Leading the path towards 5G with LTE Advanced Pro

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Progress LTE capabilities towards 5G

In parallel driving 4G and 5G to their fullest potential

Note: Estimated commercial dates. Not all features commercialized at the same time
Progress LTE capabilities towards 5G
In parallel driving 4G and 5G to their fullest potential

- Unified, more capable platform for spectrum bands below/above 6 GHz
- For new spectrum available beyond 2020, including legacy re-farming
- Fully leverage 4G investments for a phased 5G rollout
- Significantly improve cost and energy efficiency

Note: Estimated commercial dates. Not all features commercialized at the same time.
Proliferate LTE to new use cases

Connect the Internet of Things

High Performance

Low power/complexity

New ways to connect and interact

Evolving LTE-Direct

LTE V2X Communications

New classes of services

Digital TV broadcasting

Proximal awareness

Public safety

Latency-critical control

Extending the value of LTE technology and ecosystem
Extending LTE to unlicensed spectrum globally with LAA
Licensed Assisted Access (LAA) with Listen Before Talk (LBT)

Assumptions:
- 3GPP LAA evaluation model based on TR 36.889,
- two operators, 4 small-cells per operator per macro cell, outdoor,
- 40 users on same 20 MHz channel in 5 GHz, both uplink and downlink in 5 GHz,
- 3GPP Bursty traffic model with 1MB file, LWA using 802.11ac,
- DL 2x2 MIMO (no MU-MIMO), 24dBm + 3dBi Tx power in 5 GHz for LAA eNB or Wi-Fi AP.

Path to Gbps speeds
Aggregates licensed and unlicensed spectrum

2x capacity and range
Over Wi-Fi capacity in dense deployments

Seamless and robust user experience
With reliable licensed spectrum anchor

Single unified LTE network
Common management

Fair Wi-Fi coexistence
Fundamental design principle

1 Assumptions: 3GPP LAA evaluation model based on TR 36.889, two operators, 4 small-cells per operator per macro cell, outdoor, 40 users on same 20 MHz channel in 5 GHz, both uplink and downlink in 5 GHz, 3GPP Bursty traffic model 3 with 1MB file, LWA using 802.11ac, DL 2x2 MIMO (no MU-MIMO), 24dBm + 3dBi Tx power in 5 GHz for LAA eNB or Wi-Fi AP.
Scaling to connect the Internet of Things

<table>
<thead>
<tr>
<th></th>
<th>LTE Advanced (Today+)</th>
<th>LTE Cat-1</th>
<th>eMTC (Cat-M1)</th>
<th>NB-IOT (Cat-M2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;10 Mbps</td>
<td>Up to 10 Mbps</td>
<td>Up to 1 Mbps</td>
<td>10s of kbps to 100s of kbps</td>
</tr>
<tr>
<td></td>
<td>n x 20 MHz</td>
<td>20 MHz</td>
<td>1.4 MHz narrowband</td>
<td>180 kHz narrowband</td>
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</table>

LTE Advanced (Today+)

- Mobile
- Video security
- Wearables
- Object Tracking
- Utility metering
- Environment monitoring
- Connected car
- Energy Management
- Connected healthcare
- City infrastructure
- Smart buildings

LTE IoT (Release 13+)

- Significantly widening the range of enterprise and consumer use cases
Our 5G vision: a unifying connectivity fabric

Enhanced mobile broadband
- Multi-Gbps data rates
- High capacity
- Deep awareness

Higher reliability services
- Lower latency
- Higher reliability
- Higher availability
- Stronger security

Massive Internet of Things
- Lower cost
- Lower energy
- Deeper coverage
- Higher density

Unified design for all spectrum types and bands from below 1GHz to mmWave
Scalable across a broad variation of requirements

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

- **Wide area**

- **Internet of Things**

- **Higher-reliability control**

- **Enhanced mobile broadband**

- **Enhanced capacity**
  - 10 Tbps per sq. km

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

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

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

- **Higher density**
  - 1 million nodes per sq. km

- **Enhanced capacity**
  - 10 Tbps per sq. km

- **Stronger security**
  - Used in health/government/financial applications

- **Higher reliability**
  - > 99.999% packet success rate

- **Lower latency**
  - As low as 1 millisecond

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

- **Better awareness**
  - Discovery and optimization

*This presentation addresses potential use cases and potential characteristics of 5G technology. These slides are not intended to reflect a commitment to the characteristics or commercialization of any product or service of Qualcomm Technologies, Inc. or its affiliates.*
Diverse spectrum types and bands
From narrowband to ultra-wideband, TDD & FDD

