MOBILE BROADBAND TRANSFORMATION *LTE TO 5G*

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Table of Contents

Introduction

The mobile industry is in the process of massive transformation, creating vast new capabilities that will benefit businesses and society as a whole. The step from 3G to 4G was dramatic, and the advances the industry is unleashing, initially in LTE and then in 5G, will be even greater.

Standards bodies have not yet specified 5G; that process is not expected until the 2020 timeframe. But engineers have demonstrated many of 5G's expected capabilities, and some operators have stated they will deploy pre-standard networks for fixed applications as early as 2017. 5G will not replace LTE, but in most deployments will co-exist with it through at least the late-2020s with the two technologies tightly integrated in a manner transparent to users.

Many of the capabilities that will make 5G so effective are appearing in advanced forms of LTE. With carrier aggregation, for example, operators have not only harnessed the potential of their spectrum holdings to augment capacity and performance, but the technology is also the foundation for entirely new capabilities, such as operating LTE in unlicensed bands.

The computing power of today's handheld computers rivals that of past mainframe computers, powering intuitive operating systems and millions of applications. Coupled with affordable mobile broadband connectivity, these devices provide such unprecedented utility that more than three billion people are now using them.[1]

With long-term growth in smartphones and usage limited by population, innovators are turning their attention to the Internet of Things (IoT), which promises billions of new wireless connections. Enhancements to LTE followed by 5G capabilities will connect wearable computers, a vast array of sensors, and other devices, leading to better health, economic gains, and other advantages. 5G addresses not only IoT deployments on a massive scale, but also applications previously not possible that depend on ultra-reliable and low-latency communications. Although a far more fragmented market than smartphones, the benefits will be so great that the realization of IoT on a massive scale is inevitable. The only question is how, exactly, the market will evolve.

Regulatory policies are striving to keep pace, addressing complex issues that include how best to allocate and manage new spectrum, network neutrality, and privacy. Policy decisions will have a major impact on the evolution of mobile broadband.

These are exciting times for both people working in the industry and those who use the technology. This paper attempts to capture the scope of what the industry is developing, beginning with Table 1, which summarizes some of the most important advances.

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[1] GSMA, *The Mobile Economy*, 2015, available at http://www.gsmamobileeconomy.com/GSMA_Global_Mobile_Economy_Report_2015.pdf.

Table 1: Most Important Wireless Industry Developments in 2016

Development	Summary
5G Research and Development Accelerates	5G, in early stages of definition through global efforts and many proposed technical approaches, could start to be deployed close to 2020 and continue through 2030. Some operators have announced deployment of pre-standard networks for fixed deployments as early as 2017. 5G will be designed to integrate with LTE networks, and many 5G features may be implemented as LTE-Advanced Pro extensions prior to full 5G availability.
LTE Becomes the Global Cellular Standard	A previously fragmented wireless industry has consolidated globally on LTE. LTE is being deployed more quickly than any previous-generation wireless technology.
LTE-Advanced Provides Dramatic Advantages	Carrier Aggregation, a key LTE-Advanced feature that operators are deploying globally, uses available spectrum more effectively, increases network capacity, can increase user throughput rates, and provides new ways to integrate unlicensed spectrum. Other features in early stages of deployment or being tested for deployment include: Self-Organizing Network (SON) capabilities in the radio-access network, Enhanced Inter-Cell Interference Coordination (eICIC) for small cells that use the same radio channels as the macro cell, and Coordinated Multi Point (CoMP) transmission so multiple sites can simultaneously transmit coordinated signals and process signals to and from mobile users, improving cell-edge performance.
Internet of Things Poised for Massive Adoption	IoT, evolving from machine-to-machine (M2M) communications, is seeing rapid adoption, with tens of billions of connected devices expected over the next ten years. Drivers include improved LTE support, other supporting wireless technologies, and service-layer standardization such as oneM2M.
Unlicensed Spectrum Becomes More Tightly Integrated with Cellular	The industry has developed increasingly sophisticated means for Wi-Fi and cellular networks to interoperate, such as LTE-WLAN Aggregation (LWA) and LTE-WLAN Aggregation with IPSec Tunnel (LWIP), making the user experience ever more seamless. The industry is also developing versions of LTE that can operate in unlicensed spectrum, such as LTE-Unlicensed (LTE-U), LTE-Licensed Assisted Access (LTE-LAA), and MulteFire. Cellular and Wi-Fi industry members are collaborating to ensure fair co-existence.

Development	Summary
Spectrum Still Precious	Spectrum in general, and in particular licensed-band spectrum, remains a precious commodity for the industry; its value was demonstrated by the recent Advanced Wireless Services (AWS) auction in the United States that achieved record valuations. Forthcoming spectrum in the United States includes the 600 MHz band being auctioned in 2016 and the 3.5 GHz “small-cell” band that the Federal Communications Commission (FCC) is in the process of enabling. 5G spectrum will include bands above 6 GHz, called mmWave when above 30 GHz, with the potential of ten times as much spectrum as is currently available for cellular. Radio channels of 200 MHz, 500 MHz, or even wider will enable multi-Gbps peak throughput.
Small Cells Take Baby Steps, Preparing to Stride	Operators have begun installing small cells. Eventually, millions of small cells will lead to massive increases in capacity. The industry is slowly overcoming challenges that include government regulations, site acquisition, self-organization, interference management, and backhaul.
Network Function Virtualization (NFV) Emerges	New network function virtualization (NFV) and software-defined networking (SDN) tools and architectures are enabling operators to reduce network costs, simplify deployment of new services, reduce deployment time, and scale their networks. Some operators are also virtualizing the radio-access network, as well as pursuing a related development called cloud radio-access network (cloud RAN).

The main part of this paper covers exploding demand for wireless services, the path to 5G, supporting technologies and architectures, voice over LTE (VoLTE), Wi-Fi calling, LTE for public safety, options to expand capacity, and spectrum developments.

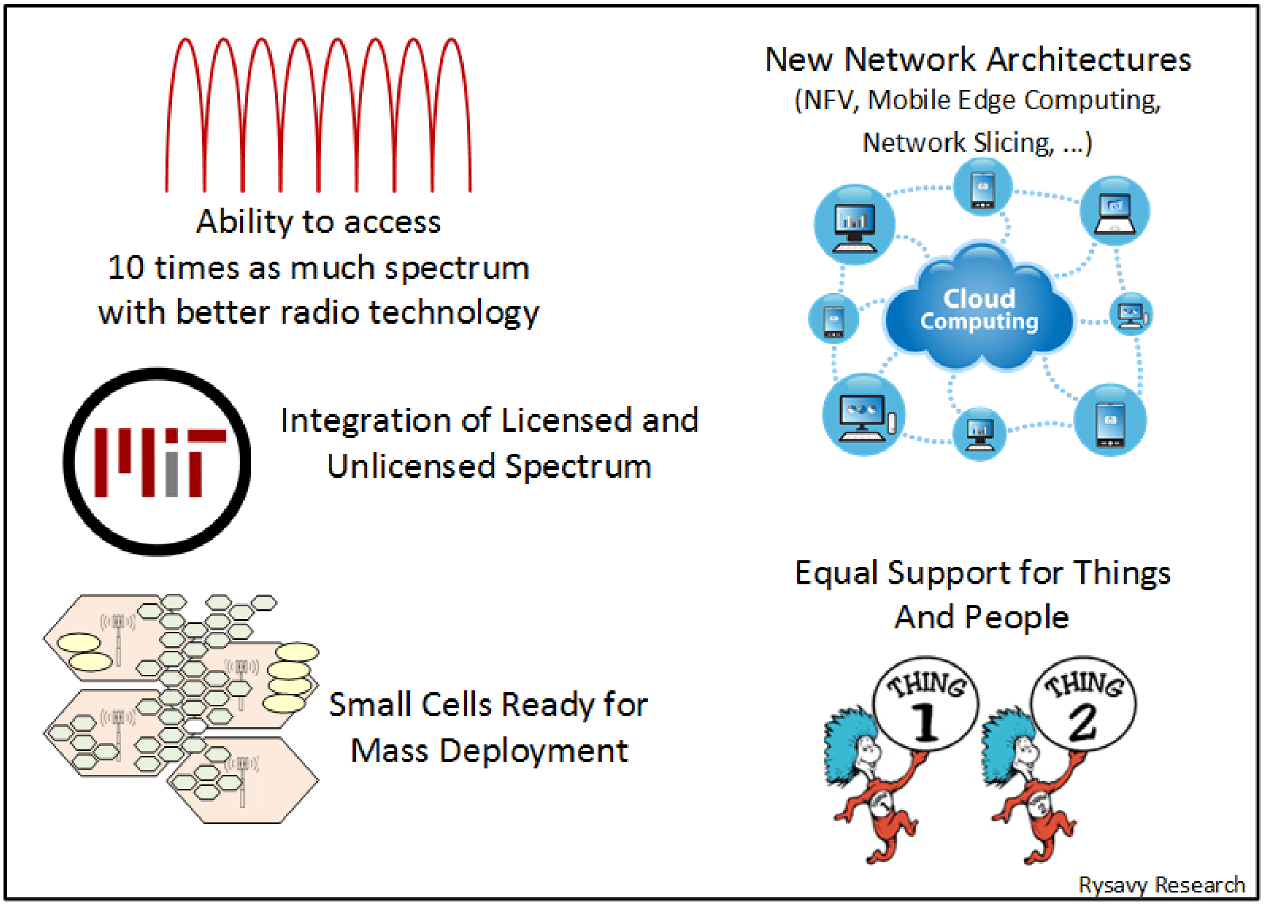
The appendix delves into more technical aspects of the following topics: data throughput, latency, UMTS/WCDMA,[2] HSPA, HSPA+, LTE, LTE-Advanced, LTE-Advanced Pro, HetNets, small cells, self-organizing networks, the Evolved Packet Core, unlicensed spectrum integration, the IP multimedia subsystem, cloud radio-access networks, broadcast/multicast services, backhaul, UMTS TDD, EDGE, and TV white spaces.

[2] Although many use the terms “UMTS” and “WCDMA” interchangeably, in this paper “WCDMA” refers to the radio interface technology used within UMTS, and “UMTS” refers to the complete system. HSPA is an enhancement to WCDMA. LTE with EPC is a completely new architecture.

Transformation

Many elements are interacting to fuel the transformation of mobile broadband, but the factors playing the most important roles are the emerging capabilities for IoT, radio advances granting access to far more spectrum, small cells about to play a much larger role, new network architectures that leverage network function virtualization and software-defined networking, and new means to employ unlicensed spectrum. Except for access to high-band spectrum, a 5G objective, these advances apply to both LTE and 5G.

Figure 1: Fundamental Transformational Elements



This section explains each of these elements in more detail, beginning with IoT.

In the past, developers used modems and networks designed for human communication for machine-type applications. This approach worked for some applications but fell short in many others. Now, new modes of network operation, initially in LTE, then enhanced further in 5G, will cater to the unique needs of a wide variety of machine applications, addressing low cost, long battery life, a wide variety of throughputs, and long communications range.

As for spectrum, throughout radio history, technology has climbed up a ladder to use higher frequencies. What were called "ultra-high frequencies" when made available for television are now considered low-band frequencies for cellular. Frequencies above 6 GHz, particularly mmWave frequencies, are the new frontier. Networks will ultimately take advantage of ten times as much spectrum as they use now, and likely even more over time. Although challenging to use because of propagation limitations, massive MIMO, beam steering, beam tracking, dual connectivity, carrier aggregation, small-cell architectures, and other methods will help mitigate the challenges at these frequencies. The result: massive increases in capacity.

In addition to accessing higher bands, cellular technologies are about to integrate unlicensed spectrum more efficiently, using technologies such as LTE-U, LAA, MulteFire, LWA, and LWIP. This integration will immediately augment small-cell capacity, improving the business case for small cells.

Small cells, on the roadmap for many years but held back by implementation difficulties such as backhaul and lack of neutral-host solutions, are on the verge of large-scale deployment, leading ultimately to ten small cells or more for every macro cell. Paving the way are better wireless backhaul solutions, neutral-host capabilities enabled by new technologies, and soon, access to mmWave bands.

Facilitating the capabilities listed above, networks are becoming programmable. Using a distributed, software-enabled network based on virtualization and new architectural approaches such as mobile-edge computing (MEC) and network slicing, operators and third parties will be able to deploy new services and applications more rapidly, and in a more scalable fashion. Centralizing radio-access network (RAN) signal processing will also play a huge role, which, depending on the deployment scenario, will increase RAN efficiency and decrease deployment cost.

