Mobile Broadband Explosion
The 3GPP Wireless Evolution

Rysavy Research for 4G Americas
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Introduction

The mobile broadband market has continued to explode thanks to pervasive adoption, ever more powerful new networks, spectacular new handheld devices, and close to two million mobile applications. Not only is mobile broadband the leading edge in innovation and development for computing, networking, Internet technology, and software, it is also transforming society.

Major developments this past year include not only 3rd Generation (3G) ubiquity, but rapid deployment of 4th Generation (4G) networks; deepening smartphone capability; tablets outselling laptops; and ever more sophisticated approaches for addressing data demands, which continue to grow unabated. The need for additional spectrum remains urgent, with new initiatives by industry and government to either make more spectrum available or to use existing spectrum more efficiently.

Through constant innovation, Universal Mobile Telecommunications System (UMTS) with High Speed Packet Access (HSPA) technology has established itself as the global mobile broadband solution. Building on the phenomenal success of Global System for Mobile Communications (GSM), the GSM-HSPA ecosystem has become the most successful communications technology family ever. Through a process of constant improvement, the GSM/Third Generation Partnership Project (3GPP) family of technologies has not only matched or exceeded the capabilities of all competing approaches but has significantly extended the life of each of its member technologies.

To leverage operator investments in HSPA, the 3GPP standards body has developed a series of enhancements called either “HSPA Evolution” or “HSPA+.” HSPA+ expands on the Wideband Code Division Multiple Access (WCDMA) approach and is complementary with the new 3GPP radio platform called 3GPP Long Term Evolution (LTE).

LTE, which uses Orthogonal Frequency Division Multiple Access (OFDMA), is seeing widespread deployment, particularly in the United States, which is leading the world in LTE deployment. Simultaneously, 3GPP—recognizing the significant worldwide investments in GSM networks—has significantly increased Enhanced Data Rates for GSM Evolution (EDGE) data capabilities through an effort called “Evolved EDGE.”

Important aspects of radio technology evolution are techniques and architectures that increase capacity and improve performance at the cell edge. These include ever more complex “smart antennas,” heterogeneous networks (HetNets), and user equipment communicating simultaneously with multiple base stations.

Combined with these improvements in radio-access technology, 3GPP has also developed major core-network architecture enhancements, such as the IP Multimedia Subsystem (IMS); the Evolved Packet Core (EPC), previously called System Architecture Evolution (SAE); and evolving means of integrating Wi-Fi, CDMA2000 and other non-3GPP technologies. These advances will facilitate increased capacity, new types of services, the integration of legacy and new networks, the convergence of fixed and wireless systems, and the transition to packet-switched voice.

This paper discusses the evolution of EDGE, HSPA enhancements, and LTE, as well as the capabilities of these technologies and their positions relative to other primary competing technologies. It explains how these technologies fit into the International Telecommunications Union (ITU) roadmap that includes International Mobile Telecommunications-Advanced (IMT-Advanced) and beyond.
The following are some of the important observations and conclusions of this paper:

- Mobile broadband – encompassing networks, devices, and applications – is becoming one of the most successful and fastest-growing industries of all time.
- Computing itself is transitioning from a PC era to a mobile era.
- Consumer and business applications have driven data demand until now, but machine-to-machine, also called Internet of Things, will generate progressively higher volumes of traffic in the future.
- Cloud computing is an ever-larger factor in data demand, involving data synchronization, backup, cloud-based applications, and streaming.
- The wireless industry is addressing exploding data demand through a combination of spectrally more efficient technology, denser deployments, small cells, HetNets, self-configuration, self-optimization, and offload.
- Initial LTE deployments have been faster than any new wireless technology previously deployed.
- LTE has become the global cellular-technology platform of choice for both GSM-UMTS and Code Division Multiple Access (CDMA)/Evolved Data Optimized (EV-DO) operators. Worldwide Interoperability for Microwave Access (WiMAX) operators are adopting LTE-Time Division Duplex (LTE-TDD).
- The wireless technology roadmap now extends through IMT-Advanced, with LTE-Advanced defined to meet IMT-Advanced requirements. LTE-Advanced is capable of peak theoretical throughput rates that exceed 1 gigabit per second (Gbps). Operators began deploying LTE-Advanced in 2013. Key capabilities include carrier aggregation, more advanced smart antennas, and better HetNet support.
- HSPA+ provides a strategic performance roadmap advantage for incumbent GSM-HSPA operators. Features such as multi-carrier operation, Multiple Input Multiple Output (MIMO), and higher-order modulation offer operators numerous options for upgrading their networks, with many of these features (including multi-carrier, higher-order modulation) being available as network software upgrades. With all planned features implemented, HSPA+ peak rates will eventually reach a top theoretical speed of 336 Mbps on the downlink and 69 Mbps on the uplink.
- Despite industry best efforts to deploy the most efficient technologies possible, overwhelming demand is already leading to isolated instances of congestion, which will become widespread unless more spectrum becomes available in the near future.
- Wi-Fi is playing an ever more important role as a means to increase data capacity. Innovations include tighter coupling to mobile broadband networks, automatic authentication and network selection, and more secure communications.
- EDGE technology has proven extremely successful and is widely deployed on GSM networks globally. Advanced capabilities with Evolved EDGE can double and eventually quadruple current EDGE throughput rates, halve latency, and increase spectral efficiency.
- EPC will provide a new core network that supports both LTE and interoperability with legacy GSM-UMTS radio-access networks and non-3GPP-based radio access networks. As part of EPC, policy-based charging and control flexibly manages quality-of-service.
(QoS), enabling new types of applications as well as more granular billing arrangements.

- Innovations such as EPC and UMTS one-tunnel architecture will “flatten” the network, simplifying deployment and reducing latency.

This paper begins with market trends, deployments, and other market statistics. It then examines the evolution of wireless technology, particularly 3GPP technologies, including spectrum considerations and spectrum policy developments, core-network evolution, and broadband-wireless deployment considerations. Next, the paper discusses other wireless technologies, including CDMA2000 and WiMAX. Finally, it compares the different wireless technologies technically, based on performance, spectral efficiency, and other features.

The appendix explains in detail the capabilities and workings of the different technologies including WCDMA, HSPA, HSPA+, LTE, LTE-Advanced, IMT-Advanced, Carrier Aggregation, Coordinated Multipoint Processing, heterogeneous networks, EPC, Wi-Fi integration, IMS, cloud RAN and network virtualization, broadcast/multicast services, EDGE and Evolved EDGE, TV white spaces, and backhaul.

\[\text{\footnote{\text{Although many use the terms “UMTS” and “WCDMA” interchangeably, in this paper we use “WCDMA” when referring to the radio interface technology used within UMTS and “UMTS” to refer to the complete system. HSPA is an enhancement to WCDMA. LTE with EPC is a completely new architecture.}}}\]
Data Explosion

Broadband communication is becoming a foundational element of the economy, supporting entire industries and transforming not only how people work, but how they lead their lives. Economists have correlated economic prosperity with the degree of broadband penetration.\(^2\)

As wireless technology represents an increasing portion of the global communications infrastructure, it is important to understand overall broadband trends. Sometimes wireless and wireline technologies compete, but in most instances, they are complementary. For the most part, backhaul transport and core infrastructure for wireless networks, including cellular and Wi-Fi, are based on wireline approaches, whether optical or copper.

To better understand the role of broadband, we discuss data consumption, wireless versus wireline capabilities, and bandwidth management.

Data Consumption

Multiple factors contribute to explosive growth in data consumption, especially powerful mobile computing platforms and fast mobile broadband networks. Despite the number of vendors and platform types available on the device side, the industry is converging on what might be considered a “standard” platform for smartphones and also one for tablets. Even if implemented differently, these platforms have the capabilities shown in Figure 1.

Figure 1: Modern Mobile Computing Platform and Data Consumption

<table>
<thead>
<tr>
<th>Modern Mobile Computing Platform:</th>
</tr>
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<tbody>
<tr>
<td>• Multiple wireless connection types</td>
</tr>
<tr>
<td>• Extremely high-resolution display</td>
</tr>
<tr>
<td>• Application platform</td>
</tr>
<tr>
<td>• HTML 5</td>
</tr>
<tr>
<td>• Multimedia</td>
</tr>
<tr>
<td>• Sync to cloud/enterprise</td>
</tr>
<tr>
<td>• Navigation</td>
</tr>
<tr>
<td>• Hotspot for other devices</td>
</tr>
</tbody>
</table>

Data Consuming Activities:
- Music streaming
- Video streaming
- Social networking
- Cloud sync/apps
- Web browsing
- Content downloading

\(^2\) For example, see ITU’s “Impact of Broadband on the Economy,” April 2012.
The rich capabilities of these mobile platforms enable their users to consume ever larger amounts of data through music and video streaming, social networking, cloud-based synchronization, Web applications, Web browsing, and content downloading.

The question is: How much data do streaming applications actually consume? Table 1 provides some values. Video rates are based on the use of advanced video compression schemes such as H.264.

**Table 1: 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></td>
<td></td>
</tr>
<tr>
<td>Small Screen Video (e.g., Feature Phone)</td>
<td>0.2</td>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium Screen Video (e.g., Smartphone, Tablet, Laptop)</td>
<td>1.0</td>
<td>450</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Larger Screen Video (e.g., 720p medium definition)</td>
<td>3.0</td>
<td>1350</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Definition (e.g., 1080p Netflix HD)</td>
<td>5.0</td>
<td>2250</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blu Ray Quality (4k video will be higher)</td>
<td>16.0</td>
<td>7200</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The hours of video add up. Sandvine, in its 2013 Global Internet Phenomena Report, shows mean usage in North America of 44.7 gigabytes (GB) per month.³ This author,

---

³ Data based on Rysavy Research analysis. Note that on May 2013, Netflix account settings indicated: “Good quality (up to 0.3 GB per hour); Better quality (up to 0.7 GB per hour); Best quality (up to 1.0 GB per hour or up to 2.3 GB per hour for HD).”

reasonably technologically oriented, consumes about 1 GB per month on his smartphone, 10 GB per month on his laptop, and 50 to 100 GB per month on movie streaming.

Alcatel Lucent reports that average LTE users consume 46 megabytes (MB) per day, amounting to 1.4 GB per month.⁵

Figure 2 shows a Cisco projection of global mobile data growth through 2017, measured in exabytes (billion gigabytes) per month, demonstrating traffic growing at a compound annual rate of 66% — resulting in thirteenfold growth over that period.

**Figure 2: Global Mobile Data Growth**⁶

![Cisco Global Mobile Data Growth](image)

Figure 3 shows another data projection, predicting 50% annual growth in data for the 2012 to 2018 period, resulting in twelvefold growth.

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**Cloud Computing**

Another trend that increases traffic is cloud computing, which can result in increased data flow through multiple types of services, as shown in Table 2.

**Table 2: Types of Cloud Services**

<table>
<thead>
<tr>
<th>Type of Cloud Service</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data synchronization and backup</td>
<td>Dropbox, Google Drive, Apple iCloud, Microsoft SkyDrive, enterprise data backup</td>
</tr>
<tr>
<td>Cloud-hosted applications</td>
<td>Google Docs, Microsoft Office 365</td>
</tr>
<tr>
<td>Music and video streaming</td>
<td>Netflix, Pandora, Spotify, Amazon Cloud Player</td>
</tr>
<tr>
<td>Machine-to-machine</td>
<td>Cloud-based services from operators and third-party providers</td>
</tr>
<tr>
<td>Mobile commerce</td>
<td>Cloud-based wallets (Apple Passport, Google Wallet, PayPal, Square), loyalty programs</td>
</tr>
</tbody>
</table>

---

**Technology Drives Demand**

Although it might seem that a more efficient technology would address escalating demand, the more efficient technology generally also provides higher performance, thus encouraging new usage models and increasing demand even further, as illustrated in Figure 4. Operators have observed this with LTE deployments, in which monthly usage amounts have been higher than for 3G networks. One vendor reports a 168% increase of LTE data consumption over 3G: 46 MB per day versus 17 MB per day.\(^8\)

Not only are users more likely to use applications that consume more bandwidth when given the opportunity, but an increasing number of applications, including Netflix and Skype, adapt their streaming rates based on available bandwidth. By doing so, they can continue to operate even when throughput rates drop. Conversely, they take advantage of higher available bandwidth to present video at higher resolution. Fortunately, application developers are becoming sensitive to bandwidth constraints and are offering options for users to reduce consumption. For example, Netflix has an account option that limits the streaming rate.

**Figure 4: Enhanced Technology Creates New Demand.**

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**Wireless Vs. Wireline**

Wireless technology is playing a profound role in networking and communications, even though wireline technologies such as fiber have inherent capacity advantages.

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The overwhelming global success of mobile telephony and now the growing adoption of mobile data conclusively demonstrate the desire for mobile-oriented communications. Mobile broadband combines high-speed data services with mobility. Thus, the opportunities are vast when considering the many diverse markets mobile broadband can successfully address. Developed countries continue to show tremendous uptake of mobile broadband services. Additionally, in developing countries, there is no doubt that 3G and 4G technology will cater to both enterprises and consumers for whom mobile broadband can be a cost-effective option competing with wireline for home use.

Relative to wireless networks, wireline networks have always had greater capacity and historically have delivered faster throughput rates. Figure 5 shows advances in typical user throughput rates and illustrates a consistent 10x advantage of wireline over wireless technologies.

**Figure 5: Wireline and Wireless Advances**

While wireless networks can provide a largely equivalent broadband experience for many applications, for ones that are extremely data intensive, wireline connections will remain a better choice for the foreseeable future. For example, users streaming Netflix movies in high definition consume about 5 Mbps. Typical LTE deployments use 10 MHz radio channels on the downlink and have a spectral efficiency of 1.4 bps/Hertz (Hz), providing LTE an average sector capacity of 14 Mbps. Thus, just three Netflix viewers could exceed sector capacity. In the United, there are approximately 1,100 subscribers, on average, per cell site\(^9\), hence about 360 for each of the three sectors commonly deployed in a cell.

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\(^9\) Source: Dr. Robert F. Roche & Lesley O’Neill, CTIA, CTIA’s Wireless Industry Indices, November 2010, at 161 (providing mid-year 2010 results and calculating 1,111 subscribers per cell site).
In dense urban deployments, the number of subscribers can be significantly higher. Therefore, just a small percentage of subscribers can overwhelm network capacity. For Blu-ray video quality that operates at around 16 Mbps, an LTE cell sector could support only one user.

Even if mobile users are not streaming full-length movies in high definition, video is finding its way into many applications, including education, social networking, video conferencing, business collaboration, field service, and telemedicine.

Over time, wireless networks will gain substantial additional capacity through the methods discussed in the next section, but they will never catch up to wireline. One can understand this from a relatively simplistic physics analysis:

- Wireline access to the premises or to nearby nodes uses fiber-optic cable.
- Capacity is based on available bandwidth of electromagnetic radiation. The infra-red frequencies used in fiber-optic communications have far greater bandwidth than radio.
- The result is that just one fiber-optic strand has greater bandwidth than the entire usable radio spectrum to 100 GHz, as illustrated in Figure 6.\(^{10}\) Meanwhile, the mobile computing industry currently has access to only .5% of this radio spectrum, growing to possibly 1% by 2020.\(^{11}\)

**Figure 6: RF Capacity Vs. Fiber-Optic Cable Capacity**

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\(^{11}\) .5% is calculated by approximating 100 GHz of usable radio spectrum and 500 MHz currently allocated to the mobile industry. The FCC National Broadband Plan calls for doubling this amount by 2020.
A dilemma of mobile broadband is that it can provide a broadband experience similar to wireline, but it cannot do so for all subscribers in a coverage area at the same time. Hence, operators must carefully manage capacity, demand, policies, pricing plans, and user expectations. Similarly, application developers must become more conscious of the inherent constraints of wireless networks.

Mobile broadband networks are best thought of as providing access to higher-capacity wireline networks. The key to improving performance and bandwidth per subscriber is reducing the size of cells and minimizing the radio path to the wireline network, thus improving signal quality and decreasing the number of people whom each cell must serve. These are the motivations for Wi-Fi offload and small-cell architectures that use picocells and femtocells.

Despite some of the inherent limitations of wireless technology relative to wireline, its fundamental appeal of providing access from anywhere means these limitations have not constrained market growth. As the decade progresses, the lines between wireline and wireless networks will blur.

**Bandwidth Management**

Given huge growth in usage, mobile operators are combining multiple approaches to manage bandwidth:

- **More spectrum.** Spectrum correlates directly to capacity, and more spectrum is becoming available globally for mobile broadband. In the U.S. market, the FCC National Broadband Plan seeks to make an additional 500 MHz of spectrum available by 2020. Multiple papers by Rysavy Research and others argue the critical need for additional spectrum.

- **Unpaired spectrum.** LTE TDD operates in unpaired spectrum. In addition, technologies such as HSPA+ and LTE permit the use of different amounts of spectrum between downlink and uplink. Additional unpaired downlink spectrum can be combined with paired spectrum to increase capacity and user throughputs.

- **Increased spectral efficiency.** Newer technologies are spectrally more efficient, meaning greater aggregate throughput in the same amount of spectrum. Wireless technologies such as LTE, however, are reaching the theoretical limits of spectral efficiency, and future gains will be quite modest, allowing for a possible doubling of LTE efficiency over currently deployed versions. See the section “Spectral Efficiency” for a further discussion.

- **Smart antennas.** Through higher-order MIMO and beamforming, smart antennas gain added sophistication in each 3GPP release and are the primary basis for increased spectral efficiency (bps/Hz).

- **Supplemental downlink.** With downlink traffic five to ten times greater than uplink traffic, operators often need to expand downlink capacity rather than uplink capacity. Using carrier aggregation, operators can augment downlink capacity by combining the capacity of separate radio channels.

---

Uplink gains combined with downlink carrier aggregation. Operators can increase network capacity by applying new receive technologies at the base station (for example, large scale antenna systems) that do not necessarily require standards support. Combined with carrier aggregation on the downlink, these receive technologies produce a high-capacity balanced network, suggesting that regulators consider licensing just downlink spectrum in some cases.

Small cells and heterogeneous networks. Selective addition of picocells to macrocells to address localized demand can significantly boost overall capacity, with a linear increase in capacity relative to number of small cells. HetNets, which also can include femtocells, hold the promise of increasing capacity gains by a factor of four and even higher with the introduction of interference cancellation in devices. Distributed antenna systems (DAS), used principally for improved indoor coverage, can also function like small cells and increase capacity. Actual gain will depend on a number of factors, including number and placement of small cells\textsuperscript{13}, user distribution, and any small-cell selection bias that might be applied.

Wi-Fi offload. Wi-Fi networks offer another means of offloading heavy traffic, especially with more Wi-Fi hotspots and more seamless connections. Wi-Fi adds to capacity because it offloads onto unlicensed spectrum. Moreover, since Wi-Fi signals cover only small areas, Wi-Fi achieves both extremely high frequency reuse and high bandwidth per square meter across the coverage area.

Higher-level sectorization. For some base stations, despite the more complex configuration involved, six sectors can prove advantageous versus the more traditional three sectors, deployed either in a 6X1 horizontal plane or 3X2 vertical plane\textsuperscript{14}.

Off-peak hours. Operators can offer user incentives or perhaps fewer restrictions on large data transfers during off-peak hours.

Quality of service (QoS). Through prioritization, certain traffic, such as non-time-critical downloads, can occur with lower priority, thus not affecting other active users.

Innovative data plans. Tiered pricing or slowing down throughput after certain data use thresholds are reached can make plans affordable for most users while discouraging excessive or abusive use.

Exploration of new methods for the future. Policy makers are evaluating how spectrum might be shared between government and commercial entities. Although a potentially promising approach for the long term, sharing raises complex issues, as discussed further in the section “Spectrum Developments.”

Figure 7 demonstrates the gains from using additional spectrum and offload. The bottom (green) curve is downlink throughput for LTE deployed in 20 MHz with 10 MHz on the downlink and 10 MHz on the uplink relative to the number of simultaneous users accessing the network. The middle (purple) curve shows how using an additional 20 MHz doubles the throughput for each user, and the top (orange) curve shows a further possible doubling through aggressive data offloading onto Wi-Fi.

\textsuperscript{13} With small-cell range expansion using a large selection bias, small cells can be distributed uniformly.

\textsuperscript{14} An example of vertical layering would be a 3X1 layer at ground level and a separate 3X1 layer for higher levels of surrounding buildings.
Figure 7: Benefits of Additional Spectrum and Offload

Improved Throughputs with More Spectrum and Offload

Market and Deployment

By July 2013, more than 6.2 billion subscribers were using GSM-HSPA\textsuperscript{15}—87\% of the world’s 7.1 billion population.\textsuperscript{16} By the end of 2018, the global mobile broadband market is expected to include more than 8.5 billion subscribers, with 7.5 billion using 3GPP technologies, representing about 90\% market share.\textsuperscript{17} Clearly, GSM-HSPA has established global dominance. Although voice still constitutes most cellular revenue, wireless data worldwide now comprises a significant percentage of average revenue per user (ARPU). In the United States, wireless data in Q1 of 2013 represented 45\% of industry revenues and is forecast to exceed 50\% of revenues in 2013, while growing to $90 billion for the year.\textsuperscript{18}

Nearly all of the 534 GSM networks in approximately 198 countries support EDGE. In addition, UMTS has been established globally and nearly all WCDMA handsets are also GSM capable, allowing WCDMA users access to the worldwide base of GSM/EDGE networks and services.

The evolution of UMTS to HSPA has gained a customer base of more than 1.4 billion people on more than 524 commercial networks. 332 HSPA networks have been upgraded

\textsuperscript{15} Source: Informa, “WCIS+,” July 2013.

\textsuperscript{16} Source: US Census Bureau, \url{http://www.census.gov/main/www/popclock.html}, July 2013

\textsuperscript{17} Source: Informa, “WCIS+,” July 2012. Note that the 2018 mobile broadband market figures include GSM/EDGE, since most GSM networks are likely to include Evolved EDGE, which provides mobile broadband capability.

\textsuperscript{18} Chetan Sharma, US Mobile Data Market Update – Q1 2013.
to HSPA+ in 131 countries.\textsuperscript{19} With the maturation of HSPA+, deployment or upgrading to HSPA+ involves minimal incremental investment.

All major U.S. operators will offer an impressive LTE footprint by the end of 2013. LTE has also been chosen by U.S. national public-safety organizations in the as their broadband technology of choice. In 2012, legislation passed in the United States that allocated the D Block spectrum for a nationwide public-safety LTE network.

\textsuperscript{19} Source: 4G Americas, July 2013.
Spectrum Developments

Spectrum continues to challenge the industry. Given this limited resource, the industry is:

- Deploying technologies that have higher spectral efficiency.
- Adapting specifications to enable operation of UMTS-HSPA and LTE in all available bands.
- Designing both FDD and TDD versions of technology to take advantage of both paired and unpaired bands.
- Designing carrier aggregation techniques in HSPA+ and LTE-Advanced that bonds together multiple radio channels (both intra- and inter-frequency bands) to improve peak data rates and efficiency.
- Deploying as many new cells (large and small) as is economically feasible.

Although all of these industry initiatives greatly expand capacity, they do not obviate the need for additional spectrum.

The FCC released a report in October 2010 that projected U.S. spectrum requirements and concluded that 275 MHz of additional spectrum would be needed within five years and 500 MHz of additional spectrum within 10 years. This forecast assumes ongoing increases in spectral efficiency from improving technologies. Credit Suisse reported in 2011 that U.S. wireless networks were already operating at 80% of capacity.

An important aspect of UMTS-HSPA and LTE deployment is for infrastructure and mobile devices to accommodate the expanding number of available radio bands. The fundamental system design and networking protocols remain the same for each band; only the frequency-dependent portions of the radios must change. As other frequency bands become available for deployment, standards bodies are adapting UMTS-HSPA and LTE for these bands as well. This includes bands such as 450 MHz and 700 MHz.

The 1710-1770 uplink was matched with the 2110-2170 downlink to allow for additional global harmonization of the 1.7/2.1 GHz band. These new spectrum bands were reserved or allocated harmoniously across North, Central and South America. The Advanced Wireless Services (AWS) band, at 1710-1755 MHz (uplink) with 2110-2155 MHz (downlink) in the United States, is providing operators additional deployment options and could eventually provide a means for LTE roaming in the Americas. Rogers is already deploying LTE in this band, and other U.S. operators are expected to do so as well. In addition, many countries in Latin America have allocated this band for mobile broadband.

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In 2012, the FCC changed the rules on the Wireless Communications Service (WCS) band, which constitutes 30 MHz of spectrum at 2.3 GHz, making 20 MHz available for mobile broadband.\textsuperscript{22}

The forthcoming 2.6 GHz frequency band in Europe, Asia, Latin America, and other parts of the world will also be a common band for LTE deployment. Unfortunately, different band plans in different parts of the world will complicate roaming on this band. Globally, operators are also refarming spectrum by limiting the spectrum used for 2G (cellular and PCS bands) to create space for 3G and 4G deployments.

Unfortunately, the process of identifying new spectrum and making it available for the industry is a lengthy one, as shown in Figure 8.

**Figure 8: Spectrum Acquisition Time\textsuperscript{23}**

The FCC is pursuing multiple avenues to make more spectrum available in the future. In the near term, the agency is repurposing 40 MHz of Mobile Satellite Services (MSS) spectrum for terrestrial use for what will be called the AWS-4 band.

The biggest opportunity areas for new spectrum in the United States currently are incentive auctions of TV-broadcasting spectrum, government spectrum from 1755 to 1850 MHz managed by the National Telecommunications and Information Administration (NTIA), and the proposed “small-cell” band from 3550 to 3650 MHz.

In June 2013, the Obama Administration announced new Administration spectrum initiatives, including directing Federal agencies to enhance the efficiency of their spectrum use, making greater capacity available for commercial networks, and funding research into spectrum sharing.

\textsuperscript{22} For further details, see “FCC Encyclopedia, Wireless Communications Service (WCS),” \url{http://www.fcc.gov/encyclopedia/wireless-communications-service-wcs}.

\textsuperscript{23} Source for historical data, \url{http://www.broadband.gov/plan/5-spectrum/}; future expectations based on Rysavy Research analysis.
Incentive Auctions

The incentive auctions will reallocate up to 120 MHz of UHF channels in the 600 MHz band that are currently used by TV broadcasters. The auctions, for which the FCC is currently developing rules, will be more complicated than past spectrum auctions, when the FCC simply reassigned or designated spectrum for commercial mobile use and then conducted an auction.

In the first of three steps, the FCC will conduct a reverse auction to determine how much spectrum broadcasters might wish to relinquish in exchange for how much compensation. It is unclear at this time how many broadcasters will participate and in what markets spectrum will be relinquished. The reverse auction is intended to provide answers to these unknowns, making it an unprecedented auction design.

The second step is to completely reorganize and repack the relinquished channels, as well as channels needed for broadcasters that want to keep broadcasting, so as to make useful blocks of spectrum for mobile broadband. This process will also be complicated. The FCC's goal is to design an auction which will result in a uniform nationwide band plan, but in some markets there may be variations from that plan.

Finally in the third and final step, mobile operators will bid for spectrum in a forward auction, similar to past spectrum auctions. As Commissioner Ajit Pai stated at 4G World in 2012, doing any one of these steps would be a challenge, but “doing them in conjunction will be daunting indeed.” The FCC hopes to conduct the final auctions in 2014, but given the complexity of the process, this date may prove optimistic.24

NTIA-Managed Spectrum

The U.S. government controls the most spectrum of any entity in the United States, with NTIA tasked to manage federal spectrum. NTIA-managed spectrum from 1755 to 1850 MHz involves a large number of government systems either migrating to other spectrum or possibly co-existing with commercial systems by using as-yet-undefined sharing approaches. One portion, 1755 to 1780 MHz, could potentially be paired with 2155 to 2180 MHz and could come to auction relatively soon. The 2155 to 2180 MHz portion legally must be auctioned and licensed by February 2015. A bill introduced by Stearns and Matsui in April 2012 seeks to repurpose the 1755 to 1780 MHz band from federal to commercial use. The industry is currently working with government to evaluate the feasibility of spectrum sharing between commercial networks and select government systems.

3550 to 3650 MHz “Small-Cell” Band

The 3550 to 3650 MHz band in the United States is now also being discussed for potential licensing. Although how useful this band will be in light of the higher frequencies involved remains to be determined, one potential application is LTE small cells. The FCC has proposed a three-tier model with incumbent access, priority access, and general

authorized access. Incumbent access will include government radar systems. The Licensed Shared Access (LSA) approach mentioned below under “Spectrum Sharing” is applicable to this band. LSA proposes a simpler two-tier model consisting of incumbents and licensed users sharing the spectrum.

Table 3 summarizes current and future spectrum allocations.

**Table 3: 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 + Specialized Mobile Radio.</td>
</tr>
<tr>
<td>1.7/2.1 GHz</td>
<td>90 MHz</td>
<td>Advanced Wireless Service (AWS) -1.</td>
</tr>
<tr>
<td>1.9 GHz</td>
<td>130 MHz</td>
<td>Personal Communications Service (PCS).</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 actually deployable.)</td>
</tr>
</tbody>
</table>

**FUTURE**

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>Amount of Spectrum</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9 GHz</td>
<td>10 MHz</td>
<td>PCH H band (1915-1920MHz UL and 1995-2000MHz DL).</td>
</tr>
<tr>
<td>1695-1710 MHz</td>
<td>15 MHz</td>
<td>Reallocation from federal to commercial use by 2015.</td>
</tr>
<tr>
<td>2000 to 2020, 2180 to 2200 MHz</td>
<td>40 MHz</td>
<td>Mobile satellite services (MSS). To become AWS-4.</td>
</tr>
<tr>
<td>600 MHz</td>
<td>Up to 120 MHz</td>
<td>Incentive auctions. FCC 2014 auction goal ambitious.</td>
</tr>
<tr>
<td>1755 to 1780 MHz</td>
<td>25 MHz</td>
<td>Could be combined with 2155 to 2180 to create AWS-3. May require spectrum sharing.</td>
</tr>
<tr>
<td>3.55 to 3.65 GHz</td>
<td>100 MHz</td>
<td>Small-cell band, shared.</td>
</tr>
</tbody>
</table>

**Harmonization**

Spectrum harmonization delivers many benefits, including higher economies of scale, lower device and consumer costs, better battery life, improved roaming, and reduced interference along borders.

As regulators make more spectrum available, it is important that they follow guidelines such as those espoused by 4G Americas:

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1. Configure licenses with wider bandwidths.
2. Group like services together.
3. Be mindful of global technology standards.
4. Pursue harmonized/contiguous spectrum allocations.
5. Exhaust exclusive use options before pursuing shared use.
6. Because not all spectrum is fungible, align allocation with demand.

Emerging technologies such as LTE benefit from wider radio channels. These wider radio channels are not only spectrally more efficient, but offer greater capacity. Figure 9 shows increasing LTE spectral efficiency obtained with wider radio channels, with 20 MHz on the downlink and 20 MHz (20+20 MHz) on the uplink showing the most efficient configuration.

