Challenges and Design Aspects for 5G Wireless Networks

John Smee, VP Engineering
Qualcomm Technologies, Inc.

Workshop on Emerging Wireless Networks
UCLA Institute for Pure and Applied Mathematics
February 7, 2017
Challenges and Design Aspects for 5G Wireless Networks

Talk Outline

• Background on evolution of cellular wireless networks
• Technical goals and timeline for 5G
• 5G design aspects
  ◦ Air interface overall
  ◦ Mobile broadband
  ◦ Mission critical
  ◦ Massive IOT
  ◦ Shared Spectrum
• Q & A and perspectives on research challenges
Mobile fueled the last 30 years—interconnecting people

1980s
Analog voice
AMPS, NMT, TACS

1990s
Digital voice
D-AMPS, GSM, IS-95 (CDMA)

2000s
Mobile broadband
WCDMA/HSPA+, CDMA2000/EV-DO

2010s
Mobile Internet
LTE, LTE Advanced
Transforming our world through intelligent connected platforms

Last 30 years
Interconnecting people

Next 30 years
Interconnecting their worlds

Utilizing unparalleled systems leadership in connectivity and compute
A unifying connectivity fabric

Always-available, secure cloud access

Enhanced mobile broadband
Mission-critical services
Massive Internet of Things

Unifying connectivity platform for future innovation

Convergence of spectrum types/bands, diverse services, and deployments, with new technologies to enable a robust, future-proof 5G platform
5G will redefine a wide range of industries

A platform for new connected services - existing, emerging and unforeseen

- Immersive entertainment and experiences
- Safer, more autonomous transportation
- Reliable access to remote healthcare
- Improved public safety and security
- Smarter agriculture
- More efficient use of energy/utilities
- More autonomous manufacturing
- Sustainable cities and infrastructure
- Digitized logistics and retail
Adaptable to diverse deployments and topologies

5G will be deployed and managed by a variety of entities

Mobile operator networks provide ubiquitous coverage—the backbone of 5G
Getting the most out of every bit of diverse spectrum

Low bands below 1 GHz: longer range for e.g. mobile broadband and massive IoT
  e.g. 600 MHz, 700 MHz, 850/900 MHz

Mid bands 1 GHz to 6 GHz: wider bandwidths for e.g. eMBB and mission-critical
  e.g. 3.4-3.8 GHz, 3.8-4.2 GHz, 4.4-4.9 GHz

High bands above 24 GHz (mmWave): extreme bandwidths
  e.g. 24.25-27.5 GHz, 27.5-29.5, 37-40, 64-71 GHz

Licensed Spectrum
  Exclusive use

Shared Spectrum
  New shared spectrum paradigms

Unlicensed Spectrum
  Shared use
Scalability to address diverse service and devices

Based on target requirements for the envisioned 5G use cases

- **Ultra-low energy**: 10+ years of battery life
- **Ultra-low complexity**: 10s of bits per second
- **Ultra-high density**: 1 million nodes per Km²
- **Extreme capacity**: 10 Tbps per Km²
- **Extreme data rates**: Multi-Gbps peak rates; 100+ Mbps user experienced rates
- **Massive Internet of Things**

**Deep coverage**
To reach challenging locations

**Mission-critical control**

**Strong security**
e.g. Health / government / financial trusted

**Ultra-high reliability**
<1 out of 100 million packets lost

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

**Ultra-low complexity**
10s of bits per second

**Extreme user mobility**
Or no mobility at all

**Enhanced mobile broadband**

**Deep awareness**
Discovery and optimization
Pioneering new technologies to meet 5G NR requirements

Based on ITU vision for IMT-2020 compared to IMT-advanced
Simplifying 5G deployments with multi-connectivity

Fully leveraging 4G LTE and Wi-Fi investments for a seamless user experience

5G NR radio access designed to utilize LTE anchor for mobility management (non-standalone) or operate stand-alone with new multi-access 5G NextGen Core Network (NGCN)
The path to 5G includes a strong LTE foundation

