Mobile Broadband Explosion

The 3GPP Wireless Evolution

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Introduction

The mobile broadband market has continued to explode thanks to widespread adoption, powerful new networks, stunning new handheld devices, and more than a million mobile applications. Mobile broadband now represents the leading edge in innovation and development for computing, networking, Internet technology, and software.

Major developments this past year include not only 3rd Generation (3G) ubiquity, but rapid deployment of 4th Generation (4G) networks; deepening smartphone capability; the availability of hundreds of thousands of mobile applications across multiple device ecosystems; the maturing of new form factors such as tablets; and a better understanding of what the industry needs to do to address data demands, which are growing exponentially. Over this past year, the need for additional spectrum has become particularly urgent, resulting in a number of new initiatives by industry and government.

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.

HSPA remains strongly positioned to be the dominant mobile-data technology for the next five to ten years. To leverage operator investments in HSPA, the 3GPP standards body has developed a series of enhancements to create “HSPA Evolution,” also referred to as “HSPA+.” HSPA+ represents a logical development of 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 this year, particularly in the U.S., 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 sophisticated “smart antennas,” heterogeneous networks (Het-nets), and user equipment communicating simultaneously with multiple base stations.

Combined with these improvements in radio-access technology, 3GPP has also spearheaded the development of major core-network architecture enhancements such as the IP Multimedia Subsystem (IMS), the Evolved Packet Core (EPC), previously called System Architecture Evolution (SAE), and more sophisticated means of integrating non-3GPP networks such as Wi-Fi. These developments 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.

The result is a balanced portfolio of complementary technologies that covers both radio-access and core networks, provides operators with maximum flexibility in how they enhance their networks over time, and supports both voice and data services.

This paper discusses the evolution of EDGE, HSPA enhancements, and LTE, as well as the capabilities of these technologies and their position relative to other primary competing technologies. It explains how these technologies fit into the International Telecommunications Union (ITU) roadmap that leads to 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.
- The wireless industry is addressing exploding data demand through a combination of spectrally more efficient technology, Het-nets, self-configuration, and self-optimization.
- LTE has exploded into existence, one of the most powerful wireless technologies ever developed.
- 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 have a smooth path to LTE-Time Division Duplex (LTE-TDD).
- Despite industry’s 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.
- The wireless technology roadmap now extends beyond IMT-Advanced with LTE-Advanced defined to meet IMT-Advanced requirements. LTE-Advanced will be capable of peak theoretical throughput rates that exceed 1 gigabit per second (Gbps). Operators will begin deploying LTE-Advanced in 2013.
- Future networks will be networks of networks, consisting of multiple-access technologies, multiple bands, widely-varying coverage areas, all self-organized and self-optimized. These Het-nets will significantly increase overall capacity.
- GSM-HSPA has an overwhelming global position in terms of subscribers, deployment, and services. Its success will continue to marginalize other wide-area wireless technologies.
- Expected to co-exist with LTE for the remainder of this decade, 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 (e.g., multi-carrier, higher-order modulation) being available as network software upgrades. With all planned features implemented, HSPA+ peak rates will eventually reach an astonishing peak theoretical speed of 336 Mbps on the downlink and 69 Mbps on the uplink.
- GSM-HSPA will comprise the overwhelming majority of subscribers over the next five to ten years, even as LTE becomes globally available.
- 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.

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1 This paper’s use of the term “GSM-HSPA” includes GSM, EDGE, UMTS, HSPA, and HSPA+. “UMTS-HSPA” refers to UMTS technology deployed in conjunction with HSPA and HSPA+ capability. LTE is considered a successor technology to UMTS-HSPA.
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. Policy-based charging and control provides flexible quality-of-service (QoS) management, enabling new types of applications, as well as billing arrangements.

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

Wi-Fi offload will play an important role in addressing demand and will become progressively more seamless for users thanks to various new 3GPP technologies, as well as industry initiatives such as HotSpot 2.0.

This paper begins with an overview of the market looking at trends, EDGE and UMTS-HSPA deployments, and market statistics. It then examines the evolution of wireless technology, particularly 3GPP technologies including spectrum considerations, core-network evolution, broadband-wireless deployment considerations, and a feature and network roadmap. Next, the paper discusses other wireless technologies including Code Division Multiple Access 2000 (CDMA2000) and WiMAX. Finally, it compares the different wireless technologies technically, based on features such as performance and spectral efficiency.

The appendix explains in detail the capabilities and workings of the different technologies including WCDMA², HSPA, HSPA+, LTE, IMT-Advanced, LTE-Advanced, IMS, EPC, Wi-Fi integration, cloud RAN, and Evolved EDGE.

Data Explosion

Broadband communication is becoming a foundational element of the entire economy, supporting entire industries, transforming not only how people work, but how they lead their lives.

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 with each other, but, in most instances, they are complementary. For the most part, backhaul transport and core infrastructure for wireless networks are based on wireline approaches, whether optical or copper. This applies as readily to Wi-Fi networks as it does to cellular networks.

Trends show explosive bandwidth growth of the Internet at large and for mobile broadband networks in particular. Cisco projects global mobile broadband traffic to grow eighteen fold from 2011 to 2016.³

This section covers data consumption, wireless versus wireline capabilities, bandwidth management, and trends in the cost of delivering mobile broadband.

Data Consumption

There are multiple factors contributing to explosive growth in data consumption, but first and foremost is the combination of powerful mobile computing platforms and fast mobile broadband networks. Despite the number of vendors and platform types available on the

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² 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.

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**

The rich capabilities of these mobile platforms enable them to consume ever larger amounts of data through activities such as music and video streaming, social networking, cloud-based synchronization and 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>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.0</td>
<td>6.9</td>
</tr>
<tr>
<td>Small Screen Video (e.g., Feature Phone)</td>
<td>0.2</td>
<td>90</td>
<td>0.5</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.0</td>
<td>10.8</td>
</tr>
<tr>
<td>Medium Screen Video (e.g., Smartphone Full-Screen Video)</td>
<td>1.0</td>
<td>450</td>
<td>0.5</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
<td>27.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.0</td>
<td>54.0</td>
</tr>
<tr>
<td>Larger Screen Video (e.g., Netflix Lower Def. on Tablet or Laptop)</td>
<td>2.0</td>
<td>900</td>
<td>0.5</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
<td>27.0</td>
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<td></td>
<td></td>
<td>2.0</td>
<td>54.0</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>4.0</td>
<td>108.0</td>
</tr>
<tr>
<td>Larger Screen Video (e.g., Netflix Higher Def. on Laptop)</td>
<td>4.0</td>
<td>1800</td>
<td>0.5</td>
<td>27.0</td>
</tr>
<tr>
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<td>1.0</td>
<td>54.0</td>
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<td>2.0</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>4.0</td>
<td>216.0</td>
</tr>
</tbody>
</table>

Video applications: telemedicine, education, social networking, entertainment.

With declining voice revenue, but increasing data revenue, cellular operators face a tremendous opportunity in continuing to develop their mobile broadband businesses. Successful execution, however, means more than just providing high speed networks. It means addressing demand that is growing at an extremely rapid rate. It also means nurturing an application ecosystem, delivering complementary services, providing a compelling customer experience, and supplying attractive devices. These are all areas in which the industry has done well.

**Wireless Versus Wireline**

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

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 compelling high-speed data services with mobility. Thus, the opportunities are limitless 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 their high-end mobile workers and consumers for whom mobile broadband can be a cost-effective option competing with digital subscriber line (DSL) for home use.
Relative to wireless networks, wireline networks have always had greater capacity and historically have delivered faster throughput rates. Figure 2 shows advances in typical user throughput rates with a consistent 10x advantage of wireline technologies over wireless technologies.

**Figure 2: Wireline and Wireless Advances**

![Diagram showing advancements in wireless and wireline technologies from 2000 to 2010](image)

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 4 Mbps. Typical LTE deployments use 10 MHz radio channels on the downlink and have a spectral efficiency of 1.4 bps/Hz, providing LTE an average sector capacity of 14 Mbps. Thus, just four Netflix viewers could exceed sector capacity. In the U.S., there are approximately 1100 subscribers on average per cell site⁴, hence about 360 for each of the three sectors commonly deployed in a 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 an increasing number of applications including education, social networking, video conferencing, business collaboration, field service, and telemedicine.

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⁴ 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).
Over time, wireless networks will gain substantial additional capacity through all 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 infrared 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, as illustrated in Figure 3.** Meanwhile, the mobile computing industry currently has access to only .5% of this radio spectrum, growing to possibly 1% by 2020.6

**Figure 3: RF Capacity Versus Fiber-Optic Cable Capacity**

A dilemma of mobile broadband is that it *can* provide a broadband experience similar to wireline, but it *cannot* do so to 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.

The way to think of mobile broadband networks is as 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. This improves signal quality, and it decreases the number of people that each cell must serve. This is


6 .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.
the fundamental basis for both Wi-Fi offload and small-cell architectures such as picocells and femtocells.

Despite some of the inherent limitations of wireless technology relative to wireline, its fundamental appeal of providing access from anywhere has 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 either employing or considering 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., the FCC National Broadband Plan seeks to make an additional 500 MHz of spectrum available by 2020. Multiple papers by Rysavy Research and others\(^7\) have argued for the critical need for additional spectrum.

- **Unpaired spectrum.** Technologies such as HSPA+ and LTE allow 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.

- **Combining uplink gains with downlink carrier aggregation.** Operators can increase network capacity by applying new receive technologies at the base station (e.g., large scale antenna systems) that do not necessarily require standards. This can be combined with added capacity on the downlink from carrier aggregation. This type of deployment flexibility suggests that regulators should consider licensing just downlink spectrum in some cases, since that is where it is generally most needed.

- **Small cells and heterogeneous networks.** Selective addition of picocells to macrocells to address localized demand can significantly boost overall capacity. Hetnets, which also can include femtocells, hold the promise of achieving capacity gains of a factor of four and potentially even higher with the introduction of interference-cancellation-based devices. The actual gain realized will depend upon a number of factors including number and placement of small cells, user distribution, and any small-cell selection bias that might be applied.

- **Wi-Fi.** Wi-Fi networks offer another means of offloading heavy traffic, especially as the number of Wi-Fi hotspots increases and connections become more seamless. Wi-Fi adds capacity since it offloads onto unlicensed spectrum. Moreover, since Wi-Fi

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signals cover only small areas, Wi-Fi achieves both extremely high frequency re-use, as well as high bandwidth per square meter across the coverage area.

- **Off-peak hours.** Operators can offer user incentives or perhaps fewer restrictions on large data transfers that occur at off-peak hours such as overnight.

- **Quality of service (QoS).** By prioritizing traffic, certain traffic such as non-time-critical downloads can execute with lower priority, thus not affecting other active users.

- **Innovative data plans.** Creative new data plans influencing consumption behavior including tiered pricing make usage affordable for most users, but discourage excessive or abusive use.

- **Explore new methods for the future.** Recently there has been a considerable amount of discussion about spectrum sharing. Although a promising approach for better spectrum utilization in the long term, spectrum sharing will require new technologies, as well as spectrum coordination, items that could take ten years or more to develop and commercialize.\(^8\)

It will take a creative blend of all of the above to make the mobile broadband market successful and to enable it to exist as a complementary solution to wired broadband.

Figure 4 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.

**Figure 4: Benefits of Additional Spectrum and Offload**

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Technology Drives Demand

A common view is that a more efficient technology can address escalating demand. This view, however, fails to take into account that the more efficient technology often provides higher performance, thus encouraging new usages, hence escalating demand further, as illustrated in Figure 5. Operators have observed this already with LTE where monthly usage amounts have been higher than for 3G networks.

Not only are users more likely to use applications that consume more bandwidth when given the opportunity, but an increasing number of applications, e.g., 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.

Figure 5: Enhanced Technology Creates New Demand.

Mobile Broadband Cost and Capacity Trends

While the cost of delivering data with wireless broadband remains higher than with wireline broadband, costs continue to decline rapidly. One vendor has calculated that in a blended HSPA/LTE network costs could go below 1 Euro per gigabyte (GByte) once penetration of mobile broadband reaches 40% and usage reaches 2 GByte per month.9

3GPP technologies clearly address proven market needs; hence their overwhelming success. The 3GPP roadmap, which anticipates continual performance and capacity

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improvements, provides the technical means to deliver on proven business models. As the applications for mobile broadband continue to expand, HSPA, HSPA+, LTE and LTE-Advanced will continue to provide a competitive platform for tomorrow’s new business opportunities.

**Wireless Data Market**

By June 2012, more than 5.6 billion subscribers were using GSM-HSPA\(^\text{10}\)—nearly three quarters of the world’s total 7.02 billion population.\(^\text{11}\) By the end of 2017, the global mobile broadband market is expected to include more than 5.6 billion subscribers of whom 5 billion will use 3GPP technologies, representing 90% market share.\(^\text{12}\) 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 represents 40% of ARPU on average, five percent higher than a year ago and expected to reach $80 billion for the year.\(^\text{13}\)

This section examines trends and deployment, and then provides market data that demonstrates the rapid growth of wireless data.

**Market Trends**

As stated in a Rysavy Research report for the Cellular Telephone Industries Association (CTIA) on mobile broadband spectrum demand, “We are at a unique and pivotal time in history, in which technology capability, consumer awareness and comfort with emerging wireless technology and industry innovation are converging to create mass-market acceptance of mobile broadband.”\(^\text{14}\)

As a consequence, this rich network and device environment is spawning the availability of a wide range of wireless applications and content. Because of its growing size—and its unassailable potential—application and content developers are making the wireless market a high priority. The result is significantly growing usage of data on devices such as smartphones and tablets. For example, Chetan Sharma reports close to 800 Mbytes data consumed on average per month for some operators.\(^\text{15}\)

Over time, data demands are expected to grow significantly. Already, data represents a much higher network load than voice. Figure 6 shows a projection by Cisco of global mobile data growth through 2016 in exabytes (billion gigabytes) per month with traffic growing at a compound annual rate of 78%.

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The key for operators is enhancing their networks to support the demands of consumer and business applications as they grow, along with offering complementary capabilities such as IP-based multimedia. Another area that will drive wireless usage is machine-to-machine (M2M) communications. Ultimately, there are billions of machines that could communicate, far more than people. One 4G Americas member company has forecast up to 50 billion overall connections in the world by 2020.

**EDGE/HSPA/HSPA+/LTE Deployment**

Most GSM networks today support EDGE, representing more than 543 networks in approximately 198 countries.17

Meanwhile, UMTS has established itself globally. Nearly all WCDMA handsets are also GSM handsets, so WCDMA users can access the wide base of GSM networks and services. There are more than 1 billion HSPA customers worldwide spanning more than 475 commercial networks. 233 networks now in 112 countries offer HSPA+.18 With HSPA+ technology maturing, deploying or upgrading to HSPA+ involves minimal incremental investment.

Worldwide there are more than 3,360 HSPA devices available.19 Devices include handsets, data cards, modems, routers, laptops, media players, and cameras.

