June 2014

The Evolution of Mobile Technologies:
1G ↔ 2G ↔ 3G ↔ 4G LTE

QUALCOMM
The mobile experience is expanding everywhere

**Billions of Mobile Connections**

- ~7 Billion
  Mobile connections, almost as many as people on Earth

- ~25 Billion
  Interconnected devices forecast in 2020

**Billions of Mobile Experiences**

- >100 Billion
  App downloads completed in 2013

- ~270 Billion
  App downloads expected in 2017

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1 Source: GSMA Intelligence, Apr. '14; 2 Source: Machina Research, '13; 3 Source: Gartner, Sep. '13
Mobile is an amazing technical achievement

**Mind-blowing Performance**
with processing power greater than the most advanced super computers of the early 1990s¹

**Jaw-dropping Graphics**
with capability to process several thousand megapixels per second²

**High Quality Multimedia²**
4K UltraHD video player/recorder
HD gaming console
5.1/7.1 surround sound system
High resolution digital camera

**Reliable Connectivity**
overcoming signal loss resulting in receiving signal 100 trillion times weaker than when it originated³

**Broadband Speeds**
with blazing fast data rates capable of 300+ Mbps⁴

**Long Battery Life**
with ability to power all these amazing experiences with less energy than it takes to power a light bulb for 15 minutes⁵

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¹ Source: Charlie White, Sep '13 & giffgaff.com, Sep '13; ² Based on latest Qualcomm® Snapdragon™ 800 series processors; ³ Based on >140 dB path loss typical in mobile; ⁴ Based on peak data rates for LTE Advanced; ⁵ Based on >2,000 mAh smartphone battery and >60W light-bulb
Connectivity is the foundation of a great mobile experience

**Connect Reliable**
Talk and browse without interruption with more bars in more places

**Connect Real-Time**
Get instant access to content with less delay for “always-on” experience

**Connect Fast**
Stream, surf, upload, and download with fast, predictable data rates

**Connect On-the-Go**
Talk and browse with seamless mobility anywhere you get a signal

**Connect Longer**
Go longer without plugging in with improved battery efficiency

**Delivering rich mobile broadband experiences**
Powered by evolving mobile technologies for better experiences

- **Mobile 1G**: AMPS, NMT, TACS
- **Mobile 2G**: D-AMPS, GSM/GPRS, cdmaOne
- **Mobile 3G**: CDMA2000/EV-DO, WCDMA/HSPA+, TD-SCDMA
- **Mobile 4G LTE**: LTE, LTE Advanced

<table>
<thead>
<tr>
<th>N/A</th>
<th>&lt;0.5 Mbps&lt;sup&gt;1&lt;/sup&gt;</th>
<th>63+ Mbps&lt;sup&gt;2&lt;/sup&gt;</th>
<th>300+ Mbps&lt;sup&gt;3&lt;/sup&gt;</th>
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<tbody>
<tr>
<td>Analog Voice</td>
<td>Digital Voice + Simple Data</td>
<td>Mobile Broadband</td>
<td>Faster and Better</td>
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</table>

<sup>1</sup> Peak data rate for GSM/GPRS, latest Evolved EDGE has peak DL data rates capable of up to 12 Mbps; <sup>2</sup> Peak data rate for HSPA+ DL 3-carrier CA; HSPA+ specification includes additional potential CA + use of multiple antennas, but no announcements to date; <sup>3</sup> Peak data rate for LTE Advanced Cat 6 with 20 + 20 MHz DL CA; LTE specification includes additional potential CA + additional use of multiple antennas, but no announcements to date
Evolving mobile technologies deliver great mobile experiences

Appreciating the magic of mobile requires understanding the evolution from 1G to 4G LTE

1. 1G established seamless mobile connectivity introducing mobile voice services

2. 2G digital wireless technologies increased voice capacity delivering mobile to the masses

3. 3G optimized mobile for data enabling mobile broadband services, and is evolving for faster and better connectivity

4. 4G LTE delivers more capacity for faster and better mobile broadband experiences, and is also expanding in to new frontiers

5. Qualcomm has been at the forefront of this evolution, pushing wireless boundaries to enable the best mobile experiences
Mobile 1G established the foundation of mobile

