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5G systems design across services

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5G to meet significantly expanding connectivity needs
Building on the transformation started in 4G LTE

- **Connecting**
  - New industries and devices

- **Enabling**
  - New services

- **Empowering**
  - New user experiences

**Scalable**
To an extreme variation of requirements

**Uniform Experience**
Improved user experiences with new ways of connecting

**Unified**
Across diverse spectrum types/bands, services and deployments
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

5G
Scalable across a broad variation of requirements

- **Wide area Internet of Things**
- **Higher-reliability control**
- **Enhanced mobile broadband**

**Deeper coverage**
To reach challenging locations

- **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

- **Better awareness**
  Discovery and optimization

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

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

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

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

Based on target requirements for the envisioned 5G use cases
In parallel: driving 4G and 5G to their fullest potential

Expanding and evolving LTE Advanced – setting the path to 5G

5G
A new much more capable 5G platform for low and high (above 6Ghz) spectrum
• Enable wide range of new services and lower cost deployment and operation
• For new spectrum available beyond 2020, including legacy re-farming

4G
LTE
LTE Advanced

Backward-compatible evolution beyond Rel-13
• Fully leverage LTE spectrum and investments
• For new spectrum opportunities available before 2020

2010
~2020
2030
Multi-connectivity across bands & technologies

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

Leverage 4G investments to enable phased 5G rollout
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
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

5G Unified Air Interface
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)
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

1 Compared to LTE's 8 HARQ interlaces

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

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\(^1\)
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 puncturing¹

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

Blank subcarriers

Blank subframes

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

Outdoor and macro coverage
FDD/TDD < 3 GHz
Sub-carrier spacing = $N$ (extended cyclic prefix)
20MHz

Outdoor and small cell
TDD > 3 GHz
Sub-carrier spacing = $2N$ (normal cyclic prefix)
80MHz

Indoor wideband
TDD e.g. 5 GHz (Unlicensed)
Sub-carrier spacing = $8N$
160MHz bandwidth

mmWave
TDD e.g. 28 GHz
Sub-carrier spacing = $16N$
500MHz bandwidth

Numerology multiplexing
With flexible guard bands (FG)

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

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**User Throughputs**

- 2x4, 20 MHz @ 2 GHz
- 2x4, 80 MHz @ 4 GHz
- 24x4, 80 MHz@ 4 GHz

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

<table>
<thead>
<tr>
<th>Antenna configuration</th>
<th>Bandwidth</th>
<th>Spectrum band</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2x4</td>
<td>2x4</td>
</tr>
<tr>
<td></td>
<td>20 MHz</td>
<td>80 MHz</td>
</tr>
<tr>
<td></td>
<td>2 GHz</td>
<td>4 GHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cell Edge UE Throughputs (Mbps)</th>
<th>2.1</th>
<th>5.7</th>
<th>22.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Cell 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>

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Source: Qualcomm simulations; Macro-cell with 17km inter-site distance, 46 dBm Tx power at base station, 20MHz@2GHz and 80MHz@4GHz BW TDD, 24x Massive MIMO. Using 5-pertantile 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
Making mmWave a reality for mobile

60 GHz chipset commercial today
For mobile devices, notebooks and access points

Qualcomm® VIVE™ 802.11ad technology for Qualcomm® Snapdragon™ 810 processor
operates in 60 GHz band with a 32-antenna array element

Qualcomm VIVE is a product of Qualcomm Atheros, Inc.; Qualcomm Snapdragon is a product of Qualcomm Technologies, Inc.
Outdoor propagation measurements

Path loss = 128dB, Azimuth = 50°
(20 dB Horn antenna pointed towards the LOS direction)

Path loss = 142dB
Azimuth = 240°
(20 dB Horn antenna pointed away from the LOS direction)

- Directional RMS delay spread not necessarily small for alternate (NLOS) paths → Important when the LOS path is blocked
- Delay spread not in the main lobe can be much larger than in the main lobe and also needs to be addressed at least during acquisition
Different propagation characteristics across sub-6 GHz & mmWave

Key takeaways from measurements

- Outdoor path loss (media loss) at 29GHz is ~20% higher than at 2.9GHz*, but generally similar in macro-features.
- Delay spread at 29GHz is higher than at 2.9GHz, but no direct correspondence between carrier frequency and delay spread (radar cross-section effect).
- RMS delay spread around 200-300 ns in outdoor and < 100 ns in indoor settings.
- Small objects contribute as incidental reflectors much more at 29GHz than at 2.9GHz.
- Small objects in boresight affect propagation at 29GHz more than at 2.9GHz due to easier diffraction around the objects at lower frequency.
- Delay spread seen with high gain directional antennas can be larger than with omni-directional antennas; using directional antenna does not inherently reduce the delay spread.

* Path loss (media loss) is referenced to 1m, i.e. total loss from a transmitter antenna to a receiver antenna is PL(1m)+PL. So defined path loss in free space is frequency independent.
Residential home measurements
Penetration loss of exterior residential walls

• Larger loss for exterior walls with increased frequency attributed to strand board construction → much smaller loss at high frequencies for plywood based sheathing
• For interior walls, median penetration loss is smaller and was less than 3dB in most measurements

Note: Values in red indicate the 50th percentile penetration loss for the bands

1. Loss averaged over specified frequency ranges
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

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

Mobility zone (area of tightly coordinated cells)
Serving cluster

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\(^2\)

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\(^1\) 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.
Efficient multiplexing of higher-reliability and nominal traffic

A more flexible design as compared to dedicated higher-reliability resources (e.g. FDM)

Higher-reliability transmission may occur at any time and cannot wait for scheduling

Nominal traffic (with new FEC & HARQ design)

Design such that other traffic can sustain puncturing from higher-reliability transmission

Opportunity for uplink RSMA non-orthogonal access using OFDM waveforms
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.
Thank you

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