LTE and 5G Innovation: Igniting Mobile Broadband
## Development

### LTE Becomes the Global Cellular Standard

A previously fragmented wireless industry has consolidated globally on LTE. LTE is being deployed faster than any previous generation of wireless technology.

### LTE-Advanced Provides Dramatic Advantages

Carrier Aggregation, a key LTE-Advanced feature that operators are deploying globally, harnesses available spectrum more effectively, increases network capacity, and can increase user throughput rates.

Other features in early stages of deployment or being tested for deployment include: Self-Organizing Network (SON) capabilities in the radio-access network, Enhanced Inter-Cell Interference Coordination (eICIC) for small cells that use the same radio channels as the macro cell, and Coordinated Multi Point (CoMP) transmission so multiple sites can simultaneously process signals from mobile users, improving cell-edge performance.

### 5G Research and Development Gains Momentum

5G, in early stages of definition through global efforts and many proposed technical approaches, could start to be deployed close to 2020 and continue through 2030.

5G will be designed to integrate with LTE networks, and many 5G features may be implemented as LTE-Advanced extensions prior to full 5G availability.

### Internet of Things Poised for Massive Adoption

IoT, also called machine-to-machine (M2M) communications, is seeing rapid adoption and expected in tens of billions of devices over the next ten years.

Drivers include improved LTE support, other supporting wireless technologies, and service-layer standardization such as OneM2M.
### Key Conclusions (2)

<table>
<thead>
<tr>
<th>Development</th>
<th>Summary</th>
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</thead>
<tbody>
<tr>
<td><strong>Spectrum Still Precious</strong></td>
<td>Spectrum remains a precious commodity for the industry; its value was demonstrated by the recent Advanced Wireless Services (AWS) auction that achieved record valuations.</td>
</tr>
<tr>
<td></td>
<td>Forthcoming spectrum in the United States includes the 600 MHz band planned for auction in 2016 and the 3.5 GHz “small-cell” band that the Federal Communications Commission (FCC) is in the process of deploying.</td>
</tr>
<tr>
<td></td>
<td>5G spectrum will include bands above 30 GHz, called mmWave, with the potential of ten times as much spectrum as is currently available for cellular. Radio channels of 1 GHz or more will enable multi-Gbps peak throughput.</td>
</tr>
<tr>
<td><strong>Unlicensed Spectrum Becomes More Tightly Integrated with Cellular</strong></td>
<td>The industry has developed increasingly sophisticated means for Wi-Fi and cellular networks to interoperate, making the user experience ever more seamless.</td>
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<tr>
<td></td>
<td>The industry is also developing versions of LTE that can operate in unlicensed spectrum.</td>
</tr>
<tr>
<td><strong>Mobile Computing Overtakes the Desktop</strong></td>
<td>The number of mobile users globally now exceeds the number of desktop users.</td>
</tr>
</tbody>
</table>
### Key Conclusions (3)

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<tr>
<td><strong>Small Cells Take Baby Steps</strong></td>
<td>Operators have begun installing small cells. Eventually, millions of small cells will lead to massive increases in capacity.</td>
</tr>
<tr>
<td></td>
<td>The industry is slowly overcoming challenges that include site acquisition, self-organization, interference management, and backhaul.</td>
</tr>
<tr>
<td><strong>Network Function Virtualization (NFV) Emerges</strong></td>
<td>New network function virtualization (NFV) and software-defined networking (SDN) tools and architectures are enabling operators to reduce network costs, simplify deployment of new services, and scale their networks.</td>
</tr>
<tr>
<td></td>
<td>Some operators are also virtualizing the radio-access network, as well as pursuing a related development called cloud radio-access network (cloud RAN).</td>
</tr>
</tbody>
</table>
Exploding Demand from Critical Mass of Multiple Factors

- 4G, 5G, Wi-Fi Networks
- Mobile Computing Platforms
- Exploding Demand Through Growing Number of Applications
- Internet of Things

Rysavy Research, 2015 White Paper
5G Data Drivers

- Ultra-high-definition, such as 4K and 8K, and 3D video.
- Augmented and immersive virtual reality.
- Realization of the tactile Internet—real-time, immediate sensing and control, enabling a vast array of new applications.
- Automotive, including autonomous vehicles, driver-assistance systems, vehicular Internet, infotainment, inter-vehicle information exchange, and vehicle pre-crash sensing and mitigation.
- Monitoring of critical infrastructure, such as transmission lines, using long-battery-life and low-latency sensors.
- Smart transportation using data from vehicles, road sensors, and cameras to optimize traffic flow.
- Mobile health and telemedicine systems that rely on ready availability of high-resolution and detailed medical records, imaging, and diagnostic video.
- Public safety, including broadband data and mission-critical voice.
- Sports and fitness enhancement through biometric sensing, real-time monitoring, and data analysis.
Global Mobile Data Growth

Global Mobile Traffic for Voice and Data 2014 to 2020

• Over 6.2 billion GSM-UMTS subscribers.

• In the U.S. wireless data represents over 50% of total revenue.

• More than 2 billion UMTS-HSPA customers worldwide across nearly 600 commercial networks.

Source: Ovum June 2015 Estimates
Global Adoption of 2G-4G Technologies 2010 to 2020

Data Source: Ovum December 2014 Estimates
Expanding Use Cases

Operator Services
- Television broadcast
- Proximity services
- Location-based
- Public safety
- Internet of Things
- Vehicle communication

Third-Party Services
- Over-the-top communication
- Cloud-based
- Other

Applications
- Millions becoming tens of millions

Multi-Network Integration and New Topologies:
- Network-level aggregation (e.g., Multipath TCP)
- Offload onto Wi-Fi
- LTE Wi-Fi Link Aggregation
- Operation of LTE in unlicensed bands
- New connection methods (relays, multi-hop, device-to-device)

Radio Network Enhancement:
- Becoming faster (peak rates of 1 Gbps+ in 4G, 20 Gbps+ in 5G)
- Densifying (smaller cells)
- Capacity increasing (more cells, more spectrum, more efficient technology)
- Shorter delays (10 msec with LTE, 1 msec with future LTE-Advanced and 5G)
- Low-cost and low-power machine options
- Centralization of radio-access network functions
## 1G to 5G

<table>
<thead>
<tr>
<th>Generation</th>
<th>Requirements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1G</td>
<td>No official requirements. Analog technology.</td>
<td>Deployed in the 1980s.</td>
</tr>
<tr>
<td>2G</td>
<td>No official requirements. Digital technology.</td>
<td>First digital systems. Deployed in the 1990s. New services such as SMS and low-rate data. Primary technologies include IS-95 CDMA (cdmaOne) and GSM.</td>
</tr>
<tr>
<td>3G</td>
<td>ITU’s IMT-2000 required 144 Kbps mobile, 384 Kbps pedestrian, 2 Mbps indoors</td>
<td>First deployment in 2000. Primary technologies include CDMA2000 1X/EV-DO and UMTS-HSPA. WiMAX.</td>
</tr>
<tr>
<td>4G (Initial Technical Designation)</td>
<td>ITU’s IMT-Advanced requirements include ability to operate in up to 40 MHz radio channels and with very high spectral efficiency.</td>
<td>First deployment in 2010. IEEE 802.16m and LTE-Advanced meet the requirements.</td>
</tr>
<tr>
<td>4G (Current Marketing Designation)</td>
<td>Systems that significantly exceed the performance of initial 3G networks. No quantitative requirements.</td>
<td>Today’s HSPA+, LTE, and WiMAX networks meet this requirement.</td>
</tr>
<tr>
<td>5G</td>
<td>ITU IMT-2020 requirements are in progress and may represent initial technical requirements for 5G.</td>
<td>Expected in 2020 timeframe. Term applied to generation of technology that follows LTE-Advanced.</td>
</tr>
</tbody>
</table>
Timeline of Cellular Generations
Network Transformation

**Wireless Network of the Present**
- Insufficient Spectrum
- Capacity Constrained
- Competitive Alternative to Wireline for Some

**Wireless Network of the Future**
- Balanced Portfolio of Licensed and Unlicensed Spectrum
- Significantly Greater Capacity
- Competitive Alternative to Wireline for Many