LTE has not only become the preferred choice for many operators as their next-generation wireless technology, but it has been chosen by national public-safety organizations in the U.S. as their broadband technology of choice. The Association of

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17 Source: 4G Americas, July 2012.


19 Source: GSA, July 2012.
Public-Safety Communications Officials (APCO) and the National Emergency Number Association (NENA) have both endorsed LTE. In 2012, legislation passed in the U.S. that allocated the D Block spectrum for a nationwide public-safety LTE network.

Though most mobile broadband growth today is still based on HSPA (with some EV-DO), LTE is now seeing rapid deployment. TeliaSonera launched the world's first commercial LTE network in Oslo and Stockholm in December 2009. Rogers is deploying LTE in Canada. In the U.S., AT&T, Sprint, MetroPCS, and Verizon have begun deploying LTE and plan on having widespread coverage by the end of 2013. Verizon indicates that by the end of 2012 that their network will cover 260 million people in more than 400 markets. AT&T plans to cover at least 140 million people in the same time period. Yankee Group predicts 136 million LTE lines in the U.S. by 2016.

Wireless Technology Evolution

This section discusses 1G to 4G designations, the evolution and migration of wireless-data technologies from EDGE to LTE, as well as the evolution of underlying wireless approaches. It emphasizes the most important technical developments in the industry. 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

There is some confusion in the industry as to what technology falls into which cellular generation, especially with significant changes in marketing designations that occurred the past few years. 1G refers to analog cellular technologies; it became available in the 1980s. 2G denotes initial digital systems, introducing services such as short messaging and lower speed data. CDMA IS-95 and GSM are the primary 2G technologies, while CDMA2000 1xRTT is sometimes called a 3G technology, because it meets the 144 kbps mobile throughput requirement. EDGE, however, also meets this requirement. 2G technologies became available in the 1990s.

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 recently WiMAX was also 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

22 Source: AT&T, private communications.
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.

However, it will require new technologies such as LTE-Advanced (in 3GPP Release 10) and IEEE 802.16m to meet these ITU IMT-Advanced requirements. 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 December 6, 2010, stated in a press release, “As the most advanced technologies currently defined for global wireless mobile broadband communications, IMT-Advanced is considered as ‘4G’, although it is recognized that this term, while undefined, may also be applied to the forerunners of these technologies, LTE and WiMAX, and to other evolved 3G technologies providing a substantial level of improvement in performance and capabilities with respect to the initial third generation systems now deployed.”

Table 2 summarizes the generations of wireless technology.

**Table 2: 1G to 4G**

<table>
<thead>
<tr>
<th>Generation</th>
<th>Requirements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1G</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>2G</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>3G</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.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WiMAX now an official 3G technology.</td>
</tr>
<tr>
<td>4G (Initial Technical Designation)</td>
<td>ITU’s IMT-Advanced requirements include ability to operate in up to 40 MHz radio channels and with very high spectral efficiency.</td>
<td>No commercially deployed technology meets requirements today. IEEE 802.16m and LTE-Advanced being designed to meet requirements.</td>
</tr>
<tr>
<td>4G (Current Marketing Designation)</td>
<td>Systems that significantly exceed the performance of initial 3G networks. No quantitative</td>
<td>Today’s HSPA+, LTE, and WiMAX networks meet this requirement.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Generation</th>
<th>Requirements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>requirements.</td>
<td></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’s 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\(^\text{25}\), which is consistent with GSM technology history. Similarly, 4G technologies coming online now may not see their peak adoption until 2030. Figure 7 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 is for 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 ten years. Within each platform, however, there is constant innovation. For example, with 2G technology, EDGE significantly improved data performance compared to initial General Packet Radio Service (GPRS) capabilities. Similarly, HSPA hugely increased data speeds compared to initial 3G capabilities. LTE and LTE-Advanced will also acquire continual improvements that include both faster speeds and greater efficiency.

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

- 1950s First commercial computers
- 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 Time Division Multiple Access (TDMA) approach, is mature and broadly deployed. Already extremely efficient, there are nevertheless opportunities for additional optimizations and enhancements. Standards bodies have already defined “Evolved EDGE,” which became available for deployment in 2011. Evolved EDGE more than

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26 Source: Rysavy Research projection based on historical data.
doubles throughput over current EDGE systems, halves latency, and increases 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, such as 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.

HSPA innovations such as dual-carrier HSPA, explained in detail in the appendix section “Evolution of HSPA (HSPA+),” coordinate the operation of HSPA on two 5 MHz 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 capabilities such as 8-carrier downlink operation 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 will coexist with both 3G systems and 2G systems. Multimode devices will function across LTE/3G and LTE/3G/2G. Beyond radio technology, EPC provides a new core architecture that enables both flatter architectures and integration of LTE with both legacy GSM-HSPA networks, as well as other wireless technologies. The combination of EPC and LTE is referred to as the Evolved Packet System (EPS).

HSPA+ and LTE are important to operators since these technologies provide the efficiency and capability being demanded by the quickly growing mobile broadband market. The cost for operators to deliver data (e.g., cost per GByte) 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.

As market demands increase, HSPA+ is attractive to some operators since it maximizes the efficiencies in existing deployments and provides high performance with the use of new advanced techniques both in spectrum that is already being utilized and also in new spectrum. Specifically:

- **Large Spectrum Utilization.** HSPA+ can now be deployed in wider bandwidths such as 10Mhz and 20Mhz. This functionality both increases peak data rates and also improves spectral efficiency.

- **Advanced MIMO.** The introduction of MIMO enhancements and the addition of more transmit and receive antennas provides improved spectral efficiency in existing spectrum.

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

As competitive pressures in the mobile broadband market intensify and as demand for more capacity continues unabated, LTE is developing deployment momentum for the reason that it offers an extremely efficient and effective way of delivering high performance, especially in new spectrum. Specifically:
- **Wider Radio Channels.** LTE can be deployed in wide radio channels (e.g., 10 MHz or 20 MHz). This increases peak data rates and also provides for more efficient spectrum utilization.

- **Easiest MIMO Deployment.** By using new radios and antennas, LTE facilitates MIMO deployment compared to 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 msec and 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 in enabling deployments where 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 is developing 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.

LTE is one of the most promising wireless-technology platforms for the future. The version being deployed today is just the beginning of a series of innovations that will increase performance, efficiency, and capabilities, as depicted in Figure 8. The enhancements shown in the 2013 to 2016 period are the ones expected from 3GPP Releases 10 and 11 and are commonly referred to as LTE-Advanced. Subsequent releases such as Release 12 and 13, however, will continue this innovation through the end of this decade.

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27 From a standards-development point of view, the term “LTE-Advanced” refers to the following features: carrier aggregation, 8X8 downlink MIMO, and 4XN4X3 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 a summary intended to provide a frame of reference for the subsequent discussion. Table 3 summarizes the key 3GPP technologies and their characteristics.

### Table 3: 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></td>
<td></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>70 kbps to 135 kbps</td>
<td>70 kbps to 135 kbps</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 spectral efficiency.</td>
<td>175 kbps to 350 kbps (Single Carrier)</td>
<td>150 kbps to 300 kbps expected</td>
</tr>
</tbody>
</table>

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**Figure 8: LTE as a Wireless Technology Platform for the Future**
<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>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&lt;sup&gt;28&lt;/sup&gt;</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</td>
<td>1 Mbps to 4 Mbps in 5/5 MHz or in 10/5 MHz</td>
</tr>
<tr>
<td></td>
<td>CDMA</td>
<td>3.8 Mbps to 17.6 Mbps with dual carrier in 10/5 MHz.</td>
<td></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></td>
<td></td>
</tr>
</tbody>
</table>

User achievable rates and greater details on typical rates are covered in Table 4 in the section “Data Throughput” later in this paper. Figure 9 shows the evolution of the different wireless technologies and their peak network performance capabilities.

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<sup>28</sup> HSPA and HSPA+ throughput rates are for a 5/5 MHz deployment. N/M MHz in this paper means 5 MHz used for the downlink and M MHz used for the uplink.
Figure 9: Evolution of TDMA, CDMA, and OFDMA Systems

<table>
<thead>
<tr>
<th></th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EDGE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evolved EDGE</td>
<td>DL: 1.89 Mbps</td>
<td>UL: 947 kbps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rel 8 HSPA+</td>
<td>DL: 42 Mbps</td>
<td>UL: 11.5 Mbps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rel 9 HSPA+</td>
<td>DL: 84 Mbps</td>
<td>UL: 23 Mbps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rel 10 HSPA+</td>
<td>DL: 168 Mbps</td>
<td>UL: 23 Mbps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rel 11 HSPA+</td>
<td>DL: 336 Mbps</td>
<td>UL: 46 Mbps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>HSPA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rel 8 LTE</td>
<td>DL: 300 Mbps</td>
<td>UL: 45 Mbps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rel 9 LTE</td>
<td>DL: 300 Mbps</td>
<td>UL: 45 Mbps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rel 10 LTE</td>
<td>DL: 1.2 Gbps</td>
<td>UL: 568 Mbps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rel 11 LTE</td>
<td>DL: &gt; 1.2 Gbps</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LTE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rel 9 LTE</td>
<td>DL: 300 Mbps</td>
<td>UL: 45 Mbps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rel 10 LTE</td>
<td>DL: 1.2 Gbps</td>
<td>UL: 568 Mbps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rel 11 LTE</td>
<td>DL: &gt; 1.2 Gbps</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CDMA2000</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EV-DO Rev B</td>
<td>DL: 14.7 Mbps</td>
<td>UL: 5.4 Mbps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EV-DO Advanced</td>
<td>DL: 14.7 Mbps</td>
<td>UL: 5.4 Mbps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>WiMAX</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed WiMAX</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WiMAX Rel 1.0</td>
<td>DL: 46 Mbps</td>
<td>UL: 4 Mbps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WiMAX Rel 1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WiMAX IEEE 802.16m</td>
<td>DL: &gt; 1 Gbps</td>
<td></td>
<td></td>
<td></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 2011, 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 referred to as 3GPP releases, and equipment vendors produce hardware that supports particular versions of each specification. It is important to realize that the 3GPP releases address 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: 29


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29 After Release 99, release versions went to a numerical designation instead of designation by year.
• **Release 5**: Completed. HSDPA. First phase of Internet Protocol Multimedia Subsystem (IMS). Full ability to use IP-based transport instead of just Asynchronous Transfer Mode (ATM) in the core network.


• **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, Het-net 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**: In development, targeted for completion end of 2012. For LTE, emphasis is on Co-ordinated Multi-Point (CoMP), carrier-aggregation enhancements, and further enhanced eICIC including devices with 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, DLCELL_Forward Access Channel (FACH) state enhancement for smart phone-type traffic, four-branch MIMO enhancements and transmissions for HSDPA, 64 QAM in the uplink, downlink multi-point transmission, and non-contiguous HSDPA carrier aggregation.

• **Release 12**: In initial planning and discussion stages. Potential enhancements include enhanced small cells/Het-nets for LTE; LTE multi-antenna/site technologies such as 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, Minimization of Test Drives (MDT),
and advanced receivers; device-to-device communication; energy efficiency; more flexible carrier aggregation; and further enhancements for HSPA+ including further DL and UL improvements and interworking with LTE.

Whereas operators and vendors actively involved in the development of wireless technology are heavily focused on 3GPP release versions, most users of the technology are more interested in particular features and capabilities such as whether a device supports HSDPA. For this reason, the detailed discussion of the technologies in this paper emphasizes features as opposed to 3GPP releases.

Spectrum

Spectrum continues to be one of the most important issues facing the industry. There are two issues to consider. One is the limited amount of spectrum available to support this dynamic industry. The other is how the industry is responding to take advantage of available technology.

Given that spectrum is a limited resource, the industry is undertaking the following initiatives to leverage all available spectrum:

- Increasing the spectral efficiency of technologies to continually increase the bits per second of data bandwidth for every available Hertz.
- Adapting specifications to enable operation of UMTS-HSPA and LTE in all available bands.
- Designing both FDD and TDD versions of technology to allow operation in 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 both peak data rates and efficiency.
- Deploying as many new cells (large and small) as is feasible.

It might be thought that new technologies such as small cells and smart antennas would obviate the need for spectrum. These technologies, however, are already on the roadmap for 3GPP evolution and, by themselves, do not sufficiently increase capacity to meet growing demand.

The FCC released a report in October 2010 that projected spectrum requirements for the U.S. and concluded that 275 MHz of additional spectrum would be needed within five years and 500 MHz of additional spectrum within ten years. This forecast assumes ongoing increases in spectral efficiency from improving technologies.

An important aspect of UMTS-HSPA and LTE deployment is the expanding number of available radio bands and the corresponding support from infrastructure and mobile-equipment vendors. The fundamental system design and networking protocols remain the same for each band; only the frequency-dependent portions of the radios have to change. As other frequency bands become available for deployment, standards bodies are adapting UMTS and LTE for these bands as well. This includes bands such as 450 MHz and 700 MHz. The FCC auctioned the 700 MHz band in the U.S. in 2008, and a number of

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Mobile operators are now deploying LTE in this band. Canada will auction the 700 MHz band in 2013.

The 1710-1770 uplink was matched with 2110-2170 downlink to allow for additional global harmonization of the 1.7/2.1GHz band. These new spectrum bands were reserved or allocated harmoniously across North, Central and South America. The availability of this band, the Advanced Wireless Services (AWS) band at 1710-1755 MHz in the U.S. 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 multiple U.S. operators are expected to as well.

The forthcoming 2.6 GHz frequency band in Europe will also play an important role. An increasing number of operators are also deploying UMTS at 900 MHz, a traditional GSM band.

Unfortunately, the process of identifying new spectrum and making it available for the industry is a lengthy one, as shown in Figure 10.

**Figure 10: Spectrum Acquisition Time**

The FCC is pursuing multiple avenues for making more spectrum available in the future. In the near term, there is potentially 90 MHz of Mobile Satellite Services (MSS) spectrum and 20 MHz of Wireless Communications Service (WCS) spectrum that could be available for use. Fifty MHz of the MSS spectrum, however, is owned by LightSquared and is currently off the table due to concerns about interference with Global Positioning Systems (GPS).

The two biggest opportunity areas for new spectrum beyond MSS and WCS are NTIA-identified government spectrum from 1755 to 1850 MHz and incentive auctions of TV-broadcasting spectrum (up to 120 MHz). With incentive auctions, the outcome depends on how many broadcasters choose to participate and under what compensation requirements.

The NTIA spectrum involves a large number of government systems either migrating to other spectrum or co-existing with commercial systems by using shared approaches that are not yet identified. 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

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federal to commercial use. To assist with making the 1755 to 1780 MHz portion available, T-Mobile has filed a request for special temporary authority with the FCC to test the deployment of commercial mobile broadband service in this band with the realization that a limited number of incumbent federal operations could remain in the band on a transitional basis.

The 3550 to 3650 MHz band in the U.S. is now also being discussed for potential licensing, although how useful this band would be due to the higher frequencies involved remains to be determined. Also, there are unknown details involving co-existence with or relocation of government radar systems that operate in this band.