1. **Licensed Spectrum**
   - Cleared spectrum for exclusive use by mobile technologies
   - Operator-deployed **base stations** provide access for subscribers

2. **Frequency Reuse**
   - Reusing frequencies without interference through geographical separation
   - Neighboring **cells** operate on different frequencies to avoid interference

3. **Mobile Network**
   - Coordinated network for seamless access and seamless mobility
   - Integrated, transparent **backhaul network** provides seamless access
   - Integrated, transparent **PSTN** (landline)
Mobile 1G was amazing, but limited

- Requires large gap of spectrum between users to avoid interference
- Support for only 1 user per channel

Spectrum is a finite resource like land; mobile spectrum is extremely valuable land (e.g., beach-front property)

Radio channels are like roads built on this land to deliver voice services to users

Analog voice consumed channel – 1 call per channel
1G analog voice was amazing, but limited

Limited Capacity
Analog transmissions are inefficient at using limited spectrum

Frequency Division Multiple Access (FDMA)*
Large frequency gap required between users to avoid interference

Limited Scalability
Analog devices are large/heavy, power inefficient, and high cost

*Example shown based on AMPS 1G technology
Mobile 2G digital technologies increased voice capacity
Delivering mobile voice services to the masses – more people, in more places

Mobile 1G
AMPS, NMT, TACS

Foundation of Mobile
Seamless Mobility

Mobile 2G
d-AMPS, GSM/GPRS,
cdmaOne

Mobile for the Masses
More Voice Capacity

1010110110011000
Early Mobile 2G technologies enabled more users per channel

- Digital voice compressed into smaller “packages”
- STILL required large gap of spectrum between users to avoid interference
- Supported >1 user per channel
- Rigid delivery schedule whether or not the user is actively talking
Mobile 2G digital wireless technologies enabled more users

Initial 2G technologies (D-AMPS, GSM) based on TDMA

More Voice Capacity
Digital transmissions enable compressed voice and multiplexing multiple users per channel

Scalable Technology
Digital components cost/weight far less plus deliver more secure signal

Time Division Multiple Access (TDMA)
Allows multiple users per radio channel with each user talking one at a time

Uncompressed Voice Signal
64 kb per second

Compressed Voice Signal
8 kb per second

>1 user per radio channel

30 kHz

Voice Encoder (Vocoder)

(pocket-sized)
Different Mobile 2G TDMA techniques were standardized

Mobile 1G (Analog)
AMPS, NMT, TACS

Mobile 2G (Digital)
D-AMPS
- Standardized as IS-54 by TIA in 1992
- Mainly in North America
- No longer utilized

Mobile 2G (Digital)
GSM
- Standardized by ETSI in 1990 (phase 1)
- Initiated in Europe
- Still widely used today (>4B connections WW\(^1\))
- Simple data services with GPRS

1 Source: GSMA Intelligence, May ’14
TDMA still required large frequency gaps to reduce interference

Also required potentially unreliable “hard” handoffs
Switch channels between adjacent cells – potential for dropped calls
CDMA utilizes all the available spectrum to support more users

- Utilize all available spectrum
- Ability to support many more users (>10x 1G) with the same spectrum
- No rigid delivery schedule – delivery truck can take advantage of when user is not talking to support more callers
- Each user information coded with a unique code
Qualcomm solved the seemingly impossible wireless challenge
CDMA enables users to share the same frequency and communicate at the same time

**Code Division Multiple Access (CDMA)**
Multiple users can talk at the same time using different languages (“codes”)
Qualcomm solved complex challenges to commercialize CDMA

1. Near-Far Power Challenge
   - Users close to the tower overpower the uplink signal minimizing capacity on the shared channel
   - **Solution:** Continuous control of transmit power based on signal strength

2. Cell-Edge Challenge
   - Interference caused by users in close proximity, on the same frequency, and communicating with different towers
   - **Solution:** Users simultaneously communicate with multiple towers at cell edge

3. Multipath Fading Challenge
   - Interference caused by the reception of the same signal over multiple paths resulting in poor signal-to-noise ratio
   - **Solution:** Advanced ("rake") receivers combine energy of multiple signal paths

**Additional benefit of simultaneous connections – more reliable handoffs**

User A
- Up to 1,000,000 X

User B
- Without Power Control
  - Signal Power at Tower
- With Power Control
  - Signal Power at Tower