<table>
<thead>
<tr>
<th>Licensed Spectrum</th>
<th>Shared Licensed Spectrum</th>
<th>Unlicensed Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleared spectrum</td>
<td>Complementary licensing</td>
<td>Multiple technologies</td>
</tr>
<tr>
<td>EXCLUSIVE USE</td>
<td>SHARED EXCLUSIVE USE</td>
<td>SHARED USE</td>
</tr>
</tbody>
</table>

- **Below 1 GHz**: longer range, massive number of things
- **Below 6 GHz**: mobile broadband, higher reliability services
- **Above 6 GHz including mmWave**: for both access and backhaul, shorter range
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

Diverse services and devices
- 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 deployments
- Device-to-device, mesh, relay network topologies
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)
Support diverse spectrum bands and bandwidth

Scalable bandwidth with $2^K$ subcarrier spacing

- Efficiently address range of available bandwidths, from < 1GHz to >6GHz
- Maximum FFT size, e.g., 4096, leveraged across bands and bandwidths
- Natural scaling of CP with subcarrier spacing
- Address coherence bandwidth and delay spread for different bands & deployments
- Improve processing timeline by front load control/pilot with small symbol granularity for fast HARQ turn-around

Example usage models and channel bandwidths
Support diverse latency and QoS requirements

Scalable TTI and numerology

- $2^N$ TTI per 1 ms
  - Combination with $2^K$ scalable subcarrier spacing allows nesting of smaller TTI numerologies into larger ones with guaranteed periodic overlap of control
  - Other TTI durations via bundling is possible

- Symbol duration = $2^{-M}$ ms
  - Allows finest possible granularity with TTIs scaling down to single symbol
  - Benefits low-latency in larger delay spread environments
  - Numerology multiplexing further simplified due to alignment every $2^M$ symbols
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\(^1\)

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

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

Blank subcarriers

Blank subframes

D2D

Multicast

WAN

Scalable TTI

Scalable numerology

1 Nominal 5G access to be designed such that it is capable to sustain puncturing from higher-reliability transmission or bursty interference
Natively incorporate advanced wireless technologies

Many technology enablers to meet 5G requirements and services

- Coordinated Spatial Techniques
- Full Self-Configuration
- Hyper dense deployments
- Integrated access and backhaul
- mmWave
- Multicast
- Advanced Receivers
- Massive MIMO
- More energy efficient, lower cost IoT communications
- Multi-hop & D2D communications
- Low latency & more-reliable communication
- Beamforming
- V2X

Across diverse spectrum bands and types
Massive MIMO at 4 GHz allows reuse of existing sites
Leverage higher spectrum band using same sites and same transmit power

Macro site
1.7 km inter-site distance
46 dBm transmit power

Significant Capacity Gain
Average Cell Throughput = 808 Mbps in 80 MHz

Significant Gain in Cell Edge User Throughput

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, 24x Massive MIMO
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
lower cost, lower power devices
Making mmWave a reality for mobile

Qualcomm Technologies, Inc. is setting the path to 5G mmWave

60 GHz chipset commercial today for mobile devices

Developing robust 5G mmWave for enhanced mobile broadband

Qualcomm® VIVE™ 802.11ad technology with a 32-antenna array element

28 GHz outdoor example with ~150m dense urban LOS and NLOS coverage using directional beamforming

Qualcomm VIVE is a product of Qualcomm Atheros, Inc.;
^ Based on Qualcomm Technologies Inc. simulations

Manhattan 3D map
Results from ray-tracing

0.705 inch

0.28 inch
5G standardization for 2020 launch

Note: Estimated commercial dates; \(^1\) Forward compatibility with R16 and beyond
Multi-connectivity across bands & technologies
4G+5G multi-connectivity improves coverage and mobility

- 4G & 5G macro coverage
- Simultaneous connectivity across 5G, 4G and Wi-Fi
- 4G & 5G small cell coverage
- 5G carrier aggregation with integrated MAC across sub-6GHz & above 6GHz

Leverage 4G investments to enable phased 5G rollout
Designing a unified platform for the next decade & beyond

The 5G Unified Air Interface is the foundation
Optimized OFDM-based waveforms under a flexible framework that can scale to support diverse requirements

Also, leveraging a multi-connectivity framework that makes full use of 4G LTE and Wi-Fi investments

And delivering a flexible network architecture for dynamic creation of tailored services
5G: From Concept to Reality

May 23, 2016
Arun Ghosh
Director Advanced Wireless Technology Group
AT&T Labs
Key Drivers to 5G

- Massive Connectivity
- Throughput & Capacity
- Latency
- 100x Traffic
- >100 Mbps Everywhere
- 4K Video
- Augmented Reality
- Cloud Computing
- Industrial Automation
- V2V
- IoT
- Sensor Network
- Smart Grid
- Healthcare
- Unlicensed mmWave Access
- WiFi
- Pico Sub 6GHz
- Macro Sub 6GHz
- Pico mmWave
- 5G
- 4G
- 1/10
- 1000
- 1000
- 1000
Key Enablers for 5G