Figure 11 shows a Rysavy Research projection from 2010 for the amount of spectrum that an operator will require in their busiest markets to meet anticipated demand. Given that many operators in the U.S. have about 50 to 90 MHz of spectrum, it will not be that long before additional spectrum is essential. Credit Suisse reported in 2011 that U.S. wireless networks in the U.S. were already operating at 80% of capacity.32

**Figure 11: Operator Spectrum Requirement for Busiest Markets**

![Operator Spectrum Requirement for Busiest Markets](image)

The spectrum situation varies by operator. Some may experience shortages well before others depending on multiple factors such as the amount of spectrum they have, their cell site density relative to population, type of devices they offer, and their service plans.

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As the total amount of available spectrum does become available and as technologies simultaneously become spectrally more efficient, total capacity rises rapidly, supporting more subscribers and making many new types of applications feasible.

Refer to the section "Spectrum Bands" in the appendix for further details on specific bands for UMTS and LTE.

Different countries have regulated spectrum more loosely than others. For example, operators in the United States can use any technology in any band, whereas in Europe there are greater restrictions—although efforts are underway that are resulting in greater flexibility including the use of 3G technologies in current 2G bands.

With the projected increase in the use of mobile-broadband technologies, the amount of spectrum required by the next generation of wireless technology (that is, after 3GPP LTE in projects such as IMT Advanced) could be substantial. In the U.S., the FCC in 2010 committed itself to finding an additional 500 MHz of spectrum over the next ten years as part of its national broadband plan. This would effectively double the amount of spectrum for commercial mobile radio service.

As regulators make more spectrum available, it is important that they follow guidelines such as those espoused by 4G Americas\(^{34}\):

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. 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, an essential attribute, because typical broadband usage contributes to a much higher load than a voice user. For instance, watching a YouTube video consumes 100 times as many bits per second on the downlink as a voice call.

Figure 12 shows increasing LTE spectral efficiency obtained with wider radio channels, with 20 MHz showing the most efficient configuration.

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, it will most likely necessitate that roaming operation be based on GSM or HSPA on common regional or global bands.

**Architecture Evolution and Heterogeneous Networks**

The architecture of wireless networks will evolve through fundamental changes to both the radio-access network and the core network.

One of the most important developments in radio-access architecture is the concept of heterogeneous networks. This is the idea of multiple types of cells serving a coverage area, varying in frequencies used, radius, and even radio technology used. Het-nets offer significant increases in capacity and improvements in user experience in the following ways:

- 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 an avenue to absorb traffic in areas where there are higher concentrations of users. This could include areas such as business locations, airports, sports arenas, and so forth.
- Smaller cells can also improve signal quality in areas in which the signal from the macro cell has difficulty reaching.

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35 Source: 4G Americas member company analysis.
Essential elements for practical Het-net deployment are self optimization and self configuration, especially as the industry transitions from measuring the number of cells in hundreds of thousands to millions. The appendix covers technical aspects of Het-nets 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 possible.

As for the core network, 3GPP is defining a series of enhancements to improve network performance and the range of services provided, and to enable a shift to all-IP architectures.

One way to improve core-network performance is by using 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 multiple 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, as discussed in the next section.

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

**Service Evolution**

Not only do 3GPP technologies provide continual improvements in capacity and data performance, they also evolve capabilities that expand the services available to subscribers. Key advances to expand service offerings include Fixed Mobile Convergence (FMC), IMS, and broadcasting technologies. This section provides an overview of these topics, and the appendix provides greater detail on each of these items.

FMC refers to the integration of fixed services (such as telephony provided by wireline or Wi-Fi) with mobile cellular-based services. Though FMC is still in its early stages of deployment by operators, it promises to provide significant benefits to both users and operators. For users, FMC will simplify how they communicate making it possible for them to use one device (for example, a cell phone) at work and at home where it might connect via a Wi-Fi network or a femtocell. When mobile, users connect via a cellular network. Users will also benefit from single voice mailboxes and single phone numbers, as well as the ability to control how and with whom they communicate. For operators, FMC allows the consolidation of core services across multiple-access networks. For instance, an operator could offer complete VoIP-based voice service that supports access via DSL, Wi-Fi, or 3G. FMC also offloads the macro network from data-intensive applications such as movie downloads.
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 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. These are tiny base stations that cost little more than a Wi-Fi access point, and, like Wi-Fi, femtocells 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 the femtocell approach is that any single-mode, mobile-communications device a user has can now operate using the femtocells.

IMS is another key technology for convergence. It allows access to core services and applications via multiple-access networks. IMS is more powerful than GAN, because it supports not only 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 how VoIP will (or could) be deployed in CDMA 2000 EV-DO, WiMAX, HSPA, and LTE networks. In the U.S., all LTE VoIP will be based on IMS.

IMS allows the creative blending of different types of communications and information including voice, video, Instant Messaging (IM), presence information, location, and documents. It provides application developers the means to create applications that have never before been possible, and it allows people to communicate in entirely new ways by dynamically using multiple services. For example, during an interactive chat session, a user could launch a voice call. Or during a voice call, a user could suddenly establish 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. Though IMS adoption by cellular operators has been relatively slow to date, deployment will accelerate as operators make packet voice service available for LTE.

An initiative called Rich Communications Suite (RCS), supported by many operators and vendors, builds upon 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. RCS will enable interoperability of supported features across different operators who support the suite. RCS supports both circuit-switched and packet-switched voice and can interoperate with LTE packet voice.

Core features include:

- An enhanced phone book (device and/or network based) that includes service capabilities and presence-enhanced contact information.
- Enhanced messaging (supporting text, instant messaging, and multimedia) with chat and messaging history.
- Enriched calls that include multimedia content (e.g., photo sharing, video sharing) during voice calls.

Another important new service is support for mobile TV through what is called 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 is that for content that is of common interest, for example streaming of the Olympics, broadcasting uses the radio resource much more efficiently than having separate point-to-point streams for each user. Users at a sporting event, for example, might enjoy watching replays on their smartphones, again something that is much more
efficient using multicasting. The technology supports these applications; it is a matter of operators and content providers finding offers that are appealing to users.

**Voice Support**

While 2G and 3G technologies were deployed from the beginning with both voice and data capability, LTE networks can be deployed with or without voice support. Moreover, there are a number of methods available for voice support including circuit-switched fallback (CSFB) to 2G/3G and VoIP operation. Operators deploying LTE now will use CSFB initially, and will then migrate to VoIP methods based on an approach called Voice over LTE (VoLTE). VoLTE requires the addition of infrastructure called the IP Multimedia Subsystem (IMS) to the operator core network. These approaches are covered in more detail in the LTE section of the appendix.

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 methods have been defined. VoHSPA can increase efficiency, however, and is under active consideration.36

Another voice enhancement likely to be made relatively soon, especially with VoLTE, is high-definition (HD) voice, based on voice codecs such as Adaptive Multi-Rate Wideband (AMR-WB). HD voice not only improves voice clarity and intelligibility, but it better suppresses background noise.

**Broadband-Wireless Deployment Considerations**

Much of the debate in the wireless industry is on the merits of different radio technologies, yet other factors are equally important in determining the services and capabilities of a wireless network. These factors include the amount of spectrum available, backhaul, and network topology.

Spectrum has always been a major consideration for deploying any wireless network, but it is particularly important when looking at high-performance broadband systems. HSPA and HSPA+ can deliver high throughput rates on the downlink and uplink with low latency in 5 MHz channels when deployed in single frequency (1/1) reuse. By this, we mean that every cell sector (typically three per cell) in every cell uses the same radio channel(s).

To achieve higher data rates requires wider radio channels, such as 10 or 20 MHz wide channels, in combination with emerging OFDMA radio technologies. Very few operators today, however, have access to this much spectrum. It was challenging enough for GSM operators to obtain UMTS spectrum. While channel aggregation methods in HSPA+ and LTE-Advanced combine channels for greater throughput, the lowest cost and highest efficiency is achieved by single radio channels of the greatest width possible.

Backhaul is another factor. As the throughput of the radio link increases, the circuits connecting the cell sites to the core network must be able to handle the increased load. With many cell sites today 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 emerging wireline technologies such as VDSL and optical Ethernet, as well as point-to-

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point microwave systems. An OFDMA system with 1.4 bps per hertz (Hz) of spectral efficiency in 10 MHz on three sectors has up to 42 Mbps average 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 future technologies such as LTE-Advanced, which will need even greater backhaul capability, many operators are planning 1 Gbps backhaul links.

Finally, the overall network topology also plays an important role, especially with respect to latency. Low latency is critical to achieving very high data rates, because of the way it affects Transmission Control Protocol (TCP)/IP traffic. How traffic routes through the core network—how many hops and nodes it must pass through—can influence the overall performance of the network. One way to increase performance is by using flatter architectures, meaning a less hierarchical network with more direct routing from mobile device to end system. The core EPC network for 3GPP LTE emphasizes just such a flatter architecture.

**Wi-Fi Integration and Data Offload**

As data loads increase, operators are seeking to offload some of the data traffic to other networks, particularly Wi-Fi networks. Some Wi-Fi integration technologies reduce the demand on the radio-access network, some reduce the demand on the core network, and others make the use of Wi-Fi more seamless for users. Seamless means user devices automatically connect to desired Wi-Fi networks and users do not need to actively manage these connections.

The IEEE 802.11 family of technologies has experienced rapid growth, mainly in private deployments. The latest 802.11 standard, 802.11ac, offers users 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 provides quality-of-service enabling VoIP and multimedia, 802.11i enables robust security, and 802.11r provides fast roaming, necessary for voice handover across access points. Wi-Fi networks thus are increasingly considered to be complementary to cellular wide-area networks, enhancing their attractiveness even further.

Leveraging this success, operators—including cellular operators—are offering hotspot service in public areas such as airports, fast-food restaurants, and hotels. For the most part, hotspots are complementary with cellular-data networks, because the hotspot can provide broadband services in extremely dense user areas and the cellular network can provide broadband services across much larger areas. One 4G Americas member estimates that 40% of traffic can potentially be offloaded based on the following observations\(^{37}\):

- About 80% of traffic is indoors
- About 80% of traffic is from smartphones

\(^{37}\) Source: Nokia Siemens Networks white paper, “Deployment Strategies for Heterogeneous Networks,” 2012. 80% X 80% X 80% X 80% = 40%.
About 80% of smartphones have Wi-Fi
About 80% of smartphone users take advantage of Wi-Fi connections

Wi-Fi has huge inherent capacity for two reasons. First, a large amount of spectrum (approximately 500 MHz) is available across 2.4 GHz and 5 GHz bands. Second, the spectrum is used in small coverage areas, resulting in high frequency reuse. The result is much higher bps rates per square meter of coverage than with wide-area networks.

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.\textsuperscript{38} It also facilitates encrypted communications over the radio link.\textsuperscript{39} Building on this foundation, the Wireless Broadband Alliance (WBA) is pursuing techniques to more tightly integrate hotspots into mobile operators’ networks.

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 (e.g., internal portals) that can only be accessed 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. See the section “Wi-Fi Integration” in the appendix for technical details on 3GPP and other industry initiatives related to Wi-Fi.

**Network Deployment**

Operators have deployed UMTS-HSPA worldwide. Although UMTS involves a new radio-access network, several factors facilitate deployment. First, most UMTS cell sites can be collocated in GSM cell sites enabled by multi-radio cabinets that can accommodate GSM/EDGE, as well as UMTS equipment. Second, much of the GSM/GPRS core network can be used. This means that all core-network elements above the Serving GPRS Support Node (SGSN) and Mobile Switching Center (MSC)—the Gateway GPRS Support Node (GGSN), the Home Location Register (HLR), billing and subscriber administration systems, service platforms, and so forth—need, at most, a software upgrade to support 3G UMTS-HSPA. And while early 3G deployment used separate 2G/3G SGSNs and 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.

New features are being designed so that the same upgraded UMTS radio channel can support a mixture of terminals. In other words, a network supporting Release 5 features (for example, HSDPA) can support Release 99, Release 5, and Release 6 terminals (for example, HSUPA) operating in a Release 5 mode. This flexibility assures the maximum

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\textsuperscript{38} For example, user devices can be authenticated based on their SIM credentials. Or users can register or click through an agreement, and then not to have to redo that with future associations.

\textsuperscript{39} 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.
degree of forward- and backward-compatibility. Note also that most UMTS terminals today support GSM as will LTE terminals, thus facilitating use across large coverage areas and multiple networks.

Users largely don’t even need to know to what type of network they are connected, because their multimode GSM-HSPA or GSM-HSPA-LTE devices can seamlessly hand off between networks.

The upgrade to LTE is relatively straightforward, with new LTE infrastructure having the ability to reuse a significant amount of the UMTS-HSPA cell site and base station including using the same shelter, tower, antennas, power supply and climate control. Different vendors have different, so-called “zero-footprint” solutions, allowing operators to use empty space to enable re-use of existing sites without the need for any 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 that operators can use empty space in an old base station for LTE baseband cards, thus enabling re-use of existing sites without the need for any new floor space, as mentioned previously.

Base station equipment is available for many bands including the 1.7/2.1 GHz AWS band and the 700 MHz bands in the U.S. On the device side, multi-mode chipsets will enable devices to easily operate across UMTS and LTE networks.

There are many different scenarios that operators will use to migrate from their current networks to future technologies such as LTE. Figure 13 presents various scenarios including operators who today are using CDMA2000, UMTS, GSM and WiMAX. For example, as shown in the first bar, a CMDA2000 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, could 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, could migrate 1xRTT users to LTE including voice service.
3GPP and 3GPP2 both have specified detailed migration options to LTE. One option for GSM operators that have not yet committed to UMTS, and do not have an immediate pressing 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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Source: A 4G Americas member company.
Competing Technologies

Although GSM-HSPA 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 2012, there were 120 EV-DO Rel. 0 networks, 140 EV-DO Rev. A networks, and 10 EV-DO Rev B networks deployed worldwide.\(^{41}\)

Currently deployed network versions are based on 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 to 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\(^{42}\) and between 600 kbps and 1.4 Mbps for EV-DO Rev. A.\(^{43}\)

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.\(^{44}\) 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 addressing problems such as jitter. No operators have announced VoIP deployment plans for EV-DO.

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.


\(^{44}\) Source: 4G Americas member company.
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.

There are also a number of planned improvements for CDMA2000 1xRTT in a version referred to as 1X Advanced that will significantly increase voice capacity. CDMA operators are not only considering 1X Advanced as a means to increase voice capacity, but as a means to free up spectrum to support more data services such as deploying more EV-DO carriers or deploying LTE.

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

1. Loose coupling. This involves little or no inter-system 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.

**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—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, perceived WiMAX advantages were no longer apparent.

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 2012, this network was available in 80 cities across the U.S. and covered over 130 million people. Clearwire, however, has started deploying LTE, and indicates it will have 31 cities covered by the first half of 2013.  

The original specification, IEEE 802.16, was completed in 2001 and intended primarily for telecom backhaul applications in point-to-point, line-of-sight configurations using spectrum above 10 GHz. This original version of 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

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45 Source: Clearwire home Web page.