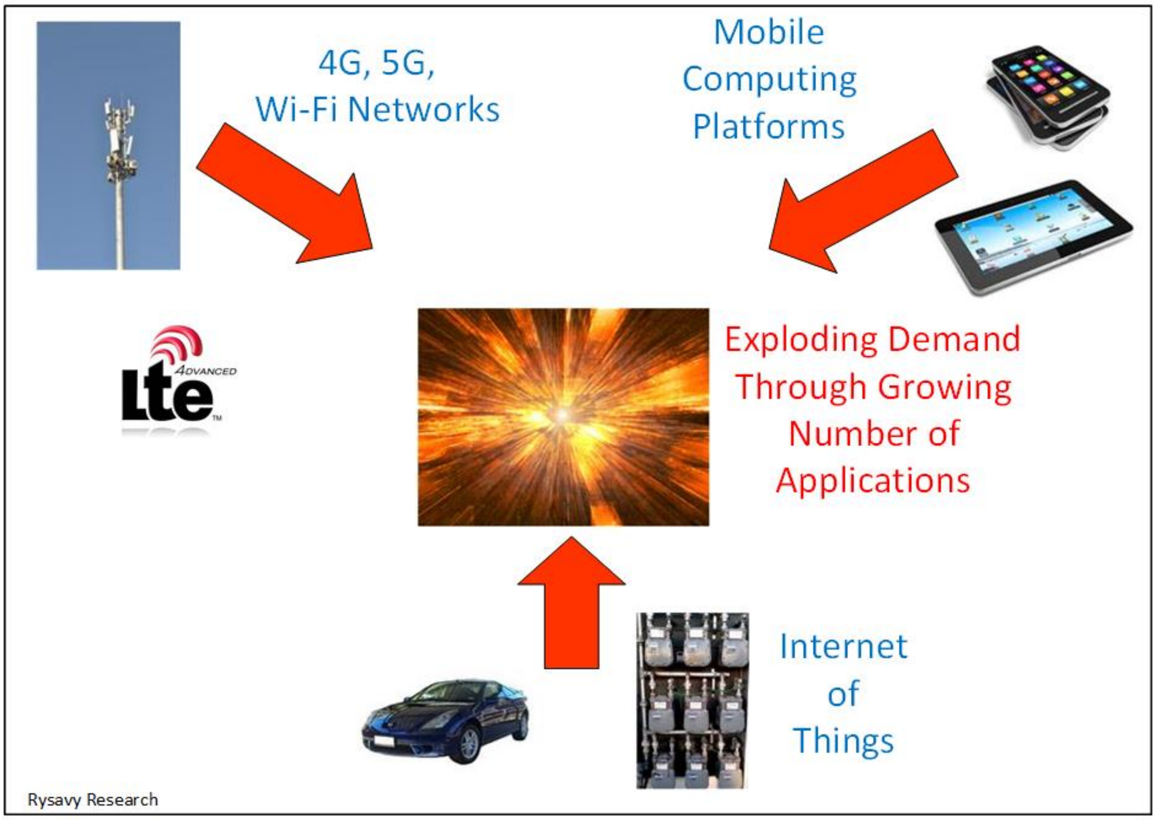
This paper lists the dozens of other innovations also fueling mobile and cellular technology transformation. Together, these transformed networks will mean that for millions, and ultimately billions, of people, wireless connections will be the only connections that people need. These networks will also provide the foundation for entire new industries, ones not even conceived.

Exploding Demand

Mobile broadband satisfies an inherent human and business need: to do more without being tied to a physical location. Two technology trajectories have collided and reached critical mass: handheld computing and fast wireless connections. This combined computing and communications platform inspires the innovation that has produced millions of applications.

Until now, human interaction has driven wireless demand, but communicating machines will be a third trajectory that expands demand even further. What types of things communicate and how they do so will vary far more than human communication. Predicting whether, over the next decade, the Internet of Things contributes to demand by a factor of ten or a hundred is impossible. IoT's massive impact, however, is inevitable.

Figure 2: Exploding Demand from Critical Mass of Multiple Factors



This section explores these various demand factors.

Smartphones and Tablets

Today's smartphones and tablets have raw capability that makes millions of mobile applications possible:

- Processors clocked at over 1 GHz.
- Memory ranging from 16 GB to 128 GB and able to store thousands of songs and many hours of video.
- Motion processing.

- Multiple radio interfaces, including 2G to 4G, Bluetooth, Wi-Fi, and GPS.
- High-definition screens exceeding the resolution of human eyes.
- High-performance still and motion cameras.
- Sophisticated, multi-tasking operating systems.
- Voice recognition and artificial intelligence.

Because they always carry these devices, users are likely to use a wider variety of applications than at a stationary computer. The rich capabilities of these mobile platforms enable users to consume ever larger amounts of data through music and video streaming, social networking, cloud synchronization, cloud/Web-based applications, Web browsing, content downloading, navigation, transportation, and more.

Application Innovation

When planning 4G network technology, who could have predicted applications such as Uber and Lyft, which combine location information with mapping and online payment, and now are disrupting the taxi industry and even challenging notions of private vehicle ownership? While some applications of new technology can be predicted, many cannot.

More efficient technology not only addresses escalating demand, it also provides higher performance, thus encouraging new usage models and further increasing demand. For example, in one study, Android 4G smartphone users averaged 2.4 GB monthly usage compared with 1.1 GB for 3G smartphone users.[3]

Today's smartphones and tablets, dominated by the iOS and Android ecosystems, in combination with sophisticated cloud-based services, provide a stable, well-defined application environment, allowing developers to target billions of users. Developers have an increasing number of tools at their fingertips to develop mobile applications, including:

- Ever richer platform-specific development tools.
- Increasing capability in Web-based tools, such as HTML5, for applications that operate across multiple platforms. Hybrid HTML5/native apps are also becoming common.
- New application programming interfaces (APIs) for accessing mobile-specific functions, including WebRTC (Web Real Time Communications), speech, short message service (SMS), multimedia messaging service (MMS), in-app messaging, address books, advertising, and device capabilities.
- Cloud-based support for applications and application services, such as notifications, IoT support, and mobile-commerce. Future growth will depend on consistent, easy-to-use services that simplify application development.

Of concern to many companies in the wireless industry, however, are new network neutrality rules that could hamper innovation. By restricting prioritization, for example, the

[3] Ovum, *Smartphone & tablet usage trends & insights*, 2015.

rules seem to fail to recognize that traffic from different applications inherently have different quality-of-service requirements.[4]

Internet of Things

Current M2M and Internet of Things applications include vehicle infotainment, connected healthcare, transportation and logistics, connected cars, home security and automation, manufacturing, construction and heavy equipment, energy management,[5] video surveillance, environmental monitoring, smart buildings, wearable computing, object tracking, and digital signage. Municipalities, evaluating the concept of "smart cities," are exploring how to optimize pedestrian and vehicular traffic, connect utility meters, and deploy trash containers that can report when they need emptying.

Although promising, the IoT market is also challenging, with varying communications requirements, long installation lifetimes, power demands that challenge current battery technology, cost sensitivity, security and data privacy concerns, unsuitability of conventional networking protocols for some applications, and other factors that developers must address. Streamlining processes and developing supporting infrastructure will take time. The IoT opportunity is not uniform; it will eventually comprise thousands of markets. Success will occur one sector at a time, with triumphs in one area providing building blocks for the next.

Cloud-based support platforms and standardized interfaces are essential for development and deployment of IoT applications. For example, oneM2M is developing a service layer that can be embedded in hardware and software to simplify communications with application servers.[6]

To address the IoT opportunity, 3GPP is defining progressive LTE refinements that will occur over multiple 3GPP releases. These refinements include low-cost modules in Release 13 that approach 2G module pricing and enable multi-year battery life. See the section "Internet of Things and Machine-to-Machine" in the appendix for more details.

Video Streaming

Video represents the greatest usage of data on smartphones. Just an hour a day of mobile video at 1.0 Mbps throughput, typical with YouTube or Netflix, consumes 13.5 GB per month. See the Appendix section "Data Consumed by Video" for a quantification of data consumed by video for multiple usage scenarios.

An increasing number of video applications adapt their streaming rates based on available bandwidth. By doing so, they can continue to operate even when throughput rates drop. Conversely, they take advantage of higher available bandwidth to present video at higher resolution. Fortunately, application developers are becoming sensitive to bandwidth constraints and are offering options for users to reduce consumption.

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[4] For further discussion, see Rysavy Research, *How Wireless is Different – Considerations for the Open Internet Rulemaking*, September 12, 2014. Available at http://www.rysavy.com/Articles/2014-09-Wireless-Open-Internet.pdf.

[5] See for example, 5G PPP, *5G and Energy*, Sep 2015. Available at https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-White_Paper-on-Energy-Vertical-Sector.pdf.

[6] OneM2M home page: http://onem2m.org/.

Cloud Computing

Cloud computing inherently increases data consumption because it requires communications for all operations. Examples include data synchronization and backup, cloud-based applications (such as email, word processing, and spreadsheets), automatic photo uploads, and music and video streaming.

5G Data Drivers

Futurists can predict some 5G applications, but many others will arise as industries evolve or come into existence to take advantage of new network capabilities. Some potential applications of 5G include:

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

Some of these applications are already being addressed by 4G, but 5G's lower costs, higher throughputs, and lower latency will hasten realization of their potential.

In addition, a growing percentage of users will be able to rely on 5G as their only form of broadband connection, continuing the cord-cutting trend that began with voice service.

Global Mobile Adoption

Figure 3 shows the often-cited Cisco projection of global mobile data consumption through 2020, measured in exabytes (billion gigabytes) per month, demonstrating traffic growing at a compound annual rate of 53%.

Figure 3: Global Mobile Data 2015 to 2020[7]

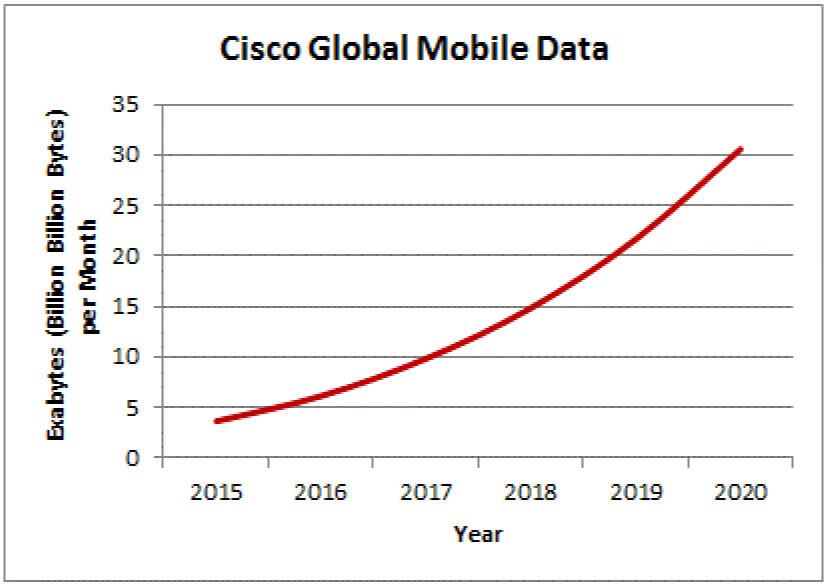
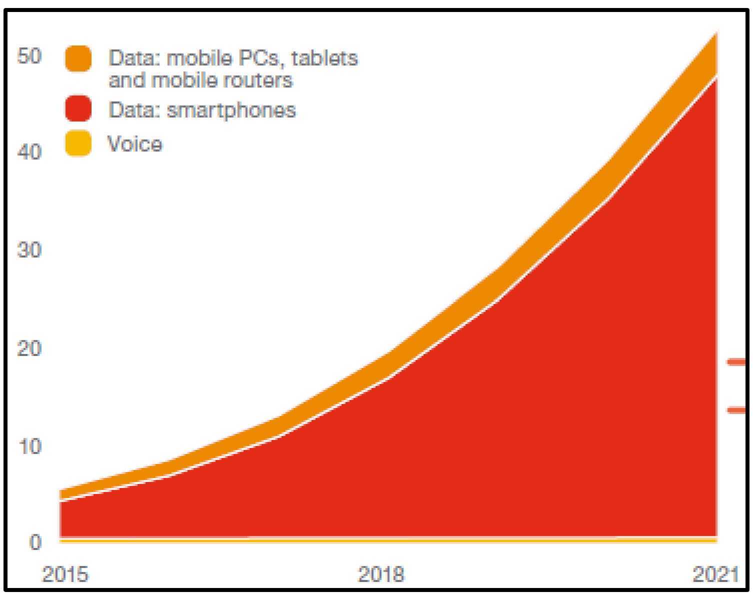


Figure 4 shows another data projection, predicting 45% annual growth in data for the 2015-to-2021 period, resulting in eight-fold growth.

Figure 4: Global Mobile Voice and Data (Exabytes/Month) 2015 to 2021[8]



[7] Cisco, *Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2015-2020*, February 2016.

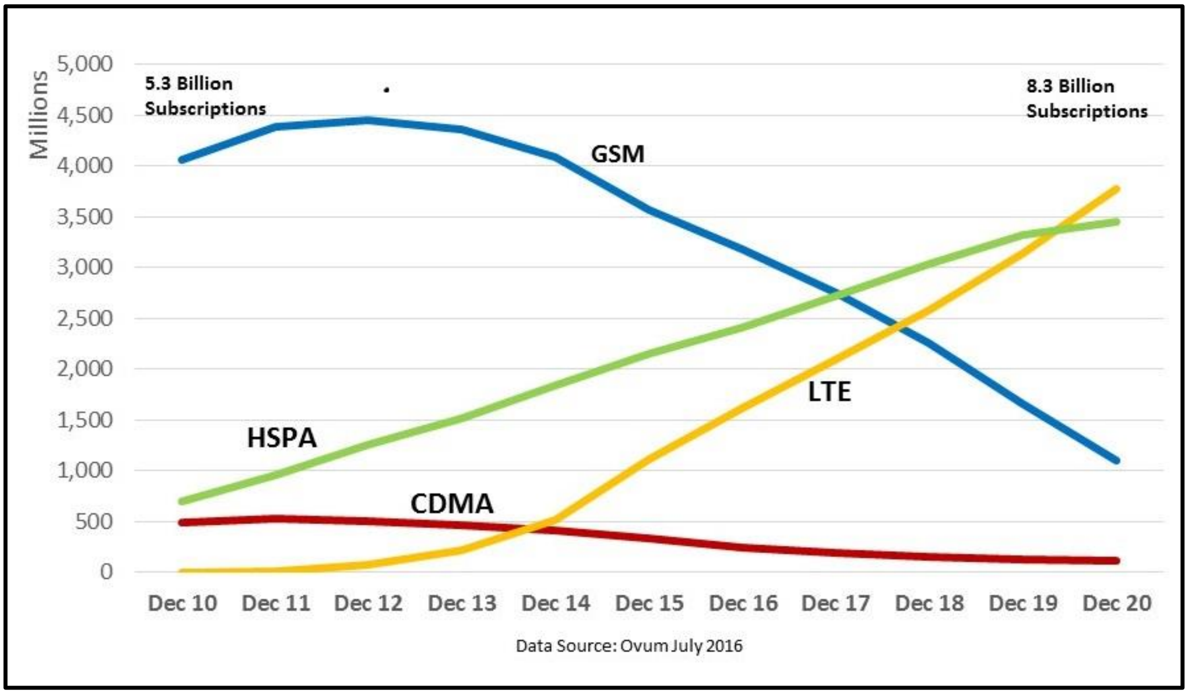
[8] Ericsson, *Ericsson Mobility Report on the Pulse of the Networked Society*, June 2016.