Note: Estimated commercial dates. Not all features commercialized at the same time.
Continue to evolve LTE in parallel to become a critical part of the 5G Platform

5G NR standardization progressing for 2019 launches

R15 5G Work Items
R16 5G Work Items
R17 + 5G evolution

5G NR R15 launches
5G NR R16 launches

Accelerating 5G NR\(^1\) with trials & early deployments

Gigabit LTE & LTE IoT deployments

Note: Estimated commercial dates. 1 The latest plenary meeting of the 3GPP Technical Specifications Groups (TSG#72) has agreed on a detailed workplan for Release-15; 2 Forward compatibility with R16 and beyond
Challenges and Design Aspects for 5G Wireless Networks

**Talk Outline**

- Background on evolution of cellular wireless networks
- Technical goals and timeline for 5G
- 5G design aspects
  - Air interface overall
  - Mobile broadband
  - Mission critical
  - Massive IOT
  - Shared Spectrum
- Q & A and perspectives on research challenges
OFDM family is the right choice for 5G mobile broadband and beyond

Adapted for scaling to an extreme variations of 5G requirements

Spectral efficiency
Efficient framework for MIMO spatial multiplexing

Low complexity
Low complexity receivers even when scaling to wide bandwidths

Frequency localization
Windowing can effectively minimizes in-band and out-of-band emissions

Lower power consumption
Single-carrier OFDM well suited for efficient uplink transmissions

Asynchronous multiplexing
Co-exist with optimized waveforms and multiple access for wide area IoT

1 Weighted Overlap Add; 2 Such as Resource Spread Multiple Access (RSMA) - more details later in presentation
OFDM with WOLA\(^1\) windowing

Substantially increases frequency localization

PSD of CP-OFDM with WOLA at the transmitter

Key for 5G service multiplexing
Mitigate interference between flexible sub-carriers

OFDM with WOLA windowing
Effectively reduces in-band and out-of-band emissions

Windowed OFDM proven in LTE system today
Alternative OFDM-approaches, such as FBMC and UFMC, add complexity with marginal benefits

\(^1\) Weighted Overlap Add

Source: Qualcomm Research, assuming 12 contiguous data tones, 60 symbols per run, 1000 runs. CP length is set to be roughly 10% of the OFDM symbol length. For Tx-WOLA, raised-cosine edge with rolloff $\alpha \approx 0.078$ is used.
Optimizing for diverse services and deployments

**5G NR Downlink**
Unified downlink design

- Mobile Broadband
- Massive IoT
- Mission-critical

**CP-OFDM\(^1\) + OFDMA**
Also recommended for D2D and inter-cell communications to maximize Tx/Rx design reuse

**5G NR Uplink**
Optimized for different deployments

- **Macro cell**
  - SC-OFDM\(^1\) + SC-FDMA
  - To maximize device energy efficiency

- **Small cell**
  - CP-OFDM\(^1\) + OFDMA
  - To maximize spectral efficiency

**Mission-critical**
- Low energy single-carrier\(^2\)
  - CP-OFDM / SC-OFDM\(^1\)

**Optimized for different services**

**Resource Spread Multiple Access (RSMA)\(^3\)**
Grant-free transmissions efficient for sporadic transfer of small data bursts with asynchronous, non-orthogonal, contention-based access

Download Qualcomm Research whitepaper for detailed analysis:
https://www.qualcomm.com/documents/5g-research-waveform-and-multiple-access-techniques

---

1. With time domain windowing as common in LTE systems today;
2. Such as SC-FDE and GMSK;
3. Mission-critical service may also use OFDMA/SC-FDMA for applications that may be scheduled.
A flexible framework with forward compatibility

Efficiently multiplex envisioned and future 5G services on the same frequency

1. Blank resources may still be utilized, but are designed in a way to not limit future feature introductions;
2. Nominal 5G access to be designed such that it is capable to sustain puncturing from mission-critical transmission or bursty interference