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) makes the most sense in licensed bands. Current WiMAX profiles emphasize TDD operation. Mobile WiMAX networks are not backward-compatible with IEEE 802.16-2004 networks.

Vendors deliver WiMAX Forum-certified equipment that conforms to subsets of IEEE 802.16e-2005 or IEEE 802.16-2009 as defined today. The IEEE itself does not define a certification process.

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 and unclear 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 to 10 MHz radio channels, there is no evidence indicating that WiMAX will have 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. 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 they don't interfere with each other.

Although IEEE 802.16e exploits significant radio innovations similar to HSPA+ and LTE, it faces challenges such as economies of scale and technology maturity. Very few operators today have access to spectrum for WiMAX that would permit them to provide widespread coverage.

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In reference to economies of scale, GSM-HSPA subscribers number in the billions. Even over the next five years, the number of WiMAX subscribers is likely to be quite low. Infonetics Research projects 132 million subscribers by 2016.\(^48\)

One specific area in which WiMAX has a technical disadvantage is cell size. In fact, 3G systems have a significant link budget advantage over mobile WiMAX because of soft-handoff diversity gain and an FDD duplexing advantage over TDD.\(^49\) Arthur D. Little reports that the radii of typical HSPA cells will be two to four times greater than typical mobile WiMAX cells for high-throughput operation.\(^50\) One vendor estimates that for the same power output, frequency, and capacity, mobile WiMAX requires 1.7 times more cell sites than HSPA.\(^51\) Given that many real world deployments of HSPA will occur at frequencies such as 850 MHz, and LTE at 700 MHz, WiMAX deployments at 2.5 GHz are at a significant disadvantage.

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 in TDD 3:1 DL:UL using 2X2 MIMO with a peak rate of 46 Mbps.

**Comparison of Wireless Technologies**

This section of the paper compares the different wireless technologies looking at throughput, latency, spectral efficiency, and market position. Finally, the paper presents a table that summarizes the competitive position of the different technologies across multiple dimensions.

**Data Throughput**

Data throughput is an important metric for quantifying network throughput performance. Unfortunately, the ways in which various organizations quote throughput statistics vary tremendously. This often results 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.” This refers to the fastest possible transmission speed over the radio link, and it 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 percent lower (or more) than this layer-2 value. Even if the radio network can deliver this speed, other aspects of the network—such as the backhaul from base station to operator-infrastructure network—can often constrain throughput rates to levels below the radio-link rate.

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\(^{49}\) With a 2:1 TDD system, the reverse link only transmits one third of the time. To obtain the same cell edge data rates, the mobile system must transmit at 4.77 dB higher transmit power.


\(^{51}\) Source: Ericsson public white paper, “HSPA, the undisputed choice for mobile broadband, May 2007.”
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 loading (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. This paper refers to this rate as the "peak user rate." Average rates, however, are lower than this peak rate and 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 U.S., also quote typical throughput rates. These rates are based on throughput tests the operators have done across their operating networks and incorporate a higher level of network loading. Although the operators do not disclose the precise methodology they use to establish these figures, the values provide a good indication of what users can typically expect.

Table 4 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 those associated with future technologies.

The projected typical rates for HSPA+ and LTE show a wide range. This is because these technologies are designed to exploit favorable radio conditions to achieve very high throughput rates. Under poor radio conditions, however, throughput rates are lower.

**Table 4: 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><strong>EDGE (type 2 MS)</strong></td>
<td>473.6 kbps</td>
<td>473.6 kbps</td>
</tr>
<tr>
<td><strong>EDGE (type 1 MS) (Practical Terminal)</strong></td>
<td>236.8 kbps</td>
<td>200 kbps peak 70 to 135 kbps typical</td>
</tr>
<tr>
<td><strong>Evolved EDGE (type 1 MS)</strong></td>
<td>1184 kbps</td>
<td>1 Mbps peak 350 to 700 kbps typical expected (Dual)</td>
</tr>
</tbody>
</table>

---

52 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).

53 Type 1 mobile, 10 slots downlink (dual carrier), DBS-12 (118.4 kbps/slot).

54 Type 1 mobile, 4 slots uplink, UBS-12 (118.4 kbps/slot).
<table>
<thead>
<tr>
<th>Downlink</th>
<th>Uplink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Network Speed</td>
<td>Peak and/or Typical User Rate</td>
</tr>
<tr>
<td><strong>Evolved EDGE (type 2 MS)</strong>&lt;sup&gt;55&lt;/sup&gt;</td>
<td>1894.4&lt;sup&gt;55&lt;/sup&gt; kbps</td>
</tr>
<tr>
<td><strong>UMTS WCDMA Release 99</strong></td>
<td>2.048 Mbps</td>
</tr>
<tr>
<td><strong>UMTS WCDMA Release 99 (Practical Terminal)</strong></td>
<td>384 kbps peak</td>
</tr>
<tr>
<td><strong>HSDPA Initial Devices (2006)</strong></td>
<td>1.8 Mbps</td>
</tr>
<tr>
<td><strong>HSDPA</strong></td>
<td>14.4 Mbps</td>
</tr>
<tr>
<td><strong>HSPA&lt;sup&gt;58&lt;/sup&gt; Initial Implementation</strong></td>
<td>7.2 Mbps</td>
</tr>
<tr>
<td><strong>HSPA</strong>&lt;sup&gt;59&lt;/sup&gt;</td>
<td>14.4 Mbps</td>
</tr>
<tr>
<td><strong>HSPA+ (DL 64 QAM, UL 16 QAM, 5/5 MHz)</strong></td>
<td>21.6 Mbps</td>
</tr>
</tbody>
</table>

---

<sup>55</sup> A type 2 Evolved EDGE MS can receive on up-to-6 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).

<sup>56</sup> Type 2 mobile, 16 slots downlink (dual carrier) at DBS-12 (118.4 kbps/slot).

<sup>57</sup> Type 2 mobile, 8 slots uplink, UBS-12 (118.4 kbps/slot).

<sup>58</sup> High Speed Packet Access (HSPA) consists of systems supporting both High Speed Downlink Packet Access (HSDPA) and High Speed Uplink Packet Access (HSUPA).

<sup>59</sup> Typical downlink and uplink throughput rates based on AT&T press release, June 4, 2008

<sup>60</sup> 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></th>
<th>Uplink</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak Network Speed</td>
<td>Peak and/or Typical User Rate</td>
<td>Peak Network Speed</td>
<td>Peak and/or Typical User Rate</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>
</tr>
<tr>
<td>HSPA+ (2X2 MIMO, DL 64 QAM, UL 16 QAM, 5/5 MHz)</td>
<td>42 Mbps</td>
<td></td>
<td>11.5 Mbps</td>
<td></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>
<td>11.5 Mbps</td>
<td>1 Mbps to 4 Mbps typical</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></td>
<td>23 Mbps</td>
<td></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></td>
<td>23 Mbps</td>
<td></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></td>
<td>69 Mbps</td>
<td></td>
</tr>
<tr>
<td>LTE (2X2 MIMO, 10/10 MHz)</td>
<td>70 Mbps</td>
<td>6.5 to 26.3 Mbps</td>
<td>35 Mbps</td>
<td>6.0 to 13.0 Mbps</td>
</tr>
<tr>
<td>LTE (4X4 MIMO, 20/20 MHz)</td>
<td>300 Mbps</td>
<td></td>
<td>71 Mbps</td>
<td></td>
</tr>
</tbody>
</table>


62 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.

63 Assumes 64 QAM. Otherwise 22 Mbps with 16 QAM.

64 Assumes 64 QAM. Otherwise 45 Mbps with 16 QAM.
<table>
<thead>
<tr>
<th>Downlink</th>
<th>Uplink</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak Network Speed</strong></td>
<td><strong>Peak and/or Typical User Rate</strong></td>
</tr>
<tr>
<td>LTE Advanced (8X8 MIMO, 20/20 MHz, DL 64 QAM, UL 64 QAM)</td>
<td>1.2 Gbps</td>
</tr>
<tr>
<td>CDMA2000 1XRTT</td>
<td>153 kbps</td>
</tr>
<tr>
<td>CDMA2000 1XRTT</td>
<td>307 kbps</td>
</tr>
<tr>
<td>CDMA2000 EV-DO Rel 0</td>
<td>2.4 Mbps</td>
</tr>
<tr>
<td>CDMA2000 EV-DO Rev A</td>
<td>3.1 Mbps</td>
</tr>
<tr>
<td>CDMA2000 EV-DO Rev B (3 radio channels 5/5 MHz)</td>
<td>14.7 Mbps proptional increase of Rev A typical rates based on number of carriers.</td>
</tr>
<tr>
<td>CDMA2000 EV-DO Rev B Theoretical (15 radio channels 20/20 MHz)</td>
<td>73.5 Mbps</td>
</tr>
<tr>
<td>WiMAX Release 1.0 (10 MHz TDD, DL/UL=3, 2x2 MIMO)</td>
<td>46 Mbps</td>
</tr>
<tr>
<td>WiMAX Release 1.5</td>
<td>TBD</td>
</tr>
<tr>
<td>IEEE 802.16m</td>
<td>&gt; 1 Gbps</td>
</tr>
</tbody>
</table>

66 Assuming use of 64 QAM.
**HSPA+ Throughput**

Performance measurements of HSPA+ networks show significant gains over HSPA. Figure 14 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 the techniques employed by HSPA+, including higher-order modulation and MIMO.

**Figure 14: HSPA+ Performance Measurements Commercial Network (5/5 MHz)**

![Cumulative Distribution Function of Throughput Values](image)

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

Figure 15 shows the benefit of dual-carrier operation (no MIMO employed), which essentially doubles throughputs over single carrier.

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68 Source: 4G Americas member company contribution.
Figure 15: Dual-Carrier HSPA+ Throughputs\textsuperscript{69}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure15}
\caption{Dual-Carrier HSPA+ Throughputs.}
\end{figure}

\textsuperscript{69} Source: 4G Americas member company contribution. 64 QAM.
**LTE Throughput**

Figure 16 shows the result of a drive test in a commercial LTE network with a 10 MHz carrier demonstrating 20 to 50 Mbps throughput rates across much of the coverage area. Throughput rates would double with 2 x 20 MHz carriers.

**Figure 16: Drive Test of Commercial European LTE Network (2 X 10MHz)**

70 Source: Ericsson.
Figure 17 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.

**Figure 17: LTE Throughput in Various Modes**

![Graph showing LTE throughput in various modes](image)

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

1. RF Conditions and User Speed. Peak rates depend on optimal conditions. Under suboptimal conditions, such as being at the edge of the cell or if the user is moving at high speed, throughput rates will be lower.

2. Network Loading. Like all wireless systems, the throughput rates will go down as more users simultaneously use the network. This is largely a linear degradation.

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3. Protocol Overhead. Peak rates are generally stated for the physical layer. Due to overhead at other layers, actual data payload throughput rates may be lower by approximately 5% to 20%. The precise amount depends on the size of packets. Larger packets (e.g., file downloads) result in a lower overhead ratio.

Figure 18 shows how throughput rates can vary by number of active users and radio conditions. The higher curves are for better radio conditions.

**Figure 18: LTEActual Throughput Rates Based on Conditions**

![Diagram showing LTE Actual Throughput Rates Based on Conditions. The graph illustrates how throughput rates can vary by number of active users and radio conditions. The higher curves are for better radio conditions.](Diagram)
**Latency**

Just 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 HSDPA networks having latency as low as 70 milliseconds (msec). HSPA+ brings latency down even further, as will 3GPP LTE. Ongoing improvements in each technology mean that all of these values will go down as vendors and operators fine-tune their systems. Figure 19 shows the latency of different 3GPP technologies.

**Figure 19: Latency of Different Technologies**

The values shown in Figure 19 reflect measurements of commercially deployed technologies. Some vendors have reported significantly lower values in networks using their equipment, such as 150 msec for EDGE, 70 msec for HSDPA, and 50 msec for HSPA+. With further refinements and the use of 2 msec Transmission Time Interval (TTI) in the HSPA uplink, 25 msec roundtrip is a realistic goal. LTE will reduce latency even further, to as low as 10 msec in the radio-access network.

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73 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.

LTE/SAE Trial Initiative (LSTI) measured LTE round-trip times ranging from 18 to 28 msec.75

**Spectral Efficiency**

To better understand the reasons for deploying the different data technologies and to better predict the evolution of capability, it is useful to examine 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 will be of paramount importance. Keeping all other things equal such as frequency band, amount of spectrum, and cell site spacing, an 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. Delivering broadband services to large numbers of users can best be achieved with high spectral-efficiency systems, especially because the only other alternatives are using more spectrum or deploying more cell sites including Het-nets.

Increased spectral efficiency, however, comes at a price. It generally implies 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. One core aspect of evolving wireless technology is managing the complexity associated with achieving higher spectral efficiency. The reason technologies such as OFDMA are attractive is that they allow higher spectral efficiency with lower overall complexity, especially with a larger bandwidth; thus their use in technologies such as LTE and WiMAX.

The roadmap for the EDGE/HSPA/LTE family of technologies provides a wide portfolio of options to increase spectral efficiency. The exact timing for deploying these options is difficult to predict, because much will depend on the growth of the wireless data market and what types of applications become popular.

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 20, 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 [SNR] of the communications link.) Figure 20 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. Note that differences do exist in the design of the MAC layer (layer 2), and this may result in lower than expected performance in some cases as described previously.

The curves in Figure 20 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 msec. Frames are well within the coherence time of the channel, because they are typically 20 msec 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 Shannon bound only applies to a single link; techniques such as MIMO using multiple links would have a higher bound. It does indicate, however, that link-layer performance is reaching theoretical limits. As such, the focus of future technology enhancements should be on improving system performance aspects that maximize the experienced

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76 Source: A 4G Americas member company.
Signal to Noise Ratios (SNRs) in the system rather than on investigating new air interfaces that attempt to improve the link-layer performance.

Examples of technologies that improve SNR in the system are those that minimize interference through intelligent antennas or interference coordination/cancellation between sectors and cells. Note that MIMO techniques using spatial multiplexing to potentially 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 21 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 than those shown below. 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 21 are not all the 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 0.3 bits per second (bps)/Hertz (Hz)/sector. 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) will effectively double HSDPA spectral efficiency. The addition of dual-carrier operation and 64 QAM will increase spectral efficiency by about 15 percent, and MIMO can increase spectral efficiency by another 15 percent, 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, operators can deploy either MIMO or dual-carrier operation. With Release 9, dual-carrier operation can be combined with MIMO.

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77 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.

78 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.
With respect to actual deployment, some enhancements, such as 64 QAM, will be simpler for some operators 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 will be achievable in Release 10 using 8X2 MIMO in combination with SU/MU MIMO switching (which provides a 60% gain over 2X2 MIMO) or in Release 11 using 4X2 MIMO and CoMP (which provides a 32% gain over 4X2 MIMO).