In June 2016, more than 5.6 billion subscribers were using GSM-HSPA[9]—75% of the world's 7.4 billion population.[10] By the end of 2020, the global mobile broadband market is expected to include nearly 8.5 billion subscribers, with 8.3 billion using 3GPP technologies, representing about 98% market share.[11] Chetan Sharma Consulting anticipates 2016 U.S. cellular data revenues to exceed $142 billion.[12]

The evolution of UMTS to HSPA has gained a worldwide customer base of more than two billion people on over 600 commercial networks.

LTE has experienced faster deployment than any mobile technology ever developed. All major U.S. operators now offer nationwide LTE coverage. LTE has also been chosen by U.S. national public-safety organizations as their broadband technology of choice. As shown in Figure 5, 2G GSM has peaked, and LTE subscriptions exceed CDMA. Both HSPA and LTE subscriptions will continue to rise through the rest of the decade.

Figure 5: Global Adoption of 2G-4G Technologies 2010 to 2020[13]



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[9] Ovum, June 2016. Excludes LTE subscribers.

[10] U.S. Census Bureau, "U.S. and World Population Clock," http://www.census.gov/popclock/, accessed March 28, 2016.

[11] Ovum, July 2015. Note that the 2018 mobile broadband market figures include GSM/EDGE, since most GSM networks are likely to include Evolved EDGE, which provides mobile broadband capability.

[12] Chetan Sharma, *US Wireless Market Update – Q1 2016*.

[13] 5G Americas Webinar, "The Future of Mobile Broadband in the Americas," Feb. 24, 2015.

IoT is growing rapidly as well, although connections so far are well below phone-type connections. GSMA reports that, in developed economies, cellular IoT connections reached 137.2 million in Q3 of 2015, a 25% year-on-year increase.[14]

[14] GSMA, *GSMA Intelligence, Global cellular market trends and insight — Q4 2015,* Dec. 2016.

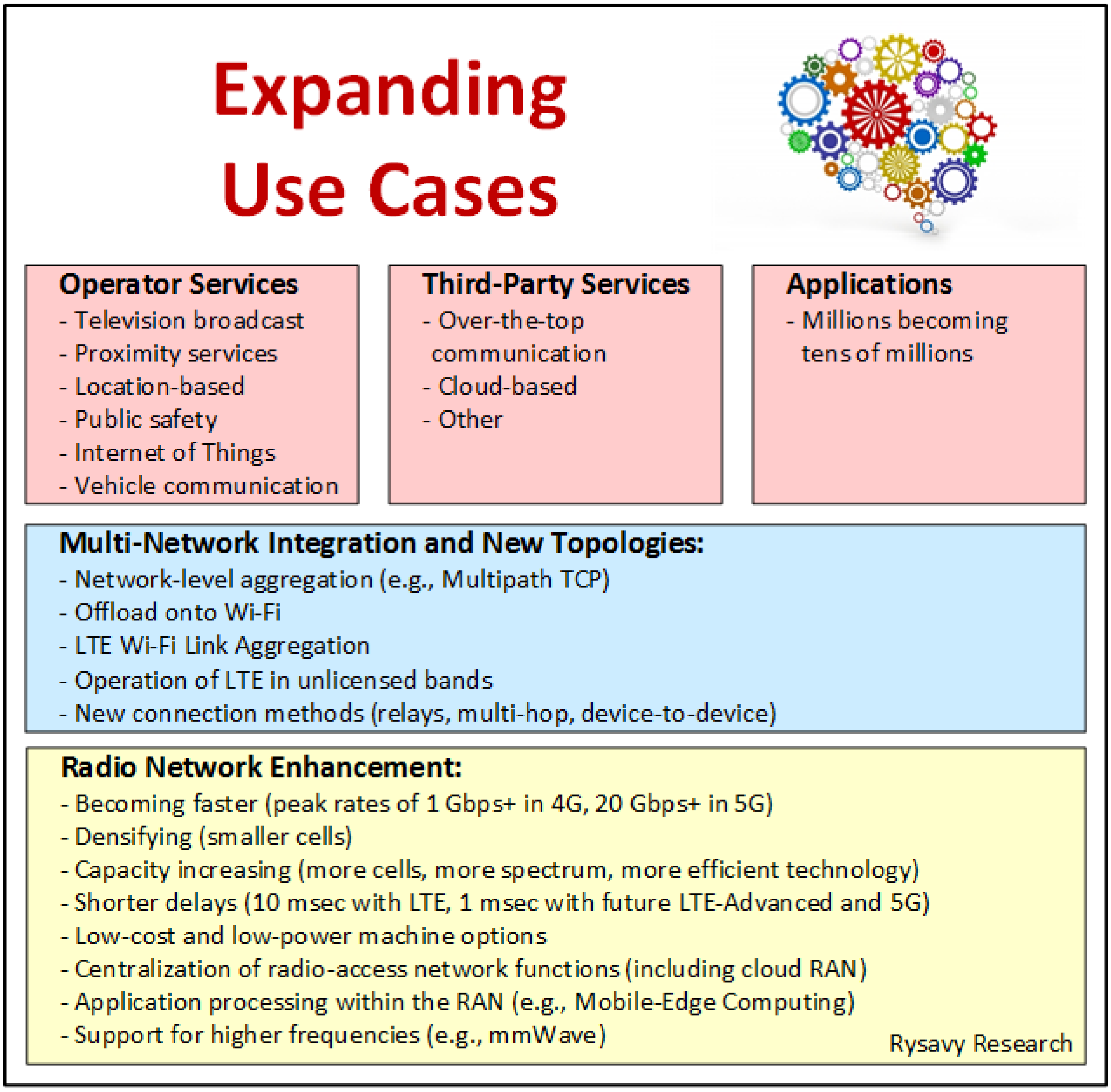
The Path to 5G

Mobile broadband, an ever-growing and highly visible component of the internet, is impacting every aspect of life, changing how people socialize, how businesses operate, and how governments and their citizens interact. This section includes expanding use cases, 1G-to-5G evolution, 4G LTE advances, 5G use cases, 5G concepts and architectures, information-centric networking, phasing of 5G releases, and an overview of 3GPP releases.

Expanding Use Cases

Many wireless technology discussions focus on radio capabilities, but other equally important aspects include use cases, the services built on top of the technology, how different networks integrate with one another, and the topology of the networks. As summarized in Figure 6, all of these aspects are expanding, making mobile/wireless technology the foundation for other enterprises, including business-process optimization, consumer electronics, M2M, connected devices, and a multitude of vertical industries.

Figure 6: Expanding Use Cases



1G to 5G Evolution

The dawn of 5G is quickly approaching, a dawn that will be constructed from millions of ideas, methods, algorithms, and processes. Just as 4G LTE became available when previous technologies, such as HSPA, could be further improved, 5G enters the stage when the roadmap for LTE has not been exhausted. And just as 2G coexists today with 3G and 4G, 5G will coexist with previous generations of technology.

For historical context, "1G" refers to analog cellular technologies that became available in the 1980s. "2G" denotes initial digital systems that became available in the 1990s and that introduced services such as short messaging and lower-speed data. 3G requirements were specified by the International Telecommunication Union (ITU) as part of the International Mobile Telephone 2000 (IMT-2000) project, for which significant voice capacity improvement was a focus and 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 are the primary 3G technologies. 3G technologies began to be deployed early last decade.

In 2008, the ITU issued requirements for IMT-Advanced, which many people initially used as a definition of 4G. The focus on 4G was to improve data coverage, capacity, and quality of experience. Requirements included operation in up-to-40 MHz radio channels and extremely high spectral efficiency. The ITU required peak spectral efficiency of 15 bps/Hz and recommended operation in up-to-100 MHz radio channels, resulting in a theoretical throughput rate of 1.5 Gbps. In 2009 and 2010, the term "4G" became associated with mobile broadband technologies deployed at the time, such as HSPA+, WiMAX, and initial LTE deployments. Today, 4G usually refers to HSPA+ or LTE.

Although the industry is preparing for 5G, LTE capabilities will continue to improve in LTE-Advanced Pro through the rest of the decade. Many of these enhancements will come through incremental network investments. Given the scope of global wireless infrastructure, measured in hundreds of billions of dollars, offering users the most affordable service requires operators to leverage investments they have already made. 5G will eventually play an important role, but it must be timed appropriately so that the jump in capability justifies the new investment. Many of the features planned for 5G may in fact be implemented as LTE-Advanced Pro extensions prior to full 5G availability.

5G groups researching next-generation wireless architecture and requirements include, among others, the International Telecommunication Union (ITU),[15] the European Union's 5G Infrastructure Public-Private-Partnership (5G PPP), which is the framework for several projects, including METIS II (Mobile and wireless communications Enablers for the Twenty-twenty Information Society), and Next Generation Mobile Networks (NGMN). Finally, 5G Americas is actively involved in developing the vision and requirements of 5G for North, Central, and South America. 5G Americas has signed an MoU to collaborate with 5G-PPP.[16]

The ITU, the standardization group of the United Nations, has set the following standardization timetable in its IMT-2020 project:[17]

- 2016-2017: Definition of technical performance requirements, evaluation criteria and methods, and submission templates.
- 2018-2019: Submission of proposals.
- 2019: Evaluation of proposed technologies.
- 2020: Publication of IMT-2020 specifications.

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15 International Telecommunication Union, "Working Party 5D (WP 5D) - IMT Systems," http://www.itu.int/ITU-R/index.asp?category=study-groups&rlink=rwp5d&lang=en, accessed March 19, 2015.

16 5GPPP, "5G-PPP MoU with 4G Americas," March 2, 2015. http://5g-ppp.eu/5g-ppp-mou-with-4g-amererica s/

17 ITU, "ITU towards 'IMT for 2020 and beyond'," http://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Pages/default.aspx, viewed May 27, 2016.

Wireless technology has progressed to the extent that significant new capabilities are inevitable, making 5G a possible alternative to wireline broadband for many subscribers.[18]

Table 2 summarizes the generations of wireless technology.

Table 2: 1G to 5G

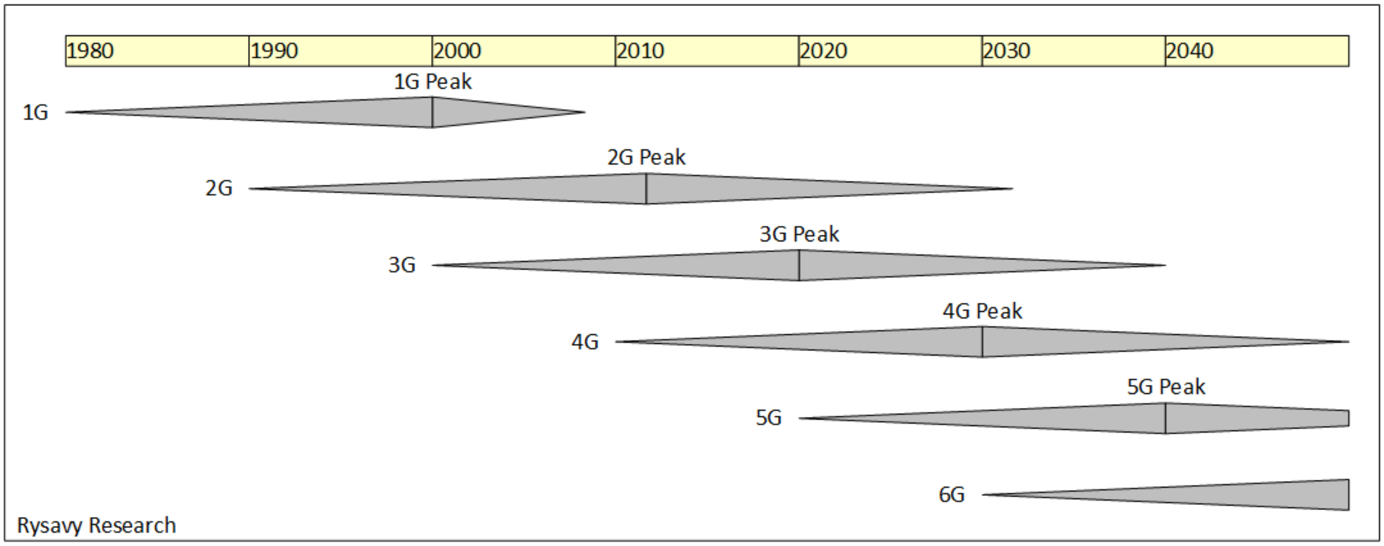
Generation	Requirements	Comments
1G	No official requirements. Analog technology.	Deployed in the 1980s.
2G	No official requirements. Digital technology.	First digital systems. Deployed in the 1990s. New services such as SMS and low-rate data. Primary technologies include IS-95 CDMA (cdmaOne), IS-136 (D-AMPS), and GSM.
3G	ITU's IMT-2000 required 144 Kbps mobile, 384 Kbps pedestrian, 2 Mbps indoors.	First deployment in 2000. Primary technologies include CDMA2000 1X/EV-DO and UMTS-HSPA. WiMAX.
4G (Initial Technical Designation)	ITU's IMT-Advanced requirements include the ability to operate in up-to-40-MHz radio channels and with very high spectral efficiency.	First deployment in 2010. IEEE 802.16m and LTE-Advanced meet the requirements.
4G (Current Marketing Designation)	Systems that significantly exceed the performance of initial 3G networks. No quantitative requirements.	Today's HSPA+, LTE, and WiMAX networks meet this requirement.
5G	ITU IMT-2020 has defined technical requirements for 5G.	Expected in 2020 timeframe, with some trial and demonstration networks deployed in advance.

[18] Rysavy Research, "How will 5G compare to fiber, cable or DSL?" Fierce Wireless, May 2014. Available at http://www.rysavy.com/Articles/2014-05-5G-Comparison-Wireline.pdf.