**Network Design: Present**
- Larger cells on average
- Some small cells
- Some advanced radio methods
- Wi-Fi and cellular mostly operate independently
- Limited sharing of spectrum with government
- Frequencies: current cellular (600 MHz to 2.5 GHz)
- Total spectrum used: approximately 1 GHz

**Network Design: Future**
- Smaller cells on average
- Many small cells
- Many advanced radio methods (smart antennas, etc.)
- Unlicensed- and licensed-spectrum technologies work together in integrated network
- Selective sharing of spectrum with government
- Frequencies: current cellular bands and higher frequencies, including mmWave
- Total spectrum used: many GHz

*Rysavy Research*
5G Combining of LTE and New Radio Technologies

- Existing Cellular Bands
  - LTE for extended period
  - Eventually 5G radio

- New 5G Bands
  - Wide radio bands
  - 5G radio methods

Core 5G Network Integrates Existing LTE in Cellular Bands with 5G Radio in New Bands

Rysavy Research
Evolution to 5G Including LTE Improvements and Potential New 5G Radio Methods
## Key 5G Technology Elements under Investigation

<table>
<thead>
<tr>
<th>Key 5G Technology Element</th>
<th>Description</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Massive MIMO</strong></td>
<td>Extension of MIMO concept to hundreds of antennas at the base station.</td>
<td>Increase of spectral efficiency, at least doubling, with 5X to 10X gains theorized.</td>
</tr>
<tr>
<td><strong>10 GHz or higher bands</strong></td>
<td>Most cellular today is below 3 GHz, but new technology allows operation in 10 GHz to 100 GHz for small cells.</td>
<td>Vast new spectrum amounts available (as much as 10X or more) as well as wider radio channels (1 or 2 GHz) enabling much higher data rates.</td>
</tr>
<tr>
<td><strong>New multi-carrier radio transmission</strong></td>
<td>LTE uses OFDM, but other potential multi-carrier schemes include Filter-Bank Multi-Carrier (FBMC) transmission, Universal Filtered Multi-Carrier (UFMC) transmission, and Generalized Frequency-Division Multiplexing (GFDM).</td>
<td>Lower latency on uplink transmission due to lower synchronization requirements. Potentially better suited for spectrum sharing because the transmission operates in more confined spectrum.</td>
</tr>
<tr>
<td><strong>Non-Orthogonal Multiple Transmission</strong></td>
<td>Orthogonality in OFDM avoids interference and creates high capacity, but requires extensive signaling and increases delay. Non-Orthogonal Multiple Access (NOMA) and Sparse Coded Multiple Access (SCMA) could complement orthogonal access by taking advantage of advanced interference-cancellation techniques.</td>
<td>Reduced latency for small payloads.</td>
</tr>
<tr>
<td><strong>Shared Spectrum Access</strong></td>
<td>Current LTE systems assume dedicated spectrum. Future wireless systems (LTE and 5G) will interface with planned Spectrum Access Systems that manage spectrum among primary (incumbent, e.g., government), secondary (licensed, e.g., cellular), and tertiary (unlicensed) users.</td>
<td>More efficient use of spectrum for scenarios in which incumbents use spectrum lightly.</td>
</tr>
<tr>
<td><strong>Advanced Inter-Node Coordination</strong></td>
<td>LTE already uses techniques such as inter-cell interference coordination and Coordinated Multi-Point. In 5G, cloud RANs will enable better coordination across base stations.</td>
<td>Higher network capacity.</td>
</tr>
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## Key 5G Technology Elements under Investigation

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<tr>
<td><strong>Simultaneous Transmission Reception</strong></td>
<td>Current cellular systems cannot transmit and receive simultaneously in the exact same spectrum. By using advanced interference cancellation methods, future systems could potentially do so, especially in low-power transmission environments such as small cells.</td>
<td>Doubling of capacity. Potential improvements in radio-access control.</td>
</tr>
<tr>
<td><strong>Multi-Radio-Access-Technologies</strong></td>
<td>LTE already integrates with Wi-Fi, and plans include operation in unlicensed spectrum. 5G will need to integrate even more tightly with Wi-Fi, 4G, and 3G systems. Virtualization methods may facilitate such integration by enabling instantiation of network functions on demand.</td>
<td>Users automatically obtain the most suitable network based on their requirements and network loads.</td>
</tr>
<tr>
<td><strong>Device-to-Device Communication</strong></td>
<td>LTE already includes a limited form of device-to-device communication. 5G could use this form of communication to extend coverage and to transfer the same data to multiple units more efficiently.</td>
<td>More efficient network use and improved access to data for users.</td>
</tr>
<tr>
<td><strong>Wireless Access/Backhaul Integration</strong></td>
<td>Today, wireless backhaul and access are based on different technologies. 5G could be designed to handle both functions, essentially making the wireless link a multi-hop network.</td>
<td>Greater flexibility in deploying dense networks.</td>
</tr>
<tr>
<td><strong>Flexible Networks</strong></td>
<td>Network function virtualization is becoming common in LTE. 5G will be fully virtualized based on NFV and software-defined networking.</td>
<td>Lower deployment and operating costs. Faster rollout of new services.</td>
</tr>
</tbody>
</table>
Most Important Features of LTE-Advanced

• **Carrier Aggregation.** Already in use, operators can aggregate radio carriers in the same band or across disparate bands to improve throughputs (under light network load), capacity, and efficiency. Carrier aggregation can also combine FDD and TDD, as well as licensed and unlicensed bands.

• **Coordinated Multi Point.** Expected in the 2015-2016 timeframe, CoMP is a process by which multiple base stations or cell sectors process a UE signal simultaneously, or coordinate the transmissions to a UE, improving cell-edge performance and network efficiency. Initial usage will be on the uplink because no changes are required to user equipment (UE).

• **HetNet Support.** Also expected in the 2015-2016 timeframe, HetNets integrate macro cells and small cells. A key feature is enhanced intercell interference coordination (eICIC), which enhances the ability of a macro and a small cell to use the same spectrum. This approach is valuable when the operator cannot dedicate spectrum to small cells. Operators are currently evaluating eICIC, and at least one operator has deployed it.

• **Self-Organizing Networks.** With SON, networks can automatically configure and optimize themselves, a capability that will be particularly important as small cells begin to proliferate. Vendor-specific methods are common for 3G networks, and trials are now occurring for 4G LTE standards-based approaches.
LTE: Platform for the Future

2010 to 2012

Initial Deployments
- 5 or 10 MHz Radio Channels
- 2x2 Multiple Input Multiple Output (MIMO) Antennas
- Initial Self-Optimization/Organization for Auto Configuration

2013 to 2016

Higher Capacity/Throughput and/or Efficiency
- Wider Radio Channels: 20 MHz
- Carrier Aggregation: up to 100 MHz
- Advanced Antenna Configurations
- More Advanced MIMO (Higher Order, Multi-User, Higher Mobility)
- Coordinated Multipoint Transmission
- Hetnets (Macrocells/Picocells/Femtocells)
- Hetnet Self Optimization/Organization
- More Intelligent and Seamless Offload

Greater Capabilities
- Voice Widely Handled in the Packet Domain
- Policy-Based Quality of Service

Enables more users, more applications and a better experience
## Characteristics of 3GPP Technologies

<table>
<thead>
<tr>
<th>Technology Name</th>
<th>Type</th>
<th>Characteristics</th>
<th>Typical Downlink Speed</th>
<th>Typical Uplink Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSPA</td>
<td>WCDMA</td>
<td>Data service for UMTS networks. An enhancement to original UMTS data service.</td>
<td>1 Mbps to 4 Mbps</td>
<td>500 Kbps to 2 Mbps</td>
</tr>
<tr>
<td>HSPA+</td>
<td>WCDMA</td>
<td>Evolution of HSPA in various stages to increase throughput and capacity and to lower latency.</td>
<td>1.9 Mbps to 8.8 Mbps in 5+5 MHz</td>
<td>1 Mbps to 4 Mbps in 5+5 MHz or in 10+5 MHz</td>
</tr>
<tr>
<td>LTE</td>
<td>OFDMA</td>
<td>New radio interface that can use wide radio channels and deliver extremely high throughput rates. All communications handled in IP domain.</td>
<td>6.5 to 26.3 Mbps in 10+10 MHz</td>
<td>6.0 to 13.0 Mbps in 10+10 MHz</td>
</tr>
<tr>
<td>LTE- Advanced</td>
<td>OFDMA</td>
<td>Advanced version of LTE designed to meet IMT-Advanced requirements.</td>
<td>Significant gains through carrier aggregation</td>
<td></td>
</tr>
</tbody>
</table>
Evolution of CDMA and OFDMA Systems

Throughput rates are peak theoretical network rates for that technology release. Dates refer to expected initial commercial network deployment except 2013, which shows technologies that year. X+Y MHz indicates X MHz used on the downlink and Y MHz used on the uplink.
3GPP Releases (1)


- **Release 5**: Completed. HSDPA. First phase of IMS. Full ability to use IP-based transport instead of just Asynchronous Transfer Mode (ATM) in the core network.