**Forward compatibility**
With support for ‘blank’ resources

**Integrated framework**
That can support diverse deployment scenarios and network topologies

**Mission-critical transmissions**
May occur at any time; design such that other traffic can sustain puncturing

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

**Self-contained integrated subframe**
UL/DL scheduling info, data and acknowledgement in the same sub-frame

**Dynamic uplink/downlink**
Faster switching for more flexible capacity based on traffic conditions
### Scalable numerology with scaling of subcarrier spacing

#### Efficiently address diverse spectrum, deployments and services

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Subcarrier spacing</th>
<th>Example usage models and channel bandwidths</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Outdoor and macro coverage</strong></td>
<td>e.g. 15 kHz</td>
<td></td>
</tr>
<tr>
<td>FDD/TDD &lt;3 GHz</td>
<td>e.g. 1, 5, 10 and 20 MHz</td>
<td></td>
</tr>
<tr>
<td><strong>Outdoor and small cell</strong></td>
<td>e.g. 30 kHz</td>
<td></td>
</tr>
<tr>
<td>TDD &gt; 3 GHz</td>
<td>e.g. 80/100 MHz</td>
<td></td>
</tr>
<tr>
<td><strong>Indoor wideband</strong></td>
<td>e.g. 60 kHz</td>
<td></td>
</tr>
<tr>
<td>TDD e.g. 5 GHz (Unlicensed)</td>
<td>e.g. 160 MHz</td>
<td></td>
</tr>
<tr>
<td><strong>mmWave</strong></td>
<td>e.g. 120 kHz</td>
<td></td>
</tr>
<tr>
<td>TDD e.g. 28 GHz</td>
<td>e.g. 500 MHz</td>
<td></td>
</tr>
</tbody>
</table>
Self-contained integrated subframe design

UL/DL scheduling info, data and acknowledgement in the same sub-frame

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

Add'l headers
Ctrl (Tx)
Data (Tx)
Example: TDD downlink

Guard Period

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

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

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

Faster, more flexible TDD switching and turn around, plus support for new deployment scenarios and forward compatibility
5G NR design innovations across diverse services

Massive IoT
- Low complexity narrowband
- Low power modes for deep sleep
- Efficient signaling
- Grant-free uplink transmissions
- Optimized link budget
- Managed multi-hop mesh

Enhanced Mobile Broadband
- Wider bandwidths
- Mobilizing mmWave
- Shared spectrum
- Device-centric mobility

Mission-Critical Control
- Low-latency with bounded delay
- Efficient multiplexing with nominal traffic
- Grant-free uplink transmissions
- Simultaneous redundant links
- Reliable device-to-device links
- Optimized PHY/pilot/HARQ

• Dynamic, low-latency TDD/FDD
• Massive MIMO
• Advanced channel coding
• Native HetNet and multicast support
5G Enhancing mobile broadband

Extreme throughput
Ultra-low latency
Uniform experience
Massive MIMO is a key enabler for higher spectrum bands
Allows reuse of existing sites and same transmit power at e.g. 4 GHz

- 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, 2x4 Massive MIMO
Realizing the mmWave opportunity for mobile broadband

**Extreme bandwidth opportunity**
- Extreme bandwidths capable of Multi-Gbps data rates
- Flexible deployments (integrated access/backhaul)
- High capacity with dense spatial reuse

**Mobilizing mmWave challenge**
- Robustness due to high path loss and susceptibility to blockage
- Device cost/power and RF challenges at mmWave frequencies

---

Learn more at: [www.qualcomm.com/documents/promise-5g-mmwave-how-do-we-make-it-mobile](http://www.qualcomm.com/documents/promise-5g-mmwave-how-do-we-make-it-mobile)
Delivering advanced 5G NR channel coding

ME-LDPC\(^1\) codes more efficient than today’s LTE Turbo codes at higher data rates