The interval between each significant technology platform has been about ten years. Within each platform, however, innovation surges unabated. For example, with 2G technology, EDGE significantly improved data performance compared with initial General Packet Radio Service (GPRS) capabilities. Similarly, HSPA hugely increased data speeds compared with initial 3G capabilities. LTE and LTE-Advanced are also acquiring continual improvements that include faster speeds, greater efficiency, and the ability to aggregate spectrum more flexibly.

Figure 7 presents the timeline of technology generations, including past and future, showing initial deployment, the year of the peak number of subscribers, and decline. Each cellular generation spans multiple decades, with peak adoption occurring some 20 years after initial deployment. 6G deployment in 2030, though highly speculative, is consistent with deployment of previous generations.

Figure 7: Timeline of Cellular Generations



4G LTE Advances

As competitive pressures in the mobile broadband market intensified, and as demand for capacity persistently grew, LTE became the favored 4G solution because of its high data throughputs, low latency, and high spectral efficiency. Specifically:

- **Wider Radio Channels.** LTE can be deployed in wide radio channels (for example, 10 MHz or 20 MHz) with carrier aggregation now up to 640 MHz. This increases peak data rates and uses spectrum more effectively.
- **Easiest MIMO Deployment.** By using new radios and antennas, LTE facilitates MIMO deployment, in contrast to the logistical challenges of adding antennas for MIMO to existing legacy technologies. Furthermore, MIMO gains are maximized because all user equipment supports it from the beginning.
- **Best Latency Performance.** For some applications, low latency (packet traversal delay) is as important as high throughput. With a low transmission-time interval (TTI) of 1 millisecond (msec) and a flat architecture (fewer nodes in the core network), LTE has the lowest latency of any cellular technology.

In the same way that 3G coexists with 2G systems in integrated networks, LTE systems coexist with both 3G and 2G systems, with devices capable of 2G, 3G, and 4G modes. Beyond radio technology, the Evolved Packet Core (EPC) provides a new core architecture that is flatter and integrates with both legacy GSM-HSPA networks and other wireless technologies, such as CDMA2000 and Wi-Fi. The combination of EPC and LTE is referred to as the Evolved Packet System (EPS).

The cost for operators to deliver data (for example, cost per GB) is almost directly proportional to the spectral efficiency of the technologies in use. LTE has the highest spectral efficiency of any specified technology to date.

LTE is available in both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) modes. Many deployments will be based on FDD in paired spectrum. The TDD mode, however, is important for deployments in which paired spectrum is unavailable. Instances of TDD deployment include China, Europe at 2.6 GHz, U.S. Broadband Radio Service (BRS) spectrum at 2.6 GHz, and the forthcoming 3.5 GHz small-cell band.

The versions of LTE most widely deployed today (Releases 8 through 12) are just the first in a series of innovations that will increase performance, efficiency, and capabilities. Enhancements in the 2013 to 2016 period are the ones defined in 3GPP Releases 10, 11, and 12 and are commonly referred to as LTE-Advanced.[19] Subsequent releases, such as Releases 13 and 14, which specifies LTE-Advanced Pro, will continue innovating through the end of this decade.

Acknowledging that different operators may have different priorities, the following list roughly ranks the most important features of LTE-Advanced and LTE-Advanced Pro for the 2016 to 2020 timeframe:

1. **Carrier Aggregation.** With this capability, already in use, operators can aggregate radio carriers in the same band or across disparate bands to improve throughputs (under light network load), capacity, and efficiency. Carrier aggregation can also combine FDD and TDD and is the basis of LTE-U and LTE-LAA. As examples, in 2015, AT&T aggregated 700 MHz with AWS, and 700 MHz with PCS. T-Mobile aggregated 700 MHz with AWS, and AWS with PCS.[20] Operators are testing three-carrier aggregation in 2016,[21] and eventually, operators may aggregate four carriers.[22] Rel-13 introduced support for carrier aggregation of up to 32 carriers.

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[19] From a strict standards-development point of view, the term "LTE-Advanced" refers to the following features: carrier aggregation, 8X8 downlink MIMO, and 4XN uplink MIMO with N the number of receive antennas in the base station.

[20] AT&T band combinations are 3GPP Band 13 + Band 4, Band 17 + Band 4, and Band 17 + Band 2. T-Mobile band combinations are Band 12 + Band 4, Band 12 + Band 2, and Band 4 + Band 2.

[21] For example, see Fierce Wireless, "T-Mobile testing three-channel carrier aggregation on LTE network," June 7, 2016, available at http://www.fiercewireless.com/story/t-mobile-testing-three-channel-carrier-aggregation-lte-network/2016-06-07.

[22] For carrier aggregation to operate, both the network and the device have to support the particular band combination. Legacy devices typically do not support new network aggregation capabilities.

2. **VoLTE.** Initially launched in 2015 and with deployments accelerating in 2016, VoLTE enables operators to roll out packetized voice for LTE networks.[23]

3. **Tighter Integration of LTE with Unlicensed Bands.** LTE-U became available for testing in 2016, and 3GPP completed specifications for LAA in Release 13, with deployment expected around 2018. MulteFire, building on LAA, will operate without requiring a licensed-carrier anchor. LTE/Wi-Fi Aggregation through LWA and LWIP are other options for operators with large Wi-Fi deployments.

4. **Enhanced Support for IoT.** Release 13 will bring Category M1, a low-cost device option, along with Narrowband IoT (NB-IoT), a version of the LTE radio interface specifically for IoT devices, called Category NB1.

5. **Dual Connectivity.** Release 12 introduced the capability to combine carriers from different sectors and/or base stations (i.e. evolved Node Bs [eNBs]) through a feature called Dual Connectivity. Two architectures were defined: one that supports Packet Data Convergence Protocol (PDCP) aggregation between the different eNBs and one that supports separate S1 connections on the user plane from the different eNBs to the EPC.

6. **256 QAM Downlink and 64 QAM Uplink.** Defined in Release 12 and ready for deployment in 2016, higher-order modulation increases user throughput rates in favorable radio conditions.

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

8. **HetNet Support.** Also expected in the 2016 timeframe, HetNets integrate macro cells and small cells. A key feature is enhanced inter-cell interference coordination (eICIC), which improves the ability of a macro and a small cell to use the same spectrum. This approach is valuable when the operator cannot dedicate spectrum to small cells. Operators are currently evaluating eICIC, and at least one operator has deployed it.[24] Further enhanced ICIC (feICIC) introduced in Rel-11 added advanced interference-cancellation receivers into devices.

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

Other key features that will become available in the 2016-to-2020 timeframe include full-dimension MIMO, vehicle-to-vehicle and vehicle-to-infrastructure communications, enhanced Multimedia Broadcast/Multicast Services (eMBMS), User-Plane Congestion Management (UPCON), and device-to-device communication (targeted initially at public-safety applications).

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[23] For example, T-Mobile reported that VoLTE comprised 51% of total voice call minutes in the Q1of 2016, compared to 9% in Q1 of 2015. *T-Mobile Investor Factbook Q1-2016.*

[24] Fierce Wireless, "SK Telecom teams with Nokia Networks on eICIC," January 2015.

The appendix explains these features and quantifies performance gains, and Figure 8 illustrates the transition from LTE to LTE-Advanced and LTE-Advanced Pro, which include these features.

Figure 8: LTE to LTE-Advanced Pro Migration[25]

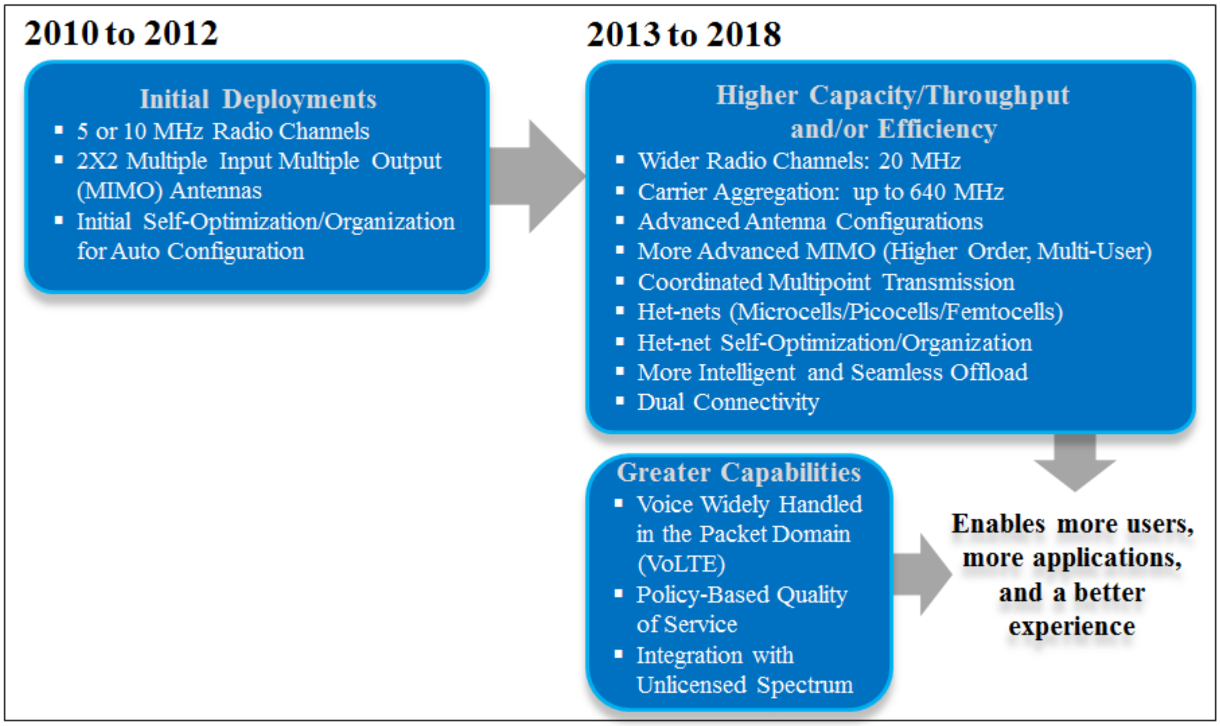
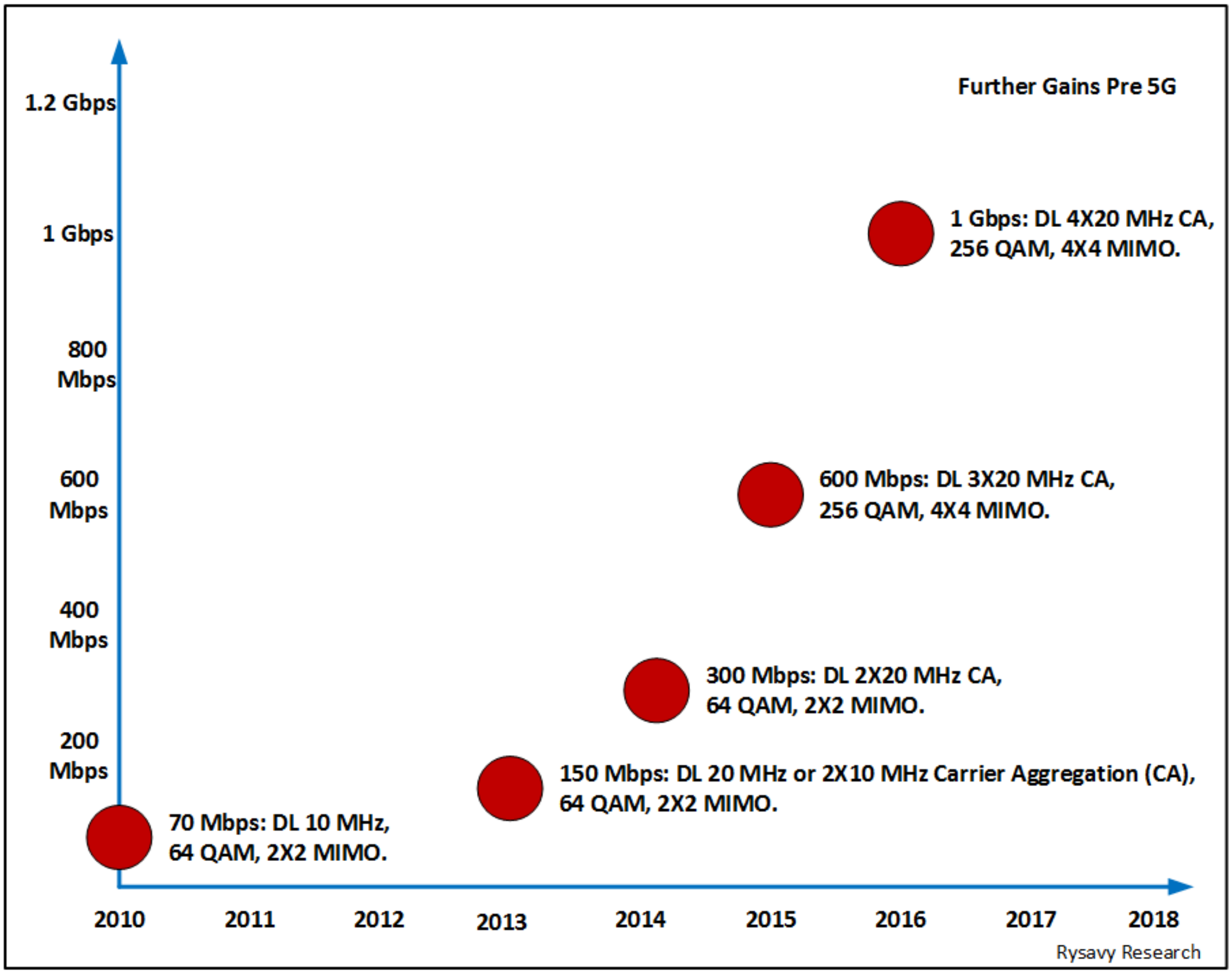


Figure 9 illustrates gains in peak downlink speeds through carrier aggregation, higher-order MIMO, higher-order modulation.