LTE spectral-efficiency values are slightly lower than last year’s version of this paper, because of more refined assumptions that better match realistic available devices.

LTE is even more spectrally efficient with wider channels, such as 10 and 20 MHz, although most of the gain is realized at 10 MHz. LTE TDD has spectral efficiency that is within 1 or 2% of LTE FDD.79

Similar gains to those for HSPA and LTE are available for CDMA2000. CDMA2000 spectral efficiency values assume seven carriers deployed in 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, like MRxD and MIMO, are applied. WiMAX Release 1.0 includes 2X2 MIMO. Enhancements to WiMAX will come with Release 1.5, as well as in 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. Many of the innovations planned for LTE and LTE Advanced could be available in IEEE 802.16m. The main reason that HSPA+ with MIMO is shown as more spectrally efficient than WiMAX Release 1.0 with MIMO is because HSPA MIMO supports closed-loop operation with precode weighting and multi-codeword MIMO, which enables the use of SIC receivers. Other reasons are that HSPA supports incremental-redundancy HARQ, while WiMAX supports only Chase combining HARQ, and that WiMAX has larger control overhead in the downlink than HSPA, because the uplink in WiMAX is fully scheduled. OFDMA technology requires scheduling to avoid two mobile devices transmitting on the same tones simultaneously. An uplink MAP zone in the downlink channel does this scheduling.

LTE has higher spectral efficiency than WiMAX Release 1.0 for a number of reasons 80:

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79 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.
- Closed-loop operation with precoded weighting.
- Multi-codeword MIMO, which enables the use of SIC receivers.
- Lower Channel Quality Indicator delay through use of 1 msec frames instead of 5 msec frames.
- Greater control channel efficiency.
- Incremental redundancy in error correction.
- Finer granularity of modulation and coding schemes.

WiMAX Release 1.5 addresses some of these items, thus will have increased spectral efficiency. Expected features include reduced MAC overhead, adaptive modulation and coding, and other physical-layer enhancements.

One available improvement for LTE spectral efficiency not shown in the figure is successive interference cancellation. This will result in a gain of 5% in a low-mobility environment and a gain of 10 to 15% in environments such as picocells in which there is cell isolation.

Table 5 summarizes the most important features of LTE and WiMAX technology that impact spectral efficiency.

**Table 5: LTE and WiMAX Features**

<table>
<thead>
<tr>
<th>Feature</th>
<th>LTE</th>
<th>WiMAX Release 1.0</th>
<th>WiMAX Release 1.5</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple Access</td>
<td>OFDM in downlink, Discrete Fourier Transform (DFT)-spread OFDM in uplink</td>
<td>OFDM in downlink and uplink</td>
<td>OFDM in downlink and uplink</td>
<td>DFT-spread OFDM reduces the peak-to-average power ratio and reduces terminal complexity, requires one-tap equalizer in base station receiver.</td>
</tr>
<tr>
<td>Uplink Power Control</td>
<td>Fractional path-loss compensation</td>
<td>Full path-loss compensation</td>
<td>Full path-loss compensation</td>
<td>Fractional path-loss compensation enables flexible tradeoff between average and cell-edge data rates.</td>
</tr>
<tr>
<td>Scheduling</td>
<td>Channel dependent in time and frequency domains</td>
<td>Channel dependent in time domain</td>
<td>Channel dependent in time and frequency domains</td>
<td>Access to the frequency domain yields larger scheduling gains.</td>
</tr>
<tr>
<td>MIMO Scheme</td>
<td>Multi-codeword (horizontal), closed loop with pre-coding</td>
<td>Single codeword (vertical)</td>
<td>Single codeword (vertical), with rank-adaptive MIMO (TDD) and with closed-loop pre-coding (FDD)</td>
<td>Horizontal encoding enables per-stream link adaptation and successive interference cancellation receivers.</td>
</tr>
<tr>
<td>Modulation and Coding Scheme Grani...</td>
<td>Fine granularity (1-2 dB apart)</td>
<td>Coarse granularity (2-3 dB apart)</td>
<td>Coarse granularity (2-3 dB apart)</td>
<td>Finer granularity enables better link adaptation precision.</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Feature</th>
<th>LTE</th>
<th>WiMAX Release 1.0</th>
<th>WiMAX Release 1.5</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid Automatic Repeat Request (ARQ)</td>
<td>Incremental redundancy</td>
<td>Chase combining</td>
<td>Chase combining</td>
<td>Incremental redundancy is more efficient (lower SNR required for given error rate).</td>
</tr>
<tr>
<td>Frame Duration</td>
<td>1 msec subframes</td>
<td>5 msec subframes</td>
<td>5 msec subframes</td>
<td>Shorter subframes yield lower user plane delay and reduced channel quality feedback delays.</td>
</tr>
<tr>
<td>Overhead / Control Channel Efficiency</td>
<td>Relatively low overhead</td>
<td>Relatively high overhead</td>
<td>Relatively high overhead apart from reduction in pilots</td>
<td>Lower overhead improves performance.</td>
</tr>
</tbody>
</table>

Figure 22 compares the uplink spectral efficiency of the different systems.
The implementation of HSUPA in HSPA significantly increases uplink capacity, as does Rev. A and Rev. B of 1xEV-DO, compared to Rel. 0. OFDM-based systems can exhibit improved uplink capacity relative to CDMA technologies, but this improvement depends on factors such as the scheduling efficiency and 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. 1X4 receive diversity 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 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

81 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.
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 23 compares voice spectral efficiency.

**Figure 23: Comparison of Voice Spectral Efficiency**

![Figure 23: Comparison of Voice Spectral Efficiency](image)

Figure 23 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 (e.g., static, indoors) channel conditions. UMTS has dynamic adaptation between vocoder rates, enabling enhanced voice quality compared to 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 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 exhibiting greater than 1% frame-error rate). Depending on the specific enhancements implemented, voice capacity could double over existing circuit-switched systems. It should be noted, however, that the gains are not related specifically to the use of VoIP; rather, gains relate to advances in radio techniques applied to the data channels. Many of

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82 Source: 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.
these same advances may also be applied to current circuit-switched modes. Other benefits of VoIP, however, are driving the migration to packet voice. Among these benefits is a consolidated IP core network for operators and sophisticated multimedia applications for users.

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 MHz with EVRC-A and reaches voice capacity of 120 Erlangs in 5 MHz with the use of Quasi-Linear Interference Cancellation (QLIC) and EVRC-B at 6 kbps.

There are a number of planned improvements for CDMA2000 in a project called 1X Advanced that will result in significantly increased 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. With respect to codecs, in VoIP systems such as LTE and WiMAX, a variety of codecs can be used. The figures show performance assuming specific codecs at representative bit rates. For codecs such as EVRC (Enhanced Variable Rate Codec), the bit rate shown is an average value.

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

Cost, Volume, and Market Comparison

So far, this paper has compared wireless technologies on the basis of technical capability and demonstrated that many of the different options have similar technical attributes. This is for the simple reason that they employ many of the same approaches.

There is a point of comparison, however, in which the differences between the technologies diverge tremendously; namely, the difference in volume involved including subscribers and the amount of infrastructure required. This difference should translate to dramatically reduced costs for the highest-volume solutions, specifically GSM-HSPA-LTE. Based on projections, 3GPP subscribers will exceed 7.8 billion by the year 2017, dwarfing other technologies. See Figure 24 for details.

In the chart above, HSPA subscriptions reach 3.4 billion by year-end 2016 and 4 billion by year-end 2017. The growth rate of LTE increases significantly over the five year span with 654 million subscribers at year-end 2016 rising to 1 billion LTE subscribers by year-end 2017.

**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 and other mobile platforms, such as tablets, increase their penetration levels, they will continue driving explosive growth in data usage, application availability, 3G/4G deployment, and revenue. In one of the most significant industry developments of 2012, LTE service has become broadly available in the U.S. reaching a large percentage of the population. Coupled with advances in HSPA, mobile broadband is now being used by huge segments of the population.

The growing success of mobile broadband, however, mandates augmentation of capacity to which the industry has responded by using more efficient technologies, deploying more cell sites, planning for sophisticated 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 soon. In the U.S., operators are
starting to face increased urgency to augment their capacity through new spectrum. While there have been some encouraging developments, industry is concerned that substantive additions to spectrum may take many years.

Through constant innovation, the 3GPP family of technologies has proven itself as the predominant wireless network solution and offers operators and subscribers a true mobile-broadband advantage. With UMTS-HSPA, the technologies’ advantages provide for broadband services that deliver increased data revenue. There will also be ongoing enhancements to HSPA+, such as small-cell support, which will make it a viable technology for many years to come. With LTE now the most widely chosen technology platform for the forthcoming decade, the advantages offer 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 4G 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 technology. With continued evolution, peak data rates will continue to increase, spectral efficiency will improve, and latency will decrease. The result is support for more users with more supported applications.

Because of practical benefits and deployment momentum, the migration path from EDGE to 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. Currently more than 476 commercial HSPA networks are already 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 innovations such as Het-nets, more advanced carrier aggregation, CoMP, and relays.

Not only expected continual improvements in radio technology, but improvements to the core network through flatter architectures—particularly EPC—will reduce latency, speed applications, simplify deployment, enable all services in the IP domain, and allow a common core network to support LTE, legacy GSM-HSPA systems, and also non-3GPP networks such as Wi-Fi.

With the continued growth in mobile computing, powerful mobile platforms, an increasing amount of mobile content, and hundreds of thousands of mobile applications, mobile broadband has become a huge industry. EDGE/HSPA/LTE provides one of the most robust portfolios of mobile-broadband technologies, and it is an optimum framework for realizing the potential of this market.
Appendix: Technology Details

The EDGE/HSPA/LTE family of data technologies provides ever-increasing capabilities that support ever more demanding applications. It is important to understand the needs enterprises and consumers have for these services. The obvious needs are 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, which examines each technology individually, details how the progression from EDGE to HSPA to LTE is one of increased throughput, enhanced security, reduced latency, improved QoS, and increased spectral efficiency.

It is also 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 2 Mbps
- High definition video: 4 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 even 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 70 msec, and LTE lower than this. The combination of low latency and high throughput translates to a broadband experience for users in which applications are extremely responsive.

In this section, we provide a technical explanation of spectrum bands, EDGE, HSPA, LTE, IMT-Advanced and LTE-Advanced, IMS, Het-nets and SON, EPC, Evolved EDGE, and TV white spaces.

Spectrum Bands

3GPP technologies operate in a wide range of radio bands. As new spectrum becomes available, 3GPP updates its specifications for these bands.

It should be noted that although the support of a new frequency band may be introduced in a particular release, the 3GPP standard also specifies ways to implement devices and infrastructure operating on any frequency band, according to release anterior 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 6 shows the UMTS FDD bands.
Universal Mobile Telecommunications System (UMTS) Time Division Duplex (TDD) bands are the same as the LTE TDD bands.

Table 7 shows the LTE Frequency Division Duplex (FDD) and TDD bands.

**Table 6: UMTS FDD Bands**

<table>
<thead>
<tr>
<th>Operating Band</th>
<th>UL Frequencies</th>
<th>DL frequencies</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 - 849 MHz</td>
<td>869 - 894 MHz</td>
</tr>
<tr>
<td>VI</td>
<td>830 - 840 MHz</td>
<td>875 - 885 MHz</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>


**Table 7: 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></td>
<td>$F_{UL\text{ low}}$ - $F_{UL\text{ high}}$</td>
<td>$F_{DL\text{ low}}$ - $F_{DL\text{ high}}$</td>
<td></td>
</tr>
</tbody>
</table>

$^{84}$ Source: 3GPP Technical Specification 25.104, V11.1.0.

$^{85}$ Source: 3GPP Technical Specification 36.104, V11.0.0.


<table>
<thead>
<tr>
<th>1</th>
<th>1920 MHz – 1980 MHz</th>
<th>2110 MHz – 2170 MHz</th>
<th>FDD</th>
</tr>
</thead>
<tbody>
<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>1452.9 MHz – 1474.9 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>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.

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**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 for users, 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 that supports multiple radio-access networks including GSM, EDGE, WCDMA, HSPA, and evolutions of these technologies. This is called the UMTS multi-radio network, and it gives operators...
maximum flexibility in providing different services across their coverage areas (see Figure 25).

**Figure 25: UMTS Multi-radio Network**

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 over users 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-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 an 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.

---

86 Spread spectrum systems can either be direct sequence or frequency hopping.
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. This capability is essential for expanding the scope of supported applications, particularly multimedia applications including packetized video telephony and VoIP.

**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. Operators with Release 99 networks are upgrading them to HSPA capability. In advance of Release 6, the uplink in HSDPA (Release 5) networks uses the Release 99 approach.

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. This satisfies many communications-oriented applications.

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.

WCDMA has lower network latency than EDGE, with about 100 to 200 msec measured in actual networks. Although UMTS Release 99 offers attractive data services, these services become much more efficient and more powerful with HSPA.

**HSDPA and HSUPA**

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,

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87 Initial UMTS networks had peak uplink rates of 64 kbps or 128 kbps, but many deployments emphasize 384 kbps.
HSPA was deployed throughout the Americas. This section covers technical aspects of HSDPA, while the next section covers HSUPA.

**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 also has significantly lower latency, measured today on some networks as low as 70 msec on the data channel.

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 powerful new techniques such as fast scheduling. The higher spectral efficiency and higher data rates not only enable new classes of applications, but also support a greater number of users accessing the network.

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. The result is that resources are assigned in both time (the TTI interval) and code domains (the HS-PDSCH channels). Figure 26 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 27 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 significantly higher spectral efficiency. The system also makes sure that each user receives a minimum level of throughput. This approach is sometimes called proportional fair scheduling.
Higher Order Modulation: HSDPA uses both the modulation used in WCDMA—namely QPSK—and, under good radio conditions, an advanced modulation scheme—16 QAM. The benefit of 16 QAM is that 4 bits of data are transmitted in each radio symbol as opposed to 2 bits with QPSK. Data throughput is increased with 16 QAM, while QPSK is available under adverse conditions. HSPA Evolution will add 64 QAM modulation to further increase throughput rates. Note that 64 QAM was available in Release 7, and the combination of MIMO and 64 QAM became available this year 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. The process of selecting and quickly updating the optimum modulation and coding rate is referred to as fast link adaptation. This is done in close coordination with fast scheduling, as described above.

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, a greater range of applications that function well, and increased productivity.

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 are close to
4 Mbps for 7.2 Mbps devices, assuming other portions of the network (for example, backhaul) can support the high throughput rates.

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.

HSPA technology is not standing still. Advanced radio technologies are becoming available. Among these technologies are mobile-receive diversity and equalization (for example, Minimum Mean Square Error [MMSE]), which improve the quality of the received radio signal prior to demodulation and decoding. This improvement enables not only higher peak HSDPA throughput speeds but makes these speeds available over a greater percentage of the coverage area.

**HSPA**

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 is standardized in Release 6. It results in an approximately 85 percent increase in overall cell throughput on the uplink and more than a 50 percent 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.