- **High Efficiency**
  - Significant gains over LTE Turbo - particularly for large block sizes suitable for MBB

- **Low Complexity**
  - Easily parallelizable decoder scales to achieve high throughput at low complexity

- **Low Latency**
  - Efficient encoding/decoding enables shorter TTI

Designing Polar coding for control channels

---

\(^1\) Multi-Edge Low-Density Parity-Check;
Device-centric mobility management in 5G NR

Control plane improvements to improve energy and overhead efficiency

Edgeless mobility zone
(area of tightly coordinated cells)

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 Minimum system information is broadcast periodically, other system information available on demand; may dynamically revert to broadcast system info when needed, e.g. system info changes
Connecting massive Internet of Things

Power efficient
Low complexity
Long range
5G NR will bring new capabilities for the massive IoT

NB-IoT continuing to evolve beyond Release 13—foundation of Narrowband 5G

Scales down LTE to address the broadest range of IoT use cases

Optimizes to lowest cost/power for delay-tolerant, low-throughput IoT use cases; evolving with new features such as VoLTE and positioning support

3GPP 5G NR further enhances massive IoT with new capabilities such as RSMA\textsuperscript{1} & multi-hop mesh

\textsuperscript{1} Resource Spread Multiple Access
Non-orthogonal RSMA for efficient IoT communications

Characterized by small data bursts in 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 massive # of things

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, in e.g. 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.
Enabling mission-critical services

- High reliability
- Ultra-low latency
- High availability
5G NR will enable new mission-critical control services
A platform for tomorrow’s more autonomous world

- 1ms e2e latency
  Faster, more flexible frame structure; also new non-orthogonal uplink access

- Ultra-high reliability
  Ultra-reliable transmissions that can be time multiplexed with nominal traffic through puncturing

- Ultra-high availability
  Simultaneous links to both 5G and LTE for failure tolerance and extreme mobility

- Strong e2e security
  Security enhancements to air interface, core network, & service layer across verticals¹

¹ Also exploring alternative roots of trust beyond the SIM card
Efficient mission-critical multiplexing with other services

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

One TTI

Nominal traffic
(with new FEC and HARQ design)

Design such that other traffic can sustain puncturing from mission-critical transmission

Mission-critical transmission
may occur at any time and cannot wait for scheduling

Opportunity for uplink RSMA non-orthogonal access using OFDM waveforms
New 5G design allows for optimal trade-offs

E.g. leveraging wider bandwidths to offset mission-critical capacity reductions

Latency vs. capacity...

Reliability vs. capacity...

But wider bandwidth can offset reductions

Mission-critical capacity

Latency

Mission-critical capacity

e.g. 1e-2 BLER

Example: 2X bandwidth for 3x capacity gain

Mission-critical capacity

Latency

e.g. 1e-4 BLER

1 Low BLER Block Error Rate, required to achieve high-reliability with a hard delay bound

2 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 Shared Spectrum
5G NR will natively support all different spectrum types

NR shared spectrum will support new shared spectrum paradigms

- **Licensed Spectrum**
  - Exclusive use

- **Shared Spectrum**
  - New shared spectrum paradigms

- **Unlicensed Spectrum**
  - Shared use

**High bands above 24 GHz (mmWave)**
- Extreme bandwidths

**Mid bands 1GHz to 6 GHz**
- Wider bandwidths for e.g. eMBB and mission-critical

**Low bands below 1 GHz**
- Longer range for e.g. mobile broadband and massive IOT
The FCC is driving key spectrum initiatives to enable 5G
Across low-band, mid-band, and high-band including mmWave

- **Low-band**
  - Broadcast Incentive Auction
  - First stage auction opened up 126 MHz in 600 MHz band
  - Spectrum availability timing aligns with 5G

- **Mid-band**
  - Citizens Broadband Radio Service
  - Opening up 150 MHz in 3.5 GHz band
  - 3-tier spectrum sharing with incumbents, PAL\(^1\), and GAA\(^2\)
  - CBRS Alliance formally launched to drive an LTE-based ecosystem