[25] 5G Americas/Rysavy Research

Figure 9: Successive Gains in Peak LTE Downlink Throughput[26]



5G Use Cases (ITU and 3GPP)

The ITU, in its 5G recommendations, divides use cases into three main categories, as shown in Figure 10.

1. **Enhanced Mobile Broadband (eMBB).** eMBB is the most obvious extension of LTE capability, providing higher speeds for applications such as streaming, Web access, video conferencing, and virtual reality. Highest speeds will occur in small cells with limited movement speed of end users, such as with pedestrians.

2. **Massive Machine-Type Communications (mMTC).** Massive machine-type communications extends LTE Internet of Things capabilities—for example, NB-IoT—to support huge numbers of devices, lower cost, enhanced coverage, and long battery life.

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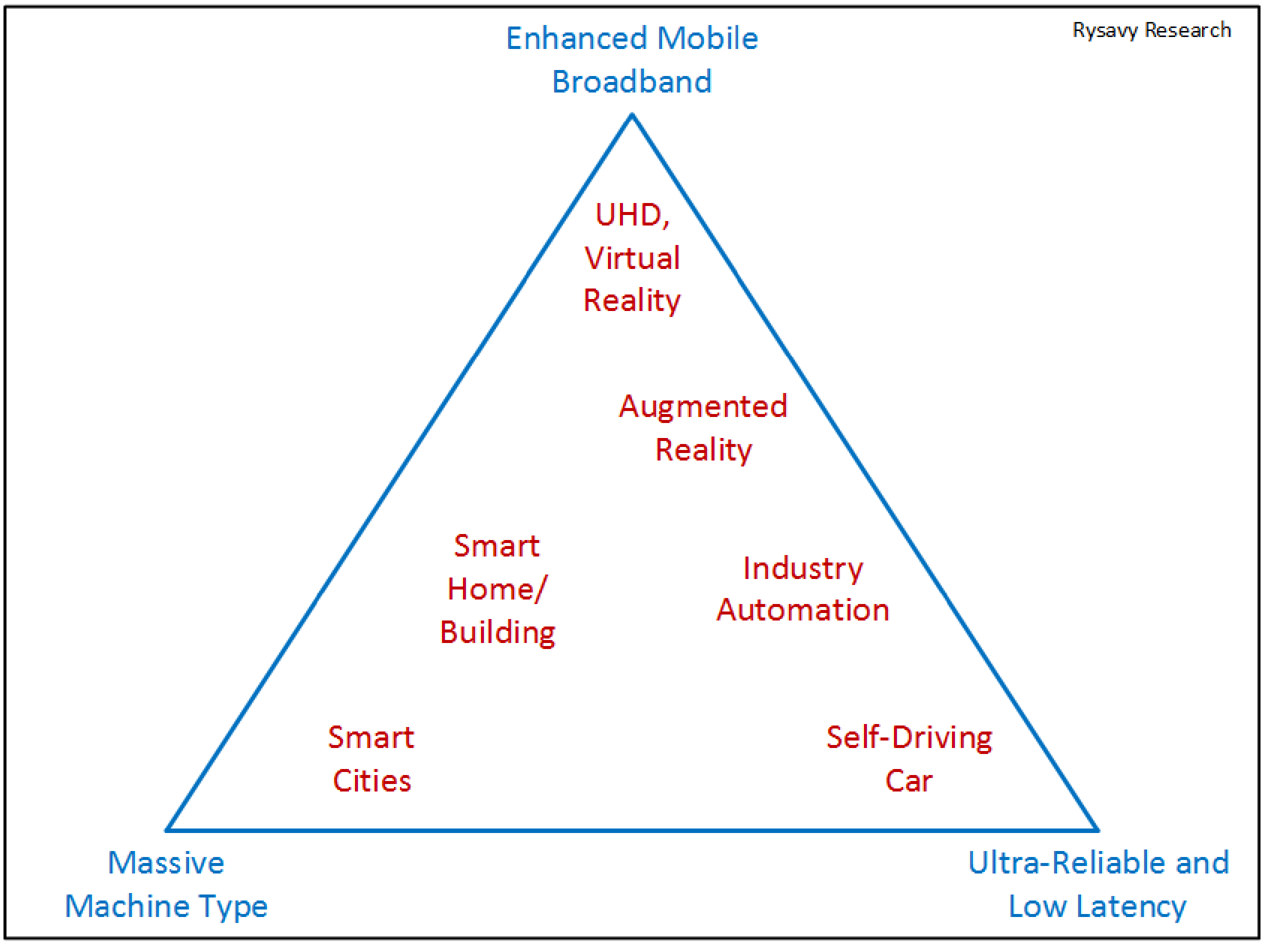
[26] Rysavy Research analysis based on information about commercially available chipsets. Not all LTE features are available simultaneously, and thus throughputs do not necessarily scale linearly with items such as bandwidth.

3. **Ultra-Reliable and Low Latency Communications (URLLC).** Of the three categories, URLLC expands the number of possible wireless applications. Driven by high dependability and extremely short network traversal time, URLLC will enable mission-critical applications, industrial automation, drone control, new medical applications, and self-driving cars. These types of applications are potentially the ones that will deliver the greatest societal benefits, yet unfortunately, at least in the United States, they could be undermined by the Open Internet Order. This category is also referred to as critical machine type communications (cMTC).

Figure 10: ITU Use Case Model[27]



3GPP, in studying 5G, has methodically identified multiple specific use cases in a project called "SMARTER," which are consistent with ITU's model.[28] 3GPP's service dimensions include:

[27] For background, see ITU, *IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond*, Recommendation ITU-R M.2083-0, Sep. 2015.

[28] 3GPP TR22.891, *Feasibility Study on New Services and Markets Technology Enablers*; TR22.861 (Massive Internet of Things); TR22.862 (Critical Communications); TR 22.863 (Enhanced Mobile Broadband); TR22.864 (Network Operation).

- Massive Internet of Things (eHealth, wearables, eCity, eFarm).
- Critical Communications (e.g., vehicles, drones, industry robots).
- Enhanced Mobile Broadband (e.g., augmented reality, virtual reality, ultra-high definition).
- Network Operation (e.g., network slicing, connectivity/routing, migration/interworking).

Using small cells and mmWave radio channels, a 5G network built for capacity could deliver 1 Tbps/km^2 or higher, enabling 5G to compete with wireline broadband services.[29]

5G Technical Objectives

Table 3 shows the ITU's objectives for IMT-2020 (5G) relative to IMT-Advanced (4G).

Table 3: ITU Objectives for IMT-2020 compared with IMT-Advanced[30]

	IMT-Advanced	IMT-2020
Peak Data Rate	DL: 1 Gbps UL: 0.05 Gbps	DL: 20 Gbps UL: 10 Gbps
User Experienced Data Rate	10 Mbps	100 Mbps
Spectrum Efficiency	1 (normalized)	3X over IMT-Advanced
Peak Spectral Efficiency	DL: 15 bps/Hz UL: 6.75 bps/Hz	DL: 30 bps/Hz UL: 15 bps/Hz
Mobility	350 km/h	500 km/h
User Plane Latency	10 msec	1 msec[31]
Connection Density	100 thousand devices/sq.km.	1 million devices sq./km.
Network Energy Efficiency	1 (normalized)	100X over IMT-Advanced
Area Traffic Capacity	0.1 Mbps/sq. m.	10 Mbps/sq. m. (hot spots)

[29] Rysavy Research analysis. See also *Nokia, Ten key rules of 5G deployment, Enabling 1 Tbit/s/km^2 in 2030*, 2015.

[30] ITU Working Party 5D, *IMT-2020 Background*, Revision 1 to Document 5D/TEMP/60-E, Mar. 1, 2016. See also ITU Working Party 5D, *Requirements Related to Technical Performance for IMT-2020 Radio Interfaces,* Mar. 2, 2016 and 3GPP TR 38.913, *Study on Scenarios and Requirements for Next Generation Access Technologies (Release 14),* V0.3.0, Mar. 2016.

[31] Per 3GPP TR 38.913 (V0.3.0, Mar. 2016), 0.5 msec for DL and 0.5 msec for UL for URLCC and 4 msec for UL and 4 msec for DL for eMBB.

	IMT-Advanced	IMT-2020
Bandwidth	Up to 20 MHz/radio channel (up to 100 MHz aggregated)	Up to 1 GHz (single or multipole RF carriers)

In supporting different usage scenarios, not all of these objectives will necessarily be simultaneously available. For example, an IoT application may need to support a large number of devices but at lower throughput rates, while a vehicular application may need high mobility and low latency.

Other expected enhancements include:

- Deep coverage for machines buried within environments.
- Extremely low energy demands for many years of battery operation.
- Low complexity options for inexpensive machine communications.
- Auto-awareness through discovery and self-optimization.

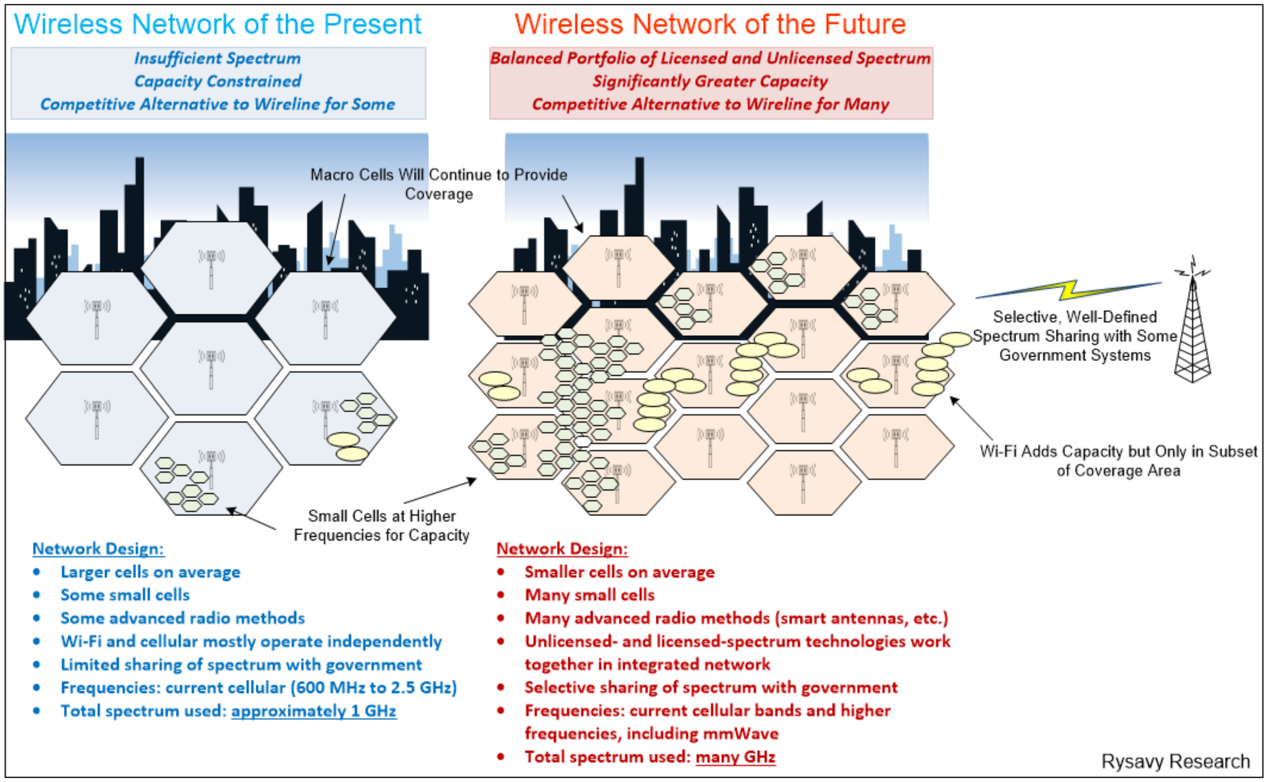
5G Concepts and Architectures

Standards bodies have not yet defined 5G requirements, but various groups are analyzing the possibilities of what might constitute 5G for network deployments in 2020 or beyond. Often stated goals of 5G include:

- Being able to support a greater number of end systems, including IoT applications, at lower average revenue than 4G systems.
- Peak data rates of multi Gbps (see Table 3 above).
- More uniform user experience across the coverage area.
- Support for many frequencies, including existing cellular bands and frequencies above 6 GHz.
- Hierarchical/planned and ad hoc deployment models.
- Use of licensed and unlicensed bands.
- Equal support for human-type and machine-type communications. Includes highly efficient small-data transmission.
- Advanced spectrum sharing, possibly based on spectrum-sharing approaches being developed for the 3.5 GHz band.

Figure 11 shows the transformation of networks, moving from today's LTE-Advanced networks to future LTE-Advanced and eventually 5G networks.

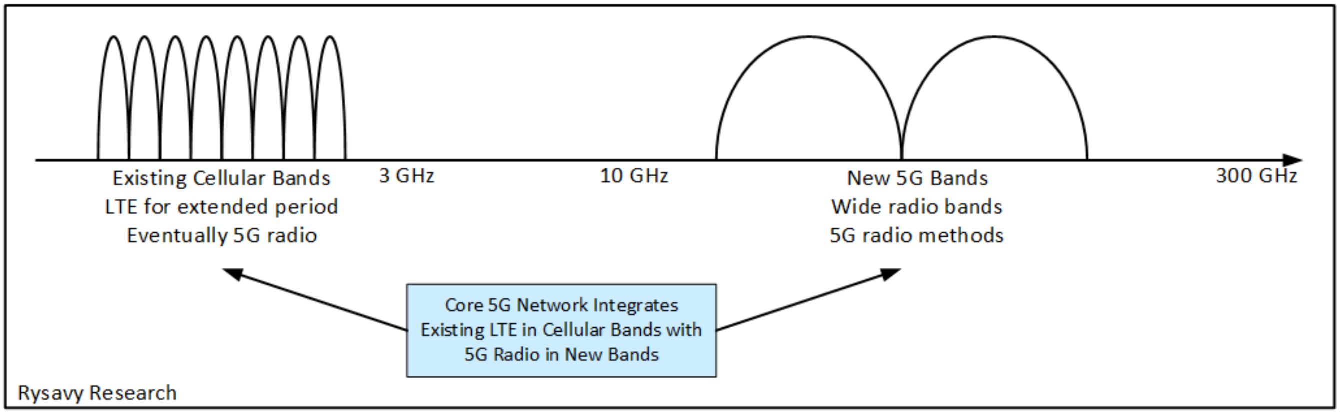
Figure 11: Network Transformation[32]



The fundamental decision for 5G is how to best leverage existing technology investments in LTE while exploiting new spectrum and new technology capabilities. 5G design emphasizes ways to combine existing 4G LTE networks with capabilities provided by 5G. One such approach is to use enhanced LTE in existing frequency bands and to provide interworking with access in new bands that span a wide range of frequencies, as shown in Figure 12.

