  Increase coverage and minimize interference
- Tighter interworking with sub 6 GHz
  Increase robustness and faster system acquisition
- Phase noise mitigation in RF components
  For lower cost, lower power devices
Directional beamforming improves mmWave coverage and reduces interference

28GHz: Outdoor to Outdoor Path Loss & Coverage

- Both very high and low SINRs observed
- Interference seems to matter at 100-200m ISD, but not at all at 300m

- ~150m dense urban LOS and NLOS coverage using directional beamforming

* Mahattan 3D map, Results from ray-tracing
Device-centric mobility management in 5G
Control plane improvements to improve energy and overhead efficiency

Lightweight mobility for device energy savings
- Apply COMP-like\(^1\) concepts to the control plane
- Intra-zone mobility transparent to the device

Less broadcast for network energy savings
- Low periodic beacon for initial discovery of device(s)
- On-demand system info (SIB) when devices present\(^2\)

---

\(^1\) Coordinated MultiPoint is an LTE Advanced feature to send and receive data to and from a UE from several access nodes to ensure the optimum performance is achieved even at cell edges.

\(^2\) May dynamically revert to broadcast system info when needed, e.g. system info changes.
Non-orthogonal RSMA for more efficient IoT communications

Characterized by small data bursts in the 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 high device density

Better link budget

Downlink remains OFDM-based for coexistence with other services
Support for multi-hop mesh with WAN management

Problem: uplink coverage  |  Due to low power devices and challenging placements, e.g. in basement
Solution: managed uplink mesh  |  Uplink data relayed via nearby devices—uplink mesh but direct downlink.

1 Greater range and efficiency when using licensed spectrum, e.g. protected reference signals. Network time synchronization improves peer-to-peer efficiency.
Hard latency bound and PHY/MAC design

Single-cell multi-user evaluation/queueing model

1. Causes of packet drop: a, last transmission fails at Rx; b, delay exceeds deadline at Tx queues
2. Low BLER Block Error Rate, required to achieve higher-reliability with a hard delay bound
3. All data based on Qualcomm simulations with approximate graphs and linear scales. 3x gain when increasing from 10MHz to 20MHz for 1e-4 BLER.

5G design must consider the tradeoffs among capacity, latency and reliability

Example: 2X bandwidth for 3x capacity gain

- e.g. 1e-2 BLER
- e.g. 1e-4 BLER

1. Latency
   - e.g. 1e-2 BLER
   - e.g. 1e-4 BLER

2. Capacity
   - Example: 2X bandwidth for 3x capacity gain
Thank you

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