3GPP Releases (2)

- **Release 7**: Completed. Provides enhanced GSM data functionality with Evolved EDGE. Specifies HSPA+, which includes higher order modulation and MIMO. Performance enhancements, improved spectral efficiency, increased capacity, and better resistance to interference. Continuous Packet Connectivity (CPC) enables efficient “always-on” service and enhanced uplink UL VoIP capacity, as well as reductions in call set-up delay for Push-to-Talk Over Cellular (PoC). Radio enhancements to HSPA include 64 Quadrature Amplitude Modulation (QAM) in the downlink and 16 QAM in the uplink. Also includes optimization of MBMS capabilities through the multicast/broadcast, single-frequency network (MBSFN) function.

- **Release 8**: Completed. Comprises further HSPA Evolution features such as simultaneous use of MIMO and 64 QAM. Includes dual-carrier HSDPA (DC-HSDPA) wherein two downlink carriers can be combined for a doubling of throughput performance. Specifies OFDMA-based 3GPP LTE. Defines EPC and EPS.

- **Release 9**: Completed. HSPA and LTE enhancements including HSPA dual-carrier downlink operation in combination with MIMO, Multimedia Broadcast Multicast Services (MBMS), HSDPA dual-band operation, HSPA dual-carrier uplink operation, EPC enhancements, femtocell support, support for regulatory features such as emergency user-equipment positioning and Commercial Mobile Alert System (CMAS), and evolution of IMS architecture.
3GPP Releases (3)

• **Release 10:** Completed. Specifies LTE-Advanced that meets the requirements set by ITU’s IMT-Advanced project. Key features include carrier aggregation, multi-antenna enhancements such as enhanced downlink eight-branch MIMO and uplink MIMO, relays, enhanced LTE Self-Organizing Network capability, Evolved Multimedia Broadcast Multicast Services (eMBMS), HetNet enhancements that include eICIC, Local IP Packet Access, and new frequency bands. For HSPA, includes quad-carrier operation and additional MIMO options. Also includes femtocell enhancements, optimizations for M2M communications, and local IP traffic offload.

• **Release 11:** Completed. For LTE, emphasis is on Coordinated Multi Point (CoMP), carrier-aggregation enhancements, devices with interference cancellation, development of the Enhanced Physical Downlink Control Channel (EPDCCH), and further enhanced eICIC including devices with CRS (Cell-specific Reference Signal) interference cancellation. The release includes further DL and UL MIMO enhancements for LTE. For HSPA, provides eight-carrier on the downlink, uplink enhancements to improve latency, dual-antenna beamforming and MIMO, CELL_Forward Access Channel (FACH) state enhancement for smartphone-type traffic, four-branch MIMO enhancements and transmissions for HSDPA, 64 QAM in the uplink, downlink multipoint transmission, and noncontiguous HSDPA carrier aggregation. Wi-Fi integration is promoted through S2a Mobility over GPRS Tunneling Protocol (SaMOG). An additional architectural element called Machine-Type Communications Interworking Function (MTC-IWF) will more flexibly support machine-to-machine communications.
3GPP Releases (4)

- **Release 12**: Completed. Enhancements include improved small cells/HetNets for LTE, LTE multi-antenna/site technologies (including Active Antenna Systems), Dual Connectivity, 256 QAM modulation option, further CoMP/MIMO enhancements, enhancements for interworking with Wi-Fi, enhancements for MTC, SON, support for emergency and public safety, Minimization of Drive Tests (MDT), advanced receivers, device-to-device communication (also referred to as proximity services), group communication enablers in LTE, addition of Web Real Time Communication (WebRTC) to IMS, energy efficiency, more flexible carrier aggregation, dynamic adaptation of uplink-downlink ratios in TDD mode, further enhancements for HSPA+, small cells/HetNets, Scalable-UMTS, and FDD-TDD carrier aggregation.

- **Release 13**: Some of the items under consideration include radio-access network sharing, 32-carrier aggregation, License Assisted Access (LAA), LTE Wi-Fi Aggregation (LWA), isolated operation for public safety, application-specific congestion management, user-plane congestion management, enhancement to WebRTC interoperability, architecture enhancement for dedicated core networks, enhancement to proximity-based services, mission-critical push-to-talk, group communications, CoMP enhancements, small cell enhancements, machine-type communications enhancements, VoLTE enhancements, SON enhancements, shared network enhancements, and enhanced circuit-switched fallback.
## Types of Cells and Characteristics

<table>
<thead>
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<th>Type of Cell</th>
<th>Characteristics</th>
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<tbody>
<tr>
<td><strong>Macro cell</strong></td>
<td>Wide-area coverage. LTE supports cells up to 100 km in range, but typical distances are .5 to 5 km radius. Always installed outdoors.</td>
</tr>
<tr>
<td><strong>Microcell</strong></td>
<td>Covers a smaller area, such as a hotel or mall. Range to 2 km, 5-10W, and 256-512 users. Usually installed outdoors.</td>
</tr>
<tr>
<td><strong>Picocell</strong></td>
<td>Indoor or outdoor. Outdoor cells also called “metrocells.” Typical range 15 to 200 meters outdoors and 10 to 25 meters indoors, 1-2W, 64-128 users. Deployed by operators primarily to expand capacity.</td>
</tr>
<tr>
<td><strong>Consumer Femtocell</strong></td>
<td>Indoors. Range to 10 meters, less than 50 mW, and 4 to 6 users. Capacity and coverage benefit. Usually deployed by end users using their own backhaul.</td>
</tr>
<tr>
<td><strong>Enterprise Femtocell</strong></td>
<td>Indoors. Range to 25 meters, 100-250 mW, 16-32 users. Capacity and coverage benefit. Deployed by operators.</td>
</tr>
<tr>
<td><strong>Distributed antenna system.</strong></td>
<td>Expands indoor or outdoor coverage. Same hardware can support multiple operators (neutral host) since antenna can support broad frequency range and multiple technologies. Indoor deployments are typically in larger spaces such as airports. Has also been deployed outdoors for coverage and capacity expansion.</td>
</tr>
<tr>
<td><strong>Remote radio head (RRH)</strong></td>
<td>Uses baseband at existing macro site or centralized baseband equipment. If centralized, the system is called “cloud RAN.” Requires fiber connection.</td>
</tr>
<tr>
<td><strong>Wi-Fi</strong></td>
<td>Primarily provides capacity expansion. Neutral-host capability allows multiple operators to share infrastructure.</td>
</tr>
<tr>
<td><strong>“Super Wi-Fi”</strong></td>
<td>Name used by some people for white-space technology. Not true Wi-Fi. Better suited for fixed wireless than mobile wireless.</td>
</tr>
</tbody>
</table>
Small Cell Challenges

Challenges:
- Site acquisition
- Multiple operators have to deploy cells
- Backhaul
- Interference Coordination
- Management
- Power

Rysavy Research
# Small Cell Approaches

<table>
<thead>
<tr>
<th>Small-Cell Approach</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro plus small cells in select areas.</td>
<td>Significant standards support. Femtocells or picocells can use same radio carriers as macro (less total spectrum needed) or can use different radio carriers (greater total capacity).</td>
</tr>
<tr>
<td>Macro in licensed band plus LTE operation in unlicensed bands.</td>
<td>Being considered for 3GPP Release 13 and available for deployment 2017 or 2018. Promising approach for augmenting LTE capacity in scenarios where operator is deploying LTE small cells.</td>
</tr>
</tbody>
</table>
| Macro (or small-cell) cellular in licensed band plus Wi-Fi. | Extensively used today with increased use anticipated. Particularly attractive for expanding capacity in coverage areas where Wi-Fi infrastructure exists but small cells with LTE do not.  