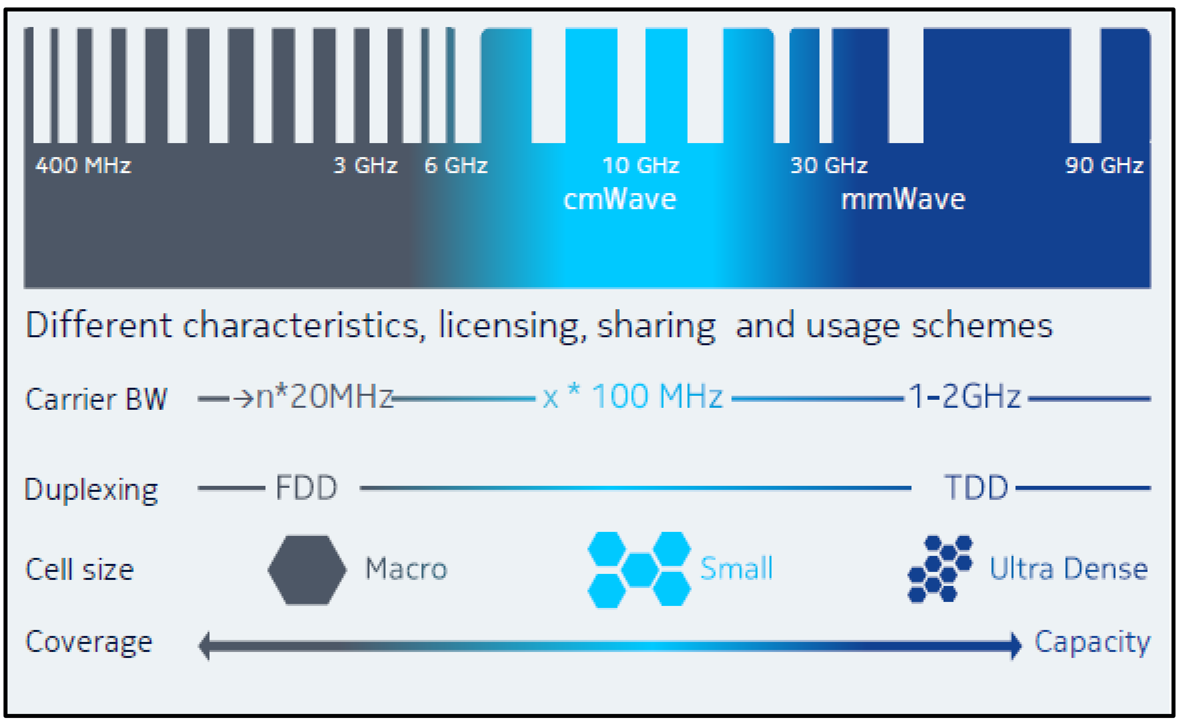
[32] See also Rysavy Research infographic, "Mobile Broadband Networks of the Future," April 2014. Available at http://www.rysavy.com/Articles/2014-05-Networks-of-the-Future-Infographic.pdf.

Figure 12: 5G Combining of LTE and New Radio Technologies



As shown in Figure 13, higher-frequency bands in 5G will provide capacity with smaller cells, and lower bands will provide coverage with larger cells. This is similar to the approach taken in 4G.

Figure 13: Characteristics of Different Bands[33]

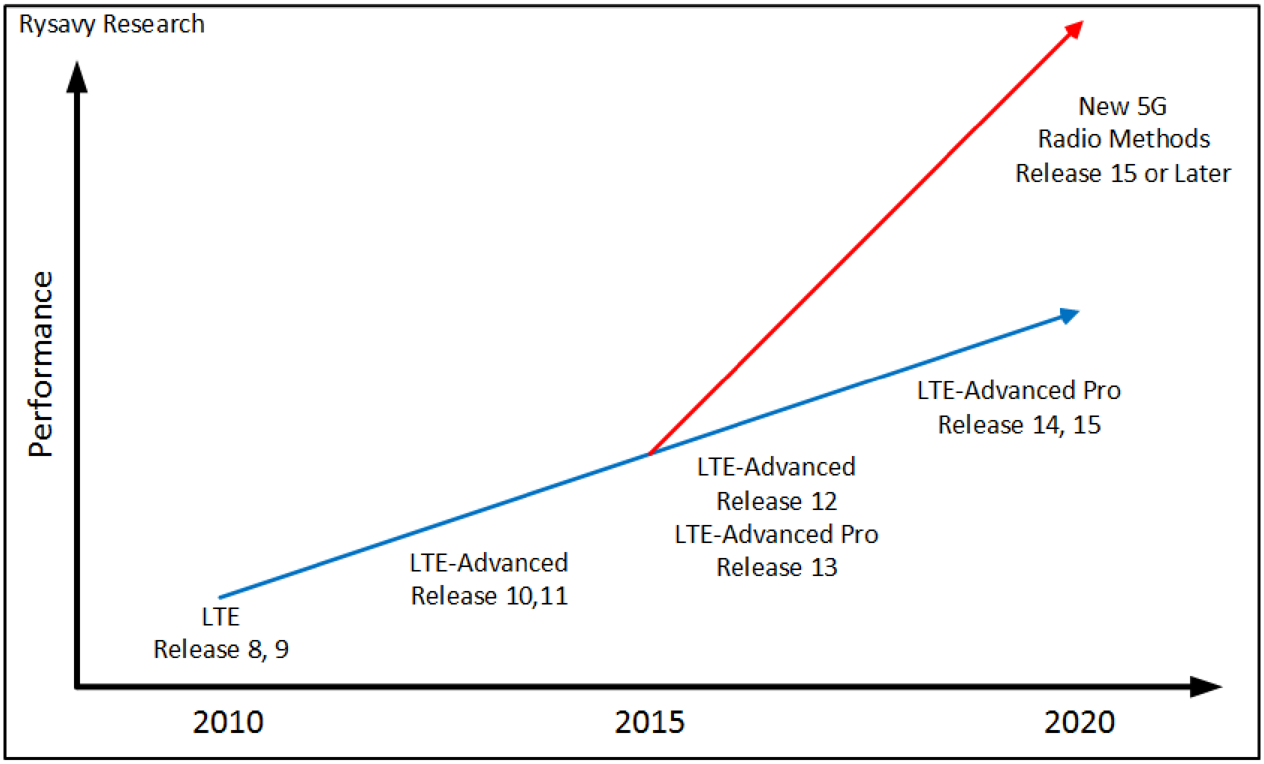


One decision of 5G is whether to use LTE-like radio access in new 5G bands or to instead invent dramatically new radio-access technologies, as shown in Figure 14. New radio

[33] Nokia, *Vision & Priorities for Next Generation Radio Technology*, 3GPP RAN workshop on 5G, Sep. 17-18, 2015.

methods would boost performance and could co-exist with future versions of LTE. Release 14, underway, has a study item that addresses the question of the 5G new radio (NR).

Figure 14: Evolution to 5G Including LTE Improvements and Potential New 5G Radio Methods



While many deployments will integrate LTE and NR, some operators could choose NR-only deployments.

With the mindset of leveraging LTE investments and providing interoperability with LTE networks while increasing performance, the specific technologies designers are evaluating for 5G include the items explained in Table 4.

Table 4: Key 5G Technology Elements under Investigation

Key 5G Technology Element	Description	Benefit
Massive MIMO	Extension of MIMO concept to hundreds of antennas at the base station, enabling spatial multiplexing and beamforming.	A tripling of spectral-efficiency over LTE-Advanced configurations expected.[34]

[34] See, for example, FP7 MAMMOET, *Massive MIMO: The Scalable 5G Technology*, 2016. See also https://massivemimo.eu/.

Key 5G Technology Element	Description	Benefit
	Networks could provide coverage by beams instead of cells.	
6 GHz or higher bands	Most cellular today is below 3 GHz, but new technology allows operation in 6 GHz to 100 GHz for small cells.	Vast new spectrum amounts available (as much as 10X or more) as well as wider radio channels (up to 1 GHz) enabling much higher data rates.
New multi-carrier radio transmission	LTE uses OFDM, but other potential multi-carrier schemes include Filter-Bank Multi-Carrier (FBMC) transmission, Universal Filtered Multi-Carrier (UFMC) transmission, and Generalized Frequency-Division Multiplexing (GFDM).	Lower latency on uplink transmission due to lower synchronization requirements. Potentially better suited for spectrum sharing because the transmission operates in more confined spectrum.
Non-Orthogonal Multiple Transmission	Orthogonality in OFDM avoids interference and creates high capacity but requires extensive signaling and increases delay. Non-Orthogonal Multiple Access (NOMA) and Sparse Coded Multiple Access (SCMA) could complement orthogonal access by taking advantage of advanced interference-cancellation techniques.	Reduced latency for small payloads.
Shared Spectrum Access	Current LTE systems assume dedicated spectrum. Future wireless systems (LTE and 5G) could interface with planned Spectrum Access Systems that manage spectrum among primary (incumbent, e.g., government), secondary (licensed, e.g., cellular), and tertiary (unlicensed) users.	More efficient use of spectrum for scenarios in which incumbents use spectrum lightly.
Advanced Inter-Node Coordination	LTE already uses techniques such as inter-cell interference coordination and Coordinated Multi-Point. In 5G, cloud RANs will enable better coordination across base stations.	Higher network capacity.

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

Key 5G Technology Element	Description	Benefit
Cloud RAN Support	Centralization of RAN functions, such as the medium-access control (MAC) layer and above.	Facilitation of neutral-host cells, lower deployment cost, higher performance.
Network Slicing	Using NVF and SDN as a foundation, network slicing creates virtual wireless services dedicated for specific use cases.	Greater service flexibility.
Future Proofing	A lean system that minimizes the number of broadcasted signals. For example, reference signals could be transmitted jointly with the payload.	Improves performance (efficiency and coverage) and facilitates deployment of new RAN capabilities in the future.[35]

Of the technology elements above, use of higher frequencies, such as above 6 GHz, represents one of the greatest opportunities for higher throughputs and higher capacity. This benefit derives from the potential availability of ten times the amount of spectrum as is currently available, with multiple GHz of contiguous spectrum. But these higher frequencies, especially mmWave frequencies (above 30 GHz), are suitable only over short distances, as explained below. The combination of lower and higher frequencies is therefore crucial for 5G operation. Lower bands could be devoted to coverage and control, while higher bands could provide opportunistic access for high data rates. The lower and higher spectrum bands could operate in a carrier-aggregation or dual connectivity mode, or could use higher-layer aggregations such as multipath TCP and Multipath Quick UDP Internet Connections (MP-QUIC).

Compared with lower frequencies, mmWave frequencies suffer from worse propagation characteristics, even in line-of-sight conditions, because the comparatively smaller aperture area of the receiver's antenna requires some form of beamforming at the transmit side, and potentially even at the receive side. Fortunately, the smaller form factors of mmWave antennas allow for dense packing of antenna arrays. Experimental systems using antenna arrays have demonstrated reliable communications at 28 GHz, even in dense, urban, non-line-of-sight conditions, for distances up to 200 meters.[36] Arrays at the terminal side are space-constrained, but some basic beamforming at the terminal is possible. On the base station side, the arrays may include hundreds of antennas in an approach called "massive MIMO."

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[35] For further details and for other 5G methods under investigation, see METIS II white paper, *Preliminary Views and Initial Considerations on 5G RAN Architecture and Functional Design*, Mar. 8, 2016. Available at https://metis-ii.5g-ppp.eu/wp-content/uploads/5G-PPP-METIS-II-5G-RAN-Architecture-White-Paper.pdf. See also 5G PPP Architecture Working Group, *View on 5G Architecture*, Jul 2016, available at https://5g-ppp.eu/white-papers/.

[36] Samsung, *5G Vision,* February 2015. Available at http://www.samsung.com/global/business-images/insights/2015/Samsung-5G-Vision-0.pdf.

Figure 15 shows how an increasing number of antenna elements can extend coverage through tighter beams. A 77 X 77 antenna array (6,000 elements) can exceed a kilometer at 3.5 GHz (33 dBm transmit power) and reach over 800 meters, even at 30 GHz.

Figure 15: Range Relative to Number of Antenna Elements[37]

Extreme densification is another way that 5G networks will achieve massive increases in capacity. 3G networks reached densities of four to five base stations per sq. km, 4G networks eight to 10, but 5G networks may reach densities of 40 to 50.[38] A likely 5G architecture will use the macro cell for control information, coverage, and fallback, but small cells, often operating at higher frequencies, for high-bandwidth data communication. Either wireless connections or fiber will provide backhaul. Figure 16 shows how such an approach could also employ beamforming and beam tracking when using mmWave bands in the small cells.