**Figure 9: LTE Spectral Efficiency as Function of Radio Channel Size**

![LTE Spectral Efficiency Chart](chart.png)

Of some concern in this regard is that spectrum for LTE is becoming available in different frequency bands in different countries. For instance, initial US deployments will be at 700 MHz, in Japan at 1500 MHz, and in Europe at 2.6 GHz. Thus, with so many varying spectrum bands, roaming operation will most likely need to be based on GSM or HSPA on common regional or global bands.

The organization tasked with global spectrum harmonization is the International Telecommunications Union, which periodically holds World Radiocommunications Conferences (WRC).  

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27 Source: 4G Americas member company analysis.
Harmonization occurs at multiple levels:

1. Allocation of radio frequencies to a mobile service in the ITU frequency allocation table.
2. Establishment of global or regional frequency arrangements, including channel blocks and specific duplexing modes.
3. Development of detailed technical specifications and standards, including system performance, RF performance, and co-existence with other systems in neighboring bands.
4. Assignment for frequency blocks with associated technical conditions and specifications to appropriate operators and service providers.²⁹

Figure 10 shows the harmonization process.

**Figure 10: Spectrum Harmonization³⁰**

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³⁰ Source: 4G Americas member contribution.
The ITU WRC is planning its next conference for 2015.31

**Unlicensed Spectrum**

Wi-Fi, an unlicensed wireless technology, has experienced huge success due to high throughput rates, ease of use for consumers, extensive deployment by businesses, widespread availability in public places, and large amounts of available spectrum.

For mobile operators, Wi-Fi can offload a certain amount of data traffic, relieving some stress from capacity demands. To make offload work more effectively, the industry is working to more tightly bind Wi-Fi functionality with cellular operation, as discussed below in more detail under “Wi-Fi Integration and Data Offload.”

Wi-Fi uses spectrum efficiently because its small coverage areas result in high-frequency reuse and high data density (bps per square meter). Less efficient are white-space unlicensed networks, sometimes called “super Wi-Fi,” that have large coverage areas, because the throughput per square meter is much lower. While white-space networks may be a practical broadband solution in rural or undeveloped areas, they face significant challenges in urban areas that already have mobile and fixed broadband available.32

**Spectrum Sharing**

In 2012, the President’s Council of Advisors on Science and Technology issued a report titled, “Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth,” which recommended spectrum sharing between government and commercial entities.

On the surface, spectrum sharing between a government application, such as radar or satellite, and a commercial network appears to be efficient, especially if the government application operates in only some areas or for only some of the time. From a technical perspective, sharing may eventually lead to more efficient spectrum use, but excessive emphasis on sharing in the short term could needlessly slow deployment and use of productive spectrum.

Assessing the many parameters involved in a shared approach will take significant time. For instance, the AWS 1755-1780 MHz spectrum band controlled by the U.S. National Telecommunications and Information Administration (NTIA) represents an opportunity to provide additional internationally harmonized spectrum to the mobile broadband industry and could be shared initially with wireless carriers. Yet some initial investigations into spectrum sharing in the 1755-1780 MHz band reveal that technologists don’t yet know how to measure meaningful interference to incumbent systems.

Hence, focusing on a small number of bands so that government and industry can together learn how best to share seems prudent. In this regard, the proposed 3.55 GHz small-cell band appears to be an ideal candidate, but regulators must be careful not to overreach. If rules are too restrictive or complex, or if availability of spectrum is too

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31 Agenda available at [http://www.itu.int/dms_pub/itu-r/oth/12/01/R12010000014A01PDFFE.pdf](http://www.itu.int/dms_pub/itu-r/oth/12/01/R12010000014A01PDFFE.pdf).

unpredictable, operators may choose to look elsewhere, resulting in underuse of the spectrum.

Spectrum sharing models can range from simple to extremely complex:

- Geographical (already occurs in the AWS band using exclusion zones).
- Temporal (easy if times are well-defined, otherwise potentially complex).
- Database-driven (requires new infrastructure as shown in Figure 11.) A spectrum market system is an optional component, and would add to complexity.

**Figure 11: Spectrum Sharing Architecture**

![Spectrum Sharing Architecture Diagram](image)

The European Telecommunications Standards Institute (ETSI) is developing standards to support spectrum sharing under an approach called "Licensed Shared Access."[^33] For further discussion, refer to a Rysavy Research 2012 paper on spectrum sharing.[^34]

[^33]: See ETSI Technical Report TR 103 113, "Electromagnetic compatibility and Radio spectrum Matters (ERM); System Reference document (SRdoc); Mobile broadband services in the 2300 MHz-2400 MHz frequency band under Licensed Shared Access regime.

Wireless Technology Evolution

This section discusses 1G to 4G designations, the evolution and migration of wireless-data technologies from EDGE to LTE, architecture evolution, Wi-Fi integration and data offload, Rich Communications Suite, multicast and broadcast, voice support, and backhaul.

Progress in 3GPP has occurred in multiple phases, first with EDGE and then UMTS, followed by today’s enhanced 3G capabilities, such as HSPA, HSPA+, which is continually evolving, and LTE, which is evolving to LTE-Advanced, with work already occurring on specification releases beyond the initial one for LTE-Advanced. Meanwhile, underlying approaches have evolved from Time Division Multiple Access (TDMA) to CDMA, and now from CDMA to OFDMA, which is the basis of LTE.

Transition to 4G

Cellular technologies span multiple generations. 1G refers to analog cellular technologies that became available in the 1980s. 2G denotes initial digital systems that became available in the 1990s, and which introduced services such as short messaging and lower-speed data. CDMA IS-95 and GSM are the primary 2G technologies, while CDMA2000 1xRTT is technically a 3G technology because it meets the 144 Kbps mobile throughput requirement. EDGE, however, also meets this requirement.

3G requirements were specified by the ITU as part of the International Mobile Telephone 2000 (IMT-2000) project, for which digital networks had to provide 144 Kbps of throughput at mobile speeds, 384 Kbps at pedestrian speeds, and 2 Mbps in indoor environments. UMTS-HSPA and CDMA2000 EV-DO are the primary 3G technologies, although WiMAX has also been designated as an official 3G technology. 3G technologies began to be deployed last decade.

The ITU issued requirements for IMT-Advanced in 2008, which many people used as a definition of 4G. Requirements include operation in up-to-40 MHz radio channels and extremely high spectral efficiency. The ITU requires peak spectral efficiency of 15 bps/Hz and recommends operation in up-to-100 MHz radio channels, resulting in a theoretical throughput rate of 1.5 Gbps. Previous to the publication of the requirements, 1 Gbps was frequently cited as a 4G goal.

In 2009 and 2010, the term “4G” became associated with currently deployed mobile broadband technologies such as HSPA+ and WiMAX. In what seemed an acknowledgement of these developments, the ITU on Dec. 6, 2010, stated in a press release that it accepted the use of the 4G term for systems that provided a substantial level of improvement in performance and capabilities over initial 3G systems. 35

Table 4 summarizes the generations of wireless technology through 4G. The requirements for 5G are yet to be determined.

Table 4: 1G to 4G

<table>
<thead>
<tr>
<th>Generation</th>
<th>Requirements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1G</strong></td>
<td>No official requirements.</td>
<td>Deployed in the 1980s.</td>
</tr>
<tr>
<td></td>
<td>Analog technology.</td>
<td></td>
</tr>
<tr>
<td><strong>2G</strong></td>
<td>No official requirements.</td>
<td>First digital systems.</td>
</tr>
<tr>
<td></td>
<td>Digital technology.</td>
<td>Deployed in the 1990s.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>New services such as SMS and low-rate data.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Primary technologies include IS-95 CDMA and GSM.</td>
</tr>
<tr>
<td><strong>3G</strong></td>
<td>ITU’s IMT-2000 required 144 Kbps mobile, 384 Kbps pedestrian, 2 Mbps indoors</td>
<td>Primary technologies include CDMA2000 1X/EV-DO and UMTS-HSPA. WiMAX now an official 3G technology.</td>
</tr>
<tr>
<td><strong>4G (Initial Technical Designation)</strong></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>No commercially deployed technology meets requirements today. IEEE 802.16m and LTE-Advanced meet the requirements.</td>
</tr>
<tr>
<td><strong>4G (Current Marketing Designation)</strong></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>
</tbody>
</table>

Despite rapid deployments of LTE networks, it will be the middle of the decade before a large percentage of subscribers will actually be using LTE (or LTE-Advanced). During these years, most networks and devices will support the full scope of the 3GPP family of technologies (GSM-EDGE, HSPA, HSPA+, and LTE). The history of wireless-network deployment provides a useful perspective. GSM, which in 2009 was still growing its subscriber base, was specified in 1990, with initial networks deployed in 1991. The UMTS Task Force established itself in 1995, Release 99 specifications were completed in 2000, and HSPA+ specifications were completed in 2007. Although it has been more than a decade since work began on the technology, only now is UMTS deployment and adoption starting to surge.
Qualcomm reports an 18- to 20-year period between introduction of a technology and its peak usage\textsuperscript{36}, which is consistent with the history of GSM technology. Similarly, mobile broadband technologies coming online now may not see their peak adoption until 2030. Figure 12 shows the relative adoption of technologies over a multi-decadal period, and the length of time it takes for any new technology to be adopted widely on a global basis. The top line shows the total number of subscribers. The GSM/EDGE curve shows the number of subscribers for GSM/EDGE. The area between the GSM/EDGE curve and the UMTS/HSPA curve represents the number of UMTS/HSPA subscribers, and the area between the UMTS/HSPA curve and LTE curve is the number of LTE subscribers.

The interval between each significant technology platform has been about 10 years. Within each platform, however, there is constant innovation. For example, with 2G technology, EDGE significantly improved data performance compared with initial General Packet Radio Service (GPRS) capabilities. Similarly, HSPA hugely increased data speeds compared with initial 3G capabilities. LTE and LTE-Advanced will also acquire continual improvements that include both faster speeds and greater efficiency.

**Figure 12: Relative Adoption of Technologies\textsuperscript{37}**

These technology platform shifts every 10 years are similar to the computing industry, which has experienced the following major shifts:

- 1950s First commercial computers


\textsuperscript{37} Source: Rysavy Research projection based on historical data.
1960s Mainframes
1970s Mini-computers
1980s Desktop PCs
1990s Internet
2000s Web computing
2010s Mobile computing

**3GPP Evolutionary Approach**

3GPP standards development falls into three principal areas: radio interfaces, core networks, and services.

With respect to radio interfaces, rather than emphasizing any one wireless approach, 3GPP’s evolutionary plan is to recognize the strengths and weaknesses of every technology and to exploit the unique capabilities of each one accordingly. GSM, based on a TDMA approach, is mature and broadly deployed. Already extremely efficient, there are Nevertheless opportunities for additional optimizations and enhancements, including “Evolved EDGE,” which became available for deployment in 2011. Evolved EDGE more than doubles throughput over current EDGE systems while halving latency and increasing spectral efficiency.

Meanwhile, CDMA was chosen as the basis of 3G technologies including WCDMA for the frequency division duplex (FDD) mode of UMTS and Time Division CDMA (TD-CDMA) for the time division duplex (TDD) mode of UMTS. The evolved data systems for UMTS, namely HSPA and HSPA+, introduce enhancements and optimizations that help CDMA-based systems largely match the capabilities of competing systems, especially in 5 MHz spectrum allocations.

Dual-carrier HSPA, explained in detail in the appendix section “Evolution of HSPA (HSPA+),” coordinates the operation of HSPA on two 5 MHz radio carriers for higher throughput rates. In combination with MIMO, dual-carrier HSPA will achieve peak network speeds of 84 Mbps, and quad-carrier HSPA will achieve peak rates of 168 Mbps. Release 11 defines 8-carrier downlink operation that will double maximum theoretical throughput rates to 336 Mbps.

Given some of the advantages of an Orthogonal Frequency Division Multiplexing (OFDM) approach, 3GPP specified OFDMA as the basis of its LTE effort. LTE incorporates best-of-breed radio techniques to achieve performance levels beyond what may be practical with some CDMA approaches, particularly in larger channel bandwidths. In the same way that 3G coexists with 2G systems in integrated networks, LTE systems coexist with both 3G systems and 2G systems, with devices capable of 2G, 3G, and 4G modes. Beyond radio technology, EPC provides a new core architecture that is flatter and integrates with both legacy GSM-HSPA networks and other wireless technologies like CDMA2000 and Wi-Fi. The combination of EPC and LTE is referred to as the Evolved Packet System (EPS).

The cost for operators to deliver data (for example, cost per GB) is almost directly proportional to the spectral efficiency of the technologies. LTE has the highest spectral efficiency of any specified technology to date, making it one of the essential technologies as the market matures.
Meanwhile, HSPA+ is attractive to some operators because it maximizes the efficiencies in existing deployments and provides high performance via the use of new advanced techniques. Specifically:

- **Large Spectrum Utilization.** HSPA+ can be deployed in wider bandwidths of 10 MHz and 20 MHz\(^{38}\), increasing peak data rates and spectral efficiency.

- **Advanced MIMO.** MIMO enhancements and additional transmit and receive antennas improve spectral efficiency.

- **Good Coverage Performance.** Soft handover and other techniques improve coverage, especially at the edge of the cell.

As competitive pressures in the mobile broadband market intensify and as demand for capacity persistently grows, LTE is developing deployment momentum because it efficiently delivers high performance, especially in new spectrum. Specifically:

- **Wider Radio Channels.** LTE can be deployed in wide radio channels (for example, 10 MHz or 20 MHz). This increases peak data rates and uses spectrum more effectively.

- **Easiest MIMO Deployment.** By using new radios and antennas, LTE facilitates MIMO deployment compared with the logistical challenges of adding antennas for MIMO to existing deployments of legacy technologies. Furthermore, MIMO gains are maximized because all user equipment supports it from the beginning.

- **Best Latency Performance.** For some applications, low latency (packet traversal delay) is as important as high throughput. With a low transmission-time interval (TTI) of 1 millisecond (msec) and a flat architecture (fewer nodes in the core network), LTE has the lowest latency of any cellular technology.

LTE is available in both FDD and TDD modes. Many deployments will be based on FDD in paired spectrum. The TDD mode, however, will be important for deployments in which paired spectrum is unavailable. LTE TDD will be deployed in China, will be available for Europe at 2.6 GHz, and will operate in the U.S. Broadband Radio Service (BRS) 2.6 GHz band.

To address ITU’s IMT-Advanced requirements, 3GPP has specified LTE-Advanced, a technology that will have peak theoretical rates of more than 1 Gbps. See the appendix section “LTE Advanced” for a detailed explanation.

The version of LTE most widely deployed today (Release 8) is just the beginning of a series of innovations that will increase performance, efficiency, and capabilities, as depicted in Figure 13. The enhancements shown in the 2013 to 2016 period are the ones expected from 3GPP Releases 10, 11, and 12 and are commonly referred to as LTE-Advanced.\(^{39}\) Subsequent releases, such as Release 13 and 14, however, will continue innovating through the end of this decade.

\(^{38}\) 20 MHz would constitute four downlink radio carriers, each 5 MHz.

\(^{39}\) From a strict standards-development point of view, the term “LTE-Advanced” refers to the following features: carrier aggregation, 8X8 downlink MIMO, and 4XN uplink MIMO with N the number of receive antennas in the base station.”
Although later sections quantify performance and the appendix of this white paper presents functional details of the different technologies, this section provides an overview as a frame of reference, beginning with Table 5, which summarizes the key 3GPP technologies and their characteristics.

**Table 5: 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>GSM</td>
<td>TDMA</td>
<td>Most widely deployed cellular technology in the world. Provides voice and data service via GPRS/EDGE.</td>
<td>160 Kbps to 200 Kbps</td>
<td>80 Kbps to 160 Kbps</td>
</tr>
<tr>
<td>EDGE</td>
<td>TDMA</td>
<td>Data service for GSM networks. An enhancement to original GSM data service called GPRS.</td>
<td>175 Kbps to 350 Kbps expected (Single Carrier)</td>
<td>150 Kbps to 300 Kbps expected</td>
</tr>
<tr>
<td>Evolved EDGE</td>
<td>TDMA</td>
<td>Advanced version of EDGE that can double and eventually quadruple throughput rates, halve latency and increase</td>
<td>160 Kbps to 200 Kbps</td>
<td>80 Kbps to 160 Kbps</td>
</tr>
<tr>
<td>Technology Name</td>
<td>Type</td>
<td>Characteristics</td>
<td>Typical Downlink Speed</td>
<td>Typical Uplink Speed</td>
</tr>
<tr>
<td>-----------------</td>
<td>------</td>
<td>-----------------</td>
<td>------------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>UMTS</td>
<td>CDMA</td>
<td>3G technology providing voice and data capabilities. Current deployments implement HSPA for data service.</td>
<td>200 to 300 Kbps</td>
<td>200 to 300 Kbps</td>
</tr>
<tr>
<td>HSPA(^{40})</td>
<td>CDMA</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>CDMA</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(^{41})</td>
<td>1 Mbps to 4 Mbps in 5+5 MHz or in 10+5 MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.8 Mbps to 17.6 Mbps with dual carrier in 10+5 MHz.</td>
<td></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>Increased over original version of LTE</td>
<td>Increased over original version of LTE</td>
</tr>
</tbody>
</table>

User achievable rates and additional details on typical rates are covered in

\(^{40}\) HSPA and HSPA+ throughput rates are for a 5+5 MHz deployment.

\(^{41}\) “5+5 MHz” means 5 MHz used for the downlink and 5 MHz used for the uplink.
Table 6 in the section “Data Throughput,” later in this paper. Figure 14 shows the evolution of the different wireless technologies and their peak network performance capabilities.

**Figure 14: Evolution of TDMA, CDMA, and OFDMA Systems**

<table>
<thead>
<tr>
<th>Year</th>
<th>Technology</th>
<th>DL</th>
<th>UL</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>Evolved EDGE</td>
<td>1.89 Mbps</td>
<td>947 kbps</td>
</tr>
<tr>
<td>2013</td>
<td>Rel 9 HSPA+</td>
<td>168 Mbps</td>
<td>23 Mbps</td>
</tr>
<tr>
<td>2014</td>
<td>Rel 10 HSPA+</td>
<td>336 Mbps</td>
<td>69 Mbps</td>
</tr>
<tr>
<td>2015</td>
<td>Rel 11 HSPA+</td>
<td>568 Mbps</td>
<td>40 Mbps</td>
</tr>
<tr>
<td>2016</td>
<td>Rel 12 HSPA+</td>
<td>69 Mbps</td>
<td>40 Mbps</td>
</tr>
<tr>
<td>2017</td>
<td>Rel 12 LTE</td>
<td>1.2 Gbps</td>
<td></td>
</tr>
</tbody>
</table>

Throughput rates are peak theoretical network rates for that technology release. Dates refer to expected initial commercial network deployment except 2012, which shows technologies that year. There are no public announcements of deployment of WiMAX Rel 1.5 nor IEEE 802.16m. X+Y MHz indicates X MHz used on the downlink and Y MHz used on the uplink.

The development of GSM and UMTS–HSPA happens in stages corresponding to 3GPP specification releases, with each release addressing multiple technologies. For example, Release 7 optimized Voice over Internet Protocol (VoIP) for HSPA but also significantly enhanced GSM data functionality with Evolved EDGE. A summary of the different 3GPP releases is as follows:

42 After Release 99, release versions went to a numerical designation instead of designation by year.


- **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, 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.

- **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 MIMO and uplink MIMO, relays, enhanced LTE Self Optimizing Network (SON) capability, eMBMS, HetNet enhancements that include enhanced Inter-Cell Interference Coordination (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 Co-ordinated 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 8-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. An additional architectural element called Machine-Type Communications Interworking Function (MTC-IWF) will more flexibly support machine-to-machine communications.

- **Release 12**: In development, completion expected by the end of 2014. Enhancements include improved small cells/HetNets for LTE; LTE multi-antenna/site technologies, including 3D MIMO/beamforming and further CoMP/MIMO enhancements; new procedures and functionalities for LTE to support diverse traffic types; enhancements for interworking with Wi-Fi; enhancements for Machine Type Communications (MTC), SON, support for emergency and public safety; Minimization of Test Drives (MDT); advanced receivers; device-to-device communication, also referred to as proximity services; addition of Web Real Time Communication (WebRTC) to IMS; energy efficiency; more flexible carrier aggregation; further enhancements for HSPA+, including further DL and UL improvements and interworking with LTE; improved link budget for MTC; small cells/HetNets; and Scalable-UMTS.

**Architecture Evolution and Heterogeneous Networks**

The architecture of wireless networks is evolving through changes to both the radio-access network and the core network.

One of the most important developments in radio-access architecture is heterogeneous networks, with multiple types of cells serving a coverage area, varying in frequencies used, radius, and even radio technology used. HetNets offer significant increases in capacity and improvements in user:

- Smaller cells such as open femtocells (home-area coverage) and picocells (city-block-area coverage) inherently increase capacity because each cell serves a smaller number of users.
- Strategic placement of picocells within the macro cell provides means to absorb traffic in areas where there are higher concentrations of users. This could include business locations, airports, sports arenas, and so forth.
- Smaller cells can also improve signal quality in areas where the signal from the macro cell is weak.

Essential elements for practical HetNet deployment are self-optimization and self-configuration, especially as the industry transitions from hundreds of thousands of cells to millions. The appendix covers technical aspects of HetNets in the section, “Heterogeneous Networks and Self-Optimization.” While promising in the long term, one challenge in deploying a large number of small cells is backhaul since access to fiber is not necessarily available and line-of-sight microwave links are not necessarily feasible. Management is another challenge. Figure 15 depicts the challenges.
As for the core network, 3GPP is defining a series of enhancements to improve network performance and the range of services provided, some of which will stem from a shift to all-IP architectures.

One way to improve core-network performance is through flatter architectures. The more hierarchical a network, the more easily it can be managed centrally; the tradeoff, however, is reduced performance, especially for data communications, because packets must traverse and be processed by more nodes in the network.

In Release 8, 3GPP defined an entirely new core network, called the EPC, previously referred to as SAE. The key features and capabilities of EPC include:

- Reduced latency and higher data performance through a flatter architecture.
- Support for both LTE radio-access networks and interworking with GSM-HSPA radio-access networks.
- The ability to integrate non-3GPP networks such as WiMAX and Wi-Fi.
- Optimization for all services provided via IP.
- Sophisticated, network-controlled, quality-of-service architecture.
Another core network development is the new infrastructure to support voice in the packet domain through the IP Multimedia Subsystem (IMS). IMS also enables new services and applications, as discussed in the next section.

This paper provides further details in the sections in the appendix on HSPA Evolution (HSPA+), LTE, EPC, and IMS.

**Wi-Fi Integration and Data Offload**

As data loads increase, operators are seeking to offload some data traffic to other networks, particularly Wi-Fi networks. Some Wi-Fi integration technologies reduce demand on the radio-access network, some reduce demand on the core network, and others make the use of Wi-Fi more seamless for users, meaning user devices automatically and securely connect to desired Wi-Fi networks. Some people consider Wi-Fi as part of HetNets, while others do not. For now, we will discuss them separately.

The IEEE 802.11 family of technologies has experienced rapid growth, mainly in private deployments. The latest 802.11 standard, 802.11ac, offers peak theoretical throughputs in excess of 1 Gbps and improved range through use of higher-order MIMO. Complementary 802.11 standards increase the attraction of the technology: 802.11e for QoS enables VoIP and multimedia; 802.11i provides robust security; 802.11r delivers fast roaming, necessary for voice handover across access points; and 802.11u enables better hotspot operation.

Leveraging this success, operators—including cellular operators—are offering hotspot service in public areas including airports, fast-food restaurants, shopping malls, and hotels.

One 4G Americas member estimates that 40% of traffic can potentially be offloaded based on the following observations:

- About 80% of traffic is indoors.
- About 80% of traffic is from smartphones.
- About 80% of smartphones have Wi-Fi.
- About 80% of smartphone users take advantage of Wi-Fi connections.

Different amounts of traffic can be offloaded depending on the assumptions used. Over time, however, an increasing percentage of traffic will be carried by small cells, whether Wi-Fi or cellular.

Wi-Fi has huge inherent capacity for two reasons. First, a large amount of spectrum (approximately 500 MHz) is available across the 2.4 GHz and 5 GHz bands. Second, the spectrum is used in small coverage areas, resulting in high frequency reuse and much higher throughput rates per square meter of coverage versus wide-area networks. Nevertheless, due to huge demand, many public Wi-Fi networks at airports, hotels, convention centers, and other areas are experiencing congestion. Although offloading onto Wi-Fi can reduce traffic on the core network, the Wi-Fi network does not necessarily

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43 Source: Nokia Siemens Networks white paper, “Deployment Strategies for Heterogeneous Networks,” 2012. 80% X 80% X 80% X 80% = 40%.
have greater spare capacity than the cellular network. The goal of future integrated cellular/Wi-Fi networks is to intelligently load balance between the two technologies.

One recently completed industry initiative is Hotspot 2.0, also called Next Generation Hotspot. Using the IEEE 802.11u standard that allows devices to determine what services are available from an access point, HotSpot 2.0 simplifies the process by which users connect to hotspots, automatically identifying roaming partnerships and simplifying authentication and connections. It also provides for encrypted communications over the radio link. Devices and networks based on Release 1 of HotSpot 2.0 are available, and work has begun on Release 2, under which the network, rather than the device, will control connections.

Integration between mobile broadband and Wi-Fi networks can either be loose or tight. Loose integration means data traffic routes directly to the Internet and minimizes traversal of the operator network. This is called “local breakout.” Tight integration means data traffic, or select portions, may traverse the operator core network. This is beneficial in situations in which the operators offer value-added services (such as internal portals) that can be accessed only from within the core.

Essential to successful data offload is providing a good subscriber experience. This mandates measures such as automatically provisioning subscriber devices with the necessary Wi-Fi configuration options and automatically authenticating subscribers on supported public Wi-Fi networks. There are many stakeholders working toward tighter integration between Wi-Fi and cellular networks. See the section “Wi-Fi Integration” in the appendix for technical details on 3GPP and other industry standards and initiatives.

Service Evolution

Not only do 3GPP technologies provide continual improvements in capacity and data performance, they also expand available services, including Fixed Mobile Convergence (FMC), IMS, and broadcasting technologies. This section provides an overview of these topics, and the appendix goes into greater detail.

FMC refers to the integration of fixed services (such as telephony provided by wireline or Wi-Fi) with mobile cellular-based services. For users, FMC simplifies how these services communicate, making it possible for them to use one device at work, where it connects via a Wi-Fi network or macrocellular network, and at home, where it might connect via a Wi-Fi network or femtocell. Users can also benefit from single voice mailboxes and single phone numbers, as well as controlling how and with whom they communicate. For operators, FMC allows the consolidation of core services across multiple-access networks. For instance, an operator can offer complete VoIP-based services that operate over Digital Subscriber Line (DSL), Wi-Fi, or mobile broadband. FMC can also offload data-intensive applications like video streaming from the macro network.

There are various approaches for FMC, including Generic Access Network (GAN), formerly known as Unlicensed Mobile Access (UMA); femtocells; and IMS. With GAN, GSM-HSPA

44 For example, user devices can be authenticated based on their SIM credentials. Or users can register or click through an agreement, and then not need to redo that with future associations.

45 The IEEE 802.11i standard has provided encryption for 802.11 communications for many years; however, most hotspots have not implemented this encryption, whereas Hotspot 2.0 does.
devices can connect via Wi-Fi or cellular connections for both voice and data. UMA/GAN is a 3GPP technology, and it has been deployed by a number of operators, including T-Mobile in the United States.

An alternative to using Wi-Fi for the “fixed” portion of FMC is femtocells, tiny base stations that cost little more than a Wi-Fi access point, and, like Wi-Fi, leverage a subscriber’s existing wireline-broadband connection (for example, DSL). Instead of operating on unlicensed bands, femtocells use the operator’s licensed bands at very low power levels. The key advantage of femtocells is that any single-mode, mobile-communications device a user has can access the femtocell.

IMS is another important convergence technology, offering access to core services and applications via multiple-access networks. IMS is more powerful than GAN because it not only supports FMC but also a much broader range of potential applications. Although defined by 3GPP, the Third Generation Partnership Project 2 (3GPP2), CableLabs and WiMAX have adopted IMS. IMS is the VoIP platform for CDMA 2000 EV-DO, WiMAX, HSPA, and LTE networks.

IMS allows the creative blending of different types of communications and information, including voice, video, instant messaging (IM), presence information, location, and documents. Application developers can create applications never before possible, and users can communicate in entirely new and dynamic ways.

For example, during an interactive text-based chat session, a user could launch a voice call. Or during a voice call, a user could suddenly add a simultaneous video connection, or start transferring files. While browsing the Web, a user could decide to speak to a customer-service representative. IMS will be a key platform for all-IP architectures for both HSPA and LTE. Although IMS adoption by cellular operators was initially slow, deployment will accelerate as operators make packet voice service available for LTE.

**Rich Communications Suite**

An initiative called Rich Communications Suite (RCS), supported by many operators and vendors, builds on IMS technology to provide a consistent feature set, as well as implementation guidelines, use cases, and reference implementations. RCS uses existing standards and specifications from 3GPP, OMA, and GSMA and enables interoperability of supported features across operators that support the suite. RCS supports both circuit-switched and packet-switched voice and can interoperate with LTE packet voice.

Core features include:

- User capability exchange or service discovery with which users can know the capabilities of other users.
- Enhanced (IP-based) messaging (supporting text, IM, and multimedia) with chat and messaging history.
- Enriched calls that include multimedia content (such as photo or video sharing) during voice calls. This could become the primary way operators offer video calling.

**Multicast and Broadcast**

Another important new service is video streaming via multicast or broadcast functions. 3GPP has defined multicast/broadcast capabilities for both HSPA and LTE. Although Mobile TV services have experienced little business success so far, the fact remains that
broadcasting uses the radio resource much more efficiently than having separate point-to-point streams for each user. For example, users at a sporting event might enjoy watching replays on their smartphones. The technology supports these applications; it is a matter of operators and content providers finding appealing applications. The appendix covers technical aspects in more detail.

**Voice Support**

While 2G and 3G technologies were deployed from the beginning with both voice and data capabilities, LTE networks can be deployed with or without voice support. Moreover, there are two methods available: circuit-switched fallback (CSFB) to 2G/3G and VoIP. Most operators deploying LTE now are using CSFB initially and migrating to VoIP methods with Voice over LTE (VoLTE) that uses IMS, and which will see initial deployments at the end of 2013 and volumes ramping up in 2014 to 2015.

For the time being, 3GPP operators with UMTS/HSPA networks will continue to use circuit-switched voice for their 3G connections, although packet voice over HSPA (VoHSPA) methods have been defined. VoHSPA can increase efficiency and is under active consideration, as are enhancements to WCDMA circuit-switched voice.