- **High-band**
  - Spectrum Frontiers Ruling\(^3\)
  - Opening up 11 GHz in multiple mmWave bands
  - 70% of newly opened spectrum is shared or unlicensed
  - Unanimously approved by FCC with additional candidate bands identified for IMT-2020

---

1 Priority Access Licenses to be auctioned; 2 General Authorized Access; 3 FCC ruling FCC 16-89 on 7/14/2016 allocated 3.25 MHz of licensed spectrum and 7.6 MHz of shared/unlicensed spectrum.
Shared/unlicensed spectrum is important for 5G

Unlocking more spectrum

Shared spectrum can unlock spectrum that is lightly used by incumbents

High spectrum utilization

Spectrum sharing has the potential to increase spectrum utilization

A lot of spectrum may be shared/unlicensed

FCC recent decision on high-band spectrum included a significant portion of shared/unlicensed

---

1) FCC ruling FCC 16-89 on 7/14/2016 allocated 3.25 MHz of licensed spectrum and 7.6 MHz of shared/unlicensed spectrum.
Pioneering 5G shared spectrum today

Building on LTE-U/LAA, LWA, CBRS/LSA and MulteFire

5G New Radio (NR)
Sub 6Ghz + mmWave

5G

Spectrum aggregation
- LTE-U / LAA
- NR based LAA

Technology aggregation
- LWA (LTE + Wi-Fi)
- Multi-connectivity: NR, LTE, Wi-Fi

Tiered sharing (incumbents)
- CBRS, LSA
- NR based tiered sharing

Standalone unlicensed
- MulteFire
- NR based MulteFire

LTE Advanced Pro
Spectrum below 6 GHz

1) Licensed-Assisted Access (LAA), LTE Wi-Fi Link Aggregation (LWA), Citizen Broadband Radio Service (CBRS), Licensed Shared Access (LSA)
LTE is the high performance option in unlicensed spectrum

### LAA ~2X coverage outdoors compared to Wi-Fi

<table>
<thead>
<tr>
<th>Mbps</th>
<th>Wi-Fi</th>
<th>LAA</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;10</td>
<td>24% of route</td>
<td>60% of route</td>
<td>x2.5</td>
</tr>
<tr>
<td>&gt;1</td>
<td>39% of route</td>
<td>71% of route</td>
<td>x1.8</td>
</tr>
<tr>
<td>&gt;0</td>
<td>47% of route</td>
<td>82% of route</td>
<td>x1.7</td>
</tr>
</tbody>
</table>

World’s first over-the-air LAA trial in Nov. 2015 together with Deutsche Telekom

### MulteFire by itself offers >2X capacity over Wi-Fi

- Median throughput gain
- 2X gain
- Wi-Fi only baseline

---

1) Single small cell, LAA based on 3GPP release 13; LWA using 802.11ac; LTE on 10 MHz channel in 2600 MHz licensed spectrum with 1W transmit power; terminal transmit power 0.2W, mobility speed 6-8 mph; 2) Based on geo-binned measurements over test route; 3) Indoor, single 20 MHz channel in 5 GHz; 80% 20% traffic split between down- and uplink, bursty traffic generated with 4 Mb files arriving with exponential inter arrival times, high traffic load with buffer occupancy at 50% in downlink and 20% in uplink for Wi-Fi only baseline, 4 APs per operator, 2 operators, office building size 120m x 50m, propagation model 3GPP indoor hotspot (InH), Wi-Fi is 802.11ac, MIMO 2x2, no MU-MIMO
CBRS introduces a 3-tiered shared spectrum

Enables to open up 150 MHz spectrum while incumbents are still using it

Tier 1
Incumbents

Tier 2
Priority Access Licenses (PAL)

- Incumbents are protected from interference from PAL and GAA
- PAL has priority over GAA, licensed via auction, 10 MHz blocks, up to 7 licenses