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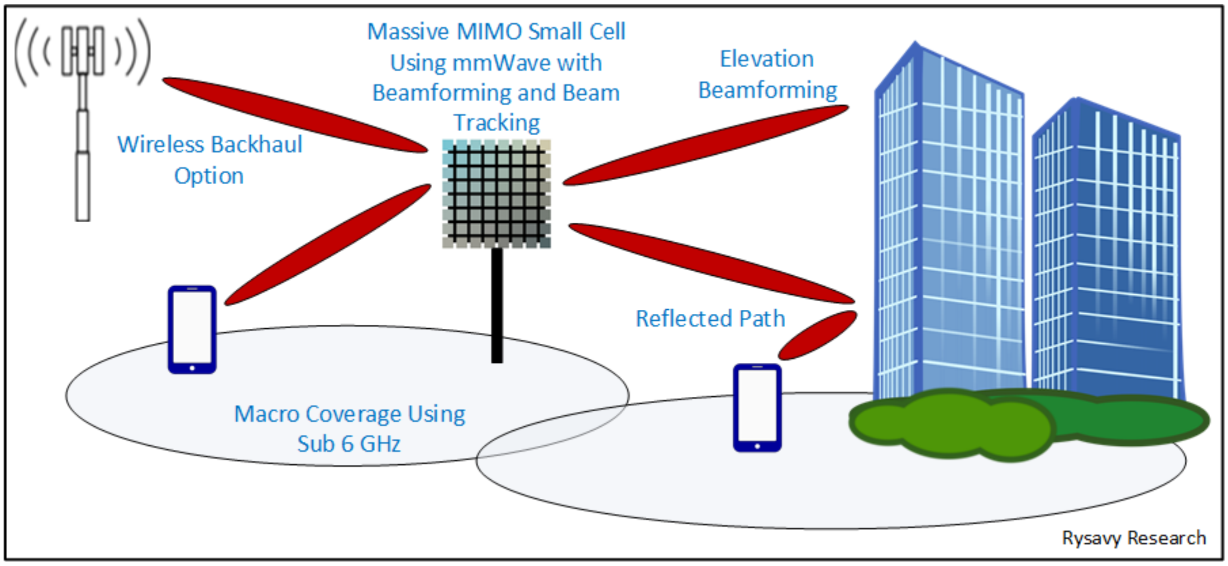
[37] Dr. Seizo Onoe, NTT DOCOMO, presentation at Brooklyn 5G Summit, Apr. 21, 2016. Used by permission.

[38] IEEE Wireless Communications, *5G Ultra-Dense Cellular Networks,* Feb. 2016.

Figure 16: 5G Likely Architecture for Low Band/High Band Integration.



Other technical approaches researchers are investigating in conjunction with 5G include flexible mobility, context-aware networking, and moving networks.[39]

In combination, the various methods expected in 5G will provide users in mmWave-band hotspot coverage at least a 100-fold increase in throughput over LTE, achieved by:

- Five- to 10-fold gains due to fewer users in each small cell.
- 10-fold gains from access to much larger amounts of spectrum.
- Three-fold gains or more from improved spectral efficiency using technologies such as massive MIMO.

Information-Centric Networking

For many usage scenarios, wireless networks provide broadband access to the internet, a network that itself is evolving. The internet is based on a node-centric design developed forty years ago. The point-to-point method of communication the internet uses has functioned well for a vast array of applications but is not optimal for the way content is developed and distributed today. Industry and academic organizations are researching a concept called "Information-Centric Networking." ICN seeks a new approach of in-network caching that distributes content on a large scale, cost-efficiently and securely.

Most internet content uses Uniform Resource Identifiers (URIs) to locate objects and define specific location-dependent IP addresses. This approach, however, causes problems when content moves, sites change domains, or content is replicated and each copy appears as a different object. Developments such as peer-to-peer overlays and content distribution networks (such as Akamai) that distribute cached copies of content are a first step toward an information-centric communication model.

[39] For more details, refer to *4G Americas' Recommendations on 5G Requirements and Solutions*, October 2014.

ICN is built from the ground up on the assumption of mobility, so it eliminates the mobility overlays on which current mobile broadband networks depend. The approach will be able to place information anywhere in the network with immediate and easy retrieval.

Key principles of ICN include:

- The architecture inherently supports user mobility.
- Network operations are name-based instead of address- or node-based.
- The network itself stores, processes, and forwards information.
- Intrinsic security guarantees the integrity of every data object.

The goal of ICN is to simplify the storage and distribution of gigantic amounts of content while reducing the amount of traffic and latency users face when accessing the content. The internet cannot just be replaced, however, so in initial stages, ICN would operate as an overlay, and over time would assume an increasing percentage of the functions within the internet. ICN would not discard IP; rather, it seeks to generalize the routing concept to enrich networking with new capabilities.

Some technology aspects of ICN include:

- Information retrieval from multiple sources without needing to know the location of the information.
- Multipath communications that improves user performance and traffic load balancing.
- Subsequent requests for the same data will be served locally without needing to fetch it from original repository.
- Elimination of the name-to-location indirection associated with Domain Name Service (DNS).

Because mobility is such a central aspect of ICN, mobile network operators are in a unique position to participate in ICN-related research and development, and to do so as part of 5G development. ICN has not progressed to a level at which 3GPP specification work could include it, so instead promoters are ensuring that 5G specification work does not preclude it. With this approach, operators in the 2020s will have the option of overlaying ICN capability on their 5G networks. ICN could even be implemented as a 5G network slice for mobile and end-systems capable of ICN.

5G Phased Release

So that operators can deploy initial 5G capabilities without every detail of the 5G system defined, developers are planning on a two-phase approach, as Figure 17 depicts. The first phase, planned for 3GPP Release 15, could introduce a new 5G radio while retaining an LTE core network, the 5G control plane using LTE signaling, and the 5G user plane either connecting directly to the LTE core or connecting via a collocated LTE base station.

The second phase, planned for 3GPP Release 16, will likely define a 5G core network architecture to which both the 5G and LTE RAN connect directly.[40] For minimal latency, the 5G core network will likely be deployed in a distributed fashion.

Figure 17: Two-Phase Approach to 5G Deployment

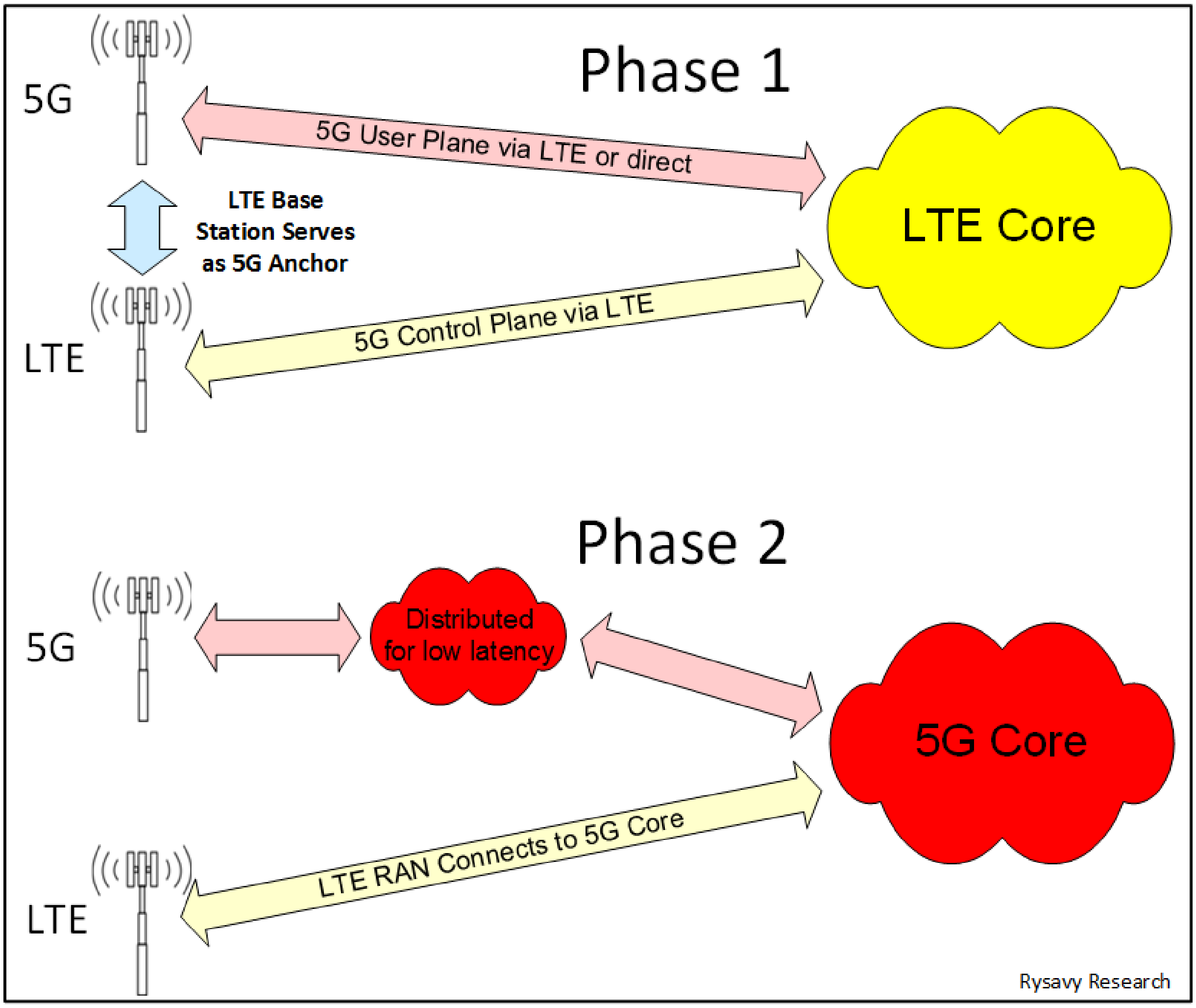
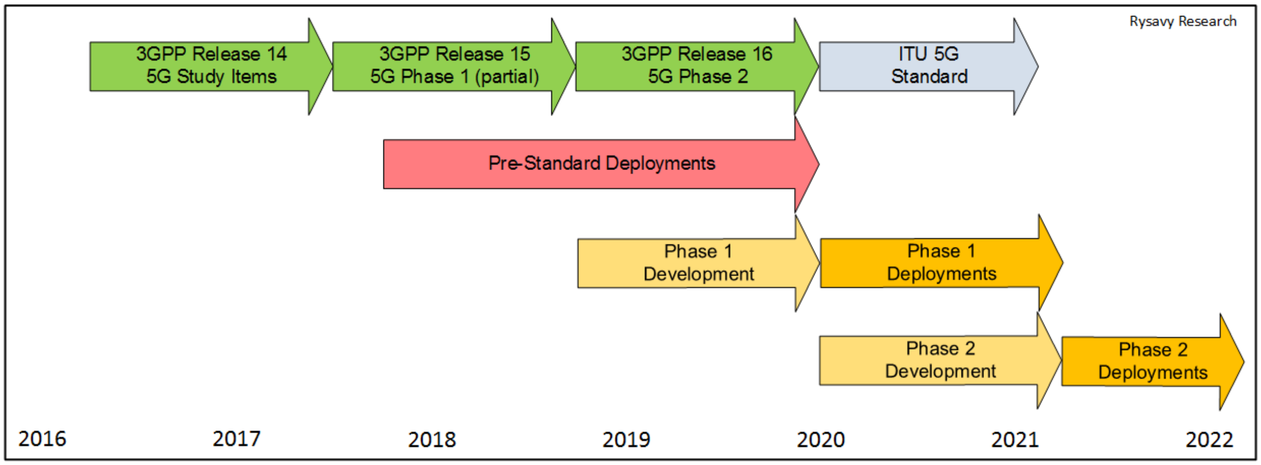


Figure 18 shows the approximate schedule for 5G development and deployment.

[40] See discussion of 5G architecture options at http://www.3gpp.org/ftp/tsg_ran/TSG_RAN/TSGR_72/Docs/RP-161249.zip.

Figure 18: 5G Schedule[41]



3GPP Releases

3GPP standards development falls into three principal areas: radio interfaces, core networks, and services. Progress in the 3GPP family of technologies has occurred in multiple phases, first with GSM, then GPRS, EDGE, UMTS, HSPA, HSPA+, LTE, LTE-Advanced, and now LTE-Advanced Pro. Underlying radio approaches have evolved from Time Division Multiple Access (TDMA) to CDMA to Orthogonal Frequency Division Multiple Access (OFDMA), which is the basis of LTE. 3GPP is also involved in standardization of 5G technology.

Table 5 summarizes the key 3GPP technologies and their characteristics.

Table 5: Characteristics of 3GPP Technologies

Technology Name	Type	Characteristics	Typical Downlink Speed	Typical Uplink Speed
HSPA[42]	WCDMA	Data service for UMTS networks. An enhancement to original UMTS data service.	1 Mbps to 4 Mbps	500 Kbps to 2 Mbps

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[41] Rysavy Research integration of multiple sources of information, including 3GPP, "3GPP on track to 5G," June 27, 2016, http://www.3gpp.org/news-events/3gpp-news/1787-ontrack_5g, viewed July 6, 2016 and "RAN 5G Workshop - The Start of Something," http://www.3gpp.org/news-events/3gpp-news/1734-ran_5g, September 19, 2015, viewed May 25, 2016.

[42] HSPA and HSPA+ throughput rates are for a 5+5 MHz deployment.

Technology Name	Type	Characteristics	Typical Downlink Speed	Typical Uplink Speed
HSPA+	WCDMA	Evolution of HSPA in various stages to increase throughput and capacity and to lower latency.	1.9 Mbps to 8.8 Mbps in 5+5 MHz[43] 3.8 Mbps to 17.6 Mbps with dual carrier in 10+5 MHz	1 Mbps to 4 Mbps in 5+5 MHz or in 10+5 MHz
LTE	OFDMA	New radio interface that can use wide radio channels and deliver extremely high throughput rates. All communications handled in IP domain.	6.5 to 26.3 Mbps in 10+10 MHz[44]	6.0 to 13.0 Mbps in 10+10 MHz
LTE-Advanced	OFDMA	Advanced version of LTE designed to meet IMT-Advanced requirements.	Significant gains through carrier aggregation, 4X2 and 4X4 MIMO, and 256 QAM modulation.	