Using VoLTE, operators are planning high-definition (HD) voice using the new Adaptive Multi-Rate Wideband (AMR-WB) voice codec. HD voice not only improves voice clarity and intelligibility, it better suppresses background noise. HD voice will initially function only between callers on the same network, however.

Other advantages of LTE’s packetized voice include being able to combine it with other services, such as video calling; faster call setup; and high voice spectral efficiency.

See the appendix for more detail on HSPA and LTE voice support.

**Backhaul**

As radio link throughput increases, the circuits connecting cell sites to the core network must be able to handle the increased load. With many cell sites today still serviced by just a small number of T1/E1 circuits, each able to carry only 1.5/2.0 Mbps, operators are in the process of upgrading backhaul capacity to obtain the full benefit of next-generation wireless technologies. Approaches include very-high-bit-rate digital subscriber line (VDSL), optical Ethernet, point-to-point microwave systems, millimeter-wave radio, and potentially even mesh-based Wi-Fi.

An LTE system with 1.4 bps per hertz (Hz) of downlink spectral efficiency in 10 MHz on three sectors has up to 42 Mbps average downlink cell throughput. Additionally, any technology’s ability to reach its peak spectrum efficiency is somewhat contingent on the system’s ability to reach the instantaneous peak data rates allowed by that technology. For example, a system claiming spectrum efficiency of 1.4 bps/Hz (as described above) might rely on the ability to reach 100 Mbps instantaneously to achieve this level of spectrum efficiency. Any constraint on the transport system below 100 Mbps will restrict the range of achievable throughput and, in turn, impact the spectral efficiency of the system. To provide the greatest flexibility in moving forward with LTE-Advanced, which

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will need even greater backhaul capability, many operators are planning 1 Gbps backhaul links. See the appendix for additional backhaul discussion.

**Network Deployment**

While early 3G deployments used separate 2G/3G Serving GPRS Support Nodes (SGSNs) and Mobile Switching Centers (MSCs), all-new MSC and/or SGSN products are capable of supporting both GSM and UMTS-HSPA radio-access networks. Similarly, new HSPA equipment is upgradeable to LTE through a software upgrade.

A candidate feature for Release 12 is scalable UMTS, which uses one-quarter or one-half the normal 5 MHz radio channel width. This flexibility could facilitate UMTS deployment for some operators, particularly those refarming GSM spectrum, which operates in smaller spectrum allocations. Scalable UMTS scales the chip rate via a method referred to as “time dilation.”

The upgrade to LTE has proven relatively straightforward, with new LTE infrastructure having the ability to reuse a significant amount of the UMTS-HSPA cell site and base station infrastructure, including using the same shelters, towers, antennas, power supplies, and climate control. Some vendors have different, so-called “zero-footprint” solutions that allow operators to use empty space to enable reuse of existing sites without the need for new floor space.

An operator can add LTE capability simply by adding an LTE baseband card. New multi-standard radio units (HSPA and LTE), as well as LTE-only baseband cards, are mechanically compatible with older building practices, so operators can use empty space in an old base station for LTE baseband cards, thus enabling reuse of existing sites without the need for new floor space, as mentioned previously.

Base station equipment is available for many bands, including 700 MHz, 1.7/2.1 GHz AWS, 1900 PCS, and 2.6 GHz BRS. On the device side, gear with multimode chipsets can easily operate across UMTS and LTE networks.

Figure 16 presents various scenarios for deploying LTE, including operators that today are using CDMA2000, UMTS, GSM, and WiMAX. For example, as shown in the first bar, a CDMA2000 operator in Scenario A could defer LTE deployment to the longer term. In Scenario B, in the medium term, the operator could deploy a combination of 1xRTT, EV-DO Rev A/B, and LTE, and, in the long term, migrate EV-DO data traffic to LTE. In Scenario C, a CDMA2000 operator with just 1xRTT could introduce LTE as a broadband service and, in the long term, migrate 1xRTT users to LTE, including voice service.

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47 For further details, refer to Qualcomm, “Scalable UMTS (S-UMTS) – Solution for Fragmented Spectrum Refarming,” February 2013.
3GPP and 3GPP2 have both specified detailed migration options to LTE. One option for GSM operators that have not yet committed to UMTS, and do not have an immediate need to do so, is to migrate directly from GSM/EDGE or Evolved EDGE to LTE with networks and devices supporting dual-mode GSM-EDGE/LTE operation.

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48 Source: A 4G Americas member company.
Other Wireless Technologies

Although GSM/HSPA/LTE networks are dominating global cellular-technology deployments, operators are deploying other wireless technologies to serve both wide and local areas. This section of the paper looks at the relationship between GSM/UMTS/LTE and some of these other technologies.

**CDMA2000**

CDMA2000, consisting principally of One Carrier Radio Transmission Technology (1xRTT) and One Carrier-Evolved, Data-Optimized (1xEV-DO) versions, is the other major cellular technology deployed in many parts of the world. 1xRTT is currently the most widely deployed CDMA2000 version. In June 2013, there were 114 EV-DO Rel. 0 networks, 174 EV-DO Rev. A networks, and 12 EV-DO Rev B networks deployed worldwide.49

Current networks use either Rel. 0, Rev. A, or Rev-B radio-interface specifications. EV-DO Rev. A incorporates a more efficient uplink, which has spectral efficiency similar to that of HSUPA. Operators started to make EV-DO Rev. A commercially available in 2007 and EV-DO Rev. B available in 2010.

EV-DO uses many of the same techniques for optimizing spectral efficiency as HSPA, including higher order modulation, efficient scheduling, turbo-coding, and adaptive modulation and coding. For these reasons, it achieves spectral efficiency that is virtually the same as HSPA. The 1x technologies operate in the 1.25 MHz radio channels, compared with the 5 MHz channels UMTS uses, resulting in lower theoretical peak rates, although average throughputs for high-level network loading are similar. Under low- to medium-load conditions, because of the lower peak achievable data rates, EV-DO or EV-DO Rev. A achieves a lower typical performance level than HSPA. Operators have quoted 400 to 700 kilobits per second (Kbps) typical downlink throughput for EV-DO Rev. 0 and between 600 Kbps and 1.4 Mbps for EV-DO Rev. A.51

Although in the past it was not possible to have simultaneous voice and data sessions with 1X voice and EV-DO data, this is now possible with a capability called Simultaneous 1X Voice and EV-DO Data (SVDO), available in some new handset chipsets.52 Similarly, devices can simultaneously have 1X voice and LTE data sessions using a capability called Simultaneous Voice and LTE (SVLTE).

EV-DO could also eventually provide voice service using VoIP protocols through EV-DO Rev. A, which includes a higher-speed uplink, QoS mechanisms in the network, and protocol optimizations to reduce packet overhead, as well as the ability to address problems such as jitter. No operators have announced VoIP deployment plans for EV-DO.

52 Source: 4G Americas member company.
3GPP2 has also defined EV-DO Rev. B, which can combine up to 15 1.25 MHz radio channels in 20 MHz, significantly boosting peak theoretical rates to 73.5 Mbps. More likely, an operator would combine three radio channels in 5 MHz. Such an approach, by itself, does not necessarily increase overall capacity, but it does offer users higher peak-data rates.

Beyond EV-DO Rev. B, 3GPP2 in 2010 finalized the specifications for EV-DO Rev. C. Beyond Rev. B, however, the industry tends to use the term “DO Advanced.” One important feature of DO Advanced is network load balancing that connects mobile devices to less loaded sectors even if the signal is weaker.

1X Advanced will significantly increase voice capacity over CDMA2000 1xRTT. CDMA operators are not only considering 1X Advanced to increase voice capacity, but also to free up spectrum to support more data services via additional EV-DO radio carriers or LTE.

3GPP2 has defined technical means to integrate CDMA2000 networks with LTE along two available approaches:

1. **Loose coupling.** This involves little or no intersystem functionality, and resources are released in the source system prior to handover execution.

2. **Tight coupling.** The two systems intercommunicate with network-controlled make-before-break handovers. Tight coupling allows maintenance of data sessions with the same IP address. This will likely involve a more complex implementation than loose coupling.

CDMA2000 is clearly a viable and effective wireless technology and, to its credit, many of its innovations have been brought to market ahead of competing technologies. Globally, however, most CDMA2000 operators plan to deploy LTE.

**WiMAX**

WiMAX was developed as a potential alternative to cellular technology for wide-area wireless networks. Based on OFDMA and accepted by the ITU as an IMT-2000 (3G technology) under the name “OFDMA TDD Wireless Metropolitan Area Network” (WMAN), WiMAX tried to challenge existing wireless technologies by promising greater capabilities and greater efficiencies than alternative approaches. But as WiMAX, particularly mobile WiMAX, was deployed, vendors continued to enhance HSPA, and operators accelerated their LTE deployments. Consequently, WiMAX advantages were no longer perceived as compelling.

WiMAX has gained the greatest traction in developing countries as an alternative to wireline deployment. In the United States, Clearwire, Sprint Nextel, and others (Intel, Google, Comcast, Time Warner Cable, and Bright House Networks) created a joint venture to deploy a nationwide WiMAX network. In June 2013, this network was available in 80 U.S. cities and covered more than 130 million people.\(^3\) Clearwire, however, has started deploying TDD-LTE, which will be the basis of further network expansion.

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\(^3\) Source: Clearwire home Web page.
The original specification, IEEE 802.16, was completed in 2001 and was intended primarily for telecom backhaul applications in point-to-point, line-of-sight configurations using spectrum above 10 GHz. IEEE 802.16 uses a radio interface based on a single-carrier waveform.

The next major step in the evolution of IEEE 802.16 occurred in 2004 with the release of the IEEE 802.16-2004 standard. It added multiple radio interfaces, including one based on OFDM-256 and one based on OFDMA. IEEE 802.16-2004 also supports point-to-multipoint communications, sub-10 GHz operation, and non-line-of-sight communications. Like the original version of the standard, operation is fixed, meaning that subscriber stations are typically immobile. Potential applications include wireless Internet Service Provider (ISP) service and local telephony bypass (as an alternative to cable modem or DSL service). Vendors can design equipment for either licensed or unlicensed bands.

IEEE 802.16e-2005, and then IEEE 802.16-2009, added mobility capabilities including support for radio operation while mobile, handovers across base stations, and handovers across operators. Unlike IEEE 802.16-2004, which operates in both licensed and unlicensed bands, IEEE 802.16e-2005 (referred to as mobile WiMAX) uses licensed bands. Current WiMAX profiles emphasize TDD operation. Mobile WiMAX networks are not backward-compatible with IEEE 802.16-2004 networks.

Current mobile WiMAX networks use 2X2 MIMO or 4X2 MIMO, TDD, and 10 MHz radio channels in a profile defined by the WiMAX Forum known as WiMAX Wave 2 or, more formally, as WiMAX System Profile 1.0. Beyond Release 1.0, the WiMAX Forum defined a profile called WiMAX Release 1.5. This profile includes various refinements intended to improve efficiency and performance and could be available for deployment in a similar timeframe as LTE.

Release 1.5 enhancements include Medium Access Control (MAC) overhead reductions for VoIP (persistent scheduling), handover optimizations, load balancing, location-based services support, Frequency Division Duplex (FDD) operation, 64 QAM in the uplink, downlink adaptive modulation and coding, closed-loop MIMO (FDD mode only), and uplink MIMO. There are no current Release 1.5 deployment plans.

A subsequent version, Mobile WiMAX 2.0, has been designed to address the performance requirements of ITU IMT-Advanced Project and is standardized in a new IEEE standard, IEEE 802.16m. It is uncertain whether 802.16m will ever be commercialized.

WiMAX employs many of the same mechanisms as HSPA to maximize throughput and spectral efficiency, including high-order modulation, efficient coding, adaptive modulation and coding, and Hybrid Automatic Repeat Request (HARQ). The principal difference from HSPA is IEEE 802.16e-2005’s use of OFDMA. In 5 MHz to 10 MHz radio channels, there is no evidence indicating that WiMAX has any performance advantage compared with HSPA+.

Relative to LTE, WiMAX has the following technical disadvantages: 5 msec frames instead of 1 msec frames, Chase combining instead of incremental redundancy, coarser granularity for modulation and coding schemes, and vertical coding instead of horizontal coding.\(^{54}\) One deployment consideration is that TDD requires network synchronization. It

is not possible for one cell site to be transmitting and an adjacent cell site to be receiving at the same time. Different operators in the same band must either coordinate their networks or have guard bands to ensure that networks don’t interfere with one another.

Although IEEE 802.16e exploits significant radio innovations, similar to HSPA+ and LTE, it faces challenges from economies of scale. Compared with GSM/HSPA/LTE subscribers numbering in the billions, Infonetics Research in 2012 projected 132 million WiMAX subscribers by 2016. There do not appear to be recent projections on WiMAX growth from other sources, but momentum for WiMAX is declining as LTE becomes ever more established.

With respect to spectral efficiency, WiMAX is comparable to HSPA+, as discussed in the section “Spectral Efficiency” that follows. As for data performance, HSPA+ in Release 8—with a peak rate of 42 Mbps—essentially matches mobile WiMAX in 10 MHz TDD 3:1 Downlink:Uplink (DL:UL) using 2X2 MIMO with a peak rate of 46 Mbps.

Comparison of Wireless Technologies

This section of the paper compares different wireless technologies, looking at throughput, latency, spectral efficiency, and market position.

**Data Throughput**

Data throughput is an important metric for quantifying network throughput performance. Unfortunately, the ways in which various organizations quote throughputs vary tremendously, often resulting in misleading claims. The intent of this paper is to realistically represent the capabilities of these technologies.

One method of representing a technology’s throughput is what people call “peak throughput” or “peak network speed,” which refers to the fastest possible transmission speed over the radio link and is generally based on the highest order modulation available and the least amount of coding (error correction) overhead. Peak network speed is also usually quoted at layer 2 of the radio link. Because of protocol overhead, actual application throughput may be 10% to 20% lower (or more) than this layer-2 value.

Another method is to disclose throughputs actually measured in deployed networks with applications such as File Transfer Protocol (FTP) under favorable conditions, which assume light network load (as low as one active data user in the cell sector) and favorable signal propagation. This number is useful because it demonstrates the high-end, actual capability of the technology in current deployments, referred to in this paper as the “peak user rate.” Average rates are lower than this peak rate and are difficult to predict because they depend on a multitude of operational and network factors. Except when the network is congested, however, the majority of users should experience throughput rates higher than one-half of the peak achievable rate.

Some operators, primarily in the United States, also quote typical throughput rates, which are based on throughput tests the operators have done across their operating networks and incorporate a higher level of network load. Although the operators do not disclose the precise methodologies they use to establish these figures, the values provide a good indication of what users can realistically expect.
Table 6 presents the technologies in terms of peak network throughput rates, peak user rates (under favorable conditions), and typical rates. It omits values that are not yet known, such as for future technologies.

The projected typical rates for HSPA+ and LTE show a wide range because these technologies exploit favorable radio conditions to achieve high throughput rates, but under poor radio conditions throughput rates are lower.
### Table 6: Throughput Performance of Different Wireless Technologies (Blue Indicates Theoretical Peak Rates, Green Typical)

<table>
<thead>
<tr>
<th></th>
<th>Downlink</th>
<th>Uplink</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak Network Speed</td>
<td>Peak and/or Typical User Rate</td>
</tr>
<tr>
<td>EDGE (type 2 MS)</td>
<td>473.6 Kbps</td>
<td>473.6 Kbps</td>
</tr>
<tr>
<td>EDGE (type 1 MS)</td>
<td>236.8 Kbps</td>
<td>200 Kbps peak</td>
</tr>
<tr>
<td>(Practical Terminal)</td>
<td></td>
<td>160 to 200 Kbps typical</td>
</tr>
<tr>
<td>Evolved EDGE</td>
<td>1184 Kbps$^{59}$</td>
<td>1 Mbps peak</td>
</tr>
<tr>
<td>(type 1 MS)$^{58}$</td>
<td></td>
<td>350 to 700 Kbps typical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Dual Carrier)</td>
</tr>
<tr>
<td>Evolved EDGE</td>
<td>1894.4$^{62}$ Kbps</td>
<td>947.2 Kbps$^{63}$</td>
</tr>
<tr>
<td>(type 2 MS)$^{61}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evolved EDGE</td>
<td>6.4 Mbps</td>
<td></td>
</tr>
<tr>
<td>(16 carriers)$^{64}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^{56}$ Assumes four-to-five downlink timeslot devices (each timeslot capable of 40 Kbps).

$^{57}$ Assumes two-to-four uplink timeslot devices (each timeslot capable of 40 Kbps).

$^{58}$ A type 1 Evolved EDGE MS can receive on up-to-ten timeslots using two radio channels and can transmit on up-to-four timeslots in one radio channel using 32 QAM modulation (with turbo coding in the downlink).

$^{59}$ Type 1 mobile, 10 slots downlink (dual carrier), DBS-12(118.4 Kbps/slot).

$^{60}$ Type 1 mobile, 4 slots uplink, UBS-12 (118.4 Kbps/slot).

$^{61}$ A type 2 Evolved EDGE MS can receive on up-to-six timeslots using two radio channels and can transmit on up-to-eight timeslots in one radio channel using 32 QAM modulation (with turbo coding in the downlink).

$^{62}$ Type 2 mobile, 16 slots downlink (dual carrier) at DBS-12 (118.4 Kbps/slot).

$^{63}$ Type 2 mobile, 8 slots uplink, UBS-12 (118.4 Kbps/slot).

$^{64}$ Based on subsequent features through Release 12, 16 downlink carriers, 200 kbps per carrier, 8 PSK MIMO.
<table>
<thead>
<tr>
<th></th>
<th>Downlink</th>
<th></th>
<th></th>
<th>Uplink</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Peak</td>
<td>Peak and/or Typical</td>
<td>Peak</td>
<td>Typical</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Network</td>
<td>User Rate</td>
<td>Network Speed</td>
<td>User Rate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UMTS WCDMA Release 99</td>
<td>2.048 Mbps</td>
<td></td>
<td></td>
<td>768 Kbps</td>
<td></td>
</tr>
<tr>
<td>UMTS WCDMA Release 99 (Practical Terminal)</td>
<td>384 Kbps</td>
<td>350 Kbps peak</td>
<td>384 Kbps</td>
<td>350 Kbps peak</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>200 to 300 Kbps typical</td>
<td></td>
<td>200 to 300 Kbps typical</td>
<td></td>
</tr>
<tr>
<td>HSDPA Initial Devices (2006)</td>
<td>1.8 Mbps</td>
<td>&gt; 1 Mbps peak</td>
<td>384 Kbps</td>
<td>350 Kbps peak</td>
<td></td>
</tr>
<tr>
<td>HSDPA</td>
<td>14.4 Mbps</td>
<td></td>
<td></td>
<td>384 Kbps</td>
<td></td>
</tr>
<tr>
<td>HSPA^65 Initial Implementation</td>
<td>7.2 Mbps</td>
<td>&gt; 5 Mbps peak</td>
<td>2 Mbps</td>
<td>&gt; 1.5 Mbps peak</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>700 Kbps to 1.7 Mbps typical</td>
<td></td>
<td>500 Kbps to 1.2 Mbps typical</td>
<td></td>
</tr>
<tr>
<td>HSPA</td>
<td>14.4 Mbps</td>
<td></td>
<td></td>
<td>5.76 Mbps</td>
<td></td>
</tr>
<tr>
<td>HSPA+ (DL 64 QAM, UL 16 QAM, 5+5 MHz)</td>
<td>21.6 Mbps</td>
<td>1.9 Mbps to 8.8 Mbps typical</td>
<td>11.5 Mbps</td>
<td>1 Mbps to 4 Mbps typical</td>
<td></td>
</tr>
<tr>
<td>HSPA+ (2X2 MIMO, DL 16 QAM, UL 16 QAM, 5+5 MHz)</td>
<td>28 Mbps</td>
<td></td>
<td>11.5 Mbps</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

^65 High Speed Packet Access (HSPA) consists of systems supporting both High Speed Downlink Packet Access (HSDPA) and High Speed Uplink Packet Access (HSUPA).

^66 Typical downlink and uplink throughput rates based on AT&T press release, June 4, 2008

^67 Source: 4G Americas member company analysis. Assumes Release 7 with 64 QAM and F-DPCH. Single user. 50% loading in neighboring cells. Higher rates expected with subsequent 3GPP releases.
<table>
<thead>
<tr>
<th></th>
<th>Downlink</th>
<th>Uplink</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Peak Network Speed</td>
<td>Peak and/or Typical User Rate</td>
</tr>
<tr>
<td>HSPA+ (2X2 MIMO, DL 64 QAM, UL 16 QAM, 5+5 MHz)</td>
<td>42 Mbps</td>
<td>11.5 Mbps</td>
</tr>
<tr>
<td>HSPA+ (DL 64 QAM, UL 16 QAM, Dual Carrier, 10+5 MHz)</td>
<td>42 Mbps</td>
<td>Approximate doubling of 5+5 MHz rates - 3.8 to 17.6 Mbps.</td>
</tr>
<tr>
<td>HSPA+ (2X2 MIMO DL, DL 64 QAM, UL 16 QAM, Dual Carrier, 10+10 MHz)</td>
<td>84 Mbps</td>
<td>23 Mbps</td>
</tr>
<tr>
<td>HSPA+ (2X2 MIMO DL, DL 64 QAM, UL 16 QAM, Quad Carrier, 20+10 MHz)</td>
<td>168 Mbps</td>
<td>23 Mbps</td>
</tr>
<tr>
<td>HSPA+ (2X2 MIMO DL and UL, DL 64 QAM, UL 16 QAM, Quad Carrier, 40+10 MHz)</td>
<td>336 Mbps</td>
<td>69 Mbps</td>
</tr>
<tr>
<td>LTE (2X2 MIMO, 10+10 MHz)</td>
<td>70 Mbps</td>
<td>6.5 to 26.3 Mbps$^68$</td>
</tr>
<tr>
<td>LTE (4X4 MIMO, 20+20 MHz)</td>
<td>300 Mbps</td>
<td>71 Mbps$^70$</td>
</tr>
<tr>
<td>LTE Advanced (8X8 MIMO, 20+20 MHz, DL 64 QAM, UL 64 QAM)</td>
<td>1.2 Gbps</td>
<td>568 Mbps</td>
</tr>
</tbody>
</table>

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$^68$ Source: 4G Americas member company analysis for downlink and uplink. Assumes single user with 50% load in other sectors. AT&T and Verizon are quoting typical user rates of 5-12 Mbps on the downlink and 2-5 Mbps on the uplink for their networks.

$^69$ Assumes 64 QAM. Otherwise 22 Mbps with 16 QAM.

$^70$ Assumes 64 QAM. Otherwise 45 Mbps with 16 QAM.
<table>
<thead>
<tr>
<th></th>
<th>Downlink</th>
<th>Uplink</th>
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<tbody>
<tr>
<td></td>
<td><strong>Peak Network Speed</strong></td>
<td><strong>Peak and/or Typical User Rate</strong></td>
</tr>
<tr>
<td>CDMA2000 1XRTT</td>
<td>153 Kbps</td>
<td>130 Kbps peak</td>
</tr>
<tr>
<td>CDMA2000 1XRTT</td>
<td>307 Kbps</td>
<td>307 Kbps</td>
</tr>
<tr>
<td>CDMA2000 EV-DO Rel 0</td>
<td>2.4 Mbps</td>
<td>&gt; 1 Mbps peak</td>
</tr>
<tr>
<td>CDMA2000 EV-DO Rev A</td>
<td>3.1 Mbps</td>
<td>&gt; 1.5 Mbps peak</td>
</tr>
<tr>
<td></td>
<td></td>
<td>600 Kbps to 1.4 Mbps typical</td>
</tr>
<tr>
<td></td>
<td>Proportional increase of Rev A typical rates based on number of carriers.</td>
<td>5.4 Mbps</td>
</tr>
<tr>
<td>CDMA2000 EV-DO Rev B (3 radio channels 5+5 MHz)</td>
<td>14.7 Mbps</td>
<td>Proportional increase of Rev A typical rates based on number of carriers.</td>
</tr>
<tr>
<td></td>
<td>73.5 Mbps</td>
<td>27 Mbps</td>
</tr>
<tr>
<td>WiMAX Release 1.0 (10 MHz TDD, DL/UL=3, 2x2 MIMO)</td>
<td>46 Mbps</td>
<td>1 to 5 Mbps typical</td>
</tr>
<tr>
<td>WiMAX Release 1.5</td>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>


72 Assuming use of 64 QAM.

### HSPA+ Throughput

Performance measurements of HSPA+ networks show significant gains over HSPA. Figure 17 shows the cumulative distribution function of throughput values in a commercially deployed Release 8 HSPA+ network in an indoor-coverage scenario. The figure shows significant performance gains from higher-order modulation and MIMO.

**Figure 17: HSPA+ Performance Measurements Commercial Network (5+5 MHz)**

The figure shows a reasonably typical indoor scenario in a macro-cell deployment. Under better radio conditions, HSPA+ will achieve higher performance results.

Figure 18 shows the benefit of dual-carrier operation (no MIMO employed), which essentially doubles throughputs over single carrier operation.

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<thead>
<tr>
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<th>Downlink</th>
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<tr>
<td></td>
<td>Peak</td>
<td>Peak and/or Typical</td>
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<tr>
<td></td>
<td>Network</td>
<td>User Rate</td>
<td>Network</td>
</tr>
<tr>
<td>Speed</td>
<td>Speed</td>
<td></td>
<td>Speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>and/or</td>
</tr>
<tr>
<td>IEEE 802.16m</td>
<td>&gt; 1 Gbps</td>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>

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74 Source: 4G Americas member company contribution.
Figure 18: Dual-Carrier HSPA+ Throughputs\textsuperscript{75}

\textsuperscript{75} Source: 4G Americas member company contribution. 64 QAM.
**LTE Throughput**

Figure 19 shows the result of a drive test in a commercial LTE network with a 10 MHz downlink carrier demonstrating 20 Mbps to 50 Mbps throughput rates across much of the coverage area. Throughput rates would double with a 20+20 MHz configuration.

**Figure 19: Drive Test of Commercial European LTE Network (10+10 MHz)**

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76 Source: Ericsson.
Figure 20 provides additional insight into LTE downlink throughput, showing layer 1 throughput simulated at 10 MHz bandwidth using the Extended Vehicular A 3 km/hour channel model. The figure shows the increased performance obtained with the addition of different orders of MIMO. Note how throughput improves based on higher signal to noise ratio (SNR).

**Figure 20: LTE Throughput in Various Modes**

Actual throughput rates that users experience are lower than the peak rates and depend on a variety of factors:

1. RF Conditions and User Speed. Peak rates depend on optimal conditions. Suboptimal conditions include being at the edge of the cell or moving at high speed, resulting in lower throughput.

---

2. **Network Loading.** Like all wireless systems, throughput rates go down as more devices simultaneously use the network. Throughput degradation is linear.

Figure 21 shows how dramatically throughput rates can vary by number of active users and radio conditions. The higher curves are for better radio conditions.

**Figure 21: LTE Actual Throughput Rates Based on Conditions**

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**Latency**

As important as throughput is network latency, defined as the round-trip time it takes data to traverse the network. Each successive data technology from GPRS forward reduces latency, with LTE networks having latency as low as 15 msec. Ongoing improvements in each technology mean that all of these values will go down as vendors and operators fine-tune their systems. Figure 22 shows the latency of different 3GPP technologies.

**Figure 22: Latency of Different Technologies**

![Latency Graph](image)

The values shown in Figure 22 reflect measurements of commercially deployed technologies, with EDGE Release 4 having sub-100-msec latency, EDGE Release 7 achieving 70 to 95 msec, HSPA+ 25 to 30 msec, and LTE 15 to 20 msec.

**Spectral Efficiency**

The evolution of data services is characterized by an increasing number of users with ever-higher bandwidth demands. As the wireless data market grows, deploying wireless technologies with high spectral efficiency is of paramount importance. Keeping all other things equal, including frequency band, amount of spectrum, and cell site spacing, an

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79 Source: 4G Americas member companies. Measured between subscriber unit and a node immediately external to wireless network. Does not include Internet latency. Note that there is some variation in latency based on network configuration and operating conditions.
increase in spectral efficiency translates to a proportional increase in the number of users supported at the same load per user—or, for the same number of users, an increase in throughput available to each user.

Increased spectral efficiency, however, comes at a price because it generally involves greater complexity for both user and base station equipment. Complexity can arise from the increased number of calculations performed to process signals or from additional radio components. Hence, operators and vendors must balance market needs against network and equipment costs. OFDMA technologies are attractive because they achieve higher spectral efficiency with lower overall complexity, especially in larger bandwidths. The roadmap for the EDGE/HSPA/LTE family of technologies provides a wide portfolio of options that increase spectral efficiency.

When determining the best area on which to focus future technology enhancements, it is interesting to note that HSDPA, 1xEV-DO, and IEEE 802.16e-2005 all have highly optimized links—that is, physical layers. In fact, as shown in Figure 23, the link layer performance of these technologies is approaching the theoretical limits as defined by the Shannon bound. (The Shannon bound is a theoretical limit to the information transfer rate [per unit bandwidth] that can be supported by any communications link. The bound is a function of the Signal to Noise Ratio of the communications link.) Figure 23 also shows that HSDPA, 1xEV-DO, and IEEE 802.16e-2005 are all within 2 to 3 decibels (dB) of the Shannon bound, indicating that there is not much room for improvement from a link-layer perspective.
The curves in Figure 23 are for an Additive White Gaussian Noise Channel (AWGN). If the channel is slowly varying and the frame interval is significantly shorter than the coherence time, the effects of fading can be compensated for by practical channel estimation algorithms—thus justifying the AWGN assumption. For instance, at 3 km per hour, and fading at 2 GHz, the Doppler spread is about 5.5 Hz. The coherence time of the channel is thus 1 second (sec)/5.5 or 180 m sec. Frames are well within the coherence time of the channel, because they are typically 20 m sec or less. As such, the channel appears “constant” over a frame and the Shannon bound applies. Furthermore, significantly more of the traffic in a cellular system is at slow speeds (for example, 3 km/hr or less) rather than at higher speeds. The Shannon bound is consequently also relevant for a realistic deployment environment.

As the speed of the mobile station increases and the channel estimation becomes less accurate, additional margin is needed. This additional margin, however, would impact the different standards fairly equally.

The focus of future technology enhancements is on improving system performance aspects that reduce interference to maximize the experienced Signal to Noise Ratios (SNRs) in the system and antenna techniques (such as MIMO) that exploit multiple links

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80 Source: A 4G Americas member company.
rather than on investigating new air interfaces that attempt to improve link-layer performance.

MIMO techniques using spatial multiplexing to increase the overall information transfer rate by a factor proportional to the number of transmit or receive antennas do not violate the Shannon bound because the per-antenna transfer rate (that is, the per-communications link transfer rate) is still limited by the Shannon bound.