LTE Wi-Fi Aggregation (being specified in Release 13) is another approach, as is Multipath TCP. |
| Wi-Fi only.                                              | Low-cost approach for high-capacity mobile broadband coverage, but impossible to provide large-area continuous coverage without cellular component.                  |
Global Small Cell Forecast

## Wireless Networks for IoT

<table>
<thead>
<tr>
<th>Technology</th>
<th>Coverage</th>
<th>Characteristics</th>
<th>Standardization/ Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GSM/GPRS</strong></td>
<td>Wide area. Huge global coverage.</td>
<td>Lowest-cost cellular modems, risk of network sunsets. Low throughput.</td>
<td>3GPP</td>
</tr>
<tr>
<td><strong>HSPA</strong></td>
<td>Wide area. Huge global coverage.</td>
<td>Low-cost cellular modems. Higher power, high throughput.</td>
<td>3GPP</td>
</tr>
<tr>
<td><strong>LTE</strong></td>
<td>Wide area. Increasing global coverage.</td>
<td>Wide area, expanding coverage, cost/power reductions in successive 3GPP releases. Low to high throughput options.</td>
<td>3GPP</td>
</tr>
<tr>
<td><strong>Wi-Fi</strong></td>
<td>Local area.</td>
<td>High throughput, higher power.</td>
<td>IEEE</td>
</tr>
<tr>
<td><strong>ZigBee</strong></td>
<td>Local area.</td>
<td>Low throughput, low power.</td>
<td>IEEE</td>
</tr>
<tr>
<td><strong>Bluetooth Low Energy</strong></td>
<td>Personal area.</td>
<td>Low throughput, low power.</td>
<td>Bluetooth Special Interest Group</td>
</tr>
<tr>
<td><strong>LoRa</strong></td>
<td>Wide area. Emerging deployments.</td>
<td>Low throughput, low power. Unlicensed bands (sub 1 GHz, such as 900 MHz in the U.S.)</td>
<td>LoRa Alliance</td>
</tr>
<tr>
<td><strong>Sigfox</strong></td>
<td>Wide area. Emerging deployments.</td>
<td>Low throughput, low power. Unlicensed bands (sub 1 GHz such as 900 MHz in the U.S.)</td>
<td>Sigfox</td>
</tr>
<tr>
<td><strong>OnRamp Wireless</strong></td>
<td>Wide area. Emerging deployments.</td>
<td>Low throughput, low power. Using 2.4 GHz ISM band.</td>
<td>OnRamp Wireless (founding member of IEEE 802.15.4k)</td>
</tr>
<tr>
<td><strong>Weightless</strong></td>
<td>Wide area. Expected deployments.</td>
<td>Low throughput, low power. Unlicensed bands (sub 1 GHz such as TV White Space and 900 MHz in the U.S.)</td>
<td>Weightless Special Interest Group</td>
</tr>
</tbody>
</table>
Roaming Using Hotspot 2.0

Hotspot 2.0 facilitates roaming across networks.

Automatic, secure connection

Operator A

Operator B

Enterprise

Rysavy Research, 2015 White Paper
# Approaches for Using Unlicensed Spectrum

<table>
<thead>
<tr>
<th>Technology</th>
<th>Attributes</th>
</tr>
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<tbody>
<tr>
<td>Wi-Fi</td>
<td>Ever-more-sophisticated means to integrate Wi-Fi in successive 3GPP Releases.</td>
</tr>
<tr>
<td>Release 10-12 LTE-U</td>
<td>Approach for operating LTE in unlicensed spectrum.</td>
</tr>
<tr>
<td>Release 13 Licensed-Assisted Access</td>
<td>Standards-based approach for operating LTE in unlicensed spectrum.</td>
</tr>
</tbody>
</table>
ETSI NFV High-Level Framework
Evolution of RCS Capability

- **Messaging Evolution**
  - SMS
  - MMS
  - Stand Alone and conversational messaging
  - IMS messaging
  - Store & Forward
  - One-to-one Chat and group chat
  - File transfer
  - Sharing in chat/group chat
  - Same messaging experience on multiple devices

- **Telephony Evolution**
  - CS telephony (voice)
  - HD Voice
  - IMS Voice
  - Video sharing (one-way)
  - Video Calling
  - Group calls
  - Calling with tablets and PCs (secondary devices)

- **Contact Management Evolution**
  - Backup and restore
  - Multi device synchronization
  - Device centric address book
  - Capability discovery
  - Selfie's / Pictures
  - Social presence status
  - Tag lines
### Summary of 3GPP LTE Features to Support Public Safety

<table>
<thead>
<tr>
<th>3GPP Rel-8</th>
<th>3GPP Rel-9</th>
<th>3GPP Rel-10</th>
<th>3GPP Rel-11</th>
<th>3GPP Rel-12</th>
<th>3GPP Rel-13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobile data connections</td>
<td>Location services and positioning support for LTE</td>
<td>Physical layer enhancements to increase data throughput (including LTE-Advanced features)</td>
<td>High power devices for Band 14 - 1.25 Watts for public safety devices significantly improving the coverage of an LTE network, benefitting public safety users and reducing network deployment costs.</td>
<td>Group Communication System Enablers for LTE</td>
<td>Mission Critical Push-to-Talk</td>
</tr>
<tr>
<td>Basic support for Voice over LTE (telephony)</td>
<td>Multimedia Broadcast / Multicast Service</td>
<td>Relays for LTE, e.g. to allow a base station mounted on a fire vehicle to relay communications from firefighters in a basement back to the network.</td>
<td></td>
<td>Proximity-based Services</td>
<td>Enhancements to Proximity-based Services</td>
</tr>
<tr>
<td>Support for LTE Band 14</td>
<td>E911 or emergency calling support</td>
<td></td>
<td></td>
<td>Isolated E-UTRAN Operation for Public Safety</td>
<td>Isolated E-UTRAN Operation for Public Safety</td>
</tr>
<tr>
<td>a rich set of QoS priority and pre-emption features</td>
<td>Enhanced Home LTE base station: “Cell On Wheels”</td>
<td></td>
<td></td>
<td>MBMS Enhancements</td>
<td>MBMS Enhancements</td>
</tr>
<tr>
<td>Highly secure authentication and ciphering.</td>
<td>Self-Organizing Networks (SONs)</td>
<td></td>
<td></td>
<td></td>
<td>3GPP work ongoing - completion expected 1Q2015</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3GPP work started - completion expected 2016</td>
<td></td>
</tr>
</tbody>
</table>

Nokia, *LTE networks for public safety services*, 2014
Sharing Approaches for Public Safety Networks
RF Capacity Versus Fiber-Optic Cable Capacity

Achievable Fiber-Optic Cable Capacity Per Cable (Area Denotes Capacity)

Additional Fiber Strands Readily Available

Additional Fiber Strands Readily Available

Achievable Capacity Across Entire RF Spectrum to 100 GHz
Dimensions of Capacity

- Spectral Efficiency of Technology
- Amount of Spectrum
- Smallness of Cell (Amount of Frequency Reuse)
Bandwidth Management

- More spectrum
- Unpaired spectrum
- Supplemental downlink
- Spectrum sharing
- Increased spectral efficiency
- Smart antennas
- Uplink gains combined with downlink carrier aggregation
- Small cells and heterogeneous networks
- Offload to unlicensed spectrum
- Higher-level sectorization
- Off-peak hours
- Quality of service management
Benefits of Spectrum and Offload

![Graph showing improved throughputs with more spectrum and offload. The graph compares LTE (10+10 MHz), LTE (20+20 MHz), and LTE (20+20 MHz), Offload scenarios. The x-axis represents simultaneous users in cell sector, and the y-axis represents downlink throughput per user in Mbps.](image)

Rysavy Research
Spectrum Acquisition Time
# United States Current and Future Spectrum Allocations