Such an improved uplink benefits users in a number of ways. For instance, some user applications transmit large amounts of data from the mobile station such as sending video clips or large presentation files. For future applications like VoIP, improvements will balance the capacity of the uplink with the capacity of the downlink.

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, which can benefit many applications as much as improved throughput. HSUPA can operate with or without HSDPA in the downlink, although it is likely that most networks will 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. Future devices will ultimately approach speeds close to 5 Mbps, although only with the addition of interference cancellation methods that boost SNR.

Beyond throughput enhancements, HSUPA also significantly reduces latency. In optimized networks, latency will fall below 50 msec, relative to current HSDPA networks at 70 msec. And with a later introduction of a 2 msec TTI, latency will be as low as 30 msec.

**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 11. These include advanced receivers, multi-carrier operation, MIMO, Continuous Packet Connectivity, Higher-Order Modulation and One Tunnel Architecture.

**Advanced Receivers**

One important area is advanced receivers for which 3GPP has specified a number of designs. These designs include 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 a 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 results in an almost doubling of downlink capacity when employed in conjunction with techniques such as channel equalization. Receive diversity is effective even for small devices such as 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, are 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 performing 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 28—actually exploits multipath, relying on signals to travel across different uncorrelated communications paths. This results in multiple data paths effectively operating somewhat in parallel and, through appropriate decoding, in a multiplicative gain in throughput.

**Figure 28: MIMO Using Multiple Paths to Boost Throughput and Capacity**

Tests of MIMO have proven very promising in WLANs operating in relative isolation in which interference is not a dominant factor. Spatial multiplexing MIMO should also benefit HSPA “hotspots” serving local areas such as airports, campuses, and malls, where the technology will increase capacity and peak data rates. 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 percent over mobile-receive diversity. Relative to a 1x1 antenna system, however, 2X2 MIMO can deliver cell throughput gains of about 80 percent. 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 is considering uplink dual-antenna beamforming and 2X2 MIMO for HSPA+ in Release 11.

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88 For further details on these techniques, refer to the 4G Americas white paper “Mobile Broadband: The Global Evolution of UMTS-HSPA. 3GPP Release 7 and Beyond.”
**Continuous Packet Connectivity**

In Release 7, Continuous Packet Connectivity (CPC) enhancements reduce the uplink interference created by the dedicated physical control channels of packet data users when those channels have no user data to transmit. This, in turn, 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, which consumes the most power, because the radio can turn off between VoIP packets. See Figure 29.

*Figure 29: Continuous Packet Connectivity*

![Figure 29: Continuous Packet Connectivity](image)

**Higher Order Modulation**

Another way of increasing performance is to use higher order modulation. HSPA uses 16 QAM on the downlink and QPSK on the uplink. But radio links can achieve higher throughputs—adding 64 QAM on the downlink and 16 QAM on the uplink—precisely what is added in HSPA+. Higher order modulation requires a better SNR, which is enabled through other enhancements such as receive diversity and equalization.

**HSPA+**

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 11 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.

Depending on the features implemented, HSPA+ can exceed the capabilities of IEEE 802.16e-2005 (mobile WiMAX) in the same amount of spectrum. This is mainly because MIMO in HSPA supports closed-loop operation with precoding weighting, as well as multicode-word MIMO, and it enables the use of SIC receivers. It is also partly because HSPA supports Incremental Redundancy (IR) and has lower overhead than WiMAX.

Table 8 summarizes the capabilities of HSPA and HSPA+ based on various methods.

**Table 8: HSPA Throughput Evolution**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Downlink (Mbps) Peak Data Rate</th>
<th>Uplink (Mbps) Peak Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSPA as defined in Release 6</td>
<td>14.4</td>
<td>5.76</td>
</tr>
<tr>
<td>Release 7 HSPA+ DL 64 QAM, UL 16 QAM, 5/5 MHz</td>
<td>21.1</td>
<td>11.5</td>
</tr>
<tr>
<td>Release 7 HSPA+ 2X2 MIMO, DL 16 QAM, UL 16 QAM, 5/5 MHz</td>
<td>28.0</td>
<td>11.5</td>
</tr>
<tr>
<td>Release 8 HSPA+ 2X2 MIMO DL 64 QAM, UL 16 QAM, 5/5 MHz</td>
<td>42.2</td>
<td>11.5</td>
</tr>
<tr>
<td>Release 8 HSPA+ (no MIMO) Dual Carrier, 10/5 MHz</td>
<td>42.2</td>
<td>11.5</td>
</tr>
<tr>
<td>Release 9 HSPA+ 2X2 MIMO, Dual Carrier DL and UL, 10/10 MHz</td>
<td>84.0</td>
<td>23.0</td>
</tr>
<tr>
<td>Release 10 HSPA+ 2X2 MIMO, Quad Carrier DL, Dual Carrier UL, 20/10 MHz</td>
<td>168.0</td>
<td>23.0</td>
</tr>
<tr>
<td>Release 11 HSPA+ 2X2 MIMO DL and UL, 8 Carrier 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 below 50 msec and improved packet call setup time of below 500 msec.

The prior discussion emphasizes throughput speeds, but HSPA+ will also more than double HSPA capacity as well as reduce latency below 50 msec. Sleep-to-data-transfer times of less than 500 msec will improve users’ “always-connected” experience, and reduced power consumption with VoIP will result in talk times that are more than 50 percent higher.

From a deployment point of view, operators will be able to 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.

**Multi-Carrier HSPA**

3GPP defined a capability in Release 8 for dual-carrier HSPA operation. This approach coordinates the operation of HSPA on two adjacent 5 MHz carriers so that data transmissions can achieve higher throughput rates, as shown in Figure 30. The work item assumes two adjacent carriers, downlink operation and no MIMO. In this configuration, it is possible to achieve a doubling of the 21 Mbps maximum rate available on each channel to 42 Mbps.

**Figure 30: Dual-Carrier Operation with One Uplink Carrier**

There are a number of benefits to this approach:

- 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.

By scheduling packets across two carriers, there is better resource utilization, resulting in what is called trunking gain. Multi-user diversity also improves because there are more users to select from.

Release 9 allows for 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)

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 a dual-carrier operation.

Figure 31 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 31: Dual-Carrier Performance**  

![Cumulative Distribution Function](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.

Multiflow transmission with HSPA+ also enhances Het-net operation in which picocell coverage can be expanded within a macrocell coverage area, as shown in Figure 32.

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90 Source: 4G Americas member company contribution.
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-data traffic 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, there was broad industry consensus to standardize the fast dormancy feature in 3GPP Release 8 by providing 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. The network on receipt of this message 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.

Thereby, the feature mitigates the impact on network signaling traffic whilst reducing the latency for any follow-on packet-switched data transmission compared to when the feature is not supported and significantly improves UE battery efficiency.

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Field test results have shown fast dormancy improves standby time for a UMTS device by as much as 30% to 40%. Figure 33 provides an example of the battery life improvement due to fast dormancy for this scenario. 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.

Figure 33: Battery Life Improvement with Fast Dormancy

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92 Source: 4G Americas member contribution.
One-Tunnel Architecture

Another way HSPA performance can be improved is through a flatter architecture. In Release 7, there is the option of a one-tunnel architecture by which the network establishes a direct transfer path for user data between RNC and GGSN, while the SGSN still performs all control functions. This brings several benefits such as eliminating hardware in the SGSN and simplified engineering of the network.

There is also an integrated RNC/NodeB option in which RNC functions are integrated in the Node B. This is particularly beneficial in femtocell deployments, as an RNC would otherwise need to support thousands of femtocells. The integrated RNC/NodeB for HSPA+ has been agreed-upon as an optional architecture alternative for packet-switched-based services.

These new architectures, as shown in Figure 34, are similar to the EPC architecture, especially on the packet-switched core network side in which they provide synergies with the introduction of LTE.

Figure 34: HSPA One-Tunnel Architecture

HSPA, HSPA+, and other advanced functions provide a compelling advantage for UMTS over competing technologies: The ability today to support voice and data services on the same carrier and across the whole available radio spectrum; to offer these services simultaneously to users; to deliver data at ever-increasing broadband rates; and to do so in a spectrally efficient manner.

HS-FACH AND HS-RACH

In Release 7, a new capability called High-Speed Access Forward Access Channel (HS-FACH), illustrated in Figure 35, reduces setup time to practically zero and provides a more efficient way of carrying application signaling for always-on applications. The network accomplishes this by using the same HSDPA power/code resources for access requests (CELL_FACH state) as for dedicated packet transfer (CELL_DCH). This allows 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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In Release 8, the concept 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 referred to as the enhanced CELL_FACH operation.

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, 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.

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**HS-RACH and FE-FACH**

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.\footnote{Source: Ericsson, “3G Evolution: HSPA and LTE for Mobile Broadband,” E. Dahlman, et al, Elsevier, 2008.}

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).

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

Figure 36 summarizes the key capabilities and benefits of the features being deployed in HSPA+.

\textbf{Figure 36: Summary of HSPA Functions and Benefits}\footnote{Source: 4G Americas member contribution.}

\begin{itemize}
  \item \textbf{Uplink DTX + downlink DRX} \rightarrow \textbf{Lower UE power consumption}
  \item \textbf{CS voice over HSPA} \rightarrow \textbf{Higher voice capacity}
  \item \textbf{Downlink 64QAM, MIMO, and multi carrier} \rightarrow \textbf{Higher downlink peak data rates and higher data capacity}
  \item \textbf{Uplink 16QAM, MIMO, and dual carrier} \rightarrow \textbf{Higher uplink peak data rates and higher data capacity}
  \item \textbf{L2 optimization (Flexible RLC)} \rightarrow \textbf{Higher L2 throughput and less processing requirements}
  \item \textbf{High speed FACH, High speed RACH, FE-FACH} \rightarrow \textbf{Lower latency = better response times}
  \item \textbf{Flat architecture optimization} \rightarrow \textbf{More efficient common channels = savings in channel elements}
  \item \textbf{Fewer network elements}
\end{itemize}
**HSPA Voice**

Voice support with WCDMA-dedicated channels in UMTS networks is spectrally very efficient. Moreover, current networks support simultaneous voice and data operation. There are, however, reasons to consider alternate approaches including reducing power consumption and being able to support even more users. One approach is called circuit-switched voice over HSPA. The other is Voice over Internet Protocol (VoIP).

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

HSPA channels employ many optimizations to obtain a high degree of data throughput, which is why it makes sense to use 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. There is an elegant alternative: To packetize the circuit-switched voice traffic which is already in digital form, use the HSPA channels to carry the CS voice, but then to connect the CS voice traffic back into the existing CS infrastructure (MSCs, etc.) immediately beyond the radio access network. This requires relatively straightforward changes in just the radio network and in devices. Figure 37 shows the infrastructure changes required at the Node B and within the RNC.

**Figure 37: Implementation of HSPA CS Voice**

With this approach, 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.

The many benefits of this approach, listed below, make it highly likely that operators will adopt it:

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- 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**

Once HSDPA and HSUPA are available, operators will have another option of moving voice traffic over to these high-speed data channels, which is using VoIP. This will eventually increase voice capacity, allow operators to consolidate their infrastructure on an IP platform, and enable innovative new applications that combine voice with data functions in the packet domain. VoIP is possible in Release 6, but it is enhancements in Release 7 that make it highly efficient and thus attractive to network operators. VoIP will be implemented in conjunction with IMS, discussed later in this paper.

One attractive aspect of deploying VoIP with HSPA is that 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 38 shows a system’s voice capacity with the joint operation of circuit-switched and IP-based voice services.

**Figure 38: Ability for UMTS to Support Circuit and Packet Voice Users**

![Graph showing voice capacity with VoIP](image)

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98 Source: 4G Americas member contribution.
VoIP capacity gains are quantified in detail in the main part of this paper. They 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, with HSPA+, it may not be used immediately for primary voice services. This is because 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. As a result, packet voice will likely be used initially as part of other services (for example, those based on IMS), and only over time will 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 has completed the specification for Long Term Evolution as part of Release 8. LTE allows operators the potential to achieve even higher peak throughputs in higher 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. This is where 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 highly flexible in channelization, and LTE will operate 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 MHz bandwidth.
- Uplink peak data rates up to 71 Mbps with 20 MHz bandwidth.\(^99\)
- Operation in both TDD and FDD modes.
- Scalable bandwidth up to 20 MHz covering 1.4, 3, 5, 10, 15, and 20 MHz in the study phase.
- Increased spectral efficiency over Release 6 HSPA by a factor of two to four.
- Reduced latency, to 10 msec round-trip times between user equipment and the base station, and to less than 100 msec transition times from inactive to active.

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\(^99\) 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 9 shows LTE peak data rates based on different downlink and uplink designs.

**Table 9: 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 MHz of spectrum, LTE VoIP capacity will reach almost 500 users.100

### 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 channel to 1,200 in a 20 MHz channel.

The composite signal is 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. 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) will be more impacted in high-speed conditions than LTE.

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100 Source: 3GPP Multi-member analysis.
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 40 shows how the system can assign these resource blocks to different users over both time and frequency.

**Figure 40: LTE OFDMA Downlink Resource Assignment in Time and Frequency**

By having control over which subcarriers are assigned in which sectors, LTE can easily control frequency reuse. By 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 achieves 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 41 can use those resource blocks that are not faded, something that is 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.
LTE Smart Antennas

Wireless networks can achieve significant gains by employing multiple antennas, either at the base station, the mobile device, or both. Multiple antennas can be employed 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, effectively sending data in parallel through these paths, thus increasing both throughput and spectral efficiency.

LTE uses all of these approaches.

LTE in Release 8 provides for multiple types of antenna transmission modes, through transmission mode 7, as shown in Table 10.

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101 4G Americas member contribution.
### Table 10: 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 conditions produces huge efficiency and performance gains, and is the reason that yet more advanced antenna modes are being developed for subsequent releases of LTE.

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.

There are some fundamental variables that 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 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 42 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.

**Figure 42: Decision Tree for Different Antenna Schemes**

---

The simplest mode is AC2, which is referred to as Transmit Diversity (TD) or sometimes Space Frequency Block Code (SFBC) or even Open Loop Transmit Diversity. TD can be supported under all conditions, meaning it can operate under low SINR, high mobility, and low channel rank (rank = 1). This rank means that the channel is not sufficiently scattered or de-correlated 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), which is also referred to as large-delay Cyclic Delay Diversity (CDD). This mode supports two spatial streams or two codewords. This mode, also referred to as 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, feedback is provided by the device in terms of Precoding Matrix Indication (PMI) bits. These tell the base station what precoding matrix to use in the transmitter so as 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 it can be used by the base station.

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 is specified for 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. 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. It 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 being implemented (on either the downlink or uplink or both) using antennas at 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.

**Channel Bandwidths**

LTE is designed to operate in channel bandwidths from 1.4 MHz to 20 MHz. The greatest efficiency, however, occurs with higher bandwidth. A 4G Americas member analysis predicts 40% lower spectral efficiency with 1.4 MHz radio channels and 13% lower efficiency with 3 MHz channels. The system, however, achieves nearly all of its efficiency with 5 MHz channels or wider.