Figure 24 compares the spectral efficiency of different wireless technologies based on a consensus view of 4G Americas contributors to this paper. It shows the continuing evolution of the capabilities of all the technologies discussed. The values shown are reasonably representative of real-world conditions. Most simulation results produce values under idealized conditions; as such, some of the values shown are lower (for all technologies) than the values indicated in other papers and publications. For instance, 3GPP studies indicate higher HSDPA and LTE spectral efficiencies. Nevertheless, there are practical considerations in implementing technologies that can prevent actual deployments from reaching calculated values. Consequently, initial versions of technology may operate at lower levels but then improve over time as designs are optimized. Therefore, readers should interpret the values shown as achievable, but not as the actual values that might be measured in any specific deployed network.
The values shown in Figure 24 are not all possible combinations of available features. Rather, they are representative milestones in ongoing improvements in spectral efficiency. For instance, there are terminals that employ mobile-receive diversity but not equalization.

The figure does not include EDGE, but EDGE itself is spectrally efficient at 0.6 bps/Hz using mobile receive diversity and potentially 0.7 bps/Hz with MIMO. Relative to WCDMA Release 99, HSDPA increases capacity by almost a factor of three. Type 3 receivers that include Minimum Mean Square Error (MMSE) equalization and Mobile Receive Diversity (MRxD) effectively double HSDPA spectral efficiency. The addition of dual-carrier operation and 64 QAM increases spectral efficiency by about 15%, and MIMO can increase spectral efficiency by another 15%, reaching 1.2 bps/Hz. HSPA+ exceeds WiMAX Release 1.0 spectral efficiency. Dual-carrier HSPA+ offers a gain in spectral efficiency from cross-carrier scheduling with possible gains of about 10%. With Release 8,

81 Joint analysis by 4G Americas members. 5+5 MHz FDD for UMTS-HSPA/LTE and CDMA2000, and 10 MHz TDD DL/UL=29:18 TDD for WiMAX. Mix of mobile and stationary users.

82 Source: 4G Americas member analysis. Vendor estimates for spectral-efficiency gains from dual-carrier operation range from 5% to 20%. Lower spectral efficiency gains are due to full-buffer traffic assumptions. In more realistic operating scenarios, gains will be significantly higher.
operators can deploy either MIMO or dual-carrier operation. With Release 9, dual-carrier operation can be combined with MIMO.

Some enhancements, such as 64 QAM for HSPA, are simpler to deploy than other enhancements, such as 2X2 MIMO. The former can be done as a software upgrade, whereas the latter requires additional hardware at the base station. Thus, the figure does not necessarily show the actual progression of technologies that operators will deploy to increase spectral efficiency.

Beyond HSPA, 3GPP LTE will also result in further spectral efficiency gains, initially with 2X2 MIMO, and then optionally with SIC, 4X2 MIMO, and 4X4 MIMO. The gain for 4X2 MIMO will be 20% more than LTE with 2X2 MIMO; the gain for 4X4 MIMO in combination with successive interference cancellation will be 60% more than 2X2 MIMO, reaching 2.25 bps/Hz. This assumes a simplified switched-beam approach defined in Release 8. This same spectral efficiency of 2.25 bps/Hz is also achievable in Release 10 using 8X2 MIMO in combination with SU/MU MIMO switching (which provides a 60% gain over 2X2 MIMO). CoMP, discussed in the appendix, provides a minimal contribution to spectral efficiency.

LTE is even more spectrally efficient with wider radio channels of 10+10 MHz and 20+20 MHz, although most of the gain is realized at 10+10 MHz. LTE TDD has spectral efficiency that is within 1% or 2% of LTE FDD.83

Similar gains to those for HSPA and LTE are available for CDMA2000. CDMA2000 spectral efficiency values assume seven carriers deployed in 10+10 MHz. The EV-DO Rev. 0 value assumes single receive-antenna devices. As with HSPA, spectral efficiency for EV-DO increases with a higher population of devices with mobile-receive diversity. These gains are assumed in the Rev. A spectral-efficiency value of .9 bps/Hz.

Mobile WiMAX also experiences gains in spectral efficiency as various optimizations, including mobile receive diversity (MRxD) and MIMO, are applied. WiMAX Release 1.0 includes 2X2 MIMO. Enhancements to WiMAX come with Release 1.5 and IEEE 802.16m. Because there are no commitments by any operators to deploy IEEE 802.16m networks at this time, the analysis does not include this technology.

Figure 25 compares the uplink spectral efficiency of the different systems.

83 Assumes best-effort traffic. There is a difference in performance between LTE-TDD and FDD for real-time traffic for the following reasons: a.) The maximum number of HARQ process should be made as small as possible to reduce the packet re-transmission latency. b.) In FDD, the maximum number of HARQ process is fixed and, as such, the re-transmission latency is 7ms. c.) For TDD, the maximum number of HARQ process depends on the DL:UL configurations. As an example, the re-transmission latency for TDD config-1 is 9ms. d.) Because of higher re-transmission latency, the capacity of real-time services cannot be scaled for TDD from FDD based on the DL:UL ratio.
The implementation of HSUPA in HSPA significantly increases uplink capacity, as does Rev. A and Rev. B of 1xEV-DO, compared with Rel. 0. OFDM-based systems can exhibit improved uplink capacity relative to CDMA technologies, but this improvement depends on scheduling efficiency and other factors, as well as the exact deployment scenario.

With LTE, spectral efficiency increases by use of receive diversity. Initial systems will employ 1X2 receive diversity (two antennas at the base station). 1X4 diversity will increase spectral efficiency by 50% to 1.0 bps/Hz and 1X8 diversity will provide a further 20% increase from 1.0 bps/Hz to 1.2 bps/Hz. These receive diversity improvements could also be implemented on HSPA+ and CDMA2000 networks.

It is also possible to employ Multi-User MIMO (MU-MIMO), which allows simultaneous transmission by multiple users on the uplink on the same physical resource to increase spectral efficiency. MU-MIMO will provide a 15% to 20% spectral efficiency gain, with

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84 Joint analysis by 4G Americas members. 5+5 MHz for UMTS-HSPA/LTE and CDMA2000, and 10 MHz DL/UL=29:18 TDD for WiMAX. Mix of mobile and stationary users.
actual gain depending on how well link adaptation is implemented. The figure uses a conservative 15% gain, showing MU-MIMO with a 1X4 antenna configuration increasing spectral efficiency by 15% to 1.15 bps/Hz and 2X4 MU-MIMO a further 15%, to 1.3 bps/Hz.

In Release 11, uplink CoMP using 1X2 will double spectral efficiency from .65 bps/Hz to 1.3 bps/Hz. Many of the techniques used to improve LTE spectral efficiency can also be applied to HSPA since they are independent of the radio interface.

Figure 26 compares voice spectral efficiency.

**Figure 26: Comparison of Voice Spectral Efficiency**

Figure 26 shows UMTS Release 99 with AMR 12.2 Kbps, 7.95 Kbps, and 5.9 Kbps vocoders. The AMR 12.2 Kbps vocoder provides superior voice quality in good (for example, static and indoor) channel conditions. UMTS has dynamic adaptation between vocoder rates, enabling enhanced voice quality compared with EVRC at the expense of capacity in situations that are not capacity limited. With the addition of mobile receive diversity, UMTS circuit-switched voice capacity could reach 120 Erlangs in 5+5 MHz.

Opportunities will arise to improve voice capacity using VoIP over HSPA channels. VoIP Erlangs in this paper are defined as the average number of concurrent VoIP users that can be supported over a defined period of time (often one hour) assuming a Poisson arrival process and meeting a specified outage criteria (often less than 2% of the users

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85 Source: Joint analysis by 4G Americas members. 5 + 5 MHz for UMTS-HSPA/LTE and CDMA2000, and 10 MHz TDD DL/UL=29:18 TDD for WiMAX. Mix of mobile and stationary users.
exhibiting greater than 1% frame-error rate). Depending on the specific enhancements implemented, voice capacity could double over existing circuit-switched systems. These gains do not derive through use of VoIP, but rather from advances in radio techniques applied to the data channels. Many of these same advances may also be applied to current circuit-switched modes.

LTE achieves very high voice spectral efficiency because of better uplink performance since there is no in-cell interference. The figure shows LTE VoIP spectral efficiency using AMR at 12.2 Kbps, 7.95 Kbps and 5.9 Kbps.

1xRTT has voice capacity of 85 Erlangs in 5+5 MHz with EVRC-A and reaches voice capacity of 120 Erlangs with the use of Quasi-Linear Interference Cancellation (QLIC) and EVRC-B at 6 Kbps.

CDMA2000 1X Advanced significantly increases voice capacity. The figure shows two features that will provide enhancement prior to the full feature set of 1X Advanced: Reverse Link Interference Cancellation (RLIC) and receive diversity in the devices, which increase voice capacity to 175 Erlangs.

VoIP for LTE can use a variety of codecs. The figures show performance assuming specific codecs at representative bit rates. For Enhanced Variable Rate Codecs (EVRCs) the figure shows the average bit rate.

WiMAX voice capacity is shown at 90 Erlangs for Release 1.0 and 105 Erlangs for Release 1.5. Changing the Downlink:Uplink (DL:UL) ratio from 29:18 to 23:24 increases spectral efficiency by 50% because now 18 data symbols per frame are allocated for the UL compared with 12. Persistent scheduling and changing the DL:UL from 23:24 to 20:27 delivers a further gain of 15%. Changing this ratio, however, may not be practical if the same carrier frequency must support both voice and data. Alternatively, voice and data can operate on different radio carriers using different TDD ratios.

**Market Comparison**

So far, this paper has compared wireless technologies on the basis of technical capability, but market volume also plays an important role because economies of scale reduce costs. Based on projections, 3GPP subscribers will exceed 7.5 billion by 2018, dwarfing other technologies. See Figure 27 for details.

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In the market forecast above, HSPA subscriptions reach 3.8 billion by year-end 2017 and 4.3 billion by year-end 2018. The growth rate of LTE increases significantly over the five-year span, with 961 million subscribers at year-end 2017, rising to 1.4 billion LTE subscribers by year-end 2018.
Conclusion
Mobile broadband has become the leading edge in innovation and development for computing, networking, and application development. There are now more smartphones shipped than personal computers. As smartphones, tablets, mobile-connected cars, and other connected platforms penetrate more deeply, they will continue to drive explosive growth in data usage, application availability, 3G/4G deployment, and revenue. In one of the most significant industry developments of 2013, LTE became available over most of the country and reached higher usage levels in the U.S. market than anywhere else in the world.

The explosive success of mobile broadband, however, mandates ongoing capacity augmentation, to which the industry has responded by using more efficient technologies, deploying more cell sites, planning for heterogeneous networks, and offloading onto either Wi-Fi or femtocells. Some governments that want to lead the mobile broadband technology revolution have responded with ambitious plans to supply more spectrum, while other governments still need to do more by providing more harmonized spectrum in the near-term. In the United States, operators are starting to face increased urgency to augment their capacity through new spectrum. While there have been encouraging developments, the industry overall is concerned that substantive additions to spectrum may take years.

Through constant innovation, the 3GPP family of technologies has proven itself the predominant wireless network solution. HSPA+ capabilities will continue growing through small-cell support and other innovations, making it a viable technology for many years to come. As for LTE, it is poised to be the most widely chosen technology platform for the forthcoming decade thanks to advantages that make it a best-of-breed, long-term solution that matches or exceeds the performance of competing approaches.

LTE is the OFDMA technology choice for higher speeds and capabilities. Yet, the migration to LTE is a long-term one. Until the middle of this decade, most subscribers will be using GSM/EDGE and HSPA/HSPA+ technologies, with significant uptake of LTE happening toward the second half of this decade.

Today, HSPA+ and LTE offer the highest peak data rates of any widely available, wide-area wireless technologies. With continued improvements, peak data rates will keep increasing, spectral efficiency will improve, and latency will decrease, thus supporting more users and applications.

Because of practical benefits and deployment momentum, the migration path from EDGE to HSPA/HSPA+ and LTE has become inevitable, as predicted by previous versions of this paper. Benefits include the ability to roam globally, huge economies of scale, widespread acceptance by operators, complementary services such as messaging and multimedia, and an astonishing variety of competitive handsets and other devices. More than 524 commercial HSPA networks are currently in operation.

Operators are quickly deploying LTE and are realizing significant capacity and performance advantages by deploying a new technology in new spectrum. Subsequent releases of LTE specifications will further boost capabilities through HetNets, more advanced carrier aggregation, CoMP, relays, and other techniques.

Not only continual improvements in radio technology, but also improvements to the core network will reduce latency, speed applications, simplify deployment, enable all services in the IP domain, and establish a common core network for LTE, legacy GSM-HSPA systems, Wi-Fi, and even CDMA2000 networks.
With the continued growth in mobile computing, powerful mobile platforms, an increasing amount of mobile content, and now close to 2 million mobile applications, mobile broadband has become a huge industry. EDGE/HSPA/LTE provides one of the most robust portfolios of mobile-broadband technologies and is an optimum framework for realizing the potential of the wireless market.
Appendix: Technology Details

The EDGE/HSPA/LTE family of data technologies provides ever-increasing capabilities that support ever more demanding applications. Services obviously need to provide broad coverage and high data throughput. Less obvious for users, but as critical for effective application performance, are the needs for low latency, QoS control, and spectral efficiency. Spectral efficiency, in particular, is of paramount concern, because it translates to higher average throughputs (and thus more responsive applications) for more active users in a coverage area. The discussion below details the progression of capability for each technology, including throughput, security, latency, QoS, and spectral efficiency.

It is helpful to specifically note the throughput requirements necessary for different applications:

- Multimedia messaging: 8 to 64 Kbps
- Video telephony: 64 to 384 Kbps
- General-purpose Web browsing: 32 Kbps to more than 1 Mbps
- Enterprise applications including e-mail, database access, and Virtual Private Networks (VPNs): 32 Kbps to more than 1 Mbps
- Video and audio streaming: 32 Kbps to 5 Mbps
- High definition video: 3 Mbps or higher

Note that EDGE already satisfies the demands of many applications. With HSPA+ and LTE, applications operate faster and the range of supported applications expands further.

Under favorable conditions, EDGE delivers peak user-achievable throughput rates close to 200 Kbps; HSPA+ delivers peak user-achievable downlink throughput rates approaching 10 Mbps; and LTE exceeds this rate, easily meeting the demands of many applications. Latency has continued to improve, too, with HSPA+ networks today having round-trip times as low as 25 msec, and LTE as low as 15 msec. The combination of low latency and high throughput translates to a broadband experience for users in which applications are extremely responsive.

This appendix covers the capabilities and workings of the different technologies including WCDMA, HSPA, HSPA+, LTE, LTE-Advanced, IMT-Advanced, LTE-Advanced, Carrier Aggregation, Coordinated Multipoint Processing, heterogeneous networks, IMS, EPC, Wi-Fi integration, IMS, cloud RAN and network virtualization, broadcast/multicast services, and EDGE and Evolved EDGE, TV white spaces, and backhaul.

Spectrum Bands

3GPP technologies operate in a wide range of radio bands. As new spectrum becomes available, 3GPP updates its specifications for these bands. Although the support of a new frequency band may be introduced in a particular release, 3GPP specifies ways to implement devices and infrastructure operating on any frequency band, according to releases previous to the introduction of that particular frequency band. For example, although band 5 (US Cellular Band) was introduced in Release 6, the first devices operating on this band were compliant with the release 5 of the standard.
Table 7 shows the UMTS FDD bands.

**Table 7: UMTS FDD Bands**

<table>
<thead>
<tr>
<th>Operating Band</th>
<th>UL Frequencies UE transmit, Node B receive</th>
<th>DL frequencies UE receive, Node B transmit</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1920 - 1980 MHz</td>
<td>2110 - 2170 MHz</td>
</tr>
<tr>
<td>II</td>
<td>1850 - 1910 MHz</td>
<td>1930 - 1990 MHz</td>
</tr>
<tr>
<td>III</td>
<td>1710-1785 MHz</td>
<td>1805 -1880 MHz</td>
</tr>
<tr>
<td>IV</td>
<td>1710-1755 MHz</td>
<td>2110-2155 MHz</td>
</tr>
<tr>
<td>V</td>
<td>824 - 849MHz</td>
<td>869-894MHz</td>
</tr>
<tr>
<td>VI</td>
<td>830-840MHz</td>
<td>875-885MHz</td>
</tr>
<tr>
<td>VII</td>
<td>2500 - 2570 MHz</td>
<td>2620 - 2690 MHz</td>
</tr>
<tr>
<td>VIII</td>
<td>880 - 915 MHz</td>
<td>925 - 960 MHz</td>
</tr>
<tr>
<td>IX</td>
<td>1749.9 - 1784.9 MHz</td>
<td>1844.9 - 1879.9 MHz</td>
</tr>
<tr>
<td>X</td>
<td>1710-1770 MHz</td>
<td>2110-2170 MHz</td>
</tr>
<tr>
<td>XI</td>
<td>1427.9 - 1447.9 MHz</td>
<td>1475.9 - 1495.9 MHz</td>
</tr>
<tr>
<td>XII</td>
<td>699 - 716 MHz</td>
<td>729 - 746 MHz</td>
</tr>
<tr>
<td>XIII</td>
<td>777 - 787 MHz</td>
<td>746 - 756 MHz</td>
</tr>
<tr>
<td>XIV</td>
<td>788 - 798 MHz</td>
<td>758 - 768 MHz</td>
</tr>
<tr>
<td>XV</td>
<td>Reserved</td>
<td>Reserved</td>
</tr>
<tr>
<td>XVI</td>
<td>Reserved</td>
<td>Reserved</td>
</tr>
<tr>
<td>XVII</td>
<td>Reserved</td>
<td>Reserved</td>
</tr>
<tr>
<td>XVIII</td>
<td>Reserved</td>
<td>Reserved</td>
</tr>
<tr>
<td>XIX</td>
<td>830 – 845 MHz</td>
<td>875 -890 MHz</td>
</tr>
<tr>
<td>XX</td>
<td>832 - 862 MHz</td>
<td>791 - 821 MHz</td>
</tr>
<tr>
<td>XXI</td>
<td>1447.9 - 1462.9 MHz</td>
<td>1495.9 - 1510.9 MHz</td>
</tr>
<tr>
<td>XXII</td>
<td>3410 – 3490 MHz</td>
<td>3510 – 3590 MHz</td>
</tr>
<tr>
<td>XXV</td>
<td>1850 -1915 MHz</td>
<td>1930 -1995 MHz</td>
</tr>
<tr>
<td>XXVI</td>
<td>814-849 MHz</td>
<td>859-894 MHz</td>
</tr>
</tbody>
</table>

Universal Mobile Telecommunications System (UMTS) Time Division Duplex (TDD) bands are the same as the LTE TDD bands.

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87 Source: 3GPP Technical Specification 25.104, V11.5.0.
Table 8 shows the LTE Frequency Division Duplex (FDD) and TDD bands.
### Table 8: LTE FDD and TDD bands

<table>
<thead>
<tr>
<th>E-UTRA Operating Band</th>
<th>Uplink (UL) operating band</th>
<th>Downlink (DL) operating band</th>
<th>Duplex Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BS receive</td>
<td>BS transmit</td>
<td></td>
</tr>
<tr>
<td></td>
<td>UE transmit</td>
<td>UE receive</td>
<td></td>
</tr>
<tr>
<td><strong>F&lt;sub&gt;UL&lt;/sub&gt; low</strong></td>
<td><strong>F&lt;sub&gt;UL&lt;/sub&gt; high</strong></td>
<td><strong>F&lt;sub_DL&lt;/sub&gt; low</strong></td>
<td><strong>F&lt;sub_DL&lt;/sub&gt; high</strong></td>
</tr>
<tr>
<td>1</td>
<td>1920 MHz – 1980 MHz</td>
<td>2110 MHz – 2170 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>2</td>
<td>1850 MHz – 1910 MHz</td>
<td>1930 MHz – 1990 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>3</td>
<td>1710 MHz – 1785 MHz</td>
<td>1805 MHz – 1880 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>4</td>
<td>1710 MHz – 1755 MHz</td>
<td>2110 MHz – 2155 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>5</td>
<td>824 MHz – 849 MHz</td>
<td>869 MHz – 894 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>6</td>
<td>830 MHz – 840 MHz</td>
<td>875 MHz – 885 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>7</td>
<td>2500 MHz – 2570 MHz</td>
<td>2620 MHz – 2690 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>8</td>
<td>880 MHz – 915 MHz</td>
<td>925 MHz – 960 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>9</td>
<td>1749.9 MHz – 1784.9 MHz</td>
<td>1844.9 MHz – 1879.9 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>10</td>
<td>1710 MHz – 1770 MHz</td>
<td>2110 MHz – 2170 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>11</td>
<td>1427.9 MHz – 1447.9 MHz</td>
<td>1475.9 MHz – 1495.9 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>12</td>
<td>699 MHz – 716 MHz</td>
<td>729 MHz – 746 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>13</td>
<td>777 MHz – 787 MHz</td>
<td>746 MHz – 756 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>14</td>
<td>788 MHz – 798 MHz</td>
<td>758 MHz – 768 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>15</td>
<td>Reserved</td>
<td>Reserved</td>
<td>FDD</td>
</tr>
<tr>
<td>16</td>
<td>Reserved</td>
<td>Reserved</td>
<td>FDD</td>
</tr>
<tr>
<td>17</td>
<td>704 MHz – 716 MHz</td>
<td>734 MHz – 746 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>18</td>
<td>815 MHz – 830 MHz</td>
<td>860 MHz – 875 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>19</td>
<td>830 MHz – 845 MHz</td>
<td>875 MHz – 890 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>20</td>
<td>832 MHz – 862 MHz</td>
<td>791 MHz – 821 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>21</td>
<td>1447.9 MHz – 1462.9 MHz</td>
<td>1495.9 MHz – 1510.9 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>22</td>
<td>3410 MHz – 3490 MHz</td>
<td>3510 MHz – 3590 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>23</td>
<td>2000 MHz – 2020 MHz</td>
<td>2180 MHz – 2200 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>24</td>
<td>1626.5 MHz – 1660.5 MHz</td>
<td>1525 MHz – 1559 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>25</td>
<td>1850 MHz – 1915 MHz</td>
<td>1930 MHz – 1995 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>26</td>
<td>814 MHz – 849 MHz</td>
<td>859 MHz – 894 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>27</td>
<td>807 MHz – 824 MHz</td>
<td>852 MHz – 869 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>28</td>
<td>703 MHz – 748 MHz</td>
<td>758 MHz – 803 MHz</td>
<td>FDD</td>
</tr>
<tr>
<td>29</td>
<td>N/A</td>
<td>717 MHz – 728 MHz</td>
<td>FDD*</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>1900 MHz – 1920 MHz</td>
<td>1900 MHz – 1920 MHz</td>
<td>TDD</td>
</tr>
<tr>
<td>34</td>
<td>2010 MHz – 2025 MHz</td>
<td>2010 MHz – 2025 MHz</td>
<td>TDD</td>
</tr>
<tr>
<td>35</td>
<td>1850 MHz – 1910 MHz</td>
<td>1850 MHz – 1910 MHz</td>
<td>TDD</td>
</tr>
<tr>
<td>36</td>
<td>1930 MHz – 1990 MHz</td>
<td>1930 MHz – 1990 MHz</td>
<td>TDD</td>
</tr>
<tr>
<td>37</td>
<td>1910 MHz – 1930 MHz</td>
<td>1910 MHz – 1930 MHz</td>
<td>TDD</td>
</tr>
<tr>
<td>38</td>
<td>2570 MHz – 2620 MHz</td>
<td>2570 MHz – 2620 MHz</td>
<td>TDD</td>
</tr>
<tr>
<td>39</td>
<td>1880 MHz – 1920 MHz</td>
<td>1880 MHz – 1920 MHz</td>
<td>TDD</td>
</tr>
<tr>
<td>40</td>
<td>2300 MHz – 2400 MHz</td>
<td>2300 MHz – 2400 MHz</td>
<td>TDD</td>
</tr>
<tr>
<td>41</td>
<td>2496 MHz – 2690 MHz</td>
<td>2496 MHz – 2690 MHz</td>
<td>TDD</td>
</tr>
<tr>
<td>42</td>
<td>3400 MHz – 3600 MHz</td>
<td>3400 MHz – 3600 MHz</td>
<td>TDD</td>
</tr>
<tr>
<td>43</td>
<td>3600 MHz – 3800 MHz</td>
<td>3600 MHz – 3800 MHz</td>
<td>TDD</td>
</tr>
<tr>
<td>44</td>
<td>703 MHz – 803 MHz</td>
<td>703 MHz – 803 MHz</td>
<td>TDD</td>
</tr>
</tbody>
</table>

**Note 1:** Band 6 is not applicable.
**Note 2:** Restricted to E-UTRA operation when carrier aggregation is configured. The downlink operating band is paired with the uplink operating band (external) of the carrier aggregation configuration that is supporting the configured Pcell.

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88 Source: 3GPP Technical Specification 36.104, V11.4.0.
UMTS-HSPA

UMTS technology is mature and benefits from research and development that began in the early 1990s. It has been thoroughly trialed, tested, and commercially deployed. UMTS employs a wideband CDMA radio-access technology. The primary benefits of UMTS include high spectral efficiency for voice and data, simultaneous voice and data capability, high user densities that can be supported with low infrastructure costs, and support for high-bandwidth data applications. Operators can also use their entire available spectrum for both voice and high-speed data services.

Additionally, operators can use a common core network, called the UMTS multi-radio network as shown in Figure 28, that supports multiple radio-access networks including GSM, EDGE, WCDMA, HSPA, and evolutions of these technologies.

Figure 28: UMTS Multi-radio Network

HSPA refers to networks that support both HSDPA and HSUPA. All new deployments today are HSPA, and many operators have upgraded their HSDPA networks to HSPA. For example, in 2008, AT&T upgraded most of its network to HSPA. By the end of 2008, HSPA was deployed throughout the Americas.

The UMTS radio-access network consists of base stations referred to as Node B (corresponding to GSM base transceiver systems) that connect to RNCs (corresponding to GSM base station controllers [BSCs]). The RNCs connect to the core network as do the BSCs. When both GSM and WCDMA access networks are available, the network can hand users over between these networks. This is important for managing capacity, as well as in areas in which the operator has continuous GSM coverage, but has only deployed WCDMA in some locations.

Whereas GSM can effectively operate like a spread-spectrum system, based on time division in combination with frequency hopping, WCDMA is a direct-sequence, spread-

89 Spread spectrum systems can either be direct sequence or frequency hopping.
spectrum system. WCDMA is spectrally more efficient than GSM, but it is the wideband nature of WCDMA that provides its greatest advantage—the ability to translate the available spectrum into high data rates. This wideband technology approach results in the flexibility to manage multiple traffic types including voice, narrowband data, and wideband data.

WCDMA allocates different codes for different channels, whether for voice or data, and it can adjust the amount of capacity, or code space, of each channel every 10 msec with WCDMA Release 99 and every 2 msec with HSPA. WCDMA creates high-bandwidth traffic channels by reducing the amount of spreading (using a shorter code) with WCDMA Release 99 and higher-order modulation schemes for HSPA. Packet data users can share the same codes as other users, or the network can assign dedicated channels to users.

To further expand the number of effectively operating applications, UMTS employs a QoS architecture for data that provides four fundamental traffic classes including:

1. **Conversational.** Real-time, interactive data with controlled bandwidth and minimum delay such as VoIP or video conferencing.

2. **Streaming.** Continuous data with controlled bandwidth and some delay such as music or video.

3. **Interactive.** Back-and-forth data without bandwidth control and some delay such as Web browsing.

4. **Background.** Lower priority data that is non-real-time such as batch transfers.

This QoS architecture, available through all HSPA versions, involves negotiation and prioritization of traffic in the radio-access network, the core network, and the interfaces to external networks such as the Internet. Consequently, applications can negotiate QoS parameters on an end-to-end basis between a mobile terminal and a fixed-end system across the Internet or private intranets. The industry has not deployed UMTS-HSPA services using QoS, and is more likely to do so with LTE, which uses a more sophisticated policy-based QoS architecture.

**UMTS Release 99 Data Capabilities**

Initial UMTS network deployments were based on 3GPP Release 99 specifications, which included voice and data capabilities. Since then, Release 5 has defined HSDPA and Release 6 has defined HSUPA. With HSPA-capable devices, the network uses HSPA (HSDPA/HSUPA) for data.

In UMTS Release 99, the maximum theoretical downlink rate is just over 2 Mbps. Although exact throughput depends on the channel sizes the operator chooses to make available, the capabilities of devices and the number of users active in the network limit the peak throughput rates a user can achieve to about 350 Kbps in commercial networks. Peak downlink network speeds are 384 Kbps. Uplink peak-network throughput rates are also 384 Kbps in newer deployments with user-achievable peak rates of 350 Kbps.\(^90\) This satisfies many communications-oriented applications.

\(^90\) Initial UMTS networks had peak uplink rates of 64 Kbps or 128 Kbps, but many deployments emphasize 384 Kbps.
Channel throughputs are determined by the amount of channel spreading. With more spreading, as in voice channels, the data stream has greater redundancy, and the operator can employ more channels. In comparison, a high-speed data channel has less spreading and fewer available channels. Voice channels use downlink spreading factors of 128 or 256, whereas a 384 Kbps data channel uses a downlink spreading factor of 8. The commonly quoted rate of more than 2 Mbps downlink throughput for UMTS can be achieved by combining three data channels of 768 Kbps, each with a spreading factor of 4.

Although UMTS Release 99 offers attractive data services, these services become much more efficient and more powerful with HSPA.

**HSDPA**

HSDPA, specified in 3GPP Release 5, is a high-performance, packet-data service that delivers peak theoretical rates of 14 Mbps. Peak user-achievable throughput rates in initial deployments are well over 1 Mbps and as high as 4 Mbps in some networks. The same radio carrier can simultaneously service UMTS voice and data users, as well as HSDPA data users.

HSDPA achieves its high speeds through techniques similar to those that push EDGE performance past GPRS including higher order modulation, variable coding, and soft combining, as well as through the addition of fast scheduling and other techniques.