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>Amount of Spectrum</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>700 MHz</td>
<td>70 MHz</td>
<td>Ultra-High Frequency (UHF).</td>
</tr>
<tr>
<td>850 MHz</td>
<td>64 MHz</td>
<td>Cellular and Specialized Mobile Radio.</td>
</tr>
<tr>
<td>1.7/2.1 GHz</td>
<td>90 MHz</td>
<td>Advanced Wireless Services (AWS)-1.</td>
</tr>
<tr>
<td>1695-1710 MHz, 1755 to 1780 MHz, 2155 to 2180 MHz</td>
<td>65 MHz</td>
<td>AWS-3. Uses spectrum sharing.</td>
</tr>
<tr>
<td>1.9 GHz</td>
<td>140 MHz</td>
<td>Personal Communications Service (PCS).</td>
</tr>
<tr>
<td>2000 to 2020, 2180 to 2200 MHz</td>
<td>40 MHz</td>
<td>AWS-4 (Previously Mobile Satellite Service).</td>
</tr>
<tr>
<td>2.3 GHz</td>
<td>20 MHz</td>
<td>Wireless Communications Service (WCS).</td>
</tr>
<tr>
<td>2.5 GHz</td>
<td>194 MHz</td>
<td>Broadband Radio Service. Closer to 160 MHz deployable.</td>
</tr>
<tr>
<td><strong>FUTURE</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>600 MHz</td>
<td>Up to 120 MHz</td>
<td>Incentive auctions.</td>
</tr>
<tr>
<td>3.55 to 3.70 GHz</td>
<td>150 MHz</td>
<td>Small-cell band with spectrum sharing and unlicensed use.</td>
</tr>
<tr>
<td>Above 5 GHz</td>
<td>Multi GHz</td>
<td>Anticipated for 5G systems in 2020 or later timeframe. Based on wavelengths, 3 GHz to 30 GHz is referred to as the cmWave band and 30 GHz to 300 GHz is referred to as the mmWave band.</td>
</tr>
</tbody>
</table>
LTE Spectral Efficiency as Function of Radio Channel Size

![Graph showing LTE spectral efficiency as a function of radio channel size. The x-axis represents MHz sizes (1.4, 3, 5, 10, 20 MHz), and the y-axis represents % efficiency relative to 20 MHz. The graph shows a gradual increase in efficiency as the channel size increases.]
Spectrum Harmonization

WRC and ITU level:
- Radio Regulation
- Report/recommendations

Regional/country level:
- Regulators

Technical Standard level:
- ETSI/3GPP, IEEE, ...

- Frequency allocation
- IMT identification

- Band plan
- Emission requirements
- FDD vs. TDD
- Licensed vs. unlicensed
- Assignment/auctioning

Initial critical step for global harmonization
- Avoid isolated band plan
- Enable new spectrum utilization

Coordination enables harmonization

Coordination among Operators (spectrum owners) is critical to prevent fragmentation

- Define operating bands
- Technical spec for each band
- Radio Access Technology (RAT)

- Network design and deployment
- Device design and deployment

Consumers with devices

Low cost multi-band multi-mode device is the key for economies of scale
## Pros and Cons of Unlicensed and Licensed Spectrum

<table>
<thead>
<tr>
<th>Unlicensed Pros</th>
<th>Unlicensed Cons</th>
<th>Licensed Pros</th>
<th>Licensed Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easy, and quick to deploy</td>
<td>Potential of other entities using same frequencies</td>
<td>Huge coverage areas</td>
<td>Expensive infrastructure</td>
</tr>
<tr>
<td>Low cost hardware</td>
<td>Difficult to impossible to provide wide-scale coverage</td>
<td>Able to manage quality of service</td>
<td>Each operator only has access to small amount spectrum</td>
</tr>
</tbody>
</table>
Propagation Losses Cellular vs. Wi-Fi

- **Cellular**
  - Free space path loss: exponent of 2
  - Terrestrial path loss: exponent of 3+
  - Even with exponent of 2:
    - Wi-Fi. 100 meters to 200 meters: signal at 25% of strength
    - Cellular. 1.0 km to 1.1 km: signal at 83% of strength

- **Wi-Fi**
  - Difficult to propagate short range network (Wi-Fi) signal
Licensed Shared Access

[Diagram showing LSA Repository, LSA Controller, Operator Network Operations, Primary Systems (Incumbents), Shared Spectrum Coverage (Small Cells), Licensed Spectrum Underlay]
United States 3.5 GHz System Currently Being Developed
Latency of Different Technologies

![Bar Chart showing latency of different technologies: EDGE Rel' 4, EDGE Rel' 7, HSPA+, LTE.](image-url)
Performance Relative to Theoretical Limits

- Shannon bound
- Shannon bound with 3dB margin
- HSDPA
- EV-DO
- IEEE 802.16e-2005

Achievable Efficiency (bps/Hz) vs. Required SNR (dB)
Comparison of Downlink Spectral Efficiency
Comparison of Uplink Spectral Efficiency
Comparison of Voice Spectral Efficiency
## Data Consumed by Different Streaming Applications

<table>
<thead>
<tr>
<th>Application</th>
<th>Throughput (Mbps)</th>
<th>MByte/hour</th>
<th>Hrs./day</th>
<th>GB/month</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audio or Music</td>
<td>0.1</td>
<td>58</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.0</td>
<td>6.9</td>
</tr>
<tr>
<td>Small Screen Video</td>
<td>0.2</td>
<td>90</td>
<td>0.5</td>
<td>1.4</td>
</tr>
<tr>
<td>(e.g., Feature Phone)</td>
<td></td>
<td></td>
<td>1.0</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.0</td>
<td>10.8</td>
</tr>
<tr>
<td>Medium Screen Video</td>
<td>1.0</td>
<td>450</td>
<td>0.5</td>
<td>6.8</td>
</tr>
<tr>
<td>(e.g., Smartphone, Tablet, Laptop)</td>
<td></td>
<td></td>
<td>1.0</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
<td>27.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.0</td>
<td>54.0</td>
</tr>
<tr>
<td>Larger Screen Video</td>
<td>3.0</td>
<td>1350</td>
<td>0.5</td>
<td>20.3</td>
</tr>
<tr>
<td>(e.g., 720p medium definition)</td>
<td></td>
<td></td>
<td>1.0</td>
<td>40.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
<td>81.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.0</td>
<td>162.0</td>
</tr>
<tr>
<td>High Definition</td>
<td>5.0</td>
<td>2250</td>
<td>0.5</td>
<td>33.8</td>
</tr>
<tr>
<td>(e.g., 1080p Netflix HD)</td>
<td></td>
<td></td>
<td>1.0</td>
<td>67.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
<td>135.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.0</td>
<td>270.0</td>
</tr>
<tr>
<td>Ultra High Definition</td>
<td>15.0</td>
<td>6750</td>
<td>0.5</td>
<td>101.3</td>
</tr>
<tr>
<td>(e.g., Netflix 4K)</td>
<td></td>
<td></td>
<td>1.0</td>
<td>202.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
<td>405.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.0</td>
<td>810.0</td>
</tr>
</tbody>
</table>

*Video applications: telemedicine, education, social networking, entertainment.*
Common core network can support multiple radio access networks
HSPA Channel Assignment - Example

[Diagram showing channel assignment over time and channelization codes for four users: User 1, User 2, User 3, User 4. Each user is assigned different codes and the assignment changes over time.]
HSPA Multi-User Diversity

Efficient scheduler favors transmissions to users with best radio conditions
### HSPA Dual-Cell Operation with One Uplink Carrier

<table>
<thead>
<tr>
<th></th>
<th>Uplink</th>
<th>Downlink</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UE1</strong></td>
<td>1 x 5 MHz</td>
<td>2 x 5 MHz</td>
</tr>
<tr>
<td><strong>UE2</strong></td>
<td>1 x 5 MHz</td>
<td>2 x 5 MHz</td>
</tr>
</tbody>
</table>
HSPA+ Het-net Using Multipoint Transmission