**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. This enables 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 support in LTE will range from no voice, to voice implemented in a circuit-switched fallback (CSFB) mode to 2G or 3G, to voice implemented over LTE using IMS.

As a pure data service, especially for laptops, voice may not be needed. But once available on handheld devices, voice will become important. The easiest implementation will be CSFB. In CSFB, the LTE network carries circuit-switched signaling over LTE interfaces. This allows 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. Terminals and networks implementing these capabilities could become available in the 2012 timeframe. GSMA has adopted the One Voice initiative in what it calls Voice over LTE (VoLTE) and is working to enable interconnection and international roaming between LTE networks through the specification IR88. With VoLTE expected in 2013, LTE voice roaming could occur in 2014 or 2015.

LTE VoIP will leverage 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.

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104 4G Americas member company analysis 2009.
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. In other words, the operator can dynamically trade off voice quality with 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 43 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.

**Figure 43: Evolution of Voice in an LTE Network**

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Source: 4G Americas member contribution.
There was one other voice approach called Voice over LTE via Generic Access (VoLGA). This method provides for circuit-switched operation through an LTE IP tunnel. 3GPP 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 where 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 44 demonstrates the synchronization between TC-SCDMA and LTE-TDD in adjacent channels.

**Figure 44: TDD Frame Co-Existence Between TD-SCDMA and LTE TDD**

For LTE FDD and TDD to coexist, large guardbands will be needed to prevent interference. The organization Next Generation Mobile Networks has a project for LTE TDD and FDD convergence.

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106 Source: A 4G Americas member company.

**SMS**

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 employ IMS infrastructure.108

**LTE-Advanced**

LTE-Advanced is a term used for the version of LTE that addresses IMT-Advanced requirements, as specified in Release 10. 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.

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 (Het-net) support including enhanced Inter-Cell Interference Coordination (eICIC).
- Relays.

The following sections describe these various features in greater detail.

**IMT-Advanced**

As mentioned earlier in this paper, 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 MHz.
- Encouragement to support wider bandwidths (e.g., 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 11 shows the requirements for cell-spectral efficiency.

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Table 11: 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 12 shows the requirements for voice capacity.

Table 12: IMT-Advanced Requirements for Voice Capacity

<table>
<thead>
<tr>
<th>Test Environment</th>
<th>Minimum VoIP Capacity (Active Users/Sector/MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor</td>
<td>50</td>
</tr>
<tr>
<td>Microcellular</td>
<td>40</td>
</tr>
<tr>
<td>Base Coverage Urban</td>
<td>40</td>
</tr>
<tr>
<td>High Speed</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 13 summarizes LTE-Advanced performance relative to IMT-Advanced requirements.

Table 13: IMT-Advanced Requirements and Anticipated 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></td>
<td>1 Gbps</td>
</tr>
<tr>
<td>Peak Data Rate Uplink</td>
<td></td>
<td>500 Mbps</td>
</tr>
<tr>
<td>Spectrum Allocation</td>
<td>Up to 40 MHz</td>
<td>Up to 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</td>
<td>15 bps/Hz</td>
<td>30 bps/Hz</td>
</tr>
</tbody>
</table>

109 Test environments are described in ITU Report ITU-R M.2135.
110 Ibid.
111 Spectral efficiency values based on four antennas at the base station and two antennas at the terminal.
<table>
<thead>
<tr>
<th></th>
<th>Peak Spectral Efficiency UL</th>
<th>Average Spectral Efficiency DL</th>
<th>Average Spectral Efficiency UL</th>
<th>Cell-Edge Spectral Efficiency DL</th>
<th>Cell-Edge Spectral Efficiency UL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.75 bps/Hz</td>
<td>2.2 bps/Hz</td>
<td>1.4 bps/Hz</td>
<td>0.06 bps/Hz</td>
<td>0.03 bps/Hz</td>
</tr>
<tr>
<td></td>
<td>15 bps/Hz</td>
<td>2.6 bps/Hz</td>
<td>2.0 bps/Hz</td>
<td>0.09 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 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 fact that currently there is greater demand on downlink traffic than uplink traffic.

Signaling to support carrier aggregation is part of Release 10, while Release 11 specifies the various band combinations.

Specific types of aggregation include:

- Intra-band on adjacent channels.
- Intra-band on non-adjacent channels.
- Inter-band (e.g., 700 MHz, 1.9 GHz).
- Inter-technology (e.g., 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.\(^\text{112}\) See Figure 45.

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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 (e.g., 10%), it results in a more uniform user experience across the cell coverage area.

Figure 46 shows an example of intra-band carrier aggregation using adjacent channels with up to 100 MHz of bandwidth supported in Release 10 core specifications. Radio-access network specifications, however, limit the number of carriers to two in Release 10 and Release 11.

**Figure 46: Release 10 LTE-Advanced Carrier Aggregation**

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113 Source: 4G Americas member contribution.

Figure 47 shows the carrier aggregation operating at different protocol layers.

**Figure 47: Carrier Aggregation at Different Protocol Layers**

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+2600 MHz)
- Band 4 and Band 13 (Verizon – AWS + Upper 700 MHz)
- Band 4 and Band 7 (Rogers, Bell – AWS + 2600 MHz)
- Band 4 and Band 17 (AT&T – AWS + Lower 700 MHz)
- Band 2 and Band 17 (AT&T – PCS + Lower 700 MHz)
- Band 4 and Band 5 (AT&T – AWS + 850 MHz)

• Band 4 and Band 12 (Cox Communications – AWS + Lower 700 MHz)
• Band 5 and Band 12 (US cellular – 850 MHz + Lower 700 MHz)
• Band 5 and Band 17 (AT&T – 850 MHz + Lower 700 MHz)
• Band 7 and Band 20 (Orange – 2600 MHz + 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 + 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 through trunking efficiency, which refers to packets being able to traverse through either of the channels, thus solving the problem of one being congested while the other is idle.

Figure 48 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 48: Gains from Carrier Aggregation**

![Figure 48](image)

**LTE-Advanced Antenna Technologies**

Beyond wider bandwidths, Release 10 extends performance through more powerful multi-antenna capabilities.

Release 10 includes significant enhancements 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 not relying on channel reciprocity. 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.

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

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116 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,
requirements, conceivably supporting a peak rate of 1 Gbps in just 40 MHz and even higher rates in wider bandwidths. This would require additional reference signals for channel estimation and for measurements such as 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 49 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 49: Single-User MIMO**

![Single-User MIMO Diagram]

Figure 50 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 50: Multi-User MIMO**

![Multi-User MIMO Diagram]

**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 (Rel-10) and is being standardized in Release-11 (Rel-11).

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117 Source: 4G Americas member contribution.

118 Source: 4G Americas member contribution.
The intent of CoMP is to closely coordinate transmissions at different cell sites, thereby achieving higher system capacity and improving cell-edge data rates. Most work for CoMP is currently planned for Release 11.

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 may be significantly improved. For the UL, signals from the UE received at multiple reception points can significantly improve the link performance. Many techniques have been described in the literature, ranging from simple interference avoidance techniques, such as Coordinated Beam Switching (CBS) and Coordinated Beam Forming (CBF), to complex joint processing techniques, such as 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 51 shows two possible levels of coordination.

**Figure 51: Different Coordination Levels for CoMP**

In one CoMP approach called coordinated scheduling, shown in Figure 52, 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, also shown in Figure 52, 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.

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119 Source: 4G Americas member contribution.
Release 11 will also implement CoMP on the uplink. This involves multiple base stations receiving uplink transmissions and jointly processing the signal. This can enable significant interference cancellation and improvements in spectral efficiency.

The performance gains expected from CoMP are under discussion in the industry. According to the 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 Het-nets without eICIC. For resource utilization of more than 35%, CoMP may provide a 17% mean gain and a 40% cell-edge. CoMP can also be used in combination with eICIC for additional gains.

**LTE-Advanced Relays**

Another capability being planned for LTE-Advanced is relays as shown in Figure 53. 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 be much improved. 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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120 **Source:** 4G Americas member contribution.

121 **Source:** 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. See http://www.3gpp.org/ftp/Specs/archive/36_series/36.819/36819-b10.zip
As demonstrated in this section, LTE-Advanced will have tremendous capability. Although initial deployments of LTE will be based on Release 8, as new spectrum becomes available in the next decade, especially if it includes wide radio channels, then LTE-Advanced will be an excellent candidate technology for these new bands. Even in existing bands, operators are likely to eventually upgrade their LTE networks to LTE-Advanced to obtain spectral efficiency gains and capabilities such as relaying.

**Heterogeneous Networks and Self-Optimization**

A fundamental concept in the evolution of next-generation networks is that they will be a blend of multiple types of networks: a network of networks. These networks will be characterized by:

- Variations in coverage areas including femtocells (either enterprise femtos or home femtos called HeNBs), picocells (also referred to as metro cells), and macro cells. Cell range can vary from 10 meters to 50 kilometers.
- Different frequency bands.
- Different technologies spanning Wi-Fi, 2G, 3G, and 4G.
- Relaying capability where 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 54 shows how different types of user equipment might access different network layers.

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122 Source: 4G Americas member contribution.
Het-nets will allow significant capacity expansion in configurations in which operators can add picocells to coverage areas served by macrocells, particularly if there are hotspots with higher user densities. Figure 55 shows two different traffic distribution scenarios. In the first, there is a uniform distribution of devices whereas, in the second, there are higher densities in the areas served by the picocells. The second scenario can result in significant capacity gains, as well as improved user throughput gains.

123 Source: 4G Americas member contribution.
One vendor calculated expected Het-net 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%.\textsuperscript{124} Furthermore, additional gains beyond what is reported here can be obtain 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.

Release 10 and Release 11 added enhanced support to manage the interference in the Het-net scenario in the time domain with Enhanced Intercell Interference Coordination.

\textsuperscript{124} 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.
(eICIC) and Further Enhanced Intercell Interference Coordination (feICIC), as well as in the frequency domain with carrier-aggregation based ICIC. As discussed next, eICIC will provide additional gains.

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

Het-net capability keeps becoming more sophisticated through successive 3GPP releases as summarized in Table 14.

**Table 14: 3GPP Het-net Evolution**

<table>
<thead>
<tr>
<th>3GPP Release</th>
<th>Het-net 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 (e.g., 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, where local small-cell signals can easily interfere with macro cells. Interference management is of particular concern in Het-nets 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 where subframe transmission can be muted to prevent interference. Figure 56 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.

The performance gains from Het-nets using eICIC in Release 10 are expected to be 25 to 50%. FeICIC in Release 11 will provide additional gains. Estimates for the gains vary and are in the range of 10% to 35%.\textsuperscript{126}

Another approach for addressing inter-layer interference cancellation in Het-nets can come from carrier aggregation with no further additions or requirements. Consider the scenario in Figure 57, 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.

\textsuperscript{125} Source: 4G Americas member contribution.

\textsuperscript{126} Source: Based on 4G Americas member contributions to Rysavy Research. For one example of projections of feICIC gains, refer to 3GPP TSG-RAN WG1 #66bis, R1-113566, Qualcomm, “eICIC evaluations for different handover biases,” http://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_66b/Docs/R1-113566.zip
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. Data can be scheduled 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 (e.g., 3 MHz or 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.

**EPC**

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

EPC will be 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 will support service continuity across heterogeneous networks, which will be important for LTE operators who must simultaneously support GSM-HSPA customers.

One important performance 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

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127 Source: 4G Americas member contribution.
and GGSN. The AGW has 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 that 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 also allows integration of non-3GPP networks such as WiMAX. EPC will use IMS as a component. It will also manage QoS across the whole system, which will be essential for enabling a rich set of multimedia-based services.

Figure 58 shows the EPC architecture.

**Figure 58: 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.

3GPP is planning to support voice in EPS through VoIP and IMS. However, there is an alternative voice approach being discussed in the industry, namely transporting circuit-switched voice over LTE, called VOLGA. This approach is not currently part of any 3GPP specifications.

The need for supporting a broader variety of applications requiring higher bandwidth and lower latency led 3GPP to alleviate the existing (UMTS Release 99) QoS principles with the introduction for EPS of a QoS Class Identifier (QCI). The QCI is a scalar 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 (e.g., scheduling weights, admission thresholds, queue management thresholds, link-layer protocol configuration, etc.). Each packet flow is mapped to a single QCI value (nine are defined in the Release 8 version of the specifications) according to the level of service required by the application. The usage 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 has been defined to allow proper 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 (e.g., bulk transfers, abusive users) can be throttled down to provide a better user experience for others.

Table 15 shows the nine QCI used by LTE.

**Table 15: 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</td>
<td>2</td>
<td>100 msec.</td>
<td>$10^{-2}$</td>
<td>Conversational</td>
</tr>
</tbody>
</table>
### (Guaranteed Bit Rate) | voice
---|---
2 GBR 4 150 msec. $10^{-3}$ **Conversational video (live streaming)**
3 GBR 3 50 msec. $10^{-3}$ **Real-time gaming**
4 GBR 5 300 msec. $10^{-5}$ **Non-conversational video (buffered streaming)**
5 Non-GBR 1 100 msec. $10^{-5}$ **IMS signaling**
6 Non-GBR 6 300 msec. $10^{-5}$ **Video (buffered streaming), TCP Web, e-mail, ftp, ...**
7 Non-GBR 7 100 msec. $10^{-3}$ **Voice, video (live streaming), interactive gaming**
8 Non-GBR 8 300 msec. $10^{-5}$ **Premium bearer for video (buffered streaming), TCP Web, e-mail, ftp, ...**
9 Non-GBR 9 300 msec. $10^{-5}$ **Default bearer for video, TCP for non-privileged users**

### Wi-Fi Integration

3GPP has evolved its thinking on how best to integrate Wi-Fi with 3GPP networks. At the same time, other industry initiatives such as that of the Wi-Fi Alliance have also tried to address the problem of hotspot roaming, namely the ability to have an account with one hotspot 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 is communicating 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 is 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. One is host-based mobility with Dual Stack Mobile IPv6 (DSMIPv6) in the client, and the other is network-based mobility with Proxy Mobile IPv6 (PMIPv6) using an intermediary node called an Enhanced Packet Data Gateway (ePDG).

Release 11, however, proposes a different approach, one that would eliminate the ePDG, as shown in Figure 59. Called SaMOG (S2a-based Mobility over GTP), there is a trusted WLAN access gateway that can interconnect multiple 3GPP-compliant access points. Traffic can route directly to the Internet or traverse the packet core.

Figure 59: Release 11 Wi-Fi Integration

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.

Separately from 3GPP, the Wi-Fi alliance has developed the Hotspot 2.0 specifications, as introduced above, in this white paper. Based on IEEE 802.11u, user devices can

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128 Specified in 3GPP TS 23.402 "Architecture enhancements for non-3GPP accesses."
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 60. 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, expected in 2013, 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.

Figure 60: Hotspot 2.0 Connection Procedure

![Diagram of Hotspot 2.0 Connection Procedure]

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. This is useful with femtocells that normally route all traffic back to the operator network. With LIPA, the UE in a home environment can access local resources such as printers, scanners, file servers, media servers, and so forth.