HSDPA achieves its performance gains from the following radio features:

- High-speed channels shared in both code and time domains
- Short TTI
- Fast scheduling and user diversity
- Higher order modulation
- Fast link adaptation
- Fast HARQ

These features function as follows:

**High-Speed Shared Channels and Short Transmission Time Interval:** First, HSDPA uses high-speed data channels called High Speed Physical Downlink Shared Channels (HS-PDSCH). Up to 15 of these channels can operate in the 5 MHz WCDMA radio channel. Each uses a fixed spreading factor of 16. User transmissions are assigned to one or more of these channels for a short TTI of 2 msec. The network can then readjust how users are assigned to different HS-PDSCH every 2 msec. Resources are thus assigned in both time (the TTI interval) and code domains (the HS-PDSCH channels). Figure 29 illustrates different users obtaining different radio resources.
Fast Scheduling and User Diversity: Fast scheduling exploits the short TTI by assigning users channels that have the best instantaneous channel conditions, rather than in a round-robin fashion. Because channel conditions vary somewhat randomly across users, most users can be serviced with optimum radio conditions and thereby obtain optimum data throughput. Figure 30 shows how a scheduler might choose between two users based on their varying radio conditions to emphasize the user with better instantaneous signal quality. With about 30 users active in a sector, the network achieves significant user diversity and much higher spectral efficiency. The system also ensures that each user receives a minimum level of throughput, an approach called proportional fair scheduling.
**Figure 30: User Diversity**

![User Diversity Diagram]

**Higher Order Modulation:** HSDPA uses both the modulation used in WCDMA—namely QPSK—and, under good radio conditions, an advanced modulation scheme—16 QAM. 16 QAM transmits 4 bits of data in each radio symbol compared to 2 bits with QPSK. Data throughput is increased with 16 QAM, while QPSK is available for adverse radio conditions. HSPA Evolution adds 64 QAM modulation to further increase throughput rates. 64 QAM became available in Release 7, and the combination of MIMO and 64 QAM became available in Release 8.

**Fast Link Adaptation:** Depending on the condition of the radio channel, different levels of forward-error correction (channel coding) can also be employed. For example, a three-quarter coding rate means that three quarters of the bits transmitted are user bits and one quarter are error-correcting bits. Fast link adaptation refers to the process of selecting and quickly updating the optimum modulation and coding rate and occurs in coordination with fast scheduling.

**Fast Hybrid Automatic Repeat Request:** Another HSDPA technique is Fast Hybrid Automatic Repeat Request (Fast Hybrid ARQ). “Fast” refers to the medium-access control mechanisms implemented in Node B (along with scheduling and link adaptation), as opposed to the BSC in GPRS/EDGE, and “hybrid” refers to a process of combining repeated data transmissions with prior transmissions to increase the likelihood of successful decoding. Managing and responding to real-time radio variations at the base station, as opposed to an internal network node, reduces delays and further improves overall data throughput.

Using the approaches just described, HSDPA maximizes data throughputs and capacity and minimizes delays. For users, this translates to better network performance under loaded conditions, faster application performance, and a greater range of applications that function well.
Field results validate the theoretical throughput results. With initial 1.8 Mbps peak-rate devices, vendors measured consistent throughput rates in actual deployments of more than 1 Mbps. These rates rose to more than 2 Mbps for 3.6 Mbps devices and then close to 4 Mbps for 7.2 Mbps devices.

In 2008, typical devices supporting peak data rates of 3.6 Mbps or 7.2 Mbps became available. Many operator networks support 7.2 Mbps peak operation, and some even support the maximum rate of 14.4 Mbps.

**HSUPA**

Whereas HSDPA optimizes downlink performance, HSUPA—which uses the Enhanced Dedicated Channel (E-DCH)—constitutes a set of improvements that optimizes uplink performance. Networks and devices supporting HSUPA became available in 2007. These improvements include higher throughputs, reduced latency, and increased spectral efficiency. HSUPA was standardized in Release 6. It results in an approximately 85% increase in overall cell throughput on the uplink and more than a 50% gain in user throughput. HSUPA also reduces packet delays, a significant benefit resulting in much improved application performance on HSPA networks.

Although the primary downlink traffic channel supporting HSDPA serves as a shared channel designed for the support of services delivered through the packet-switched domain, the primary uplink traffic channel defined for HSUPA is a dedicated channel that could be used for services delivered through either the circuit-switched or the packet-switched domains. Nevertheless, by extension and for simplicity, the WCDMA-enhanced uplink capabilities are often identified in the literature as HSUPA.

HSUPA achieves its performance gains through the following approaches:

- An enhanced dedicated physical channel.
- A short TTI, as low as 2 msec, which allows faster responses to changing radio conditions and error conditions.
- Fast Node B-based scheduling, which allows the base station to efficiently allocate radio resources.
- Fast Hybrid ARQ, which improves the efficiency of error processing.

The combination of TTI, fast scheduling, and Fast Hybrid ARQ also serves to reduce latency. HSUPA can operate with or without HSDPA in the downlink, although use the two approaches together. The improved uplink mechanisms also translate to better coverage and, for rural deployments, larger cell sizes.

HSUPA can achieve different throughput rates based on various parameters including the number of codes used, the spreading factor of the codes, the TTI value, and the transport block size in bytes.

Initial devices enabled peak user rates of close to 2 Mbps as measured in actual network deployments, while current devices have throughputs of more than 5 Mbps. Future devices could have network rates as high as 69 Mbps, as discussed further below.

Beyond throughput enhancements, HSUPA also significantly reduces latency.
**Evolution of HSPA (HSPA+)**

The goal in evolving HSPA is to exploit available radio technologies—largely enabled by increases in digital signal processing power—to maximize CDMA-based radio performance. This evolution has significantly advanced HSPA and extends the life of sizeable operator infrastructure investments.

Wireless and networking technologists have defined a series of enhancements for HSPA, beginning in Release 7 and now continuing through Release 12. These include advanced receivers, multi-carrier operation, MIMO, Continuous Packet Connectivity, Higher-Order Modulation, One Tunnel Architecture, HetNet support, and advanced voice capabilities both in circuit- and packet-switched domains.

Taking advantage of these various radio technologies, 3GPP has standardized a number of features, beginning in Release 7 including higher order modulation and MIMO. Collectively, these capabilities are referred to as HSPA+. Release 8 through Release 12 include further enhancements.

The goals of HSPA+ are to:

- Exploit the full potential of a CDMA approach.
- Provide smooth interworking between HSPA+ and LTE, thereby facilitating the operation of both technologies. As such, operators may choose to leverage the EPC planned for LTE.
- Allow operation in a packet-only mode for both voice and data.
- Be backward-compatible with previous systems while incurring no performance degradation with either earlier or newer devices.
- Facilitate migration from current HSPA infrastructure to HSPA+ infrastructure.

**Advanced Receivers**

3GPP has specified a number advanced-received designs including: Type 1, which uses mobile-receive diversity; Type 2, which uses channel equalization; and Type 3, which includes a combination of receive diversity and channel equalization. Type 3i devices, which became available in 2012, employ interference cancellation. Note that the different types of receivers are release-independent. For example, Type 3i receivers will work and provide a capacity gain in an earlier Release 5 network.

The first approach is mobile-receive diversity. This technique relies on the optimal combination of received signals from separate receiving antennas. The antenna spacing yields signals that have somewhat independent fading characteristics. Hence, the combined signal can be more effectively decoded, which almost doubles downlink capacity when done in combination with channel equalization. Receive diversity is effective even with smaller devices such as like PC Card modems and smartphones.

Current receiver architectures based on rake receivers are effective for speeds up to a few megabits per second. But at higher speeds, the combination of reduced symbol period and multipath interference results in inter-symbol interference and diminishes rake receiver performance. This problem can be solved by advanced-receiver architectures with channel equalizers that yield additional capacity gains over HSDPA with receive diversity. Alternate advanced-receiver approaches include interference cancellation and generalized rake receivers (G-Rake). Different vendors are emphasizing different
approaches. The performance requirements for advanced-receiver architectures, however, was specified in 3GPP Release 6. The combination of mobile-receive diversity and channel equalization (Type 3) is especially attractive, because it results in a large capacity gain independent of the radio channel.

What makes such enhancements attractive is that the networks do not require any changes other than increased capacity within the infrastructure to support the higher bandwidth. Moreover, the network can support a combination of devices including both earlier devices that do not include these enhancements and later devices that do. Device vendors can selectively apply these enhancements to their higher-end devices.

**MIMO**

Another standardized capability is MIMO, a technique that employs multiple transmit antennas and multiple receive antennas, often in combination with multiple radios and multiple parallel data streams. The most common use of the term “MIMO” applies to spatial multiplexing. The transmitter sends different data streams over each antenna. Whereas multipath is an impediment for other radio systems, MIMO—as illustrated in Figure 31—actually exploits multipath, relying on signals to travel across different uncorrelated communications paths. The multiple data paths effectively operate in parallel and, with appropriate decoding, in a multiplicative gain in throughput.

*Figure 31: MIMO Using Multiple Paths to Boost Throughput and Capacity*

Tests of MIMO have proven effective in WLANs operating in relative isolation where interference is not a dominant factor. Spatial multiplexing MIMO can also benefit HSPA “hotspots” serving local areas including airports, campuses, and malls. In a fully loaded network with interference from adjacent cells, however, overall capacity gains will be more modest—in the range of 20% to 33% over mobile-receive diversity. Relative to a 1x1 antenna system, however, 2X2 MIMO can deliver cell throughput gains of about 80%. 3GPP has standardized spatial multiplexing MIMO in Release 7 using Double Transmit Adaptive Array (D-TxAA).
Release 9 provides for a means to leverage MIMO antennas at the base station when transmitting to user equipment that does not support MIMO. The two transmit antennas in the base station can transmit a single stream using beam forming. This is called “single-stream MIMO” or “MIMO with single-stream restriction” and results in higher throughput rates because of the improved signal received by the user equipment.

3GPP designed uplink dual-antenna beamforming and 2X2 MIMO for HSPA+ in Release 11.

**Continuous Packet Connectivity**

Continuous Packet Connectivity (CPC) specified in Release 7 reduces the uplink interference created by the dedicated physical control channels of packet data users when those channels have no user data to transmit, which increases the number of simultaneously connected HSUPA users. CPC allows both discontinuous uplink transmission and discontinuous downlink reception, wherein the modem can turn off its receiver after a certain period of HSDPA inactivity. CPC is especially beneficial to VoIP on the uplink because the radio can turn off between VoIP packets, as shown in Figure 32.

**Figure 32: Continuous Packet Connectivity**

![Continuous Packet Connectivity Diagram](image)

**Higher Order Modulation**

Another way of increasing performance is with higher order modulation. HSPA uses 16 QAM on the downlink and QPSK on the uplink, but HSPA+ adds 64 QAM to the downlink and 16 QAM to the uplink. 3GPP has also introduced 64 QAM to the uplink for HSPA+ in Release 11. Higher order modulation requires a better SNR, achieved through receive diversity and equalization.

**Multi-Carrier HSPA**

3GPP defined dual-carrier HSPA operation in Release 8, which coordinates the operation of HSPA on two adjacent 5 MHz carriers so that data transmissions can achieve higher throughput rates, as shown in Figure 33. The work item assumed two adjacent carriers,
downlink operation and no MIMO. This configuration achieves a doubling of the 21 Mbps maximum rate available on each channel to 42 Mbps.

**Figure 33: Dual-Carrier Operation with One Uplink Carrier**

Benefits include:

- An increase in spectral efficiency of about 15%, comparable to what can be obtained with 2X2 MIMO.
- Significantly higher peak throughputs available to users, especially in lightly-loaded networks.
- Same maximum-throughput rate of 42 Mbps as using MIMO, but with a less expensive infrastructure upgrade.

Scheduling packets across two carriers better uses resources, resulting in what is called trunking gain. Multi-user diversity also improves from an increased number of users across the two channels.

Release 9 allows dual-carrier operation in combination with MIMO and without the need for the carriers to be adjacent. In fact, they can be in different bands. The additional unpaired downlink spectrum bands are sometimes called supplemental downlink bands. The different band combinations are as follows:

- Band 1 (2100 MHz) and Band 8 (900 MHz)
- Band 2 (1900 MHz) and Band 4 (2100/1700 MHz)
- Band 1 (2100 MHz) and Band 5 (850 MHz)

In addition to the above combinations, other band combinations can also be added based on operator demand.

Release 9 also supports dual-carrier operation in the uplink.

Release 10 specifies the use of up to four channels, resulting in peak downlink data rates of 168 Mbps.

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Release 11 supports eight radio channels on the downlink, resulting in a further doubling of throughput to 336 Mbps. On the uplink, devices can transmit using two antennas for either rank 1 (single stream beamforming) or rank 2 (dual-stream MIMO) transmission modes. Rank 1 beamforming helps with coverage (approximately 40%), while rank 2 MIMO helps with throughput speeds (approximately 20% median and 80% at cell edge). In addition, 64 QAM will be possible on the uplink, enabling uplink speeds to 69 Mbps in dual-carrier operation.

Figure 34 shows an analysis of dual-carrier performance using a cumulative distribution function. Cumulative Distribution Function (CDF) indicates the probability of achieving a particular throughput rate and the figure demonstrates a consistent doubling of throughput.

**Figure 34: Dual-Carrier Performance**

![Graph showing dual-carrier performance analysis.](image)

**Downlink Multiflow Transmission**

Release 11 specifies means by which two cells can transmit to the mobile station at the same time. The two cells transmit independent data, in effect a spatial multiplexing approach, improving both peak and average data.

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92 Source: 4G Americas member company contribution.
Multiflow transmission with HSPA+ also enhances HetNet operation in which picocell coverage can be expanded within a macrocell coverage area, as shown in Figure 35.

**Figure 35: HSPA+ HetNet Using Multipoint Transmission**

Multiflow enhances HSPA+ network operation using the following approaches:

- **Single Frequency Dual Cell.** The UE communicates with two different cells using the same frequency, improving cell-edge performance and providing network load balancing.

- **Dual Frequency Three Cell.** The UE communicates with two different cells using the same frequency. In addition, it communicates with one other cell on a different frequency.

- **Dual Frequency Four Cells.** The UE communicates using two instances of Single Frequency Dual Cell operation as described above.

In Release 12, 3GPP is considering the following enhancement to Multiflow operation, which is primarily targeted towards HetNet operation:

- **Dual Frequency Dual Carrier.** The UE aggregates cells on two different frequencies from two different sites.

**HSPA+ Throughput Rates**

Table 9 summarizes the capabilities of HSPA and HSPA+ based on the various methods discussed above.

**Table 9: HSPA Throughput Evolution**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Downlink</th>
<th>Uplink (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>(Mbps) Peak Data Rate</th>
<th>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 DL, Dual Carrier UL, 40+10 MHz</td>
<td>336.0</td>
<td>69.0</td>
</tr>
</tbody>
</table>

HSPA+ also has improved latency performance of as low as 25 msec and improved packet call setup time of below 500 msec.

From a deployment point of view, operators can introduce HSPA+ capabilities through either a software upgrade or hardware expansions to existing cabinets to increase capacity. Certain upgrades will be simpler than others. For example, upgrading to 64-QAM support or dual-carrier operation will be easier to implement than 2X2 MIMO for many networks. For networks that have implemented uplink diversity in the base station, however, those multiple antennas will facilitate MIMO deployment.

**Fast Dormancy**

Small-packet message traffic places an inordinate load on a network, requiring a disproportionate amount of signaling and resource utilization compared to the size of the small packet. To help mitigate these affects, User Equipment (UE) vendors trigger the Radio Resource Control (RRC) Signaling Connection Release Indication (SCRI) message to release the signaling connection and ultimately cause the release of the RRC connection between the network and UE. This causes the UE to rapidly return to idle mode, which is the most battery-efficient radio state. This is a highly desirable behavior as it greatly increases the battery life of the mobile terminal device whilst freeing up unused radio resource in the network.

If the device implementation for triggering fast dormancy is not done in an appropriate manner, however, then the resulting recurrent signaling procedures needed to re-establish the data connection, as described above, may lead to network overload. In order to overcome this drawback, Release 8 defined the fast dormancy feature that gives the network continued control over the UE RRC state transitions.
A cell indicates support for the Release 8 feature via the broadcast of an inhibit timer. The UE supporting the feature, once it has determined it has no more packet-switched data for a prolonged period, sends a SCRI conveying an explicit cause value. On receipt of this message, the network controls the resulting state transition to a more battery efficient state, such as CELL_PCH or UTRAN Registration Area Paging Channel (URA_PCH). In this way, the UE maintains the PS signaling connection and does not require the re-establishment of the RRC connection for a subsequent data transfer. In addition, the network inhibit timer prevents frequently repeated fast dormancy requests from the UE.

Fast dormancy thus mitigates the impact on network signaling traffic while reducing the latency for any follow-on packet-switched data transmission and significantly improves UE battery efficiency.

Field test results have shown fast dormancy improves standby time for a UMTS device by as much as 30% to 40%. Figure 36 provides an example of the battery life improvement due to fast dormancy. It compares two devices running concurrently on a commercial UMTS network with an e-mail sent every 17 minutes. The X-axis represents time, with the right side being how long a battery would last in the absence of fast dormancy.
One-Tunnel Architecture

Flatter architecture is another way to improve HSPA performance. Introduced in Release 7, one-tunnel architecture establishes a direct transfer path for user data between the RNC and the GGSN, while the SGSN still performs all control functions, thus eliminating hardware at the SGSN and simplifying engineering of the network.

In another HSPA+ option called integrated RNC/NodeB, RNC functions are combined in the NodeB, which is particularly beneficial in femtocell deployments, as otherwise an RNC would need to support thousands of femtocells.

These new architectures, as shown in Figure 37, are similar to the EPC architecture, especially on the packet-switched core network side in which they provide synergies with the introduction of LTE.

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94 Source: 4G Americas member contribution.
In Release 7, a new capability called High-Speed Access Forward Access Channel (HS-FACH), illustrated in Figure 38, reduces setup time to practically zero and provides a more efficient way of carrying application signaling for always-on applications. This method employs the same HSDPA power/code resources for access requests (CELL_FACH state) as for dedicated packet transfer (CELL_DCH), allowing data transmission to start during the HS-FACH state with increased data rates immediately available to the user equipment. During the HS-FACH state, the network allocates dedicated resources for transitioning the user equipment to a dedicated channel state.

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HS-RACH and FE-FACH

In Release 8, the high speed access channel described above extends to the uplink by activating the E-DCH in CELL_FACH to reduce the delay before E-DCH can be used. This feature is called High-Speed Reverse Access Channel (HS-RACH), and together with HS-FACH, is called the enhanced CELL_FACH operation.

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The RACH is intended for small amounts of data and thus has a limited data rate and can only support transmission of a single transport block. For larger amounts of data, terminals must transmit multiple times on the RACH or transition to the dedicated channel, which causes delays. Overcoming these delays can be done by transmitting data on the E-DCH while still in the CELL_FACH state. Data transmissions can thus continue uninterrupted as the state changes from CELL_FACH to CEL_DCH.97

Release 11 improves the capacity of small data bursts ten-fold on the downlink through a feature called Further Enhanced Forward Access Channel (FE-FACH). FE-FACH constitutes a total of ten separate enhancements to CELL_FACH state that build on top of HS-FACH and HS-RACH and provide:

- Improved resource utilization
- Higher throughput
- Reduction in latency
- Coverage improvement
- Longer battery life
- (RRC) Signaling overhead reduction
- Mobility improvements

Other enhancements available or planned for HSPA that are not discussed in this paper include closed-loop transmit diversity (CLTD), minimization of test drives, and Automatic Neighbor Relations (ANR).

Figure 39 summarizes the key capabilities and benefits of the features being deployed in HSPA+.

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**UMTS-HSPA Voice**

Circuit-switched voice using WCDMA dedicated channels in UMTS networks is spectrally very efficient. Moreover, current networks support simultaneous voice and data operation. Nevertheless, new voice approaches, including improved circuit-switched voice, circuit-switched voice over HSPA, and voice over Internet Protocol (VoIP), can further increase voice efficiency.

**Improved Circuit-Switched Voice (WCDMA+)**

Release 12 standardization efforts are evaluating means of improving circuit-switched voice capacity through a combination of approaches, including:

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*Source: 4G Americas member contribution.*
- Reducing transmit power overhead by eliminating the dedicated pilot and using the transmit power control bits for channel estimation.
- Implementing a new, more efficient frame format that multiplexes two voices calls by splitting the 20 msec frame into two 10 msec halves.
- Terminating frame transmissions early once they are successfully decoded.
- Using the new Enhanced Voice Services (EVS) codec.

The motivation is not necessarily to support more voice calls, but to free up resources for data. The listed improvements result in only about half the radio resources needed to carry the same number of voice calls, with the remaining resources freed for data.

**Circuit-Switched (CS) Voice over HSPA**

HSPA channels employ many optimizations for high data efficiency, which is why it makes sense to consider them to carry voice communications. Doing so with VoIP, however, requires not only supporting packetized voice in the radio channel, but also within the infrastructure network. An alternative packetizes the circuit-switched voice traffic, which is already in digital form, uses the HSPA channels to carry the CS voice, and then connects the CS voice traffic back into the existing CS infrastructure (MSCs, etc.) immediately beyond the radio access network. This approach requires relatively straightforward changes in just the radio network and in devices, as shown in Figure 40.

**Figure 40: Implementation of HSPA CS Voice**

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With CS Voice, legacy mobile phones can continue using WCDMA-dedicated traffic channels for voice communications, while new devices use HSPA channels. HSPA CS voice can be deployed with Release 7 or later networks, and includes the following benefits:

- Relatively easy to implement and deploy.
- Transparent to existing CS infrastructure.
- Supports both narrowband and wideband codecs.
- Significantly improves battery life with voice communications.
- Enables faster call connections.
- Provides a 50% to 100% capacity gain over current voice implementations.
- Acts as a stepping stone to VoIP over HSPA/LTE in the future.

**VoIP**

VoIP, another approach for HSPA introduced in Release 6 and enhanced in subsequent releases, can increase voice capacity, consolidate infrastructure on an IP platform, and enable innovative new applications that combine voice with data functions in the packet domain. VoIP operates over IMS, discussed later in this paper.

Operators can smoothly migrate users from circuit-switched operation to packet-switched operation over time. Because the UMTS radio channel supports both circuit-switched voice and packet-switched data, some voice users can be on legacy circuit-switched voice and others can be on VoIP. Figure 41 shows a system’s voice capacity with the joint operation of circuit-switched and IP-based voice services.

**Figure 41: Ability for UMTS to Support Circuit and Packet Voice Users**

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100 Source: 4G Americas member contribution.
VoIP capacity gains range from 20% to as high as 100% with the implementation of interference cancellation and the minimization of IP overhead through a scheme called Robust Header Compression (ROHC).

Whereas packet voice is the only way voice will be supported in LTE, UMTS already has a highly efficient, circuit-switched voice service and already allows simultaneous voice/data operation. Moreover, packet voice requires a considerable amount of new infrastructure in the core network. Consequently, packet voice will likely be used initially as part of other services (for example, those based on IMS), and only over time might it transition to primary voice service.

**LTE**

Although HSPA and HSPA+ offer a highly efficient broadband-wireless service that will enjoy success for the remainder of this decade and well into the next, 3GPP completed the specification for Long Term Evolution as part of Release 8. LTE offers even higher peak throughputs in wider spectrum bandwidth. Work on LTE began in 2004 with an official work item started in 2006 and a completed specification early 2009. Initial deployments began in 2010.

LTE uses OFDMA on the downlink, which is well suited to achieve high peak data rates in high-spectrum bandwidth. WCDMA radio technology is basically as efficient as OFDM for delivering peak data rates of about 10 Mbps in 5 MHz of bandwidth. Achieving peak rates in the 100 Mbps range with wider radio channels, however, would result in highly complex terminals, and it is not practical with current technology, whereas OFDM provides a practical implementation advantage. Scheduling approaches in the frequency domain can also minimize interference, thereby boosting spectral efficiency. The OFDMA approach is also flexible in channelization: LTE operates in various radio channel sizes ranging from 1.4 to 20 MHz.

On the uplink, however, a pure OFDMA approach results in high Peak to Average Ratio (PAR) of the signal, which compromises power efficiency and, ultimately, battery life. Hence, LTE uses an approach called SC-FDMA, which is somewhat similar to OFDMA, but has a 2 to 6 dB PAR advantage over the OFDMA method used by other technologies such as WiMAX.

LTE capabilities include:

- 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.\(^\text{101}\)
- Operation in both TDD and FDD modes.
- Scalable bandwidth up to 20+20 MHz covering 1.4, 3, 5, 10, 15, and 20 MHz radio carriers.
- Increased spectral efficiency over Release 6 HSPA by a factor of two to four.
- Reduced latency, to 15 msec round-trip times between user equipment and the base station, and to less than 100 msec transition times from inactive to active.

\(^{101}\) Assumes 64 QAM. Otherwise 45 Mbps with 16 QAM.
Self-optimizing capabilities under operator control and preferences that will automate network planning and will result in lower operator costs.

**LTE Throughput Rates**

The overall objective is to provide an extremely high-performance, radio-access technology that offers full vehicular speed mobility and that can readily coexist with HSPA and earlier networks. Because of scalable bandwidth, operators will be able to easily migrate their networks and users from HSPA to LTE over time.

Table 10 shows Release 8 LTE peak data rates based on different downlink and uplink designs.

**Table 10: LTE Peak Throughput Rates**

<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 is not only efficient for data but, because of a highly efficient uplink, is extremely efficient for VoIP traffic. In 10+10 MHz of spectrum, LTE VoIP capacity will reach almost 500 users.\(^{102}\)

**OFDMA and Scheduling**

LTE implements OFDM in the downlink. The basic principle of OFDM is to split a high-rate data stream into a number of parallel, low-rate data streams, each a narrowband signal carried by a subcarrier. The different narrowband streams are generated in the frequency domain, and then combined to form the broadband stream using a mathematical algorithm called an Inverse Fast Fourier Transform (IFFT) that is implemented in digital-signal processors. In LTE, the subcarriers have 15 kHz spacing from each other. LTE maintains this spacing regardless of the overall channel bandwidth, which simplifies radio design, especially in supporting radio channels of different widths. The number of subcarriers ranges from 72 in a 1.4 MHz radio channel to 1,200 in a 20 MHz radio channel.

The composite signal obtained after the IFFT is extended by repeating the initial part of the signal (called the Cyclic Prefix [CP]). This extended signal represents an OFDM symbol. The CP is basically a guard time during which reflected signals will reach the receiver. It results in an almost complete elimination of multipath-induced Intersymbol Interference (ISI), which otherwise makes extremely high data-rate transmissions problematic. The system is called orthogonal because the subcarriers are generated in the frequency domain (making them inherently orthogonal), and the IFFT conserves that characteristic.

\(^{102}\) Source: 3GPP Multi-member analysis.
OFDM systems may lose their orthogonal nature as a result of the Doppler shift induced by the speed of the transmitter or the receiver. 3GPP specifically selected the subcarrier spacing of 15 kHz to avoid any performance degradation in high-speed conditions. WiMAX systems that use a lower subcarrier spacing (~11 kHz) are more impacted in high-speed conditions than LTE.

**Figure 42: OFDM Symbol with Cyclic Prefix**

<table>
<thead>
<tr>
<th>Cyclic Prefix</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4.8 μsec)</td>
<td>(66.7 μsec)</td>
</tr>
</tbody>
</table>

The multiple-access aspect of OFDMA comes from being able to assign different users different subcarriers over time. A minimum resource block that the system can assign to a user transmission consists of 12 subcarriers over 14 symbols in 1.0 msec. Figure 43 shows how the system can assign these resource blocks to different users over both time and frequency.

**Figure 43: LTE OFDMA Downlink Resource Assignment in Time and Frequency**

By controlling which subcarriers are assigned in which sectors, LTE can easily control frequency reuse. Using all the subcarriers in each sector, the system would operate at a frequency reuse of 1; but by using a different one third of the subcarriers in each sector, the system can achieve a looser frequency reuse of 1/3. The looser frequency reduces overall spectral efficiency, but delivers high peak rates to users.
Beyond controlling frequency reuse, frequency domain scheduling, as shown in Figure 44 can use those resource blocks that are not faded, not possible in CDMA-based systems. Since different frequencies may fade differently for different users, the system can allocate those frequencies for each user that result in the greatest throughput. This results in up to a 40% gain in average cell throughput for low user speed (3 km/hour), assuming a large number of users and no MIMO. The benefit decreases at higher user speeds.

**Figure 44: Frequency-Domain Scheduling in LTE**

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**LTE Smart Antennas**

Wireless networks can achieve significant gains by employing multiple antennas, either at the base station, the mobile device, or both. LTE uses multiple antennas in three fundamentally different ways:

1. **Diversity.** So long as the antennas are spaced or polarized appropriately, the antennas provide protection against fading.

2. **Beamforming.** Multiple antennas can shape a beam to increase the gain for a specific receiver. Beamforming can also suppress specific interfering signals. Beamforming is particularly helpful for improving cell-edge performance.

3. **Spatial Multiplexing.** Often referred to as MIMO antenna processing, spatial multiplexing creates multiple transmission paths through the environment,

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103 4G Americas member contribution.
effectively sending data in parallel through these paths, thus increasing both throughput and spectral efficiency.

Table 11 shows the various antenna transmission modes.

**Table 11: LTE Transmission Modes**

<table>
<thead>
<tr>
<th>Transmission Mode</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Single-antenna transmission.</td>
</tr>
<tr>
<td>2</td>
<td>Transmit diversity.</td>
</tr>
<tr>
<td>3</td>
<td>Transmit diversity for one layer, open-loop codebook-based precoding if more than one layer.</td>
</tr>
<tr>
<td>4</td>
<td>Closed-loop codebook-based precoding.</td>
</tr>
<tr>
<td>5</td>
<td>Multi-user MIMO version of transmission mode 4.</td>
</tr>
<tr>
<td>6</td>
<td>Special case of closed-loop codebook-based precoding limited to single-layer transmission.</td>
</tr>
<tr>
<td>7</td>
<td>Non-codebook-based precoding supporting one layer.</td>
</tr>
<tr>
<td>8</td>
<td>Release 9. Non-codebook-based precoding supporting up to two layers.</td>
</tr>
<tr>
<td>9</td>
<td>Release 10. Non-codebook-based precoding supporting up to eight layers.</td>
</tr>
</tbody>
</table>

Being able to exploit different antenna modes based on local conditions produces huge efficiency and performance gains, and is the reason that 3GPP is developing even more advanced antenna modes in subsequent LTE releases.

Precoding refers to a mathematical matrix operation performed on radio symbols to determine how they are combined and mapped onto antenna ports. The precoder matrix can operate in either open-loop or closed-loop modes. For each transmission rank for a given number of transmission ports (antennas), there is a limited set of precoder matrices defined, called the codebook. This helps limit the amount of signaling needed on uplink and downlink.

Fundamental variables distinguish the different antenna modes:

- **Single base-station antenna versus multiple antennas.** Single antennas provide for Single Input Single Output (SISO), Single Input Multiple Output (SIMO) and planar-array beamforming. (Multiple Output means the UE has

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multiple antennas.) Multiple antennas at the base station provide for different MIMO modes such as 2X2, 4X2, and 4X4.

- **Single-user MIMO versus multi-user MIMO.** Release 8 only provides for single-user MIMO on the downlink. Release 10 includes multi-user MIMO.

- **Open Loop versus Closed Loop.** High vehicular speeds require open-loop operation whereas slow speeds enabled closed-loop operation in which feedback from the UE modifies the transmission. In closed-loop operation, the precoder matrix is based on this feedback.