Tier 3
General Authorized Access (GAA)

- GAA can use any spectrum not used, yields to PAL and incumbents

1) Wireless ISP transitioning from incumbent to PAL/GAA after 5 years; 2) Fixed satellite service - receiving only; 3) Citizen Broadband Radio Service (CBRS)
MulteFire helps GAA scale to multiple deployments

Multiple deployments share a wide channel—better spectrum utilization & peak-rate

Highest spectrum efficiency with one LTE-TDD deployment

Multiple LTE-TDD deployments with reduced channel size, spectrum may become underutilized

MulteFire brings trunking efficiency from sharing a wide channel to improve spectrum utilization

1) Example with one deployment (#1) with a high traffic load and two deployments (#2 and #3) with medium traffic loads; 2) Spectrum cannot always be evenly split; 3) Trunking benefits depend on relative traffic loads.
Designed to take advantage of new sharing paradigms

Flexible radio
- Scalable numerology: narrow-to-wideband
- Spectrum from sub-6GHz to mmWave
- Self-contained integrated sub-frames

Flexible unlicensed operation
- Unlicensed aggregation with licensed anchor
- Multi-connectivity: NR, LTE and/or Wi-Fi
- Stand-alone in unlicensed

Flexible spectrum sharing
- Dynamic sharing between deployments, technologies, priority tiers, etc.
- Enhanced spatial separation with mmWave
- Solutions for new spectrum sharing paradigms

5G NR
Shared spectrum

New sharing paradigms

LTE-U / LAA
LWA
MulteFire
CBRS / LSA
Shared spectrum—valuable for wide range of deployments

Extreme bandwidth by aggregating spectrum
Mobile operators provide extreme bandwidths by aggregating shared/unlicensed spectrum with licensed spectrum

Enhanced local broadband
Shared/unlicensed spectrum enables entities without licensed spectrum to offer enhanced mobile broadband

Internet of Things verticals
Shared/unlicensed spectrum opens up opportunity to service different IoT verticals, e.g., a private IoT network
Talk Outline

• Background on evolution of cellular wireless networks
• Technical goals and timeline for 5G
• 5G design aspects
  ◦ Air interface overall
  ◦ Mobile broadband
  ◦ Mission critical
  ◦ Massive IOT
  ◦ Shared Spectrum
• Q & A and perspectives on research challenges
5G requirements and design across topologies

- Hyper dense deployments
- Integrated access and backhaul
- Coordinated spatial techniques
- New shared spectrum paradigms
- Mobilizing mmWave
- Multi-connectivity
- Beam forming
- Redundant links
- Multicast
- Advanced receivers

New levels of capability and efficiency

- 10x experienced throughput
- 10x decrease in end-to-end latency
- 10x connection density
- 3x spectrum efficiency
- 100x traffic capacity
- 100x network efficiency

Based on ITU vision for IMT-2020 compared to IMT-advanced
Thank you

Follow us on:  

For more information, visit us at:  
www.qualcomm.com & www.qualcomm.com/blog

Nothing in these materials is an offer to sell any of the components or devices referenced herein.

©2013, 2015 Qualcomm Technologies, Inc. and/or its affiliated companies. All Rights Reserved.

Qualcomm is a trademark of Qualcomm Incorporated, registered in the United States and other countries. Other products and brand names may be trademarks or registered trademarks of their respective owners.

References in this presentation to “Qualcomm” may mean Qualcomm Incorporated, Qualcomm Technologies, Inc., and/or other subsidiaries or business units within the Qualcomm corporate structure, as applicable.

Qualcomm Incorporated includes Qualcomm’s licensing business, QTL, and the vast majority of its patent portfolio. Qualcomm Technologies, Inc., a wholly-owned subsidiary of Qualcomm Incorporated, operates, along with its subsidiaries, substantially all of Qualcomm’s engineering, research and development functions, and substantially all of its product and services businesses, including its semiconductor business, QCT.