IFOM, as shown in Figure 61, enables seamless offload over Wi-Fi networks. Wi-Fi offload today occurs in a fairly rudimentary manner. The device, for example, a smartphone, 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 is based on 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).
**IMS**

IP Multimedia Subsystem (IMS) is a service platform that allows operators to support IP multimedia applications. Potential applications include video sharing, PoC, VoIP, streaming video, interactive gaming, and so forth. 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, the 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 62, IMS operates just outside the packet core.

**Figure 62: IP Multimedia Subsystem**

The benefits of using IMS include handling all communication in the packet domain, tighter integration with the Internet, and a lower cost infrastructure that is based on IP building blocks used for both voice and data services. This allows operators to potentially deliver data and voice services at lower cost, thus providing these services at lower prices and further driving demand and usage.

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.

IMS is one of the most likely means that operators will use to provide voice service in LTE networks. Service Continuity, defined in Release 8, provides for a user’s entire session to continue seamlessly as the user moves from one access network to another. Release 9 expands 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 introduces 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)**

An architecture under consideration, but still in the research phase, is cloud RAN, 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 between 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. There is a standard called Common Public Radio Interface (CPRI) that addresses generic formats and protocols for such a high-speed link, but other alternatives are being investigated aimed at reducing the backhaul’s bitrate requirements.

**Figure 63: Potential Cloud RAN Approach**

**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 much more efficient approach for delivering content such as video programming to which multiple users have subscriptions. 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. Because multiple users in a cell are tuned to the same content, broadcasting and multicasting result in much greater spectrum efficiency for services such as mobile TV.

3GPP defined highly-efficient broadcast/multicast capabilities for UMTS in Release 6 with MBMS. Release 7 includes 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 will also have a broadcast/multicast capability. OFDM is particularly well-suited for broadcasting, because the 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. As such, the LTE broadcast capability, as shown in Figure 64, is expected to be quite efficient.

**Figure 64: OFDM Enables Efficient Broadcasting**

An alternate approach for mobile TV is to use an entirely separate broadcast network with technologies such as Digital Video Broadcasting–Handheld (DVB-H), which various operators around the world have opted to do. Although this requires a separate radio in the mobile device, the networks are highly optimized for broadcast.

Despite various broadcast technologies being available, market adoption has been relatively slow. Internet trends favor unicast approaches, with users viewing videos of their selection on demand.

**UMTS TDD**

Most WCDMA and HSDPA deployments are based on FDD, in which the operator uses different radio bands for transmit and receive. An alternate approach is TDD, in which both 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, especially for applications like Web browsing or multimedia downloads. A TDD radio interface can dynamically adjust the downlink-to-uplink ratio accordingly, hence balancing both forward-link and reverse-link capacity. Note that for UMTS FDD, the higher spectral efficiency achievable in the downlink versus the uplink is critical in addressing the asymmetrical nature of most 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. For this spectrum, UMTS TDD or, in the future, LTE
in TDD mode is a good choice. It is also a good choice in 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. 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 so far. 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 against 3.84 Mcps for UMTS TDD, the primary attribute of TD-SCDMA is that it is designed to support very high subscriber densities. This makes 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. It is an enhancement applicable to GPRS, which is the original packet data service for GSM networks, as well as to GSM circuit-switched services, the latter not being considered further in this document. 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. With peak user-achievable throughput rates of up to 200 kbps with EDGE using four timeslot devices, users have the same effective access speed as a modem, but with the convenience of connecting from anywhere. See Figure 65.

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129 The 1910-1920 MHz band targeted unlicensed TDD systems, but has never been used.

130 "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.
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 it 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.

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 66. 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 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 a timeslot of a Time Division Multiple Access (TDMA) frame when justified by the volume of data traffic.
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. With networks supporting DTM, users with DTM-capable devices can engage in simultaneous voice/data operation.

With respect to data performance, each data timeslot can deliver peak user-achievable data rates of up to about 50 kbps. The network can aggregate up to four of these timeslots on the downlink 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 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. In addition, any application developed for GPRS will work with EDGE.

Devices themselves are increasing in capability. Dual Transfer Mode (DTM) devices, already available from vendors, allow simultaneous voice and data communications. For example, during a voice call, users will be able to retrieve e-mail, do multimedia messaging, browse the Web, and do Internet conferencing. This is particularly useful when connecting phones to laptops via cable or Bluetooth and using them as modems.

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

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131 Source: 4G Americas member company contribution.
132 Example: WAP notification message delivered via SMS.
DTM end-to-end solution requires only a software upgrade to the GSM/EDGE radio network. There are a number of networks and devices now supporting DTM.

**Evolved EDGE**

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

Although EDGE today already serves many applications like wireless e-mail extremely well, it makes good sense to continue to evolve EDGE capabilities. From an economic standpoint, it is less costly than upgrading to UMTS, 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, and cable-modem speeds are realistically achievable.

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 environments, for example when an LTE user moves to a GSM/Evolved EDGE network to establish a (circuit-switched) voice call\(^{133}\) or when leaving LTE coverage.

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

- A 100 percent increase in peak data rates.
- A 50 percent 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.
- To achieve compatibility with existing frequency planning, thus facilitating deployment in existing networks.
- To coexist with legacy mobile stations by allowing both old and new stations to share the same radio resources.
- To avoid impacts on infrastructure by enabling improvements through a software upgrade.
- To be applicable 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 include:

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

\(^{133}\) Some initial LTE networks will be data-only, with voice operation provided by GSM.
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 percent (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.

Dual-Carrier Receiver

A key part of the evolution of EDGE is the utilization of more than one radio frequency carrier. This overcomes 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 67. Using two carriers enables the reception of twice (or more than twice for some multi-slot classes) as many radio blocks simultaneously.

Figure 67: Evolved EDGE Two-Carrier Operation

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.

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134 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 statistical improvement in the ability 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 result is that the system can allocate a larger set of time slots for data even if they are not contiguous, which otherwise is not possible. Figure 69 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.

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135 Source: 4G Americas member company contribution.
Figure 69: Probabilities of Time-Slot Assignments\textsuperscript{136}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{probabilities.png}
\caption{Probabilities of Time-Slot Assignments}
\end{figure}

**Mobile Station Receive Diversity**

Figure 70 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.

\textsuperscript{136} 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 percent of capacity. Thus, with four of these frequencies, it is possible to obtain 100 percent 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 percent and possibly to as high as 75 percent. An increase to 50 percent translates to a doubling of capacity on the 1/1 layer without requiring any new spectrum and to a 200 percent 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. This yields 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.

These enhancements are only now being considered, because factors such as processing power, variability of interference, and signal level made higher order modulations impractical for mobile wireless systems just a few years ago. Newer techniques for demodulation, however, such as advanced receivers and receive diversity, help enable their use.

Two different levels of support for higher order modulation are defined 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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137 Source: 4G Americas member company contribution.
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 16: Uplink Modulation and Coding Schemes**

<table>
<thead>
<tr>
<th>Modulation and Coding Scheme Name</th>
<th>Uplink EGPRS2 Support Level A</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>MCS-5</td>
<td></td>
<td>8-PSK</td>
<td>89.6</td>
</tr>
<tr>
<td>MCS-6</td>
<td></td>
<td>8-PSK</td>
<td>118.4</td>
</tr>
<tr>
<td>UAS-7</td>
<td></td>
<td>16 QAM</td>
<td>179.2</td>
</tr>
<tr>
<td>UAS-8</td>
<td></td>
<td>16 QAM</td>
<td>204.8</td>
</tr>
<tr>
<td>UAS-9</td>
<td></td>
<td>16 QAM</td>
<td>236.8</td>
</tr>
<tr>
<td>UAS-10</td>
<td></td>
<td>16 QAM</td>
<td>268.8</td>
</tr>
<tr>
<td>UAS-11</td>
<td></td>
<td>16 QAM</td>
<td>307.2</td>
</tr>
</tbody>
</table>

**Table 17: 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>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>UBS-5</td>
<td></td>
<td>QPSK</td>
<td>89.6</td>
</tr>
<tr>
<td>UBS-6</td>
<td></td>
<td>QPSK</td>
<td>118.4</td>
</tr>
<tr>
<td>UBS-7</td>
<td></td>
<td>16 QAM</td>
<td>179.2</td>
</tr>
<tr>
<td>UBS-8</td>
<td></td>
<td>16 QAM</td>
<td>204.8</td>
</tr>
<tr>
<td>UBS-9</td>
<td></td>
<td>16 QAM</td>
<td>236.8</td>
</tr>
<tr>
<td>UBS-10</td>
<td></td>
<td>16 QAM</td>
<td>268.8</td>
</tr>
<tr>
<td>UBS-11</td>
<td></td>
<td>32 QAM</td>
<td>355.2</td>
</tr>
<tr>
<td>UBS-12</td>
<td></td>
<td>32 QAM</td>
<td>435.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>32 QAM</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 18: Downlink Modulation and Coding Schemes**

<table>
<thead>
<tr>
<th>Modulation and Coding Scheme Name</th>
<th>Downlink HOM/HSR Support Level A</th>
<th>Modulation Type</th>
<th>Peak Throughput (kbps) – 4 slots</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCS-1</td>
<td>GMSK</td>
<td></td>
<td>35.2</td>
</tr>
<tr>
<td>MCS-2</td>
<td>GMSK</td>
<td></td>
<td>44.8</td>
</tr>
<tr>
<td>MCS-3</td>
<td>GMSK</td>
<td></td>
<td>59.2</td>
</tr>
<tr>
<td>MCS-4</td>
<td>GMSK</td>
<td></td>
<td>70.4</td>
</tr>
<tr>
<td>DAS-5</td>
<td>8-PSK</td>
<td></td>
<td>89.6</td>
</tr>
<tr>
<td>DAS-6</td>
<td>8-PSK</td>
<td></td>
<td>108.8</td>
</tr>
<tr>
<td>DAS-7</td>
<td>8-PSK</td>
<td></td>
<td>131.2</td>
</tr>
<tr>
<td>DAS-8</td>
<td>16 QAM</td>
<td></td>
<td>179.2</td>
</tr>
<tr>
<td>DAS-9</td>
<td>16 QAM</td>
<td></td>
<td>217.6</td>
</tr>
<tr>
<td>DAS-10</td>
<td>32 QAM</td>
<td></td>
<td>262.4</td>
</tr>
<tr>
<td>DAS-11</td>
<td>32 QAM</td>
<td></td>
<td>326.4</td>
</tr>
<tr>
<td>DAS-12</td>
<td>32 QAM</td>
<td></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 19: 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>GMSK</td>
<td></td>
<td>35.2</td>
</tr>
<tr>
<td>MCS-2</td>
<td>GMSK</td>
<td></td>
<td>44.8</td>
</tr>
<tr>
<td>MCS-3</td>
<td>GMSK</td>
<td></td>
<td>59.2</td>
</tr>
<tr>
<td>MCS-4</td>
<td>GMSK</td>
<td></td>
<td>70.4</td>
</tr>
<tr>
<td>DBS-5</td>
<td>QPSK</td>
<td></td>
<td>89.6</td>
</tr>
<tr>
<td>DBS-6</td>
<td>QPSK</td>
<td></td>
<td>118.4</td>
</tr>
<tr>
<td>DBS-7</td>
<td>16 QAM</td>
<td></td>
<td>179.2</td>
</tr>
<tr>
<td>DBS-8</td>
<td>16 QAM</td>
<td></td>
<td>236.8</td>
</tr>
<tr>
<td>DBS-9</td>
<td>16 QAM</td>
<td></td>
<td>268.8</td>
</tr>
<tr>
<td>DBS-10</td>
<td>32 QAM</td>
<td></td>
<td>355.2</td>
</tr>
<tr>
<td>DBS-11</td>
<td>32 QAM</td>
<td></td>
<td>435.2</td>
</tr>
<tr>
<td>DBS-12</td>
<td>32 QAM</td>
<td></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!

**Evolved EDGE Implementation**

Table 20 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.

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

139 For the near future, two carriers will be a scenario more practically realized on a notebook computer platform than handheld platforms.
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, 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 IEE 802.11 Wi-Fi, is another standard being developed for white-space spectrum.

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140 Source: 4G Americas member company contribution.

141 FCC-08-260: 2nd Report & Order.
The industry is in the very early stages of determining the viability of using white-space spectrum. In July 2012, two database administrators and one device had been certified.

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.\(^\text{142}\)

**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
CS – Convergence Sublayer
CSFB – Circuit-Switched Fallback
CTIA – Cellular Telephone Industries Association
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
EBCMCS – Enhanced Broadcast Multicast Services
EDGE – Enhanced Data Rates for GSM Evolution
EGPRS – Enhanced General Packet Radio Service
eICIC – Enhanced Inter-Cell Interference Coordination
eNodeB – Evolved Node B
EAP – Extensible Authentication Protocol
EPC – Evolved Packet Core
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
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
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
Het-net – 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
MBMS - Multimedia Broadcast/Multicast Service
Mbps – Megabits Per Second
MBR – Maximum Bit Rate
MBSFN – Multicast/broadcast, Single Frequency
MCPA – Mobile Consumer Application Platform
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
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
SoN – Self Optimizing Network
SPS – Semi-Persistent Scheduling
SR-VCC – Single Radio Voice Call Continuity
SU-MIMO – Single User MIMO
SVDO – Simultaneous 1XRTT Voice and EVDO Data
SVLTE – Simultaneous Voice and LTE
TCH – Traffic Channel
TCP/IP – Transmission Control Protocol/IP
TD – Transmit Diversity
TDD – Time Division Duplex
TDMA – Time Division Multiple Access
TD-SCDMA – Time Division Synchronous Code Division Multiple Access
TD-CDMA – Time Division Code Division Multiple Access
TIA/EIA – Telecommunications Industry Association/Electronics Industry Association
TISPAN – Telecoms and Internet converged Services and Protocols for Advanced Networks
TTI – Transmission Time Interval
UAS – Uplink EGPRS2-A Level Scheme
UBS – Uplink EGPRS2-B Level Scheme
UE – User Equipment
UICC – Universal Integrated Circuit Card
UL – Uplink
UMA – Unlicensed Mobile Access
UMB – Ultra Mobile Broadband
UMTS – Universal Mobile Telecommunications System
URA-PCH – UTRAN Registration Area Paging Channel
\( \mu s \) – Microseconds
USIM – UICC SIM
UTRAN – UMTS Terrestrial Radio Access Network
VDSL – Very High Speed DSL
VoIP – Voice over Internet Protocol
VOLGA – Voice over LTE Generic Access
VoLTE – Voice over LTE
VPN – Virtual Private Network
WAP – Wireless Application Protocol
WBA – Wireless Broadband Alliance
WCDMA – Wideband Code Division Multiple Access
WCA – Wireless Communication Service
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](http://www.4gamericas.org).
If there are any questions regarding the download of this information, please call +1 425 372 8922 or e-mail Krissy Stencil, Public Relations Coordinator at info@4gamericas.org.

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