- **Rank.** In a MIMO system, the channel rank is formally defined as the rank of the channel matrix and is a measure of the degree of scattering that the channel exhibits. For example, in a 2x2 MIMO system, a rank of one indicates a low-scattering environment, while a rank of two indicates a high-scattering environment. The rank two channel is highly uncorrelated, and is thus able to support the spatial multiplexing of two data streams, while a rank one channel is highly correlated, and thus can only support single stream transmission (the resulting multi-stream interference in a rank one channel as seen at the receiver would lead to degraded performance). Higher Signal to Interference plus Noise Ratios (SINR) are typically required to support spatial multiplexing, while lower SINRs are typically sufficient for single stream transmission. In a 4x4 MIMO system channel rank values of three and four are possible in addition to values of one and two. The number of data streams, however, or more specifically codewords in LTE is limited to a value of two. Thus, LTE has defined the concept of layers, in which the DL transmitter includes a codeword-to-layer mapping, and in which the number of layers is equal to the channel rank. An antenna mapping or precoding operation follows, which maps the layers to the antenna ports. A 4x2 MIMO system is also possible with LTE Release 8, but here the channel rank is limited to the number of UE antennas, which is equal to two.

The network can dynamically choose between different modes based on instantaneous radio conditions between the base station and the UE. Figure 45 shows the decision tree. The antenna configuration (AC) values refer to the transmission modes. Not every network will support every mode. Operators will choose which modes are the most effective and economical. AC2, 3, 4, and 6 are typical modes that will be implemented.
The simplest mode is AC2, referred to as Transmit Diversity (TD) or sometimes Space Frequency Block Code (SFBC) or even Open Loop Transmit Diversity. TD can operate under all conditions, meaning it works under low SINR, high mobility, and low channel rank (rank = 1). This rank means that the channel is not sufficiently scattered or decorrelated to support two spatial streams. Thus, in TD, only one spatial stream or what is sometimes referred as a single codeword (SCW) is transmitted. If the channel rank increases to a value of two, indicating a more scattered channel, and the SINR is a bit higher, then the system can adapt to AC3 or Open-Loop Spatial Multiplexing (OL-SM), also referred to as large-delay Cyclic Delay Diversity (CDD). This mode supports two spatial streams or two codewords. This mode, also called multiple codeword (MCW) operation, increases throughput over SCW transmission.

If the rank of the channel is one, but the device is not moving very fast or is stationary, then the system can adapt to AC6, called closed-loop (CL) precoding (or CL-rank 1 or CL-R1). In this mode, the network receives from the device with Precoding Matrix Indication (PMI) bits that inform the base station what precoding matrix to use in the transmitter to optimize link performance. This feedback is only relevant for low-mobility or stationary conditions since in high mobility conditions the feedback will most likely be outdated by the time the base station can use it.

Another mode is AC4 or Closed Loop Spatial Multiplexing (CL-SM), which is enabled for low mobility, high SINR, and channel rank of two. This mode theoretically provides the best user throughput. The figure above shows how these modes can adapt downwards to either OL TD, or if in CL-SM mode, down to either OL TD or CL R1.

---

For a 4x4 MIMO configuration, the channel rank can take on values of three and four in addition to one or two. Initial deployment at the base station, however, will likely be two TX antennas and most devices will only have 2 RX antennas, and thus the rank is limited to 2.

AC5 is MU-MIMO, which is not defined for the downlink in Release 8.

AC1 and AC7 are single antenna port modes in which AC1 uses a common Reference Signal (RS), while AC7 uses a dedicated RS or what is also called a user specific RS. AC1 implies a single TX antenna at the base station. AC7 implies an antenna array with antennal elements closely spaced so that a physical or spatial beam can be formed towards an intended user.

LTE operates in a variety of MIMO configurations. On the downlink, these include 2X2, 4X2 (four antennas at the base station), and 4X4. Initial deployment will likely be 2x2 whereas 4X4 will be most likely used initially in femtocells. On the uplink, there are two possible approaches: single-user MIMO (SU-MIMO) and multi-user MIMO (MU-MIMO). SU-MIMO is more complex to implement as it requires two parallel radio transmit chains in the mobile device, whereas MU-MIMO does not require any additional implementation at the device but relies on simultaneous transmission on the same tones from multiple mobile devices.

The first LTE release thus incorporates MU-MIMO with SU-MIMO deferred for subsequent LTE releases. An alternate form of MIMO, originally called network MIMO, and now called CoMP, relies on MIMO implemented (on either the downlink or uplink or both) using antennas across multiple base stations, as opposed to multiple antennas at the same base station. This paper explains CoMP in the section on LTE Advanced below.

Peak data rates are approximately proportional to the number of send and receive antennas. 4X4 MIMO is thus theoretically capable of twice the data rate of a 2X2 MIMO system. The spatial-multiplexing MIMO modes that support the highest throughput rates will be available in early deployments.


For advancements in LTE smart antennas, see the section below on LTE-Advanced.

IPv4/IPv6

Release 8 defines support for IPv6 for both LTE and UMTS networks. An Evolved Packet System bearer can carry both IPv4 and IPv6 traffic, enabling a UE to communicate both IPv4 and IPv6 packets (assuming it has a dual stack) while connected through a single EPS bearer. It is up to the operator, however, whether it assigns IPv4, IPv6, or both types of addresses to UE.

Communicating between IPv6-only devices and IPv4 end-points will require protocol-conversion or proxies. For further details, refer to the 4G Americas white paper, “IPv6 – Transition Considerations for LTE and Evolved Packet Core,” February 2009.

Voice Support

Voice in LTE can encompass: no voice support, voice implemented in a circuit-switched fallback (CSFB) mode using 2G or 3G; and VoIP implemented with IMS.
Initial network deployments used CSFB, with which the LTE network carries circuit-switched signaling over LTE interfaces, allowing the subscriber to be registered with the 2G/3G MSC even while on the LTE network. When there is a CS-event, such as an incoming voice call, the MSC sends the page to the LTE core network which delivers it to the subscriber device. The device then switches to 2G/3G operation to answer the call.

Voice over LTE using VoIP requires IMS infrastructure. To facilitate IMS-based voice, vendors and operators created the One Voice initiative to define required baseline functionality for user equipment, the LTE access network, the Evolved Packet Core, and for the IMS. GSMA adopted the One Voice initiative in what it calls Voice over LTE (VoLTE), specified in GSMA reference document IR.92. GSMA is also working to enable interconnection and international roaming between LTE networks through the IR.88 specification. With VoLTE available in 2013, LTE voice roaming could occur in 2014 or 2015.

LTE VoIP leverages the QoS capabilities defined for EPC, which specify different quality classes. Features available in LTE to make voice operation more efficient include Semi-Persistent Scheduling (SPS) and TTI bundling. SPS reduces control channel overhead for applications (like VoIP) that require a persistent radio resource. Meanwhile, TTI bundling improves subframe utilization by reducing IP overhead in the process optimizing uplink coverage.

Another way to increase voice capacity in LTE and to support operation in congestion situations is vocoder rate adaptation, a mechanism with which operators can control the codec rate based on network load, thus dynamically trading off voice quality against capacity.

VoLTE roaming across operators will require network-to-network interfaces between their respective IMS networks. Such roaming and interconnect will follow initial VoLTE deployments.

Single-Radio Voice Call Continuity (SR-VCC) will allow user equipment in midcall to switch to a circuit-switched network in the event that it moves out of LTE coverage. Similarly, data sessions can be handed over in what is called Packet Switched Handover (PSHO).

Figure 46 shows how an LTE network might evolve in three stages. Initially, LTE performs only data service, and the underlying 2G/3G network provides voice service via CSFB. In the second stage, voice over LTE is available, but LTE covers only a portion of the total 2G/3G coverage area. Hence, voice in 2G/3G can occur via CSFB or SR-VCC. Eventually, LTE coverage will match 2G/3G coverage, and LTE devices will use only the LTE network.

---


Another voice approach called Voice over LTE via Generic Access (VoLGA) defined circuit-switched operation through an LTE IP tunnel. 3GPP, however, has stopped official standards work that would support VoLGA.

**TDD Harmonization**

3GPP developed LTE TDD to be fully harmonized with LTE FDD including alignment of frame structures, identical symbol-level numerology, the possibility of using similar reference signal patterns, and similar synchronization and control channels. Also, there is only one TDD variant. Furthermore, LTE TDD has been designed to co-exist with TD-SCDMA and TD-CDMA/UTRA (both low-chip rate and high-chip rate versions). LTE TDD achieves compatibility and co-existence with TD-SCDMA by defining frame structures in which the DL and UL time periods can be time aligned to prevent BTS to BTS and UE to UE interference to support operation in adjacent carriers without the need for large guardbands between the technologies. This will simplify deployment of LTE TDD in countries such as China that are deploying TD-SCDMA. Figure 47 demonstrates the synchronization between TC-SCDMA and LTE-TDD in adjacent channels.

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108 Source: 4G Americas member contribution.
For LTE FDD and TDD to coexist, large guardbands will be needed to prevent interference.

**SMS in LTE**

Even if an LTE network uses CSFB for voice, LTE devices will be able to send and receive SMS messages while on the LTE network. In this case, the 2G/3G core network will handle SMS messaging, but will tunnel the message to the MME in the EPC via the SGs interface. Once an LTE network uses IMS and VoLTE for packet voice service, SMS will be handled as SMS over IP and will use IMS infrastructure.\(^\text{110}\)

**LTE-Advanced**

LTE-Advanced, as specified in Release 10, is a term used for the version of LTE that addresses IMT-Advanced requirements. The ITU ratified LTE-Advanced as IMT-Advanced in November 2010. LTE-Advanced is both backwards- and forwards-compatible with LTE, meaning LTE devices will operate in newer LTE-Advanced networks, and LTE-Advanced devices will operate in older LTE networks.

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\(^{109}\) Source: A 4G Americas member company.

\(^{110}\) For further details, refer to page 35 of the 4G Americas paper, “Coexistence of GSM, HSPA and LTE,” May 2011.
The following lists at a high level the most important features of LTE-Advanced, as well as other features planned for subsequent releases including Release 11:

- Carrier aggregation.
- Higher order downlink MIMO (up to 8X8 in Release 10).
- Uplink MIMO (two transmit antennas in the device).
- Coordinated multipoint transmission (CoMP) in Release 11.
- Heterogeneous network (HetNet) support including enhanced Inter-Cell Interference Coordination (eICIC).
- Relays.

The following sections describe these various features in greater detail.

**IMT-Advanced**

The term 4G originally applied to networks that comply with the requirements of IMT-Advanced that are articulated in Report ITU-R M.2134. Some of the key requirements or statements include:

- Support for scalable bandwidth up to and including 40+40 MHz.
- Encouragement to support wider bandwidths (such as 100+100 MHz).
- Minimum downlink peak spectral efficiency of 15 bps/Hz (assumes 4X4 MIMO).
- Minimum uplink peak spectral efficiency of 6.75 bps/Hz (assumes 2X4 MIMO).

Table 12 shows the requirements for cell-spectral efficiency.

**Table 12: IMT-Advanced Requirements for Cell-Spectral Efficiency**

<table>
<thead>
<tr>
<th>Test Environment</th>
<th>Downlink (bps/Hz)</th>
<th>Uplink (bps/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor</td>
<td>3.0</td>
<td>2.25</td>
</tr>
<tr>
<td>Microcellular</td>
<td>2.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Base Coverage Urban</td>
<td>2.2</td>
<td>1.4</td>
</tr>
<tr>
<td>High Speed</td>
<td>1.1</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 13 shows the requirements for voice capacity.

**Table 13: IMT-Advanced Requirements for Voice Capacity**

<table>
<thead>
<tr>
<th>Test Environment</th>
<th>Minimum VoIP Capacity (Active Users/Sector/MHz)</th>
</tr>
</thead>
</table>

111 Test environments are described in IT Report ITU-R M.2135.

112 Ibid.
### Table 14: IMT-Advanced Requirements and Projected LTE-Advanced Capability

<table>
<thead>
<tr>
<th>Item</th>
<th>IMT-Advanced Requirement</th>
<th>LTE-Advanced Projected Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Data Rate Downlink</td>
<td>1 Gbps</td>
<td></td>
</tr>
<tr>
<td>Peak Data Rate Uplink</td>
<td>500 Mbps</td>
<td></td>
</tr>
<tr>
<td>Spectrum Allocation</td>
<td>Up to 40+40 MHz</td>
<td>Up to 100+100 MHz</td>
</tr>
<tr>
<td>Latency User Plane</td>
<td>10 msec</td>
<td>10 msec</td>
</tr>
<tr>
<td>Latency Control Plane</td>
<td>100 msec</td>
<td>50 msec</td>
</tr>
<tr>
<td>Peak Spectral Efficiency DL(^\text{113})</td>
<td>15 bps/Hz</td>
<td>30 bps/Hz</td>
</tr>
<tr>
<td>Peak Spectral Efficiency UL</td>
<td>6.75 bps/Hz</td>
<td>15 bps/Hz</td>
</tr>
<tr>
<td>Average Spectral Efficiency DL</td>
<td>2.2 bps/Hz</td>
<td>2.6 bps/Hz</td>
</tr>
<tr>
<td>Average Spectral Efficiency UL</td>
<td>1.4 bps/Hz</td>
<td>2.0 bps/Hz</td>
</tr>
<tr>
<td>Cell-Edge Spectral Efficiency DL</td>
<td>0.06 bps/Hz</td>
<td>0.09 bps/Hz</td>
</tr>
<tr>
<td>Cell-Edge Spectral Efficiency UL</td>
<td>0.03 bps/Hz</td>
<td>0.07 bps/Hz</td>
</tr>
</tbody>
</table>

In all cases, projections of LTE-Advanced performance exceed that of the IMT-Advanced requirements.

### Carrier Aggregation

Carrier aggregation, first available in Release 10, will play an important role in providing operators maximum flexibility for using all of their available spectrum. By combining spectrum blocks, LTE can deliver much higher throughputs than otherwise possible. Asymmetric aggregation (i.e., different amounts of spectrum used on the downlink versus the uplink) provides further flexibility and addresses the greater demand on downlink traffic.

Specific types of aggregation include:

- Intra-band on adjacent channels.

---

\(^{113}\) Spectral efficiency values based on four antennas at the base station and two antennas at the terminal.
- Intra-band on non-adjacent channels.
- Inter-band (700 MHz, 1.9 GHz).
- Inter-technology (for example, LTE on one channel, HSPA+ on another). This is currently under consideration for Release 12. While theoretically promising, a considerable number of technical issues will have to be addressed. \(^{114}\) See Figure 48.

**Figure 48: Inter-Technology Carrier Aggregation**\(^ {115}\)

One anticipated benefit of inter-band aggregation is from using the lower-frequency band for users that are at the cell edge to boost their throughput rates. Though this only improves average aggregate throughput of the cell by a small amount (say, 10%), it results in a more uniform user experience across the cell coverage area.

Figure 49 shows an example of intra-band carrier aggregation using adjacent channels with up to 100+100 MHz of bandwidth supported. Radio-access network specifications, however, limit the number of carriers to two in Release 10 and Release 11.

\(^{114}\) For further details, see the 4G Americas paper, “HSPA+ LTE Carrier Aggregation,” June 2012.

\(^{115}\) Source: 4G Americas member contribution.
Figure 49: Release 10 LTE-Advanced Carrier Aggregation

![Diagram showing carrier aggregation in Release 10 LTE-Advanced UE resource pool with 100 MHz bandwidth and 20 MHz block.]

Release 8 UE uses a single 20 MHz block.

Figure 50 shows the carrier aggregation operating at different protocol layers.

Figure 50: Carrier Aggregation at Different Protocol Layers

![Diagram showing carrier aggregation at different protocol layers (RLC, MAC, PHY) with LTE and LTE-Advanced bands.]

---


CA combinations being defined in the Release 10 timeframe include:

**Intra-band contiguous:**
- Band 1 (FDD), UL[1920-1980]/DL[2110-2170]
- Band 40 (TDD), UL[2300-2400]/DL[2300-2400]

**Inter-band non-contiguous (FDD):**
- Band 1 (UL[1920-1980]/DL[2110-2170]) + Band 5 (UL[824-849]/DL[869-894])

Expanded CA combinations being defined for the Release 11 timeframe, all inter-band, and FDD include:

- Band 3 and Band 7 (TeliaSonera – 1800MHz and 2600 MHz)
- Band 4 and Band 13 (Verizon – AWS and Upper 700 MHz)
- Band 4 and Band 7 (Rogers, Bell – AWS and 2600 MHz)
- Band 4 and Band 17 (AT&T – AWS and Lower 700 MHz)
- Band 2 and Band 17 (AT&T – PCS and Lower 700 MHz)
- Band 4 and Band 5 (AT&T – AWS and 850 MHz)
- Band 4 and Band 12 (Cox Communications – AWS and Lower 700 MHz)
- Band 5 and Band 12 (US cellular – 850 MHz and Lower 700 MHz)
- Band 5 and Band 17 (AT&T – 850 MHz and Lower 700 MHz)
- Band 7 and Band 20 (Orange – 2600 MHz and 800 MHz)
- Band 1 and Band 7
- Band 3 and Band 5
- Band 3 and Band 20
- Band 8 and Band 20
- Band 1 and Band 21
- Band 1 and Band 19
- Band 11 and Band 18
- Band 1 and Band 18
- Band 3 and 8

Release 11 intra-band includes:

- Band 7
- Band 38

For the Release 12 timeframe, additional combinations will be defined. Inter-band combinations include:

- Band 2 and Band 4 (Rogers, T-Mobile USA – PCS and AWS)
- Band 3 and Band 5

Release 12 intra-band combinations include:

- Band 4 (Rogers - AWS)
- Band 1
- Band 3
- Band 25

Carrier aggregation not only improves performance by combining the capacity of two or more different radio channels, but also through trunking efficiency, which refers to packets being able to traverse through either of the channels and solving the problem of one being congested while the other is idle.
Figure 51 shows the result of one simulation study that compares download throughput rates between the blue line that shows five user devices in 700 MHz and five user devices in AWS not using CA and the pink line that shows ten user devices that have access to both bands. Assuming a lightly loaded network with CA, 50% or more users (the median) experience 91% greater throughput and 95% or more users experience 50% greater throughput. These trunking gains are less pronounced in heavily-loaded networks.

Figure 51: Gains from Carrier Aggregation

![Figure 51: Gains from Carrier Aggregation](image)

**LTE-Advanced Antenna Technologies**

Release 10 includes significant enhancements to antenna capabilities, including four-layer transmission resulting in peak spectral efficiency exceeding 15 bps/Hz. Uplink techniques fall into two categories: those relying on channel reciprocity and those that do not. With channel reciprocity, the eNB determines the channel state by processing a sounding reference signal from the UE. It then forms transmission beams accordingly. The assumption is that the channel received by the eNB is the same as the UE. Techniques that use channel reciprocity are beamforming, SU-MIMO, and MU-MIMO. Channel reciprocity works especially well with TDD since both forward and reverse links use the same frequency.

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118 Source: 4G Americas member contribution. Assumptions: lightly-loaded network, 2.0 site-to-site distance, file size is 750 Kbytes, traffic model bursty with mean inter-arrival time of five seconds,
Non-reciprocity approaches apply when the transmitter has no knowledge of the channel state. Techniques in this instance include open-loop MIMO, closed-loop MIMO, and MU-MIMO. These techniques are more applicable for higher speed mobile communications.

For the downlink, the technology can transmit in up to eight layers using an 8X8 configuration for a peak spectral efficiency of 30 bps/Hz that exceeds the IMT-Advanced requirements, conceivably supporting a peak rate of 1 Gbps in just 40+40 MHz and even higher rates in wider bandwidths. This would require additional reference signals for channel estimation and for measurements including channel quality to enable adaptive, multi-antenna transmission.

Release 10 supports a maximum number of two codewords, the same as previous LTE releases. The release specifies a new transmission mode (TM-9) that supports SU-MIMO up to rank 8 (up to 8 layers), as well as the ability to dynamically switch between SU-MIMO and MU-MIMO.

Figure 52 shows the different forms of single-user MIMO in Releases 8, 9, and 10. Rel-8 only supports a single layer, whereas 2-layer beamforming is possible in Release 9 and 8 layers are possible in Release 10 with 8 antennas at the base station.

**Figure 52: Single-User MIMO**

![Single-User MIMO Diagram]

Figure 53 shows multi-user MIMO options across different releases. Release 8 supports two simultaneous users each with one layer using four antennas while Releases 9/10 support four simultaneous users each with one layer.

**Figure 53: Multi-User MIMO**

![Multi-User MIMO Diagram]

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119 Source: 4G Americas member contribution.

120 Source: 4G Americas member contribution.
Coordinated Multipoint Processing (CoMP)

Coordinated Multi-point Transmission (CoMP) is a communications technique that can improve coverage, cell-edge throughput, and/or system spectrum efficiency by reducing interference. This technique was thoroughly studied during the development of LTE-Advanced (LTE-A) Release 10 and was standardized in Release 11.

CoMP closely coordinates transmissions at different cell sites, thereby achieving higher system capacity and improving cell-edge data rates.

The main principle of CoMP is that a UE at a cell edge location can receive signals from multiple transmission points and/or its transmitted signal can be received by multiple reception points. Consequently, if these multiple transmission points coordinate their transmissions, the DL throughput performance and coverage can improve.

For the UL, signals from the UE received at multiple reception points can significantly improve the link performance. Techniques can range from simple interference avoidance techniques, such as Coordinated Beam Switching (CBS) and Coordinated Beam Forming (CBF), to complex joint processing techniques that include Joint Transmission (JT), Joint Reception (JR), and Dynamic Point Selection (DPS).

CoMP architectures include inter-site CoMP, intra-site CoMP, as well as CoMP with distributed eNBs (i.e. an eNB with distributed remote radio heads). Figure 54 shows two possible levels of coordination.

Figure 54: Different Coordination Levels for CoMP

1. Intra-site Macro CoMP
2. Distributed eNB – Contiguous Coverage

In one CoMP approach called coordinated scheduling, shown in Figure 55, a single site transmits to the user, but with scheduling, including any associated beamforming, coordinated between the cells to reduce interference between the different cells and to increase the served user’s signal strength. In joint transmission, another CoMP approach

121 Source: 4G Americas member contribution.
also shown in Figure 55, multiple sites transmit simultaneously to a single user. This approach can achieve higher performance than coordinated scheduling, but has more stringent backhaul communications requirements. One simpler form of CoMP that will be available in Release 10, and then further developed in Release 11 is ICIC. Release 11 of LTE defines a common feedback and signaling framework for enhanced CoMP operation.

**Figure 55: Coordinated Scheduling/BF and Joint Processing CoMP Approaches**

Release 11 also implements CoMP on the uplink, by which multiple base stations receive uplink transmissions and jointly process the signal, resulting in significant interference cancellation and improvements to spectral efficiency.

The performance gains expected from CoMP are under discussion in the industry. According to 3GPP document TR 36.819, for the case of resource utilization below 35%, CoMP may provide a 5.8% performance gain on the downlink for the mean user and a 17% gain for cell-edge users relative to HetNets without eICIC. For resource utilization of more than 35%, CoMP may provide a 17% mean gain and a 40% cell-edge gain. CoMP can also be used in combination with eICIC for additional gains.

In the same 3GPP TR 36.819 document, 3GPP estimates the downlink CoMP gain in spectral efficiency, defined as average sector throughput for full buffer traffic using JT and 4x2 MU-MIMO as defined in R11, compared with 4x2 MU-MIMO based on R10, to be about 3% for intra-eNodeB CoMP, and about 9% for inter-eNodeB CoMP in the case of no delay in the backhaul used to exchange information between eNodeBs. The corresponding gains in cell-edge user throughput are 20% and 31%, respectively.

When increasing the backhaul latency to a more realistic value of 10 msec for inter-eNodeB, spectral efficiency decreases to zero and the cell edge gain decreases to 10%.

The gains for DL CoMP based on Coordinated Scheduling/Coordinated Beamforming (CS/CB) and intra-eNodeB are less than that provided by JT, with spectral efficiency at 1% and cell edge gains at 4%.

All of the above gains are for FDD networks with cross-polarized antennas at the eNodeBs. For TDD networks, the gains are higher by virtue of being able to invoke channel reciprocity and thus, infer the DL channel directly from the UL channel. For example, for intra-eNodeB CoMP with JT 4x2 MU-MIMO, the respective gains in spectral efficiency and cell edge throughput are 14% and 29%, respectively.

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122 Source: 4G Americas member contribution.

123 Source: 3GPP TR 36.819 v11.1.0, Coordinated Multi-Point Operation for LTE Physical Layer Aspects, Tables 7.3.1.2-3 and 7.3.1.2-4. September 2011.
The gains for UL CoMP based upon Joint Reception (JR) are greater than the DL gains: for intra-eNodeB CoMP the average and cell edge throughputs are increased to 22% and 40%, assuming two receive antenna paths with SU-MIMO. These respective gains increase to 31% and 66% for inter-eNodeB CoMP. In addition, UL CoMP does not require standardization and thus facilitates vendor implementation.

**User Equipment Categories**

LTE specifications define categories of UE, which mainly determine the maximum throughputs of devices but also govern the number of downlink MIMO layers, as shown in Table 15.

**Table 15: UE Categories**

<table>
<thead>
<tr>
<th>3GPP Release</th>
<th>UE Category</th>
<th>Max DL Throughput</th>
<th>Maximum DL MIMO Layers</th>
<th>Maximum UL Throughput</th>
<th>Support for UL 64 QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1</td>
<td>10.3 Mbps</td>
<td>1</td>
<td>5.2 Mbps</td>
<td>No</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>51.0 Mbps</td>
<td>2</td>
<td>25.5 Mbps</td>
<td>No</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>102.0 Mbps</td>
<td>2</td>
<td>51.0 Mbps</td>
<td>No</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>150.8 Mbps</td>
<td>2</td>
<td>51.0 Mbps</td>
<td>No</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>299.6 Mbps</td>
<td>4</td>
<td>75.4 Mbps</td>
<td>Yes</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>301.5 Mbps</td>
<td>2 or 4</td>
<td>51.0 Mbps</td>
<td>No</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>301.5 Mbps</td>
<td>2 or 4</td>
<td>102.0 Mbps</td>
<td>No</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>2998.6 Mbps</td>
<td>8</td>
<td>1497.8 Mbps</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**LTE-Advanced Relays**

Another capability being planned for LTE-Advanced is relays, as shown in Figure 56. The idea is to relay frames at an intermediate node, resulting in much better in-building penetration, and with better signal quality, user rates will improve. Relay nodes can also improve cell-edge performance by making it easier to add picocells at strategic locations.

Relays provide a means for lowering deployment costs in initial deployments in which usage is relatively low. As usage increases and spectrum needs to be allocated to access only, operators can then employ alternate backhaul schemes.

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Machine-Type Communications

Anticipating huge growth in machine-to-machine communications, Release 11 added an MTC Interworking Function and Service Capability Server. Release 12 will add link budget enhancements so that UEs can communicate even when buried deep inside buildings and equipment.

LTE Direct (Device-to-Device)

Release 12 defines a capability for devices to communicate directly with one another using LTE spectrum, a feature also called “operator-enabled proximity services.” With this capability, devices can autonomously discover nearby relevant devices and services in a battery-efficient manner. Devices broadcast their needs and services and can also passively identify services without user intervention.

Examples of applications include discovering friends and family (social matching), push advertising for relevant notifications, tourist bulletins, venue services, crime alerts, home automation, and detecting children leaving the vicinity of their homes. The service is designed to work during infrastructure failures, or even in emergencies and natural disasters. As a new means of communicating, LTE Direct could result in entirely new and innovative types of applications.

The LTE network performs configuration and authentication; however, communication can be either via the network or directly between devices. To minimize battery consumption, devices synchronously wake up for brief intervals to discover services. The impact on LTE network capacity is minimal.

As with other location-based services, operators and application developers will need to address privacy concerns.

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125 Source: 4G Americas member contribution.
**Heterogeneous Networks, Small Cells, and Self-Optimization**

A fundamental concept in the evolution of next-generation networks is the blending of multiple types of networks creating a network of networks characterized by:

- Variations in coverage areas including femtocells (either enterprise femtos or home femtos called HeNBs), picocells (also referred to as metro cells), and macrocells. Cell range can vary from 10 meters to 50 kilometers.
- Different frequency bands.
- Different technologies spanning Wi-Fi, 2G, 3G, and 4G.
- Relaying capability in which wireless links can serve as backhaul.

In LTE, femtocells can be either enterprise femtos or home stations in which case they are called HeNBs.

Figure 57 shows how different types of user equipment might access different network layers.

**Figure 57: Load Balancing with Heterogeneous Networks.**

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126 Source: 4G Americas member contribution.
HetNets will allow significant capacity expansion in configurations in which operators can add picocells to coverage areas served by macrocells, particularly if there are hot spots with higher user densities.

Small cells differentiate themselves from macrocells according to the parameters shown in Table 16.

**Table 16: Small Cell Vs. Macro Cell Parameters: Typical Values**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Small Cell</th>
<th>Macro Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission Power</td>
<td>24 dBm (0.25 W)</td>
<td>43 dBm (20 W)</td>
</tr>
<tr>
<td>Antenna Gain</td>
<td>2 dBi</td>
<td>15 dBi</td>
</tr>
<tr>
<td>Users</td>
<td>Tens</td>
<td>Hundreds</td>
</tr>
<tr>
<td>Mobility</td>
<td>30 km/hr</td>
<td>350 km/hr</td>
</tr>
</tbody>
</table>

Figure 58 shows two different traffic distribution scenarios, with a uniform distribution of devices in the first and higher densities serviced by picocells in the second. The second scenario can result in significant capacity gains, as well as improved user throughput gains.
One vendor calculated expected HetNet gains assuming no eICIC, no picocell range extension, and no eICIC. For the case of 4 picocells without picocell range extension and uniform user distribution, the median-user throughput gain compared to a macro-only configuration was 85%. For a similar case of 4 picocells but using a hotspot user distribution, the gain was much higher, 467%. Additional gains will occur with picocell range extension.

Expected picocells gains are proportionally higher depending on number of picocells, so long as a sufficient number of UEs connect to the picocells.

Source: 4G Americas member contribution. Further assumes 2X1 W picocell transmit power, cell-edge placement (planned picocell deployment), 67% of all the users within 40m of the pico locations, and 3GPP Technical Report 36.814 adapted to 700 MHz.

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127 Source: 4G Americas member contribution. Further assumes 2X1 W picocell transmit power, cell-edge placement (planned picocell deployment), 67% of all the users within 40m of the pico locations, and 3GPP Technical Report 36.814 adapted to 700 MHz.
Release 10 and Release 11 added enhanced support to manage the interference in the HetNet scenario in the time domain with Enhanced Intercell Interference Coordination (eICIC) and Further Enhanced Intercell Interference Coordination (feICIC), as well as in the frequency domain with carrier-aggregation based ICIC.