**Without Power Control**
- Signal Power at Tower

**With Power Control**
- Signal Power at Tower

**Soft (vs. Hard) Handoffs**
CDMA delivered unprecedented voice capacity and much more
Qualcomm efforts lead to new CDMA standard (IS-95) referred to as cdmaOne

**CDMA Benefits**
- Increased voice capacity by several times
- Provided more efficient use of spectrum resources
- Increased battery life in mobile devices
- Better security with CDMA encoding

**Potential Voice Capacity Improvements**

<table>
<thead>
<tr>
<th>Analog 1980s</th>
<th>GSM 1990s</th>
<th>cdmaOne 1990s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference (1x)</td>
<td>~3x</td>
<td>~14x</td>
</tr>
</tbody>
</table>

**CDMA Timeline**

- **February 1990**
  - First CDMA field trial completed by Qualcomm and NYNEX
- **March 1992**
  - Standards committee formed in Telecommunications Industry Association
- **May 1995**
  - IS-95 revision A (cdmaOne) released
- **December 1995**
  - First commercial deployment
- **December 1999**
  - cdmaOne subscribers pass 50 million worldwide (>80 operators in >30 countries)

**CDMA is the foundation for Mobile 3G technologies**

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1 Approximate total number of subscribers serviced within same spectrum based on AMPS (1G), GSM and cdmaOne technology commercial deployed in 1990s; 2 Source: CDG, [www.cdg.org](http://www.cdg.org)
CDMA established the foundation for 3G technologies
Mobile 3G evolved into two competing standards both based on CDMA

**IS-95 (cdmaOne)**
- Initial CDMA standard from Qualcomm
- May 1995

**CDMA2000**
- Uses 1.25 MHz carrier; easy migration from cdmaONE
- July 2000 (Revision A)

**EV-DO (Evolution-Data Optimized)**
- Optimized data channel for CDMA2000
- October 2000 (Release 0)

**WCDMA (UMTS)**
- Uses 5 MHz carrier; leverages GSM core network
- June 2001 (Release 99)

**HSPA (High Speed Packet Access)**
- Optimized data channel for WCDMA
- June 2004 (Release 5)

Note: ITU IMT-2000 compliant 3G standards included EDGE, TD-SCDMA, and WiMAX; CDMA2000 and WCDMA were the most commercially successful.
Mobile 3G evolved mobile for data
Introducing high-speed internet access for the first time

Mobile 1G
- AMPS, NMT, TACS

Foundation of Mobile Seamless Mobility

Mobile 2G
- D-AMPS, GSM/GPRS, cdmaOne

Mobile for the Masses
More Voice Capacity

Mobile 3G
- CDMA2000/EV-DO, WCDMA/HSPA+, TD-SCDMA

Mobile Broadband
Data Optimized

1980s 1990s 2000s
Mobile voice was amazing, but consumers wanted more

A new, insatiable demand for internet access and data services emerges

**Broadband Internet**
Consumers introduced to broadband internet access in the home/office

**The Smartphone**
Amazing innovations in device technology resulted in the era of the smartphone

**Mobile Everywhere**

Average mobile subscriptions per 100 people\(^1\)

\[ \begin{array}{ccc}
2 & \rightarrow & 39 & \rightarrow & 92 \\
1990 & & 2000 & & 2010
\end{array} \]

Thanks to 2G technologies, more and more people had a mobile subscription

\(^1\) Source: Worldbank.org for United States
EV-DO optimized 3G for data enabling mobile broadband

Data Enabled
Simple Data Services

Mobile 2G
<0.5 Mbps¹

Data Optimized
Mobile Broadband

CDMA2000/EV-DO
14.7 Mbps²

Based on peak data rate – GSM/GPRS
² Based on peak data rate for downlink EV-DO Rev. B

1 Based on peak data rate – GSM/GPRS
² Based on peak data rate for downlink EV-DO Rev. B
Qualcomm pioneered EV-DO introducing mobile broadband

**Mobile 2G**
Data Enabled

- Voice
- Voice
- Voice
- Voice
- Voice
- Voice
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- Voice
- Data
- Data