**Multi-Antenna**
- Massive MIMO
- Active Antenna
- Multiple antenna models
- MU centric

**Densification**
- Self-Backhaul
- Adapts to Transport Requirements
- Energy Efficiency

**Forward Compatible**
- Accommodate new numerology
- Accommodate new frame structure
- Use case specific PHY

**SDN/NFV**
- More open interfaces than LTE
- Separation of control and user plane

**Massive Connectivity**
- Rel 13 provides a IoT starting point
- Enable future new service classes
- Asynchronous massive connectivity
Standardization Aspects of 5G RAT
Standards and Trial Activity Timeline

- **2016**
  - 3GPP Activity

- **2017**
  - SI

- **2018**
  - WI Phase 1
  - WI Phase 2

- **2019**
  - Experimental Testbed Multi-Phases
  - Friendly User Trial
  - Pilots

- **2020**
  - Rel 17+
Key Components of NR Currently in Standardization

Currently being discussed in 3GPP SI
Well understood options/choices

Very critical to design these components the right way to have a design that will be future proof (scope of this presentation)
Forward Looking Design

Flexible UE Specific Numerology

Wide Subcarrier (emBB)
Narrow Subcarrier (mMTC)
Large CP (Broadcast)

Sub-Band filtering/windowing is used to mitigate the interference between flexible subcarriers

Self Contained Sub-Frames

Each transaction (DL/UL data or measurement) is contained within a sub-frame
MIMO Framework

**LTE Rel 10**
- 8 Tx
- Fixed codebook
- Azimuth beamforming
- SU-MIMO Feedback
- Explicit RS

**LTE Rel 13 (FD-MIMO)**
- 16 Tx
- Reconfigurable codebook
- Azimuth + Elevation beamforming
- SU-MIMO Feedback
- Explicit RS (separable in V and H)

**NR Rel 15**
- Large number of Tx (128 – 256)
- Hybrid-beamforming
- Distributed MIMO
- Programmable codebook
- New feedback mechanism (analog)?
- Azimuth + Elevation beamforming
- MU-MIMO feedback
- Scalable and hierarchical RS and beamforming design
Ultra-Dense Self-Backhaul (in-band and out-of-band)

- Simplifies transport and increases placement flexibility for ultra-scalable density
- mmWave high resolution beamforming provides a natural isolation of backhaul and access
- Should allow for fast switching and re-routing to mitigate dynamic blocking in mmWave
- L1 design (numerology, RS density, frame structure) can be different for access and backhaul

- Multi-hop multi-stage scheduling and QoS control
- Fast (L1 or L2) based switching to support concept such as UE centric virtual cell
- Flow-control on each hop
- Shared cell ID or separate cell ID

Is self-backhauling the same as relays???
Network Architecture and NFV Readiness

- Future proof design (flexible numerology and self contained frame structure)
- Minimize transmission of continuous signal and deliver most signal in a UE specific context
- No predefined timing relationship in the protocol (elastic design for flexible transport capability)
- Hierarchical RAN architecture
eLTE and NR Comparison

- NR is a non-backwards compatible 5G RAT that covers from 600MHz to 100GHz
- LTE will continue to evolve as well (eLTE)
  - New features and new interface to the 5G packet core

<table>
<thead>
<tr>
<th>Latency</th>
<th>eLTE 5 msec</th>
<th>5G 1 msec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>eLTE 20MHz</td>
<td>5G &gt;100MHz</td>
</tr>
<tr>
<td>Connectionless support</td>
<td>eLTE: No</td>
<td>5G: Yes</td>
</tr>
<tr>
<td>L1 Numerology</td>
<td>eLTE: fixed</td>
<td>5G: flexible</td>
</tr>
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</table>

- Should support UE (or use case) specific L1 (network slicing)
- Should allow for asynchronous UL access (for massive IoT)
- Should allow for arbitrary combination of non-contiguous spectrum in L1
Trials and Testbed Activities
AT&T 5G Testbed Development

Planning + Spectrum

2016

- Evaluate very basic components of 5G RAT e.g. hybrid beamforming, mmWave, link adaptation & mobility
- Test simple application such as 4K HD video

2017

- Evaluate more complex components such as dynamic TDD, self-backhauling, coordination, CoMP, handoff
- Test QoS based video and other high bandwidth services

- Evaluate 4G/5G co-existence and spectrum sharing, dual connectivity
- Test new classes of applications such as AR/VR, MEC based services, V2X

macro
15GHz + 28GHz

macro + pico
28GHz

macro + pico
mmWave + sub 6GHz