As the number of base stations increase through denser deployments and through deployment of femtocells and picocells, manual configuration and maintenance of this infrastructure becomes impractical. With SON, base stations organize and configure themselves by communicating with each other and with the core network. SONs can also self-heal in failure situations.

Self-configuration is primarily for handling simplified insertion of new eNB (base station) elements. Self-optimization includes automatic management of features such as:

- Load balancing between eNBs
- Handover parameter determination
- Static and dynamic interference control
- Management of capacity and coverage

HetNet capability keeps becoming more sophisticated through successive 3GPP releases as summarized in Table 17.

**Table 17: 3GPP HetNet Evolution**

<table>
<thead>
<tr>
<th>3GPP Release</th>
<th>HetNet Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Initial SON capabilities, most for auto configuration. Initial intercell interference coordination (ICIC) available.</td>
</tr>
<tr>
<td>9</td>
<td>More mobility options (for example, handover between HeNBs), operator customer subscriber group (SCG) lists, load-balancing, coverage and capacity improvements.</td>
</tr>
<tr>
<td>10</td>
<td>Iurh interface for HeNBs that improves coordination and synchronization, LTE time domain eICIC. Carrier-aggregation-based ICIC also defined.</td>
</tr>
<tr>
<td>11</td>
<td>Improved eICIC, further mobility enhancements.</td>
</tr>
</tbody>
</table>

Significant challenges must be addressed in these heterogeneous networks. One is near-far effects, in which local small-cell signals can easily interfere with macro cells. Interference management is of particular concern in HetNets since, by design, coverage areas of small-coverage cells overlap with the macro cell. Beginning with Release 10, eICIC introduces an approach of almost-blank subframes by which subframe transmission can be muted to prevent interference. Figure 59 illustrates eICIC for the macro layer and pico layer coordination. If a UE is on a picocell but in a location where it is sensitive to interference from the macro layer, the macro layer can mute its transmission during specific frames when the pico layer is transmitting.
LTE can also combine eICIC with interference-cancellation-based devices to minimize the harmful effects of interference between picocell and macro cells.

Figure 60 shows one 4G America member’s analysis of anticipated median throughput gains using picocells and Release 11 Further Enhanced ICIC.

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128 Source: 4G Americas member contribution.
FeICIC is also beneficial in non-hotspot scenarios. In the case of a uniform distribution of picocells, this same 4G Americas member estimates a 130% gain from FeICIC for an 8 picocell per macrocell scenario, increasing capacity from a factor of 3.3 for the picocells alone to a factor of 7.6 with the addition of FeICIC.\footnote{Source: 4G Americas member contribution. Assumes 3GPP evaluation methodology TR 36.814, carrier-aggregation UEs, macro ISD = 1732m, 700 MHz and 2GHz carrier frequency, full-buffer traffic, FDD 10+10 MHz per carrier, 6 degree antenna downtilt, 4 or 8 Picos and 30 UEs per Macro cell, hotspot distribution with 20 of 30 UEs near picos, PF scheduler, 2x2 MIMO, TU3 channel, NLOS, local partitioning algorithm.}

Further insight is available from Figure 61, which shows 5 percentile and 50 percentile throughput with and without eICIC under different conditions of range extension and almost blanked subframes.

\footnote{Assumes 3GPP evaluation methodology TR 36.814, macro ISD = 1732m, 700 MHz and 2GHz carrier frequency, full-buffer traffic, 6 degree antenna downtilt, 30 carrier-aggregation UEs per Macro cell, uniform random layout, PF scheduler, FDD, 10+10 MHz per carrier, 2x2 MIMO, TU3 channel, NLOS, local partitioning algorithm. Additional information is available at ftp://ftp.3gpp.org/tsg_ran/WG1_RL1/TSGR1_66b/Docs/R1-113383.zip.}
Another approach for addressing inter-layer interference cancellation in HetNets can come from carrier aggregation with no further additions or requirements. Consider the scenario in Figure 62, in which both the macro eNB and the pico eNB are allocated two component carriers (namely CC1 and CC2). The idea is to create a “protected” component carrier for downlink control signals and critical information (Physical Downlink Control Channel, system information and other control channels) while data can be conveniently scheduled on both component carriers through cross-carrier scheduling.

**Figure 62: Carrier-Aggregation Based ICIC**

CC1 is the primary component carrier for the macro cell, while CC2 is the primary for the pico cell; hence the protected carriers are CC1 for the macro cell and CC2 for the pico cell. The macro cell allocates a lower transmission power for its secondary CC in order to reduce interference to the pico cell’s primary component carrier. The network can

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131 Source: 4G Americas member contribution. Assume 3GPP evaluation methodology TR 36.814, 500 meter ISD, 4 picos per macro-cell area, Poisson call arrival, finite payload for each call, termination of call upon successful delivery.

132 Source: 4G Americas member contribution.
schedule data on both the primary and secondary component carriers: in the figure, users in the cell-range expansion (CRE) zone can receive data via cross-carrier scheduling from the secondary CC at subcarrier frequencies on which interference from the other cell can be reduced if the cells exchange appropriate signaling over what is called an X2 interface. Users operating close to the eNodeBs can receive data from both component carriers as their interference levels will hopefully be lower. Therefore, a CA-capable receiver will enjoy the enhanced throughput capabilities of carrier aggregation, while simultaneously receiving extra protection for control and data channels at locations with potentially high inter-layer interference.

Thus, carrier aggregation can be a useful tool for deployment of heterogeneous networks without causing a loss of bandwidth. These solutions, however, do not scale well (in Release 10 systems) to small system bandwidths (say, 3+3 MHz or 1.4+1.4 MHz radio carriers) due to control channels occupying a high percentage of total traffic. Additionally, interference between the cell reference signals (CRS) would also be significant.

**Evolved Packet Core (EPC)**

3GPP defined the Evolved Packet Core (EPC) in Release 8 as a framework for an evolution or migration of the network to a higher-data-rate, lower-latency, packet-optimized system that supports multiple radio-access technologies including LTE, as well as and legacy GSM/EDGE and UMTS/HSPA networks. EPC also integrates CDMA2000 networks and Wi-Fi.

EPC is optimized for all services to be delivered via IP in a manner that is as efficient as possible—through minimization of latency within the system, for example. It also provides service continuity across heterogeneous networks, which is important for LTE operators who must simultaneously support GSM-HSPA customers.

One important performance-enhancing aspect of EPC is a flatter architecture. For packet flow, EPC includes two network elements, called Evolved Node B (eNodeB) and the Access Gateway (AGW). The eNodeB (base station) integrates the functions traditionally performed by the radio-network controller, which previously was a separate node controlling multiple Node Bs. Meanwhile, the AGW integrates the functions traditionally performed by the SGSN and GGSN. The AGW includes both control functions, handled through the Mobile Management Entity (MME), and user plane (data communications) functions. The user plane functions consist of two elements: A serving gateway that addresses 3GPP mobility and terminates eNodeB connections, and a Packet Data Network (PDN) gateway that addresses service requirements and also terminates access by non-3GPP networks. The MME serving gateway and PDN gateways can be collocated in the same physical node or distributed, based on vendor implementations and deployment scenarios.

The EPC architecture is similar to the HSPA One-Tunnel Architecture discussed in the “HSPA+” section, which allows for easy integration of HSPA networks to the EPC. Another architectural option is to reverse the topology, so that the EPC Access Gateway is located close to the RAN in a distributed fashion to reduce latency, while the MME is centrally located to minimize complexity and cost.

EPC uses IMS as a component. It also manages QoS across the whole system, an important enabler for voice and other multimedia-based services.

Figure 63 shows the EPC architecture.
Elements of the EPC architecture include:

- Support for legacy GERAN and UTRAN networks connected via SGSN.
- Support for new radio-access networks such as LTE.
- Support for non-3GPP networks such as EV-DO and Wi-Fi. (See section below on Wi-Fi integration).
- 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 authenticating and authorizing users.
- The Policy Control and Charging Rules Function (PCRF) that manages QoS aspects.

QoS in EPS employs the QoS Class Identifier (QCI), a number denoting a set of transport characteristics (bearer with/without guaranteed bit rate, priority, packet delay budget, packet error loss rate) and used to infer nodes specific parameters that control packet forwarding treatment (such as scheduling weights, admission thresholds, queue management thresholds, or link-layer protocol configuration). The network maps each packet flow to a single QCI value (nine are defined in the Release 8 version of the specification) according to the level of service required by the application. Use of the QCI...
avoids the transmission of a full set of QoS-related parameters over the network interfaces and reduces the complexity of QoS negotiation. The QCI, together with Allocation-Retention Priority (ARP) and, if applicable, Guaranteed Bit Rate (GBR) and Maximum Bit Rate (MBR), determines the QoS associated to an EPS bearer. A mapping between EPS and pre-Release 8 QoS parameters permits interworking with legacy networks.

The QoS architecture in EPC enables a number of important capabilities for both operators and users:

- **VoIP support with IMS.** QoS is a crucial element for providing LTE/IMS voice service. (See section below on IMS).

- **Enhanced application performance.** Applications such as gaming or video can operate more reliably.

- **More flexible business models.** With flexible, policy-based charging control, operators and third-parties will be able to offer content in creative new ways. For example, an enhanced video stream to a user could be paid for by an advertiser.

- **Congestion control.** In congestion situations, certain traffic flows (bulk transfers, abusive users) can be throttled down to provide a better user experience for others.

Table 18 shows the nine QCI used by LTE.

**Table 18: 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>$10^{-5}$</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>$10^{-5}$</td>
<td>IMS signaling</td>
</tr>
<tr>
<td>6</td>
<td>Non-GBR</td>
<td>6</td>
<td>300 msec.</td>
<td>$10^{-5}$</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>$10^{-5}$</td>
<td>Premium bearer for video (buffered streaming), TCP</td>
</tr>
</tbody>
</table>
Wi-Fi Integration

3GPP has evolved its thinking on how best to integrate Wi-Fi with 3GPP networks. At the same time, the Wi-Fi Alliance and other groups have also addressed hotspot roaming, namely the ability to have an account with one public Wi-Fi network provider, but to use the services of another provider that has a roaming arrangement with the first provider.

The multiple attempts to make Wi-Fi networks universally available have made for a slightly confusing landscape of integration methods, which this section attempts to clarify. Most integration today is fairly loose and proprietary, meaning that either a device communicates data via the cellular connection or via Wi-Fi. If via Wi-Fi, the connection is directly to the Internet and bypasses the operator core network. In addition, any automatic handover to hotspots occurs only between the operator cellular network and operator-controlled hotspots. The goals moving forward are to:

1. Support roaming relationships so that users can access Wi-Fi hotspots operated by other entities.
2. Enable automatic connections so that users do not have to enter usernames and passwords. In most cases, this will mean authentication based on SIM credentials.
3. Provide secure communications on the radio link as provided by the IEEE 802.11i standard.
4. Allow policy-based mechanisms that define the rules by which devices connect to different Wi-Fi networks.
5. Enable simultaneous connections to both cellular and Wi-Fi with control over which applications use which connections.

3GPP Release 8 specified Wi-Fi integration with the EPC using two different approaches: host-based mobility with Dual Stack Mobile IPv6 (DSMIPv6) in the client; and network-based mobility with Proxy Mobile IPv6 (PMIPv6) using an intermediary node called an Enhanced Packet Data Gateway (ePDG).

Release 11, however, implements a new approach, one that eliminates the ePDG, as shown in Figure 64. Called SaMOG (S2a-based Mobility over GTP), a trusted WLAN access gateway, interconnects multiple 3GPP-compliant access points. Traffic can route directly to the Internet or traverse the packet core.
Another relevant specification is 3GPP Access Network Discovery and Selection Function (ANDSF) that provides for mechanisms by which mobile devices can know where, when, and how to connect to non-3GPP access networks, such as Wi-Fi. ANDSF operates independently of SaMOG or other ways that Wi-Fi networks might be connected.

Eventually, operators will be able to closely manage user mobile broadband and Wi-Fi connections, dynamically selecting a particular network for a user based on real-time changes in loads and application requirements.

Separately from 3GPP, the Wi-Fi alliance has developed the Hotspot 2.0 specifications. Based on the IEEE 802.11u standard, user devices can determine what roaming relationships the access point supports, and can then securely connect to the Wi-Fi network using one of these roaming arrangements, as shown in Figure 65. Hotspot 2.0 authentication is based on the Extended Authentication Protocol EAP) using SIM credentials. There are plans to enhance the Hotspot 2.0 protocols in phase 2, which will define online signup to enable non-SIM based devices to easily and securely register for services. The Wi-Fi alliance began a Hotspot 2.0 certification process for devices and access points in June 2012 and will use the designation “Wi-Fi Certified Passpoint” for compliant devices.

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Meanwhile 3GPP Release 10 defines some specific mechanisms for offloading traffic including Selected IP Traffic Offload (SIPTO), Local IP Access (LIPA), and IP Flow and Seamless Offload (IFOM).

SIPTO is mostly a mechanism to offload traffic that does not need to flow through the core such as Internet-destined traffic. SIPTO can operate on a home femtocell, which for LTE is called a Home eNodeB, or it can operate in the macro network.

Local IP Access (LIPA) provides access to local networks, useful with femtocells that normally route all traffic back to the operator network. With LIPA, the UE in a home environment can access local printers, scanners, file servers, media servers and other local resources.

IFOM, as shown in Figure 66, enables seamless offload over Wi-Fi networks. Wi-Fi offload today occurs in a fairly rudimentary manner. A smartphone, for example, has either a data session over the cellular network or over a Wi-Fi network, but not both at the same time. Handover from cellular to Wi-Fi today stops the cellular-data session and starts a new one with a different IP address over Wi-Fi. This can interrupt applications and require users to restart some applications. In contrast, IFOM allows simultaneous cellular and Wi-Fi connections and enables different traffic to flow over the different connections. A Netflix movie could stream over Wi-Fi while a VoIP call might flow over the cellular-data connection. IFOM requires the UE to implement Dual Stack Mobile IPv6 (DSMIPv6).
**IP Multimedia Service (IMS)**

IP Multimedia Subsystem (IMS) is a service platform for IP multimedia applications: video sharing, PoC, VoIP, streaming video, interactive gaming, and others. IMS by itself does not provide all these applications. Rather, it provides a framework of application servers, subscriber databases, and gateways to make them possible. The exact services will depend on cellular operators and the application developers that make these applications available to operators.

The core networking protocol used within IMS is Session Initiation Protocol (SIP), which includes the companion Session Description Protocol (SDP) used to convey configuration information such as supported voice codecs. Other protocols include Real Time Transport Protocol (RTP) and Real Time Streaming Protocol (RTSP) for transporting actual sessions. The QoS mechanisms in UMTS will be an important component of some IMS applications.

Although originally specified by 3GPP, numerous other organizations around the world are supporting IMS. These include the Internet Engineering Taskforce (IETF), which specifies key protocols such as SIP, and the Open Mobile Alliance, which specifies end-to-end, service-layer applications. Other organizations supporting IMS include the GSMA, ETSI, CableLabs, 3GPP2, The Parlay Group, the ITU, ANSI, the Telecoms and Internet Converged Services and Protocols for Advanced Networks (TISPAN), and the Java Community Process (JCP).

IMS is relatively independent of the radio-access network and can, and likely will, be used by other radio-access networks or wireline networks. Other applications include picture and video sharing that occur in parallel with voice communications. Operators looking to roll out VoIP over networks will use IMS. For example, VoLTE depends on IMS infrastructure. 3GPP initially introduced IMS in Release 5 and has enhanced it in each subsequent specification release.

As shown in Figure 67, IMS operates just outside the packet core.
The benefits of using IMS include handling all communication in the packet domain, tighter integration with the Internet, and a lower cost infrastructure based on IP building blocks for both voice and data services.

IMS applications can reside either in the operator’s network or in third-party networks including those of enterprises. By managing services and applications centrally—and independently of the access network—IMS can enable network convergence. This allows operators to offer common services across 3G, Wi-Fi, and wireline networks.

Service Continuity, defined in Release 8, provided for a user’s entire session to continue seamlessly as the user moves from one access network to another. Release 9 expanded this concept to allow sessions to move across different device types. For example, the user could transfer a video call in midsession from a mobile phone to a large-screen TV, assuming both have an IMS appearance in the network.

Release 8 introduced the IMS Centralized Services (ICS) feature, which allows for IMS-controlled voice features to use either packet-switched or circuit-switched access.

**Cloud Radio Access Network (RAN) and Network Virtualization**

Still in the research phase, cloud RAN is a distributed architecture in which multiple remote radio heads connect to a “cloud” that consists of a farm of baseband processing nodes. This approach can improve centralized processing, as is needed for CoMP, centralized scheduling, and multiflow, without the need to exchange information among many access nodes. The performance of both LTE and HSPA technologies could be enhanced by the application of Cloud RAN architectures. The term “fronthauling” has been used to describe the transport of “raw” radio signals to central processing locations.
This architecture comes at the cost of requiring high-speed, low-latency backhaul links between these radio heads and the central controller. One vendor states that carrying 10 +10 MHz of LTE with 2X2 MIMO requires 2.5 Gbps of bandwidth and less than .1 msec of delay. A standard called Common Public Radio Interface (CPRI) addresses generic formats and protocols for such a high-speed link, but other alternatives aimed at reducing the backhaul’s bitrate requirements are being investigated. The attractiveness of Cloud RAN depends in part on the cost of the fiber links between the remote radio heads and the centralized baseband processing.

**Figure 68: Potential Cloud RAN Approach**

Another form of virtualization is software-defined networking (SDN), an emerging trend in both wired and wireless networks. For cellular, SDN promises to reduce OPEX costs, simplify the introduction of new services, and improve scalability; all major infrastructure vendors are involved. The Open Networking Foundation explains that an SDN decouples the control and data planes, centralizing network state and intelligence, while abstracting the underlying network infrastructure from applications. Virtualization of network function will be a complex, multiyear undertaking and will occur in stages, as shown in Figure 69.

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135 Source: https://www.opennetworking.org/sdn-resources/sdn-library/whitepapers
Broadcast/Multicast Services

An important capability for 3G and evolved 3G systems is broadcasting and multicasting, wherein multiple users receive the same information using the same radio resource. This creates a more efficient approach to deliver video when multiple users desire the same content simultaneously. In a broadcast, every subscriber unit in a service area receives the information, whereas in a multicast, only users with subscriptions receive the information. Service areas for both broadcast and multicast can span either the entire network or a specific geographical area. Potential applications include sporting events, select news, venue-specific (shopping mall, museum) information, and even delivery of software upgrades. Giving users the ability to store and replay select content could further expand the scope of applications.

3GPP defined highly-efficient broadcast/multicast capabilities for UMTS in Release 6 with MBMS. Release 7 defined optimizations through a solution called multicast/broadcast, single-frequency network operation that involves simultaneous transmission of the exact waveform across multiple cells. This enables the receiver to constructively superpose multiple MBSFN cell transmissions. The result is highly efficient, WCDMA-based broadcast transmission technology that matches the benefits of OFDMA-based broadcast approaches.

LTE also has a broadcast/multicast capability called Evolved MBMS (eMBMS). OFDM is particularly well-suited for efficient broadcasting, as shown in Figure 70, because the

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136 Source: 4G Americas member contribution.
mobile system can combine the signal from multiple base stations, and because of the narrowband nature of OFDM. Normally, these signals would interfere with each other.

**Figure 70: OFDM Enables Efficient Broadcasting**

Despite various broadcast technologies being available, market adoption to date has been relatively slow. Internet trends have favored unicast approaches, with users viewing videos of their selection on demand, but there is increasing interest in using eMBMS with LTE to alleviate capacity demands.

**Backhaul**

Connecting sites to core networks remains a challenge, whether for small cells or macro cells, especially as networks need to deliver higher bandwidth. Fiber is the gold standard, but it is not available everywhere and can be expensive, so operators use a combination of wired and wireless links. Table 19 and Table 20 summarize the methods and capabilities of the various available approaches.

**Table 19: Wired Backhaul Methods and Capabilities**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Distance</th>
<th>Throughput Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Fiber</td>
<td>80 km</td>
<td>Hundreds of Mbps to Gbps</td>
</tr>
<tr>
<td>Bonded VDSL2</td>
<td>To 5,000 feet</td>
<td>75 Mbps down, 12 Mbps up</td>
</tr>
<tr>
<td>FTTX</td>
<td>Most urban areas</td>
<td>Up to 2.5 Gbps down, 1.5 Gbps up</td>
</tr>
<tr>
<td>DOCSIS</td>
<td>Most urban areas</td>
<td>Up to 285 Mbps down, 105</td>
</tr>
</tbody>
</table>

---

### Table 20: Wireless Backhaul Methods and Capabilities

<table>
<thead>
<tr>
<th>Technology</th>
<th>Distance</th>
<th>Line of Sight</th>
<th>Throughput Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Millimeter Wave (60 GHz)</td>
<td>1 km</td>
<td>Yes</td>
<td>1 Gbps</td>
</tr>
<tr>
<td>Millimeter Wave (70-80 GHz)</td>
<td>3 km (with speed tradeoff)</td>
<td>Yes</td>
<td>10 Gbps</td>
</tr>
<tr>
<td>Microwave (6-60 GHz)</td>
<td>Varies by frequency: 2-4 km typical at 30-42 GHz</td>
<td>Yes</td>
<td>1 Gbps+</td>
</tr>
<tr>
<td>Licensed sub 6 GHz</td>
<td>1.5 to 10 km</td>
<td>No</td>
<td>170 Mbps (20 MHz TDD), 400 Mbps+ with new technology</td>
</tr>
<tr>
<td>Unlicensed sub-6 GHz</td>
<td>Up to 250 meters</td>
<td>No</td>
<td>450 Mbps (IEEE 802.11n 3X3 MIMO)</td>
</tr>
<tr>
<td>TV White Space (802.11af-based)</td>
<td>1 to 5 km max throughput, 10 km+ possible</td>
<td>Depends on deployment model</td>
<td>80 Mbps in 6 MHz TDD with 4X4 MIMO</td>
</tr>
<tr>
<td>Satellite</td>
<td>Available everywhere</td>
<td>Yes</td>
<td>Up to 50 Mbps downlink, 15 Mbps uplink</td>
</tr>
</tbody>
</table>

**UMTS TDD**

Most WCDMA and HSDPA deployments are based on FDD, which uses different radio bands for transmit and receive. In the alternate TDD approach, transmit and receive functions alternate in time on the same radio channel. 3GPP specifications include a TDD version of UMTS, called UMTS TDD.

TDD does not provide any inherent advantage for voice functions, which need balanced links—namely, the same amount of capacity in both the uplink and the downlink. Many data applications, however, are asymmetric, often with the downlink consuming more bandwidth than the uplink. A TDD radio interface can dynamically adjust the downlink-to-uplink ratio accordingly, hence balancing both forward-link and reverse-link capacity.

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Note that for UMTS FDD, the higher spectral efficiency achievable in the downlink versus the uplink addresses the asymmetrical nature of average data traffic.

The UMTS TDD specification also includes the capability to use joint detection in receiver-signal processing, which offers improved performance.

One consideration, however, relates to available spectrum. Various countries around the world including those in Europe, Asia, and the Pacific region have licensed spectrum available specifically for TDD systems. TDD is also a good choice for any spectrum that does not provide a duplex gap between forward and reverse links.

In the United States, there is limited spectrum specifically allocated for TDD systems, the major band being BRS at 2.5 GHz used by Clearwire for WiMAX and now LTE TDD.\(^{139}\) UMTS TDD is not a good choice in FDD bands; it would not be able to operate effectively in both bands, thereby making the overall system efficiency relatively poor.

As discussed in more detail in the “WiMAX” section, TDD systems require network synchronization and careful coordination between operators or guardbands, which may be problematic in certain bands.

There has not been widespread deployment of UMTS TDD. Future TDD deployments of 3GPP technologies are likely to be based on LTE.

**TD-SCDMA**

Time Division Synchronous Code Division Multiple Access (TD-SCDMA) is one of the official 3G wireless technologies being developed, mostly for deployment in China. Specified through 3GPP as a variant of the UMTS TDD System and operating with a 1.28 megachips per second (Mcps) chip rate versus 3.84 Mcps for UMTS TDD, the primary attribute of TD-SCDMA is that it supports very high subscriber densities, making it a possible alternative for wireless local loops. TD-SCDMA uses the same core network as UMTS, and it is possible for the same core network to support both UMTS and TD-SCDMA radio-access networks.

TD-SCDMA technology is not as mature as UMTS and CDMA2000, with 2008 being the first year of limited deployments in China in time for the Olympic Games. Although there are no planned deployments in any country other than China, TD-SCDMA could theoretically be deployed anywhere unpaired spectrum is available—such as the bands licensed for UMTS TDD—assuming appropriate resolution of regulatory issues.

**EDGE/EGPRS**

Today, most GSM networks support EDGE, an enhancement to GPRS, which is the original packet data service for GSM networks.\(^{140}\) GPRS provides a packet-based IP connectivity solution supporting a wide range of enterprise and consumer applications. GSM networks with EDGE operate as wireless extensions to the Internet and give users Internet access, as well as access to their organizations from anywhere. Peak EDGE user-
achievable\textsuperscript{141} throughput rates are up to 200 Kbps. Figure 71 depicts the system architecture.

**Figure 71: GSM/GPRS/EDGE Architecture**

EDGE is essentially the addition of a packet-data infrastructure to GSM. In fact, this same data architecture is preserved in UMTS and HSPA networks, and the data architecture is technically referred to as GPRS for the core-data function in all of these networks. The term GPRS may also be used to refer to the initial radio interface, now supplanted by EDGE. Functions of the data elements are as follows:

1. The base station controller directs/receives packet data to/from the Serving GPRS Support Node (SGSN), an element that authenticates and tracks the location of mobile stations.

2. The SGSN performs the types of functions for data that the Mobile Switching Center (MSC) performs for voice. Each serving area has one SGSN, and it is often collocated with the MSC.

3. The SGSN forwards/receives user data to/from the Gateway GPRS Support Node (GGSN), which can be viewed as a mobile IP router to external IP networks. Typically, there is one GGSN per external network (for example, the Internet). The GGSN also manages IP addresses, dynamically assigning them to mobile stations for their data sessions.

Another important element is the Home Location Register (HLR), which stores users’ account information for both voice and data services. Of significance is that this same data architecture supports data services in GSM and in UMTS-HSPA networks, thereby simplifying operator network upgrades.

\textsuperscript{141} “Peak user-achievable” means users, under favorable conditions of network loading and signal propagation, can achieve this rate as measured by applications such as file transfer. Average rates depend on many factors and will be lower than these rates.
In the radio link, GSM uses radio channels of 200 kilohertz (kHz) width, divided in time into eight timeslots comprising 577 microseconds (µs) that repeat every 4.6 msec, as shown in Figure 72. The network can have multiple radio channels (referred to as transceivers) operating in each cell sector. The network assigns different functions to each timeslot such as the Broadcast Control Channel (BCCH), circuit-switched functions like voice calls or data calls, the optional Packet Broadcast Control Channel (PBCCH), and packet data channels. The network can dynamically adjust capacity between voice and data functions, and it can also reserve minimum resources for each service. This scheduling approach enables more data traffic when voice traffic is low or, likewise, more voice traffic when data traffic is low, thereby maximizing overall use of the network. For example, the PBCCH, which expands the capabilities of the normal BCCH, may be set up on an additional timeslot of a Time Division Multiple Access (TDMA) frame when justified by the volume of data traffic.

**Figure 72: Example of GSM/EDGE Timeslot Structure**

EDGE offers close coupling between voice and data services. In most networks, while in a data session, users can accept an incoming voice call, which suspends the data session, and then resume their data session automatically when the voice session ends. Users can also receive SMS messages and data notifications while on a voice call, as described below.

With respect to data performance, each data timeslot can deliver peak user-achievable data rates of up to about 40 Kbps. The network can aggregate up to five timeslots on the downlink and up to four timeslots on the uplink with current devices.

If multiple data users are active in a sector, they share the available data channels. As demand for data services increases, however, an operator can accommodate customers by assigning an increasing number of channels for data service that is limited only by that operator’s total available spectrum and radio planning.

EDGE is an official 3G cellular technology that can be deployed within an operator’s existing 850, 900, 1800, and 1900 MHz spectrum bands. EDGE capability is now largely

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142 Source: 4G Americas member company contribution.
143 Example: WAP notification message delivered via SMS.
standard in new GSM deployments. A GPRS network using the EDGE radio interface is technically called an Enhanced GPRS (EGPRS) network, and a GSM network with EDGE capability is referred to as GSM Edge Radio Access Network (GERAN). EDGE has been an inherent part of GSM specifications since Release 99. It is fully backward-compatible with older GSM networks, meaning that GPRS devices work on EDGE networks and that GPRS and EDGE terminals can operate simultaneously on the same traffic channels.

Dual Transfer Mode (DTM) devices can simultaneously communicate voice and data. DTM is a 3GPP-specified technology that enables new applications like video sharing while providing a consistent service experience (service continuity) with UMTS. Typically, a DTM end-to-end solution requires only a software upgrade to the GSM/EDGE radio network. There are a number of networks and devices supporting DTM.

A feature in Release 9 that applies to both EDGE and Evolved EDGE is the Enhanced Flexible Timeslot Assignment (EFTA), which allows for more efficient adaptation to varying uplink versus downlink transmission needs. The network allocates uplink and downlink timeslots that overlap in time, and the mobile station may either use the corresponding uplink timeslots for transmission or receive on the overlapping downlink time slot, if it has nothing to transmit. In addition, alternative EFTA multi-slot classes enable the support of as many as eight timeslots per downlink carrier (instead of five or six timeslots with multi-slot classes 30 to 45).

**Evolved EDGE**

Recognizing the value of the huge installed base of GSM networks, 3GPP worked to improve EDGE capabilities beginning in Release 7 and continuing through subsequent releases. This work was part of the GERAN Evolution effort, which also included voice enhancements not discussed in this paper.

It makes good sense to continue to evolve EDGE capabilities. From an economic standpoint, it is less costly than upgrading to UMTS or LTE, because most enhancements are designed to be software based, and it is highly asset-efficient, because it involves fewer long-term capital investments to upgrade an existing system. Evolved EDGE offers higher data rates and system capacity and reduced latency.

Other reasons to enhance EDGE capabilities are that GSM is well suited for M2M connectivity (low data volume and high numbers of transactions), GSM capability is easily included in single RAN equipment, and GSM provides ubiquitous coverage that other technologies may not necessarily provide. More efficient GSM operation also enables it to operate in smaller amounts of spectrum, freeing spectrum for HSPA and LTE.

In addition, many regions do not have licensed spectrum for deployment of a new radio technology such as UMTS-HSPA or LTE. Also, Evolved EDGE provides better service continuity between EDGE and HSPA or LTE, meaning that a user will not have a hugely different experience when moving between different network types.

Although GSM and EDGE are already highly optimized technologies, advances in radio techniques enable further efficiencies. Some of the objectives of Evolved EDGE included:

- A 100% increase in peak data rates.