1.25 MHz

Data shared with voice-optimized radio channel

**CDMA2000/EV-DO**
Data Optimized

- Voice
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- Data
- Data

1.25 MHz

Introduction of a data-only, data-optimized channel

**CDMA2000**

- Multimedia
- WWW
- Navigation

**EV-DO**

- Apps

- Give all resources to one user at a time (data optimized)

**Simple Data Services**

- Text
- Email
- NEWS Headlines

**Mobile Broadband Services**

- Multimedia
- WWW
- Navigation
- Apps
EV-DO inventions are the foundation to mobile broadband

1. **Data Optimized Channel**
   - Splits channel into time intervals enabling a single user to get all the resources at once
   - **Enables richer content**

2. **Adaptive Modulation**
   - Uses higher order modulation to get more bps per Hz for users with good signal quality
   - **Increases peak data rates**

3. **Opportunistic Scheduling**
   - Optimizes channel by scheduling users at the time instances when users have good radio signal conditions (with fairness)
   - **Increases overall capacity**
CDMA2000/EV-DO blazed the trail for WCDMA/HSPA

CDMA2000/EV-DO

1.25 MHz

Data
Give all resources to one user at a time (data optimized)

CDMA2000

EV-DO

WCDMA/HSPA

5 MHz

Data
After voice users served, remaining resources used for data based on same principles as EV-DO
Mobile 3G evolved to HSPA+ and EV-DO Rev. B
Delivering higher data rates, more capacity, and enhanced mobile broadband experiences

**Higher Order Modulation (HOM)**

Introduces 64-QAM enabling 50% more bits per second per Hz (bps/Hz)

Enabling packing 50% more data into packages

**Carrier Aggregation**

Aggregating spectrum enabling increased user and peak data rates

Aggregate channels for higher data rates
3G technologies optimized mobile for data

**EV-DO and HSPA Benefits**
- Delivered achievable throughput >2 Mbps
- Reduced operator cost for data services
- Continuous evolution for enhanced services

**Mobile Broadband Timeline**
- **1999**: Qualcomm introduces EV-DO
- **January 2002**: First EV-DO commercial launch
- **Q4 2004**: 3GPP release 6 with HSPA is published based on WCDMA technology
- **Q1 2007**: EV-DO passes 50 million connections
- **Q108**: HSPA passes 50 million connections
- **June 2008**: First HSPA+ (21 Mbps) commercial launch
- **September 2010**: First DC-HSPA+ (42 Mbps) commercial launch

**Peak Data Rate (Mbps)**
- Mobile 2G: GSM / GPRS (<0.5 Mbps)
- Mobile 3G: CDMA2000 / EV-DO (3.1 Mbps → 14.7 Mbps)
- Mobile 3G: WCDMA / HSPA (14.4 Mbps → 63+ Mbps)

**3G technologies continue to evolve**
Surpassed 2B connections in 2013

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1 Source: CDG (www.cdg.org) and 3GPP (www.3gpp.org); 2 Source: GSMA Intelligence, May ’14
Mobile 4G LTE is evolving to provide more data capacity
Delivering faster and better mobile broadband experiences

Mobile 1G
AMPS, NMT, TACS

Mobile 2G
D-AMPS, GSM/GPRS, cdmaOne

Mobile 3G
CDMA2000/EV-DO, WCDMA/HSPA+, TD-SCDMA

Mobile 4G LTE
LTE, LTE Advanced

Faster and Better Mobile Broadband
More Data Capacity

Foundation of Mobile Seamless Mobility

Mobile for the Masses
More Voice Capacity

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Mobile Broadband
Data Optimized

1980s
1990s
2000s
2010s
Mobile 4G LTE complements 3G to boost data capacity

Multimode 3G/LTE is the foundation for successful 4G LTE

4G LTE
Providing more data capacity for richer content and more connections

3G
Enabling a consistent broadband experience outside 4G LTE coverage
Delivering ubiquitous voice services and global roaming

Multimode
LTE FDD/TDD
WCDMA/HSPA+
CDMA2000/EV-DO
TD-SCDMA
GSM/GPRS
Mobile 4G LTE delivers more data capacity

- Flexible support for wider channels supporting more users
- Create spatially separated paths with more antennas
- Aggregate channels for higher data rates
Mobile 4G LTE delivers more data capacity
Download, browse, stream, and game faster than ever with faster and better connectivity