Data Rate Improvement
Median downlink data rate

1X 1.6X 3.1X
Macro, Dual-Carrier 4 Picos added Range Expansion

Range Expansion
Reduce second carrier Macro Power
CARRIER 2
Macro
CARRIER 1

Dual-Carrier Device
Pico

Rysavy Research, 2015 White Paper
## HSPA Throughput Evolution

<table>
<thead>
<tr>
<th>Technology</th>
<th>Downlink (Mbps) Peak Data Rate</th>
<th>Uplink (Mbps) Peak Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSPA as defined in Release 6</td>
<td>14.4</td>
<td>5.76</td>
</tr>
<tr>
<td>Release 7 HSPA+ DL 64 QAM, UL 16 QAM, 5+5 MHz</td>
<td>21.1</td>
<td>11.5</td>
</tr>
<tr>
<td>Release 7 HSPA+ 2X2 MIMO, DL 16 QAM, UL 16 QAM, 5+5 MHz</td>
<td>28.0</td>
<td>11.5</td>
</tr>
<tr>
<td>Release 8 HSPA+ 2X2 MIMO DL 64 QAM, UL 16 QAM, 5+5 MHz</td>
<td>42.2</td>
<td>11.5</td>
</tr>
<tr>
<td>Release 8 HSPA+ (no MIMO) Dual Carrier, 10+5 MHz</td>
<td>42.2</td>
<td>11.5</td>
</tr>
<tr>
<td>Release 9 HSPA+ 2X2 MIMO, Dual Carrier DL and UL, 10+10 MHz</td>
<td>84.0</td>
<td>23.0</td>
</tr>
<tr>
<td>Release 10 HSPA+ 2X2 MIMO, Quad Carrier DL, Dual Carrier UL, 20+10 MHz</td>
<td>168.0</td>
<td>23.0</td>
</tr>
<tr>
<td>Release 11 HSPA+ 2X2 MIMO DL and UL, 8 Carrier, Dual Carrier UL, 40+10 MHz</td>
<td>336.0</td>
<td>69.0</td>
</tr>
</tbody>
</table>

No operators have announced plans to deploy HSPA in a quad (or greater) carrier configuration. Three carrier configurations, however, have been deployed.
HSPA+ Performance, 5+5 MHz

![Graph showing indoor coverage with RSCP at -98 dBm. Key points include:
- Median: MIMO 8.2 Mbps, 64QAM 7.2 Mbps, HSPA 7.2 Mbps.
- Throughput percentages: 21% and 28% for different throughput levels.](image)
Dual Carrier HSPA+ Throughputs

Data rate (Mbps)

Relative distance to base station

100% 80% 60% 40% 20% 0%

0 10 20 30 40 50

42 DC

21

Rysavy Research, 2015 White Paper
Summary of HSPA Functions and Benefits

- **Uplink DTX + downlink DRX**
  - Lower UE power consumption

- **CS voice over HSPA, VoIP, WCDMA+**
  - Higher voice capacity or more capacity for data

- **Downlink 64QAM, MIMO, and multi carrier**
  - Higher downlink peak data rates and higher data capacity

- **Uplink 16QAM, MIMO, and dual carrier**
  - Higher uplink peak data rates and higher data capacity

- **Het-net support, pico range expansion**
  - Higher network capacity

- **High speed FACH, High speed RACH, FE-FACH**
  - Lower latency = better response times
  - More efficient common channels = savings in channel elements

- **Flat architecture optimization**
  - Fewer network elements
LTE Capabilities

- Downlink peak data rates up to 300 Mbps with 20+20 MHz bandwidth
- Uplink peak data rates up to 71 Mbps with 20+20 MHz bandwidth
- Operation in both TDD and FDD modes
- Scalable bandwidth up to 20+20 MHz, covering 1.4+1.4, 2.5+2.5, 5+5, 10+10, 15+15, and 20+20 MHz
- Reduced latency, to 15 msec round-trip time between user equipment and the base station, and to less than 100 msec transition time from inactive to active

<table>
<thead>
<tr>
<th>LTE Configuration</th>
<th>Downlink (Mbps) Peak Data Rate</th>
<th>Uplink (Mbps) Peak Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Using 2X2 MIMO in the Downlink and 16 QAM in the Uplink, 10+10 MHz</td>
<td>70.0</td>
<td>22.0</td>
</tr>
<tr>
<td>Using 4X4 MIMO in the Downlink and 64 QAM in the Uplink, 20+20 MHz</td>
<td>300.0</td>
<td>71.0</td>
</tr>
</tbody>
</table>
LTE OFDMA Downlink Resource Assignment in Time and Frequency

Minimum resource block consists of 14 symbols and 12 subcarriers
Frequency Domain Scheduling in LTE

Transmit on those resource blocks that are not faded.
LTE Antenna Schemes

Evolution of RCS API Profiles

**Profile v1.0**
- File Transfer
- Notification Channel
- Chat
- Third Party Call
- Call Notification
- Image Share
- Video Share
- ACR (Anonymous Customer Reference)
- Capability Discovery

**Profile v2.0**
- Profile v1.0
- Terminal Location
- Address Book
- Presence
- Messaging

**Profile v3.0**
- Profile v2.0
- Network Message Storage
- WebRTC Signaling
Evolution of Voice in LTE Networks
## Comparison of AMR, AMR-WB and EVS Codecs

<table>
<thead>
<tr>
<th>Features</th>
<th>AMR</th>
<th>AMR-WB</th>
<th>EVS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input and output sampling frequencies supported</td>
<td>8KHz</td>
<td>16KHz</td>
<td>8KHz, 16KHz, 32KHz, 48 KHz</td>
</tr>
<tr>
<td>Audio bandwidth</td>
<td>Narrowband</td>
<td>Wideband</td>
<td>Narrowband, Wideband, Super-wideband, Fullband</td>
</tr>
<tr>
<td>Coding capabilities</td>
<td>Optimized for coding human voice signals</td>
<td>Optimized for coding human voice signals</td>
<td>Optimized for coding human voice and general-purpose audio (music, ringtones, mixed content) signals</td>
</tr>
<tr>
<td>Bit rates supported (in kb/s)</td>
<td>4.75, 5.15, 5.90, 6.70, 7.4, 7.95, 10.20, 12.20</td>
<td>6.6, 8.85, 12.65, 14.25, 15.85, 18.25, 19.85, 23.05, 23.85</td>
<td>5.9, 7.2, 8, 9.6 (NB and WB only), 13.2 (NB, WB and SWB), 16.4, 24.4, 32, 48, 64, 96, 128 (WB and SWB only)</td>
</tr>
<tr>
<td>Number of audio channels</td>
<td>Mono</td>
<td>Mono</td>
<td>Mono and Stereo</td>
</tr>
<tr>
<td>Frame size</td>
<td>20 ms</td>
<td>20 ms</td>
<td>20 ms</td>
</tr>
<tr>
<td></td>
<td>20-25 ms</td>
<td>25 ms</td>
<td>Up to 32 ms</td>
</tr>
</tbody>
</table>
Combined Mean Opinion Score Values

EVS Compared to AMR and AMR-WB

<table>
<thead>
<tr>
<th>Reference</th>
<th>Equal bandwidth</th>
<th>Wider bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMR 12.2 kbit/s</td>
<td>EVS-NB 8.0 kbit/s</td>
<td>EVS-WB 5.9 kbit/s</td>
</tr>
<tr>
<td>AMR-WB 12.65 kbit/s</td>
<td>EVS-WB 9.6 kbit/s</td>
<td>EVS-SWB 9.6 kbit/s</td>
</tr>
<tr>
<td>AMR-WB 23.85 kbits/s</td>
<td>EVS-WB 13.2 kbit/s</td>
<td>EVS-SWB 9.6 kbit/s</td>
</tr>
</tbody>
</table>

EVS Voice Capacity Compared to AMR and AMR-WB

TDD Frame Co-Existence Between TD-SCDMA and LTE TDD
Carrier Aggregation Capabilities across 3GPP Releases

3GPP Release 10
- DL Intra-Band Contiguous
- DL Inter-Band
- Maximum 2 DL Carrier Aggregation

3GPP Release 11
- DL Intra-band non contiguous

3GPP Release 12
- 3 Downlink CA
- Two Uplink CA (Inter-Band & Intra-Band Non Contiguous)
- FDD + TDD
- Dual Connectivity

Beyond Release 12
- LAA (Licensed-Assisted Access)
- Four Downlink CA
LTE-Advanced Carrier Aggregation

LTE-Advanced Carrier Aggregation at Protocol Layers

Source: “The Evolution of LTE towards IMT-Advanced”, Stefan Parkvall and David Astely, Ericsson Research
Gains From Carrier Aggregation

![Distribution of User Experienced Throughput (700 MHz + AWS)](image-url)

- **5 UEs @ 700 MHz + 5 UEs @ AWS**
- **10 UE CA (700 MHz + AWS)**
Single-User and Multi-User MIMO

- **1 layer BF in Rel-8 with 4 antennas**
- **2 layer BF in Rel-9 with 8 antennas**
- **8 layer BF in Rel-10 with 8 antennas**