144 Single RAN means that the same equipment supports multiple wireless technologies.
A 50% increase in spectral efficiency and capacity in C/I-limited scenarios.

A sensitivity increase in the downlink of 3 dB for voice and data.

A reduction of latency for initial access and round-trip time, thereby enabling support for conversational services such as VoIP and PoC.

Compatibility with existing frequency planning, thus facilitating deployment in existing networks.

Co-existence with legacy mobile stations by allowing both old and new stations to share the same radio resources.

Minimization of impacts on infrastructure by enabling improvements through a software upgrade.

Applicability to DTM (simultaneous voice and data) and the A/Gb mode interface. The A/Gb mode interface is part of the 2G core network, so this goal is required for full backward-compatibility with legacy GPRS/EDGE.

The methods standardized in Release 7 to achieve or surpass these objectives included:

- Downlink dual-carrier reception to double the number of timeslots that can be received for a 100% increase in throughput.

- The addition of Quadrature Phase Shift Keying (QPSK), 16 QAM and 32 QAM, as well as an increased symbol rate (1.2x) and a new set of modulation/coding schemes that will increase maximum throughput per timeslot by up to 100% (EGPRS2-B). Currently, EDGE uses 8-PSK modulation.

- A reduction in overall latency. This is achieved by lowering the Transmission Time Interval (TTI) to 10 msec and by including the acknowledgement information in the data packet. These enhancements will have a dramatic effect on throughput for many applications.

- Downlink diversity reception of the same radio channel to increase the robustness in interference and to improve the receiver sensitivity. Simulations have demonstrated sensitivity gains of 3 dB and a decrease in required Carrier-to-Intermodulation Ratio (C/I) of up to 18 dB for a single co-channel interferer. Significant increases in system capacity can be achieved, as explained below.

New EDGE Evolution standardization work items in 3GPP include:

- MS-receive diversity with Voice Services over Adaptive Multi-User Channels on One Slot (VAMOS) can also be used for EDGE Evolution, which reuses existing mandatory LTE device capabilities to double spectral efficiency and provide up to a 40% increase in throughput.

- Downlink Multi-Carrier (up to 16 carriers), reusing a 20+20 MHz LTE wideband receiver at the device to provide for up to a sixteenfold throughput increase of a single-carrier connection.

- 8PSK Downlink MIMO exploiting MS receive diversity, which is a mandatory feature in an LTE device, thus doubling spectrum efficiency and throughput.

**Dual-Carrier Receiver**
A key part of the evolution of EDGE is using more than one radio frequency carrier, thus overcoming the inherent limitation of the narrow channel bandwidth of GSM. Using two radio-frequency carriers requires two receiver chains in the downlink, as shown in Figure 73. Using two carriers enables the reception of twice (or more than twice for some multi-slot classes) as many radio blocks simultaneously.

**Figure 73: Evolved EDGE Two-Carrier Operation**

<table>
<thead>
<tr>
<th></th>
<th>Slot N</th>
<th>Slot N + 1</th>
<th>Slot N + 2</th>
<th>Slot N + 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rx1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rx2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tx (1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Alternatively, the original number of radio blocks can be divided between the two carriers. This eliminates the need for the network to have contiguous timeslots on one frequency.

145 Source: 4G Americas member company contribution.
Channel capacity with dual-carrier reception improves greatly, not by increasing basic efficiencies of the air interface, but because of the statistical improvement in being able to assign radio resources, which increases trunking efficiency.

As network loading increases, it is statistically unlikely that contiguous timeslots will be available. With today’s EDGE devices, it is not possible to change radio frequencies when going from one timeslot to the next. With an Evolved EDGE dual receiver, however, this becomes possible, thus enabling contiguous timeslots across different radio channels. The system can therefore allocate a larger set of timeslots for data even if they are not contiguous, which otherwise is not possible. Figure 75 shows why this is important. As the network becomes busy, the probability of being assigned 1 timeslot decreases. As this probability decreases (X axis), the probability of being able to obtain 5 timeslots on the same radio carrier decreases dramatically. Being able to obtain timeslots across two carriers in Evolved EDGE, however, significantly improves the likelihood of obtaining the desired timeslots.

Source: 4G Americas member company contribution.
Mobile Station Receive Diversity

Figure 76 illustrates how mobile-station receive diversity increases system capacity. (BCCH refers to the Broadcast Control Channel and TCH refers to the Traffic Channel.) The BCCH carrier repeats over 12 cells in a 4/12 frequency reuse pattern, which requires 2.4 MHz for GSM. A fractionally loaded system may repeat f12 through f15 on each of the cells. This is a 1/1 frequency reuse pattern with higher system utilization, but also potentially high co-channel interference in loaded conditions.

\[\text{Source: 4G Americas member company contribution.}\]
In today’s EDGE systems, f12 through f15 in the 1/1 reuse layer can only be loaded to around 25% of capacity. Thus, with four of these frequencies, it is possible to obtain 100% of the capacity of the frequencies in the 4/12 reuse layer or to double the capacity by adding 800 KHz of spectrum.

Using Evolved EDGE and receive-diversity-enabled mobile devices that have a high tolerance to co-channel interference, however, it is possible to increase the load on the 1/1 layer from 25% to 50% and possibly to as high as 75%. An increase to 50% translates to a doubling of capacity on the 1/1 layer without requiring any new spectrum and to a 200% gain compared to a 4/12 reuse layer.

**Higher Order Modulation and Higher Symbol Rate Schemes**

The addition of higher order modulation schemes enhances EDGE network capacity with little capital investment by extending the range of the existing wireless technology. More bits-per-symbol means more data transmitted per unit time, yielding a fundamental technological improvement in information capacity and faster data rates. Use of higher order modulation exploits localized optimal coverage circumstances, thereby taking advantage of the geographical locations associated with probabilities of high C/I ratio and enabling very high data transfer rates whenever possible.

Evolved EDGE defines two different levels of support for higher order modulation for both the uplink and the downlink: EGPRS2-A and EGPRS2-B. In the uplink, EGPRS2-A level includes Gaussian Minimum Shift Keying (GMSK), 8-Phase-Shift Keying (PSK), and 16 QAM at the legacy symbol rate. This level of support reuses Modulation and Coding Schemes (MCSs) 1 through 6 from EGPRS and adds five new 16 QAM modulated schemes called uplink EGPRS2-A schemes (UAS).

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148 Source: 4G Americas member company contribution.
Table 21: Uplink Modulation and Coding Schemes

<table>
<thead>
<tr>
<th>Modulation and Coding Scheme Name</th>
<th>Uplink EGPRS2 Support Level A</th>
<th>Peak Throughput (Kbps) – 4 slots</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCS-1</td>
<td>GMSK</td>
<td>35.2</td>
</tr>
<tr>
<td>MCS-2</td>
<td>GMSK</td>
<td>44.8</td>
</tr>
<tr>
<td>MCS-3</td>
<td>GMSK</td>
<td>59.2</td>
</tr>
<tr>
<td>MCS-4</td>
<td>GMSK</td>
<td>70.4</td>
</tr>
<tr>
<td>MCS-5</td>
<td>8-PSK</td>
<td>89.6</td>
</tr>
<tr>
<td>MCS-6</td>
<td>8-PSK</td>
<td>118.4</td>
</tr>
<tr>
<td>UAS-7</td>
<td>16 QAM</td>
<td>179.2</td>
</tr>
<tr>
<td>UAS-8</td>
<td>16 QAM</td>
<td>204.8</td>
</tr>
<tr>
<td>UAS-9</td>
<td>16 QAM</td>
<td>236.8</td>
</tr>
<tr>
<td>UAS-10</td>
<td>16 QAM</td>
<td>268.8</td>
</tr>
<tr>
<td>UAS-11</td>
<td>16 QAM</td>
<td>307.2</td>
</tr>
</tbody>
</table>

The second support level in the uplink includes QPSK, 16 QAM, and 32 QAM modulation as well as a higher (1.2x) symbol rate. MCSs 1 through 4 from EGPRS are reused, and eight new uplink EGPRS2-B schemes (UBS) are added.

Table 22: Uplink Modulation and Coding Schemes with Higher Symbol Rate

<table>
<thead>
<tr>
<th>Modulation and Coding Scheme Name</th>
<th>Uplink EGPRS2 Support Level B</th>
<th>Peak Throughput (Kbps) – 4 slots</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCS-1</td>
<td>GMSK</td>
<td>35.2</td>
</tr>
<tr>
<td>MCS-2</td>
<td>GMSK</td>
<td>44.8</td>
</tr>
<tr>
<td>MCS-3</td>
<td>GMSK</td>
<td>59.2</td>
</tr>
<tr>
<td>MCS-4</td>
<td>GMSK</td>
<td>70.4</td>
</tr>
<tr>
<td>UBS-5</td>
<td>QPSK</td>
<td>89.6</td>
</tr>
<tr>
<td>UBS-6</td>
<td>QPSK</td>
<td>118.4</td>
</tr>
<tr>
<td>UBS-7</td>
<td>16 QAM</td>
<td>179.2</td>
</tr>
<tr>
<td>UBS-8</td>
<td>16 QAM</td>
<td>204.8</td>
</tr>
<tr>
<td>UBS-9</td>
<td>16 QAM</td>
<td>236.8</td>
</tr>
<tr>
<td>UBS-10</td>
<td>16 QAM</td>
<td>268.8</td>
</tr>
<tr>
<td>UBS-11</td>
<td>32 QAM</td>
<td>355.2</td>
</tr>
<tr>
<td>UBS-12</td>
<td>32 QAM</td>
<td>435.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>473.6</td>
</tr>
</tbody>
</table>
The first downlink support level introduces a modified set of 8-PSK coding schemes and adds 16 QAM and 32 QAM, all at the legacy symbol rate. Turbo codes are used for all new modulations. MCSs 1 through 4 are reused and eight new downlink EGPRS2-A level schemes (DAS) are added.

**Table 23: Downlink Modulation and Coding Schemes**

<table>
<thead>
<tr>
<th>Modulation and Coding Scheme Name</th>
<th>Downlink HOM/HSR Support Level A Modulation Type</th>
<th>Peak Throughput (Kbps) – 4 slots</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCS-1</td>
<td>GMSK</td>
<td>35.2</td>
</tr>
<tr>
<td>MCS-2</td>
<td>GMSK</td>
<td>44.8</td>
</tr>
<tr>
<td>MCS-3</td>
<td>GMSK</td>
<td>59.2</td>
</tr>
<tr>
<td>MCS-4</td>
<td>GMSK</td>
<td>70.4</td>
</tr>
<tr>
<td>DAS-5</td>
<td>8-PSK</td>
<td>89.6</td>
</tr>
<tr>
<td>DAS-6</td>
<td>8-PSK</td>
<td>108.8</td>
</tr>
<tr>
<td>DAS-7</td>
<td>8-PSK</td>
<td>131.2</td>
</tr>
<tr>
<td>DAS-8</td>
<td>16 QAM</td>
<td>179.2</td>
</tr>
<tr>
<td>DAS-9</td>
<td>16 QAM</td>
<td>217.6</td>
</tr>
<tr>
<td>DAS-10</td>
<td>32 QAM</td>
<td>262.4</td>
</tr>
<tr>
<td>DAS-11</td>
<td>32 QAM</td>
<td>326.4</td>
</tr>
<tr>
<td>DAS-12</td>
<td>32 QAM</td>
<td>393.6</td>
</tr>
</tbody>
</table>

The second downlink support level includes QPSK, 16 QAM, and 32 QAM modulations at a higher (1.2x) symbol rate. MCSs 1 through 4 are reused, and eight new downlink EGPRS2-B level schemes (DBS) are defined.
Table 24: Downlink Modulation and Coding Schemes with Higher Symbol Rate

<table>
<thead>
<tr>
<th>Modulation and Coding Scheme Name</th>
<th>Downlink HOM/HSR Support Level B</th>
<th>Modulation Type</th>
<th>Peak Throughput (Kbps) – 4 slots</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCS-1</td>
<td></td>
<td>GMSK</td>
<td>35.2</td>
</tr>
<tr>
<td>MCS-2</td>
<td></td>
<td>GMSK</td>
<td>44.8</td>
</tr>
<tr>
<td>MCS-3</td>
<td></td>
<td>GMSK</td>
<td>59.2</td>
</tr>
<tr>
<td>MCS-4</td>
<td></td>
<td>GMSK</td>
<td>70.4</td>
</tr>
<tr>
<td>DBS-5</td>
<td></td>
<td>QPSK</td>
<td>89.6</td>
</tr>
<tr>
<td>DBS-6</td>
<td></td>
<td>QPSK</td>
<td>118.4</td>
</tr>
<tr>
<td>DBS-7</td>
<td></td>
<td>16 QAM</td>
<td>179.2</td>
</tr>
<tr>
<td>DBS-8</td>
<td></td>
<td>16 QAM</td>
<td>236.8</td>
</tr>
<tr>
<td>DBS-9</td>
<td></td>
<td>16 QAM</td>
<td>268.8</td>
</tr>
<tr>
<td>DBS-10</td>
<td></td>
<td>32 QAM</td>
<td>355.2</td>
</tr>
<tr>
<td>DBS-11</td>
<td></td>
<td>32 QAM</td>
<td>435.2</td>
</tr>
<tr>
<td>DBS-12</td>
<td></td>
<td>32 QAM</td>
<td>473.6</td>
</tr>
</tbody>
</table>

The combination of Release 7 Evolved EDGE enhancements shows a dramatic potential increase in throughput. For example, in the downlink, a Type 2 mobile device (one that can support simultaneous transmission and reception) using DBS-12 as the MCS and a dual-carrier receiver can achieve the following performance:

Highest data rate per timeslot (layer 2) = 118.4 Kbps

Timeslots per carrier = 8

Carriers used in the downlink = 2

Total downlink data rate = 118.4 Kbps X 8 X 2 = 1894.4 Kbps

This translates to a peak network rate close to 2 Mbps and a user-achievable data rate of well over 1 Mbps.

Subsequent features planned through Release 12 increase peak downlink theoretical rates to 6.4 Mbps based on 200 Kbps per carrier, 16 downlink carriers, and 8 PSK MIMO operation.

**Evolved EDGE Implementation**

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149 These data rates require a wide-pulse shaping filter that is not part of Release 7.

150 For the near future, two carriers will be a scenario more practically realized on a notebook computer platform than handheld platforms.
Table 25 shows what is involved in implementing the different features defined for Evolved EDGE. For a number of features, there are no hardware changes required for the base transceiver station (BTS). For all features, Evolved EDGE is compatible with legacy frequency planning.

**Table 25: Evolved EDGE Implementation**

<table>
<thead>
<tr>
<th>Coexistence and Implementation Matrix</th>
<th>Coexistence with Legacy Frequency Planning</th>
<th>Will Operation of Legacy MS be effected?</th>
<th>BTS Hardware Impact?</th>
<th>Mobile Station Impact?</th>
<th>Core Network Impact?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver Diversity in the Mobile Station</td>
<td>Yes</td>
<td>No</td>
<td>No Impact</td>
<td>Hardware Change</td>
<td>None</td>
</tr>
<tr>
<td>Downlink Dual Carrier</td>
<td>Yes</td>
<td>No</td>
<td>No Impact</td>
<td>Hardware Change</td>
<td>None</td>
</tr>
<tr>
<td>Higher Order Modulation</td>
<td>Yes</td>
<td>No</td>
<td>Most Recent TRX are Capable</td>
<td>HW and SW Change or SW Change only</td>
<td>None</td>
</tr>
<tr>
<td>Higher Order Modulation and Increased Symbol Rate</td>
<td>Yes</td>
<td>No</td>
<td>New TRX Required</td>
<td>HW Change Likely</td>
<td>None</td>
</tr>
<tr>
<td>Latency Reduction</td>
<td>Yes</td>
<td>No</td>
<td>No Impact</td>
<td>Software Change</td>
<td>None</td>
</tr>
</tbody>
</table>

In conclusion, it is interesting to note the sophistication and capability that is achievable with, and planned for, by GSM.

**TV White Spaces**

The FCC in the US has ruled that unlicensed devices that have mechanisms to not interfere with TV broadcast channels may use TV channels that are not in use. The rules provide for fixed devices and personal/portable devices. The FCC has suggested two usage types: broadband services to homes and businesses at a higher power level to fixed devices over larger geographical areas; and wireless portable devices at a low-power level in indoor environments.

To prevent interference with TV transmissions, both device types must employ geo-location capability with 50-meter accuracy (although fixed devices can store their position during installation), as well as having the ability to access a database that lists permitted channels for a specific location. In addition, all devices must be able to sense the spectrum to detect both TV broadcasting and wireless microphone signals. The rules include transmit power limits and emission limits.

The frequency-sensing and channel-change requirements are not supported by today’s 3GPP, 3GPP2 and WiMAX technologies. The IEEE, however, has developed a standard,

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151 Source: 4G Americas member company contribution.

152 FCC-08-260: 2nd Report & Order.
IEEE 802.22, based on IEEE 802.16 concepts, that complies with the FCC requirements. IEEE 802.22 is aimed at fixed or nomadic services such as DSL replacement. IEEE 802.11af, an adaptation of IEEE 802.11 Wi-Fi, is another standard being developed for white-space spectrum.

The industry is in the very early stages of determining the viability of using white-space spectrum.

In April 2012, the FCC issued a memorandum opinion and order that modified white-space rules including increasing height above average terrain for fixed devices and the maximum permissible power spectral density for each type of device.\(^\text{153}\)

Given the industry’s move towards small-cell architectures that maximize data capacity, white-space networks, with their large coverage areas, are moving in the opposite direction. As such, they do not exploit spectrum efficiently. They are potentially well suited, however, for backhaul technology for Wi-Fi or cellular in developing countries.

Abbreviations

The following abbreviations are used in this paper. Abbreviations are defined on first use.

1G – First Generation
1xEV-DO – One Carrier Evolved, Data Optimized
1xEV-DV – One Carrier Evolved, Data Voice
1XRTT – One Carrier Radio Transmission Technology
2G – Second Generation
3G – Third Generation
3GPP – Third Generation Partnership Project
3GPP2 – Third Generation Partnership Project 2
4G – Fourth Generation (meeting requirements set forth by the ITU IMT-Advanced project)
8-PSK – Octagonal Phase Shift Keying
AAS – Adaptive Antenna Systems
ABR – Allocation Retention Priority
AGW – Access Gateway
AMR – Adaptive Multi Rate
AMR-WB – Adaptive Multi-Rate Wideband
ANDSF – Access Network Discovery and Selection Function.
ANSI – American National Standards Institute
APCO – Association of Public Safety Officials
ARP – Allocation Retention Priority
ARPU – Average Revenue Per User
ARQ – Automatic Repeat Request
ATM – Asynchronous Transfer Mode
AWGN – Additive White Gaussian Noise Channel
AWS – Advanced Wireless Services
BCCH – Broadcast Control Channel
bps – bits per second
BRS – Broadband Radio Service
BSC – Base Station Controller
BTS – Base Transceiver Station
C/I – Carrier to Intermodulation Ratio
CAPEX – Capital Expenditure
CBF – Coordinated Beam Forming
CBS – Coordinated Beam Switching
CSS3 – Cascading Style Sheets 3 (CSS3)
CDD – Cyclic Delay Diversity
CDF – Cumulative Distribution Function
CDMA – Code Division Multiple Access
CL – Closed Loop
CL-SM – Closed Loop Spatial Multiplexing
CMAS – Commercial Mobile Alert System
CMOS – Complementary Metal Oxide Semiconductor
CoMP – Coordinated Multipoint Transmission
CP – Cyclic Prefix
CPC – Continuous Packet Connectivity
CPRI – Common Public Radio Interface
CRM – Customer Relationship Management
CRS – Cell-specific Reference Signal
CS – Convergence Sublayer
CSFB – Circuit-Switched Fallback
CTIA – Cellular Telephone Industries Association
DAS – Distributed Antenna System
DAS – Downlink EGPRS2-A Level Scheme
dB – Decibel
DBS – Downlink EGPRS2-B Level Scheme
DC-HSPA – Dual Carrier HSPA
DFT – Discrete Fourier Transform
DL – Downlink
DPCCH – Dedicated Physical Control Channel
DPS – Dynamic Point Selection
DSL – Digital Subscriber Line
DSMIPv6 – Dual Stack Mobile IPv6
DTM – Dual Transfer Mode
D-TxAA – Double Transmit Adaptive Array
DVB-H – Digital Video Broadcasting Handheld
E-DCH – Enhanced Dedicated Channel
EBMCMS – Enhanced Broadcast Multicast Services
EDGE – Enhanced Data Rates for GSM Evolution
EFTA – Enhanced Flexible Timeslot Assignment
EGPRS – Enhanced General Packet Radio Service
eICIC – Enhanced Inter-Cell Interference Coordination
eMBMS – Evolved Multimedia Broadcast Multicast Services
eNodeB – Evolved Node B
EAP – Extensible Authentication Protocol
EPC – Evolved Packet Core
EPDCCH – Enhanced Physical Downlink Control Channel
ePDG – Enhanced Packet Data Gateway
EPS – Evolved Packet System
ERP – Enterprise Resource Planning
ETRI – Electronic and Telecommunications Research Institute
ETSI – European Telecommunications Standards Institute
E-UTRAN – Enhanced UMTS Terrestrial Radio Access Network
EVS – Enhanced Voice Services (codec)
FE-FACH – Further Enhanced Forward Access Channel
EV-DO – One Carrier Evolved, Data Optimized
EV-DV – One Carrier Evolved, Data Voice
EVRC – Enhanced Variable Rate Codec
FCC – Federal Communications Commission
FDD – Frequency Division Duplex
feICIC – Further enhanced ICIC
Flash OFDM – Fast Low-Latency Access with Seamless Handoff OFDM
FLO – Forward Link Only
FMC – Fixed Mobile Convergence
FP7 – Seventh Framework Programme
FTP – File Transfer Protocol
GAN – Generic Access Network
GB – Gigabyte
Gbps – Gigabits Per Second
GBR – Guaranteed Bit Rate
GByte – Gigabyte
GERAN – GSM EDGE Radio Access Network
GGSN – Gateway GPRS Support Node
GHz – Gigahertz
GMSK – Gaussian Minimum Shift Keying
GPRS – General Packet Radio Service
G-Rake – Generalized Rake Receiver
GSM – Global System for Mobile Communications
GSMA – GSM Association
HARQ – Hybrid Automatic Repeat Request
HD – High Definition
HetNet – heterogeneous network
HLR – Home Location Register
Hr – Hour
HSDPA – High Speed Downlink Packet Access
HS-FACH – High Speed Forward Access Channel
HS-PDSCH - High Speed Physical Downlink Shared Channels
HS-RACH – High Speed Reverse Access Channel
HSPA – High Speed Packet Access (HSDPA with HSUPA)
HSPA+ – HSPA Evolution
HSUPA – High Speed Uplink Packet Access
Hz – Hertz
ICIC – Inter-Cell Interference Coordination
ICS – IMS Centralized Services
ICT – Information and Communication Technologies
IEEE – Institute of Electrical and Electronic Engineers
IETF – Internet Engineering Taskforce
IFFT – Inverse Fast Fourier Transform
IFOM – IP Flow and Seamless Offload
IM – Instant Messaging
IMS – IP Multimedia Subsystem
IMT – International Mobile Telecommunications
IMT-Advanced - International Mobile Telecommunications-Advanced
IPR - Intellectual Property Rights
IP – Internet Protocol
IPTV – Internet Protocol Television
IR – Incremental Redundancy
ISI – Intersymbol Interference
ISP – Internet Service Provider
ITU – International Telecommunications Union
JCP – Java Community Process
JR – Joint Reception
JT – Joint Transmission
Kbps – Kilobits Per Second
kHz – Kilohertz
km – Kilometer
LIPA – Local IP Access
LTE – Long Term Evolution
LTE-TDD – LTE Time Division Duplex
LSTI – LTE/SAE Trial Initiative
M2M – Machine-to-machine
MAC – Medium Access Control
MB - Megabyte
MBMS - Multimedia Broadcast/Multicast Service
Mbps – Megabits Per Second
MBR – Maximum Bit Rate
MBSFN – Multicast/broadcast, Single Frequency
MCPA – Mobile Consumer Application Platform
Mcps – Megachips Per Second
MCS – Modulation and Coding Scheme
MCW – Multiple Codeword
MEAP – Mobile Enterprise Application Platforms
MediaFLO – Media Forward Link Only
MHz – Megahertz
MID – Mobile Internet Devices
MIMO – Multiple Input Multiple Output
MMSE – Minimum Mean Square Error
mITF – Japan Mobile IT Forum
MMDS – Multichannel Multipoint Distribution Service
MME – Mobile Management Entity
MRxD – Mobile Receive Diversity
MS – Mobile Station
MSA – Mobile Service Architecture
MSC – Mobile Switching Center
MTC – Machine Type Communications
MTC-IWF – Machine-Type Communications Interworking Function (MTC-IWF)
msec – millisecond
MU-MIMO – Multi-User MIMO
NENA – National Emergency Number Association
NGMC – Next Generation Mobile Committee
NGMN – Next Generation Mobile Networks Alliance
NTIA – National Telecommunications and Information Administration
OFDM – Orthogonal Frequency Division Multiplexing
OFDMA – Orthogonal Frequency Division Multiple Access
OL-SM – Open Loop Spatial Multiplexing
OMA – Open Mobile Alliance
PAR – Peak to Average Ratio
PBCCH – Packet Broadcast Control Channel
PCH – Paging Channel
PCRF – Policy Control and Charging Rules Function
PCS – Personal Communications Service
PDN – Packet Data Network
PHY – Physical Layer
PMI – Precoding Matrix Indication
PMIPv6 – Proxy Mobile IPv6
PoC – Push-to-talk over Cellular
PSH – Packet Switched Handover
PSK – Phase-Shift Keying
QAM – Quadrature Amplitude Modulation
QCI – Quality of Service Class Identifier
QLIC – Quasi-Linear Interference Cancellation
QoS – Quality of Service
QPSK – Quadrature Phase Shift Keying
RAB – Radio Access Bearer
RAN – Radio Access Network
RCS – Rich Communications Suite
REST – Representational State Transfer
RF – Radio Frequency
RNC – Radio Network Controller
ROHC – Robust Header Compression
RRC – Radio Resource Control
RRU – Remote Radio Unit
RTP – Real Time Transport Protocol
RTSP – Real Time Streaming Protocol
SAE – System Architecture Evolution
SaMOG – S2a-based Mobility over GTP
SC-FDMA – Single Carrier Frequency Division Multiple Access
SCRI – Signaling Connection Release Indication
SCW – Single Codeword
SDMA – Space Division Multiple Access
SDN – Software Defined Networking
SDP – Session Description Protocol
sec – Second
SFBA – Space Frequency Block Code
SGSN – Serving GPRS Support Node
SIC – Successive Interference Cancellation
SIM – Subscriber Identity Module
SIMO – Single Input Multiple Output
SINR – Signal to Interference Plus Noise Ratio
SIP – Session Initiation Protocol
SIPTO – Selected IP Traffic Offload
SISO – Single Input Single Output
SMS – Short Message Service
SNR – Signal to Noise Ratio
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>SoN</td>
<td>Self Optimizing Network</td>
</tr>
<tr>
<td>SPS</td>
<td>Semi-Persistent Scheduling</td>
</tr>
<tr>
<td>SR-VCC</td>
<td>Single Radio Voice Call Continuity</td>
</tr>
<tr>
<td>SU-MIMO</td>
<td>Single User MIMO</td>
</tr>
<tr>
<td>SVDO</td>
<td>Simultaneous 1XRTT Voice and EVDO Data</td>
</tr>
<tr>
<td>SVLTE</td>
<td>Simultaneous Voice and LTE</td>
</tr>
<tr>
<td>TCH</td>
<td>Traffic Channel</td>
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<tr>
<td>TCP/IP</td>
<td>Transmission Control Protocol/IP</td>
</tr>
<tr>
<td>TD</td>
<td>Transmit Diversity</td>
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<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>TD-SCDMA</td>
<td>Time Division Synchronous Code Division Multiple Access</td>
</tr>
<tr>
<td>TD-CDMA</td>
<td>Time Division Code Division Multiple Access</td>
</tr>
<tr>
<td>TIA/EIA</td>
<td>Telecommunications Industry Association/Electronics Industry Association</td>
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<tr>
<td>TISPAN</td>
<td>Telecoms and Internet converged Services and Protocols for Advanced Networks</td>
</tr>
<tr>
<td>TTI</td>
<td>Transmission Time Interval</td>
</tr>
<tr>
<td>UAS</td>
<td>Uplink EGPRS2-A Level Scheme</td>
</tr>
<tr>
<td>UBS</td>
<td>Uplink EGPRS2-B Level Scheme</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>UICC</td>
<td>Universal Integrated Circuit Card</td>
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<tr>
<td>UL</td>
<td>Uplink</td>
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<tr>
<td>UMA</td>
<td>Unlicensed Mobile Access</td>
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<tr>
<td>UMB</td>
<td>Ultra Mobile Broadband</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunications System</td>
</tr>
<tr>
<td>URA-PCH</td>
<td>UTRAN Registration Area Paging Channel</td>
</tr>
<tr>
<td>μs</td>
<td>Microseconds</td>
</tr>
<tr>
<td>USIM</td>
<td>UICC SIM</td>
</tr>
<tr>
<td>UTRAN</td>
<td>UMTS Terrestrial Radio Access Network</td>
</tr>
<tr>
<td>VAMOS</td>
<td>Voice Services over Adaptive Multi-User Channels on One Slot</td>
</tr>
<tr>
<td>VDSL</td>
<td>Very-High-Bit-Rate DSL</td>
</tr>
<tr>
<td>VoIP</td>
<td>Voice over Internet Protocol</td>
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<tr>
<td>VoHSPA</td>
<td>Voice over HSPA</td>
</tr>
<tr>
<td>VOLGA</td>
<td>Voice over LTE Generic Access</td>
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<tr>
<td>VoLTE</td>
<td>Voice over LTE</td>
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<tr>
<td>VPN</td>
<td>Virtual Private Network</td>
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<tr>
<td>WAP</td>
<td>Wireless Application Protocol</td>
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<td>WBA</td>
<td>Wireless Broadband Alliance</td>
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<tr>
<td>WCDMA</td>
<td>Wideband Code Division Multiple Access</td>
</tr>
<tr>
<td>WCS</td>
<td>Wireless Communication Service</td>
</tr>
</tbody>
</table>
Wi-Fi – Wireless Fidelity
WiMAX – Worldwide Interoperability for Microwave Access
WLAN – Wireless Local Area Network
WMAN – Wireless Metropolitan Area Network
WRC-07 – World Radiocommunication Conference 2007
Additional Information

4G Americas maintains complete and current lists of market information including HSPA, HSPA+ and LTE deployments worldwide, available for free download on its Web site: http://www.4gamericas.org.

If there are any questions regarding the download of this information, please call +1 425 372 8922 or e-mail Anna Altavas, Public Relations Coordinator at info@4gamericas.org.
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