Connect Faster

- **Wider Channels**
  Flexible support for channels up to 20 MHz enabled with OFDMA

- **More Antennas**
  Advanced MIMO techniques to create spatially separated paths; 2x2 MIMO mainstream

- **Carrier Aggregation**
  Aggregate up to 100 MHz for higher data rates – 2 carrier (2C) commercial; 3C announced\(^1\)

Connect Real-time

- **Simplified Core Network**
  All IP network with flattened architecture resulting in less equipment per transmission

- **Low Latencies**
  Optimized response times for both user and control plane improves user experience

\(^1\) As of May 2014
Mobile 4G LTE is the first global standard for mobile broadband

Global LTE network launches

- **279** Launches
- **101** Countries

Large device ecosystem

- **1,563** Devices
- **>100** Vendors

Source: GSA, Mar. '14

**LTE FDD & LTE TDD**

Two modes, common standard, same ecosystem

- **Spectrum 1**
  - **Uplink (UL)**
  - **Downlink (DL)**

- **Spectrum 2**
  - **Uplink (UL)**
  - **Downlink (DL)**

**Frequency Division Duplex (FDD)**
Paired spectrum enables better coverage

**Time Division Duplex (TDD)**
Unpaired spectrum enables asymmetrical DL/UL for more DL capacity
Mobile 3G and 4G technologies continue to evolve to deliver faster and better mobile broadband experiences.
Mobile 3G and 4G LTE continue to evolve

Delivering a faster and better mobile broadband experiences

4G LTE has evolved to LTE Advanced
Providing more data capacity and expanding into new frontiers

3G networks have continued to evolve and improve—so much so some call it 4G
Providing a consistent broadband experience outside LTE coverage
Mobile 3G/4G technologies are evolving for more data capacity

Shannon’s Law

\[ C \approx W \cdot n \cdot \log_2(1 + SNR) \]

**Capacity**  
**Spectrum**  
**Antennas**  
**Signal Quality**

**More Spectrum**
Making the best use of all spectrum types with more licensed spectrum as the top priority, e.g., ASA, ~3.5 GHz, unlicensed spectrum

**More Antennas**
Advanced multiple antenna techniques to create spatially separated data paths, e.g., 4 way receive diversity, 4x4 MIMO

**Interference Mitigation**
Advanced receivers and antenna techniques, e.g., LTE FeICIC/IC, HSPA+ advanced device receiver
LTE Advanced is evolving and expanding into new frontiers

- Extending LTE Advanced to unlicensed spectrum
- Dynamic LTE broadcast. Going beyond mobile for terrestrial TV
- LTE Direct for continuous device to device proximity awareness
- Higher spectrum bands new licensing models—Authorized Shared Access

~3.5 GHz & ASA
Qualcomm is the leader in Mobile 3G/4G technologies

Each modem generation enhances user experience and provides more capacity

Qualcomm® Gobi™ is a product of Qualcomm Technologies, Inc.
Qualcomm is the leader in Mobile 3G/4G technologies
Hiding the complexity underneath the most seamless mobile connectivity

<table>
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<tr>
<th>Technology</th>
<th>Frequency Bands</th>
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<tr>
<td>LTE FDD</td>
<td>700/850/900</td>
</tr>
<tr>
<td>LTE TDD</td>
<td>1500/1700/1900</td>
</tr>
<tr>
<td>GSM/GPRS</td>
<td>2300/2600</td>
</tr>
<tr>
<td>CDMA 1X</td>
<td>~60 RF Bands</td>
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<tr>
<td>TD-SCDMA</td>
<td>17 LTE Voice Modes</td>
</tr>
<tr>
<td>EV-DO</td>
<td></td>
</tr>
<tr>
<td>HSPA+/WCDMA</td>
<td></td>
</tr>
<tr>
<td>CDMA</td>
<td></td>
</tr>
<tr>
<td>1X</td>
<td></td>
</tr>
<tr>
<td>TD-SCDMA</td>
<td></td>
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</tbody>
</table>

The Unique Qualcomm Advantage

- Supports all technologies, bands, modes, ...

Qualcomm® Gobi™ is a product of Qualcomm Technologies, Inc.
Evolving mobile technologies deliver great mobile experiences

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