- **2 users each with 1 layer in Rel-8 with 4 antennas**
- **4 users each with 1 layer in Rel-9/10 with 8 antennas**
CoMP Levels

1. Intra-site Macro CoMP
   - Coordination is only between sectors of the same macro BTS

2. Distributed eNB – Contiguous Coverage
   - Coordination between all sectors of all macro BTSs
   - High Tx power RRH
Median Throughput of Feedback Mode 3-2 and New Codebook

![Bar chart showing median throughput with closely spaced antennas for Mode 3-1 and Mode 3-2 with different codebooks.]
Cell-Edge Throughput of Feedback Mode 3-2 and New Codebook
LTE-Advanced Relay

- Relay Link
- Direct Link
- Access Link
# LTE UE Categories

<table>
<thead>
<tr>
<th>UE Category</th>
<th>Max DL Throughput</th>
<th>Maximum DL MIMO Layers</th>
<th>Maximum UL Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.3 Mbps</td>
<td>1</td>
<td>5.2 Mbps</td>
</tr>
<tr>
<td>2</td>
<td>51.0 Mbps</td>
<td>2</td>
<td>25.5 Mbps</td>
</tr>
<tr>
<td>3</td>
<td>102.0 Mbps</td>
<td>2</td>
<td>51.0 Mbps</td>
</tr>
<tr>
<td>4</td>
<td>150.8 Mbps</td>
<td>2</td>
<td>51.0 Mbps</td>
</tr>
<tr>
<td>5</td>
<td>299.6 Mbps</td>
<td>4</td>
<td>75.4 Mbps</td>
</tr>
<tr>
<td>6</td>
<td>301.5 Mbps</td>
<td>2 or 4</td>
<td>51.0 Mbps</td>
</tr>
<tr>
<td>7</td>
<td>301.5 Mbps</td>
<td>2 or 4</td>
<td>102.0 Mbps</td>
</tr>
<tr>
<td>8</td>
<td>2998.6 Mbps</td>
<td>8</td>
<td>1497.8 Mbps</td>
</tr>
<tr>
<td>9</td>
<td>452.3 Mbps</td>
<td>2 or 4</td>
<td>51.0 Mbps</td>
</tr>
<tr>
<td>10</td>
<td>452.3 Mbps</td>
<td>2 or 4</td>
<td>102.0 Mbps</td>
</tr>
<tr>
<td>11</td>
<td>603.0 Mbps</td>
<td>2 or 4</td>
<td>51.0 Mbps</td>
</tr>
<tr>
<td>12</td>
<td>603.0 Mbps</td>
<td>2 or 4</td>
<td>102.0 Mbps</td>
</tr>
</tbody>
</table>
## Summary of IoT Features in LTE Devices

<table>
<thead>
<tr>
<th>Device Category</th>
<th>Category 3</th>
<th>Category 1</th>
<th>Category 0</th>
<th>Category M</th>
</tr>
</thead>
<tbody>
<tr>
<td>3GPP Release</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>Max. Data Rate Downlink</td>
<td>100</td>
<td>10</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>Max. Data Rate Uplink</td>
<td>50</td>
<td>5</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>Max. Bandwidth Duplex</td>
<td>20 MHz</td>
<td>20 MHz</td>
<td>20 MHz</td>
<td>1.4 MHz</td>
</tr>
<tr>
<td></td>
<td>Full</td>
<td>Full</td>
<td>Optional half-duplex</td>
<td>Optional half-duplex</td>
</tr>
<tr>
<td></td>
<td>Two</td>
<td>Two</td>
<td>One</td>
<td>One</td>
</tr>
<tr>
<td>Max. Receive Antennas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Sleep</td>
<td></td>
<td></td>
<td>Power Save Mode</td>
<td>Power Save Mode</td>
</tr>
<tr>
<td>Coverage</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Longer sleep cycles using Idle Discontinuous Reception (DRX)</td>
<td>Extended through redundant transmissions and Single Frequency Multicast</td>
</tr>
</tbody>
</table>
## LTE FDD User Throughputs Based on Simulation Analysis

<table>
<thead>
<tr>
<th>Configuration</th>
<th>User Throughput, Mbps</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Downlink (DL)</td>
<td>Uplink (UL)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>Average</td>
<td>Median</td>
</tr>
<tr>
<td>LTE FDD: Low Band, 2x2 MIMO-DL, 1x2 SIMO-UL, 10+10 MHz, R8</td>
<td>8.6</td>
<td>10.9</td>
<td>4.5</td>
</tr>
<tr>
<td>LTE FDD: High Band, 4x2 MIMO-DL, 1x4 SIMO-UL, 10+10 MHz, R8</td>
<td>10.6</td>
<td>12.2</td>
<td>5.4</td>
</tr>
<tr>
<td>LTE FDD: High Band, 2x2 MIMO-DL, 1x2 SIMO-UL, 20+20 MHz, R8</td>
<td>15.2</td>
<td>17.9</td>
<td>5.4</td>
</tr>
<tr>
<td>LTE FDD: High Band, 4x4 MIMO-DL, 1x4 SIMO-UL, 20+20 MHz, R12</td>
<td>25.4</td>
<td>29.2</td>
<td>6.9</td>
</tr>
</tbody>
</table>
Traffic is FTP-like at a 50% load with a 75/25 mix of indoor/outdoor users.

Throughput is at the medium-access control (MAC) protocol layer.

The configuration in the first row corresponds to low-frequency band operation, representative of 700 MHz or cellular, while the remaining configurations assume high-frequency band operation, representative of PCS, AWS, or WCS. (Higher frequencies facilitate higher-order MIMO configurations and have wider radio channels available.)

The downlink value for the first row corresponds to Release 8 device receive capability (Minimum Mean Square Error [MMSE]), while the values in the other rows correspond to Release 11 device receive capability (MMSE – Interference Rejection Combining [IRC]).

The uplink value for the first row corresponds to a Maximal Ratio Combining (MRC) receiver at the eNodeB, while the remaining values correspond to an IRC receiver.

Low-band operation assumes 1732 meter inter-site distance (ISD), while high-band operation assumes 500 meter ISD. The remaining simulation assumptions are listed in Table 11.

Refer to white paper for additional assumptions.
Drive Test of Commercial European LTE Network, 10+10 MHz
LTE Throughputs in Various Modes
LTE Actual Throughput Rates Based on Conditions

Load Balancing with Heterogeneous Networks

1. 3G-only UE: stays on 3G as it moves through network
2. 3G+LTE UE: moves between 3G macro, LTE macro, & LTE macro/pico
3. 3G+LTE UE: able to access 3G & LTE macros, plus LTE HeNB (femto)
Scenarios for Radio Carriers in Small Cells

- Scenario 1: Dedicated Carrier
  - Small Cell
  - Macro Cell
  - No RF interference
  - Best performance
  - Inter-frequency handover

- Scenario 2: Shared Carrier
  - Small Cell
  - Macro Cell
  - Interference between cells
  - Intra-frequency handover
  - Most popular

- Scenario 3: Straddled Carrier
  - Small Cell
  - Macro Cell
  - Macro Cell
  - Reduced interference
  - Inter-frequency handover
Traffic Distribution Scenarios
Enhanced Intercell Interference Cancellation

Pico-UEs sensitive to macro-cell interference are only scheduled in subframes where Macro use ABS. This allows scheduling of pico-UEs using larger pico node cell selection offsets (range extension).

Other pico-UEs that are closer to their serving pico node and therefore less restricted by macro-layer interference can be scheduled in any subframe.

Requires strict time-synchronization between macro & Pico

Almost blank, or MBSFN sub-frame

Sub-frame with normal transmission

One sub-frame
Median Throughput Gains
Hotspot Scenarios

- 700MHz Macro: 1.0X
- 700MHz + 2GHz Macro: 2.0X
- Dual-band Macro + 4 Picos (dual-band): 15.8X
- Dual-band Macro + 8 Picos (dual-band): 20.6X
- Dual-band Macro + eICIC/IC: 23X
- 29X

26% gain from eICIC/IC
30% gain
User Throughput Performance

With/Without eICIC for Dynamic Traffic Vs. Average Offered Load per Macro-Cell Area
Throughput Gain of Time-Domain Interference Coordination

![Diagram showing throughput gain and muting ratio as a function of average offered load.](image)
Dual Connectivity
Dual Connectivity User Throughputs
Hybrid SON Architecture
Evolved Packet System
Evolved Packet System Elements

- Flatter architecture to reduce latency
- Support for legacy GERAN and UTRAN networks connected via SGSN.
- Support for new radio-access networks such as LTE.
- The Serving Gateway that terminates the interface toward the 3GPP radio-access networks.
- The PDN gateway that controls IP data services, does routing, allocates IP addresses, enforces policy, and provides access for non-3GPP access networks.
- The MME that supports user equipment context and identity as well as authenticates and authorizes users.
- The Policy Control and Charging Rules Function (PCRF) that manages QoS aspects.
## LTE Quality of Service

<table>
<thead>
<tr>
<th>QCI</th>
<th>Resource Type</th>
<th>Priority</th>
<th>Delay Budget</th>
<th>Packet Loss</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GBR (Guaranteed Bit Rate)</td>
<td>2</td>
<td>100 msec.</td>
<td>$10^{-2}$</td>
<td>Conversational voice</td>
</tr>
<tr>
<td>2</td>
<td>GBR</td>
<td>4</td>
<td>150 msec.</td>
<td>$10^{-3}$</td>
<td>Conversational video (live streaming)</td>
</tr>
<tr>
<td>3</td>
<td>GBR</td>
<td>3</td>
<td>50 msec.</td>
<td>$10^{-3}$</td>
<td>Real-time gaming</td>
</tr>
<tr>
<td>4</td>
<td>GBR</td>
<td>5</td>
<td>300 msec.</td>
<td>$10^{-6}$</td>
<td>Non-conversational video (buffered streaming)</td>
</tr>
<tr>
<td>5</td>
<td>Non-GBR</td>
<td>1</td>
<td>100 msec.</td>
<td>$10^{-6}$</td>
<td>IMS signaling</td>
</tr>
<tr>
<td>6</td>
<td>Non-GBR</td>
<td>6</td>
<td>300 msec.</td>
<td>$10^{-6}$</td>
<td>Video (buffered streaming), TCP Web, e-mail, ftp, …</td>
</tr>
<tr>
<td>7</td>
<td>Non-GBR</td>
<td>7</td>
<td>100 msec.</td>
<td>$10^{-3}$</td>
<td>Voice, video (live streaming), interactive gaming</td>
</tr>
<tr>
<td>8</td>
<td>Non-GBR</td>
<td>8</td>
<td>300 msec.</td>
<td>$10^{-6}$</td>
<td>Premium bearer for video (buffered streaming), TCP Web, e-mail, ftp, …</td>
</tr>
<tr>
<td>9</td>
<td>Non-GBR</td>
<td>9</td>
<td>300 msec.</td>
<td>$10^{-6}$</td>
<td>Default bearer for video, TCP for non-privileged users</td>
</tr>
</tbody>
</table>
Release 11 SaMOG Wi-Fi Integration
# LTE-U, LTE-LAA, LWA Integration Approaches

<table>
<thead>
<tr>
<th>Approach</th>
<th>Radio</th>
<th>Co-Existence</th>
<th>Bands</th>
<th>Downlink/Uplink</th>
<th>Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTE-U</td>
<td>LTE</td>
<td>Duty cycle</td>
<td>5 GHz</td>
<td>DL</td>
<td>None</td>
</tr>
<tr>
<td>LTE-LAA</td>
<td>LTE</td>
<td>Listen Before Talk</td>
<td>5 GHz, 3.5 GHz under consideration</td>
<td>DL</td>
<td>3GPP Release 13</td>
</tr>
<tr>
<td>LWA</td>
<td>Wi-Fi</td>
<td>802.11</td>
<td>2.4 GHz, 5 GHz</td>
<td>DL and UL</td>
<td>3GPP Release 13</td>
</tr>
</tbody>
</table>
Bidirectional-Offloading Challenges
IP Flow and Seamless Mobility

- Internet
- Operator Core Network
- Cellular 3G/4G Radio-Access Network
- Wi-Fi Access Network

Examples:
- Operator VoIP
- Streaming Movie

Different application traffic flows can bind to the different access networks.
Hotspot 2.0 Connection Procedure

802.11u beacons with HS 2.0 support

Access Network Query Protocol

Responses to queries (operator name, roaming partners, EAP method supported)

Device chooses best AP

Secure communications

Roaming hubs, subscriber information
IP Multimedia Subsystem

IMS

Home Subscriber Server (HSS)

Call Session Control Function (CSCF) (SIP Proxy)

SIP Application Server

SIP

DIAMETER

Media Resource Function Control

Media Resource Gateway Control

4G

DSL

Wi-Fi

Multiple Possible Access Networks
Software-Defined Networking and Cloud Architectures

- Hosted Enterprise Communications (IMS, VoLTE, Collaboration)
- Platform Services (Web Hosting, App Stores, Cloud Storage)
- Cloud Controllers (WLAN, RNC, MME)
- Datacenter Orchestration (Elastic Compute, Workflow Automation)
- Software-Defined Networks
- Network Function Virtualization
- Cloud RAN (RRH + BBU)

- Analytics-Enrichment
- Internet of Everything
- M2M (Connected Vehicle, Smart Grid)
- B2B/OTT Applications Enablement
- Network Function Virtualization

- "Infrastructure Build Phase" (LTE, WiFi, Small Cell)
- "Cloud Optimization Phase" (RAN, Controllers, Gateways, Services, Applications)

Rysavy Research, 2015 White Paper
Potential Cloud RAN Approach
## Partially Centralized Versus Fully Centralized C-RAN

<table>
<thead>
<tr>
<th></th>
<th>Fully Centralized</th>
<th>Partially Centralized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport Requirements</td>
<td>Multi-Gbps, usually using fiber</td>
<td>20 to 50 times less</td>
</tr>
<tr>
<td>Applications</td>
<td>Supports eICIC and CoMP</td>
<td>Supports centralized scheduling</td>
</tr>
<tr>
<td>Complexity</td>
<td>High</td>
<td>Lower</td>
</tr>
<tr>
<td>Benefit</td>
<td>Capacity gain</td>
<td>Lower capacity gain</td>
</tr>
</tbody>
</table>
Efficient Broadcasting with OFDM

Symbol Time $T \sim 100 \mu s$

Cyclic Prefix

Useful Symbol Time

Identical signals transmitted

Note: All signals & multipath over a useful symbol time are from the same symbol & add constructively

Note: dashed lines represent multipath

Base 1

Base 2
GPRS/EDGE Architecture

- Mobile Station
- Base Transceiver Station
- Base Transceiver Station
- Mobile Station
- Base Station Controller
- Mobile Switching Center
- Home Location Register
- Serving GPRS Support Node
- Gateway GPRS Support Node
- IP Traffic
- Circuit-Switched Traffic
- GPRS/EDGE Data Infrastructure
Possible BCCH carrier configuration

Possible TCH carrier configuration

BCCH: Broadcast Control Channel – carries synchronization, paging and other signalling information
TCH: Traffic Channel – carries voice traffic data; may alternate between frames for half-rate
PDTCH: Packet Data Traffic Channel – Carries packet data traffic for GPRS and EDGE
PBCCH: Packet Broadcast Control Channel – additional signalling for GPRS/EDGE; used only if needed
Conclusion

- Mobile broadband remains at the forefront of innovation and development in computing, networking, and application development.
- LTE has become a global wireless foundation, supporting continual enhancements.
- The U.S. continues to lead the world in LTE deployment.
- LTE-Advanced innovations include carrier aggregation, already in use, and eICIC, SON, and CoMP, all capabilities about to be unleashed that will improve performance, efficiency, and capacity.
- 5G research and development efforts have accelerated, and deployment could commence close to 2020 and continue through 2030.
- 5G will be designed to integrate with LTE networks, and many 5G features may be implemented as LTE-Advanced extensions prior to full 5G availability.
- Obtaining more spectrum remains a critical priority globally.
- In the U.S., a number of initiatives could improve industry prospects—television incentive auctions for 600 MHz spectrum, the 3.5 GHz band, and more unlicensed spectrum at 5GHz.
- The future of mobile broadband, including both LTE-Advanced and 5G, is bright, with no end in sight for continued growth in capability, nor for the limitless application innovation that mobile broadband enables.