User achievable rates and additional details on typical rates are covered in the appendix section "Data Throughput."

3GPP develops specifications in releases, with each release addressing multiple technologies. For example, Release 8 defined dual-carrier operation for HSPA but also introduced LTE. Each release adds new features and improves performance of existing functionality in many different ways. Table 6 summarizes some key features of different 3GPP releases.

Table 6: Key Features in 3GPP Releases[45]

Release	Year	Key Features
99	1999	First deployable version of UMTS.
5	2002	High Speed Downlink Packet Access (HSDPA) for UMTS.

[43] "5+5 MHz" means 5 MHz used for the downlink and 5 MHz used for the uplink.

[44] 5G 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. See additional LTE throughput information in the section below, "LTE Throughput."

[45] After Release 99, release versions went to a numerical designation beginning with Release 4, instead of designation by year.

Release	Year	Key Features
6	2005	High Speed Uplink Packet Access (HSUPA) for UMTS.
7	2008	HSPA+ with higher-order modulation and MIMO.
8	2009	Long Term Evolution. Dual-carrier HSDPA.
10	2011	LTE-Advanced, including carrier aggregation and eICIC.
11	2013	Coordinated Multi Point (CoMP).
12	2015	Public safety support. Device-to-device communications. Dual Connectivity. 256 QAM on the downlink.
13	2016	LTE-Advanced Pro features. LTE operation in unlicensed bands. LTE-WLAN Aggregation. Narrowband Internet of Things.
14	2017	LTE-Advanced Pro additional features. Study item for 5G "New Radio."
15	2018	Phase 1 of 5G. First deployable version with partial functionality. Likely to emphasize enhanced-mobile-broadband use case and sub-40 GHz operation.
16	2019	Phase 2 of 5G. Full compliance with ITU IMT-2020 requirements. Likely to add >40 GHz operation, core network functions, and additional use cases for massive IoT and ultra-reliable and low-latency communications.

Refer to the Appendix section "3GPP Releases" for a more detailed listing of features in each 3GPP Release.

Supporting Technologies and Architectures

Network architects design networks using a deep and wide toolkit, including multiples types of cell sizes, integration with unlicensed spectrum, smart antennas, converged services, and virtualization.

Types of Cells

Operators have many choices for providing coverage. Lower frequencies propagate further and thus require fewer cells for coverage. The resulting network, however, has lower capacity than one with more cells, so operators have to continually evaluate cell placement with respect to both coverage and capacity.

Table 7 lists the many types of cells. Note that the distinctions, such as radius, are not absolute—perhaps one reason the term "small cell" has become popular, as it encompasses picocells, metrocells, femtocells, and sometimes Wi-Fi.

With "plug-and-play" capability derived from self-configuring and self-organizing features, small cells will increasingly be deployed in an ad hoc manner, anywhere power and backhaul are available, yet will operate in tight coordination with the rest of the network.

A proliferation of small cells inside buildings will also provide coverage from inside to outside, such as in city streets, the reverse of traditional coverage that extends from outdoor cells to inside.

Extremely dense outdoor deployments could reach 1,000 cells per square kilometer.

Table 7: Types of Cells and Typical Characteristics (Not Formally Defined)

Type of Cell	Characteristics
Macro cell	Wide-area coverage. LTE supports cells up to 100 km in range, but typical distances are .5 to 5 km radius. Always installed outdoors.
Microcell	Covers a smaller area, such as a hotel or mall. Range to 2 km, 5-10W, and 256-512 users. Usually installed outdoors.
Picocell	Indoor or outdoor. Outdoor cells, also called "metrocells." Typical range 15 to 200 meters outdoors and 10 to 25 meters indoors, 1-2W, 64-128 users. Deployed by operators primarily to expand capacity.
Consumer Femtocell	Indoors. Range to 10 meters, less than 50 mW, and 4 to 6 users. Capacity and coverage benefit. Usually deployed by end users using their own backhaul.
Enterprise Femtocell	Indoors. Range to 25 meters, 100-250 mW, 16-32 users. Capacity and coverage benefit. Deployed by operators.
Distributed antenna system.	Expands indoor or outdoor coverage. Same hardware can support multiple operators (neutral host) since antenna can support broad frequency range and multiple technologies. Indoor deployments are typically in larger spaces such as

Type of Cell	Characteristics
	airports. Has also been deployed outdoors for coverage and capacity expansion.
Remote radio head (RRH)	Uses baseband at existing macro site or centralized baseband equipment. If centralized, the system is called "cloud RAN." Requires fiber connection.
Wi-Fi	Primarily provides capacity expansion. Neutral-host capability allows multiple operators to share infrastructure.

Smalls Cells and Heterogeneous Networks

Historically, increasing the number of cell sites has been the primary method for increasing capacity, providing gains far greater than what can be achieved by improvements in spectral efficiency alone. The next wave of densification is by using what the industry calls "small cells."

Central to small-cell support is the heterogeneous network architecture, with multiple types of cells serving a coverage area, varying in frequencies used, radius, and even radio technology used.

HetNets offer significant increases in capacity and improvements, including:

1. 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.

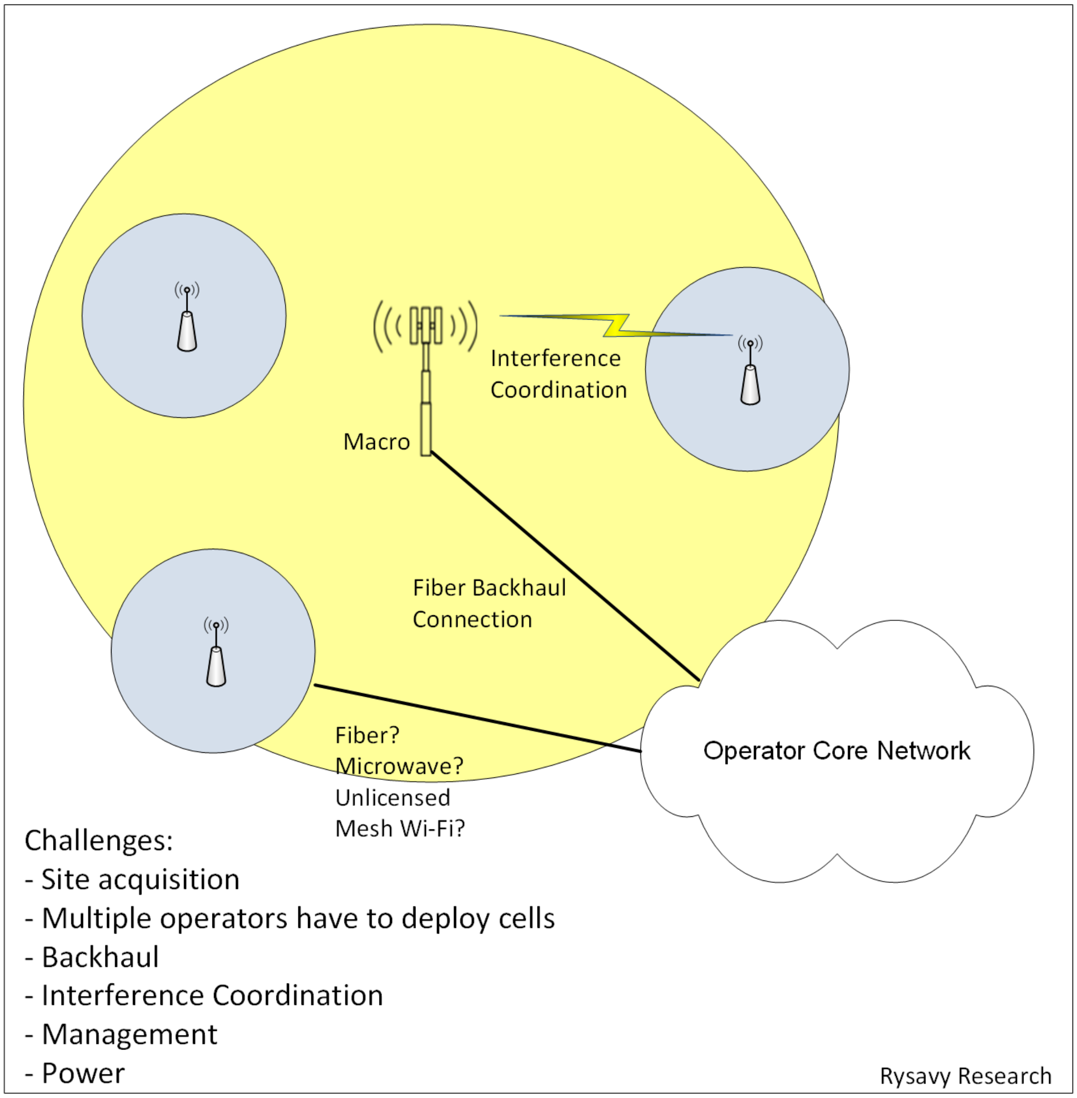
2. Strategic placement of picocells within the macro cell provides the means to absorb traffic in areas where there are higher concentrations of users. Locations can include businesses, airports, stadiums, convention centers, hotels, hospitals, shopping malls, high-rise residential complexes, and college campuses.

3. Smaller cells can also improve signal quality in areas where the signal from the macro cell is weak.

Essential elements for practical HetNet deployment are self-optimization and self-configuration, especially as the industry transitions from hundreds of thousands of cells to millions. The appendix covers technical aspects of HetNets in the sections, "Heterogeneous Networks and Small Cells" and "Self-Organizing Networks."

While promising in the long term, one immediate 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 always feasible. Site acquisition and the need for multiple operators to deploy their own cells in a coverage area are additional challenges. Figure 19 depicts the challenges.

Figure 19: Small-Cell Challenges



Despite the challenges, small cells will ultimately contribute greatly to increased network capacity. But how will small cells evolve, and what configuration will be most common? Today's small-cell deployments are still in early stages. Expanding capacity with additional spectrum remains a safer and more immediate solution, explaining why, for example, operators are deploying LTE in AWS bands to augment 700 MHz LTE services.

Table 8 lists possible configurations. Note that many of these approaches can be combined, such as using picos and Wi-Fi offload.

Table 8: Small-Cell Approaches

Small-Cell Approach	Characteristics
Macro plus small cells in select areas.	Significant standards support. Femtocells or picocells can use same radio carriers as macro (less total spectrum

Small-Cell Approach	Characteristics
	needed) or can use different radio carriers (greater total capacity).
Macro in licensed band plus LTE operation in unlicensed bands.	Promising approach for augmenting LTE capacity in scenarios where operator is deploying LTE small cells.[46] See discussion below in the section on unlicensed spectrum integration.
Macro (or small-cell) cellular in licensed band plus Wi-Fi.	Extensively used today with increased use anticipated. Particularly attractive for expanding capacity in coverage areas where Wi-Fi infrastructure exists but small cells with LTE do not. LTE Wi-Fi Aggregation (being specified in Release 13) is another approach, as are MP-TCP and MP-QUIC.
Wi-Fi only.	Low-cost approach for high-capacity mobile broadband coverage, but impossible to provide large-area continuous coverage without cellular component.

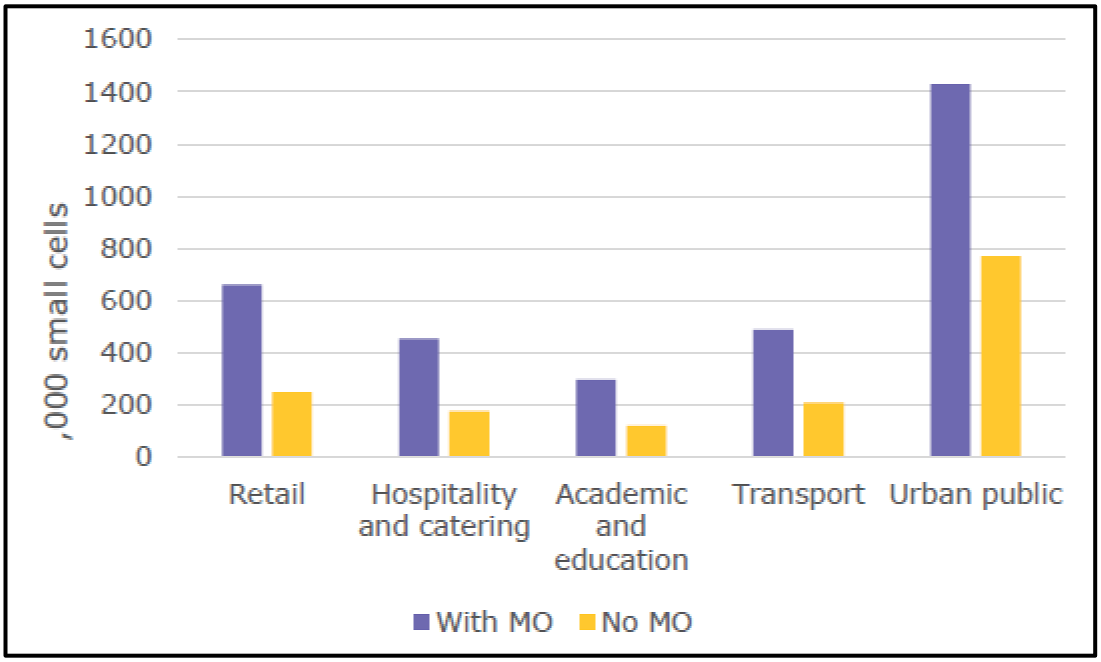
Neutral-Host Small Cells

Key factors that will accelerate deployment of small cells are multi-operator and neutral-host solutions.[47] Currently, nearly all small-cell deployments are operator-specific, but in the future, deployments supporting multiple operators could reduce the cost per operator to provide coverage. Figure 20 projects the greater number of deployments likely to occur by 2020 with and without multi-operator platforms.

[46] See Rysavy Research, "Will LTE in Unlicensed Spectrum Unlock a Vast Store of Mobile Broadband Capacity?" MIMO World, June 2014. Available at http://www.mimoworld.com/?p=2377.

[47] Small Cell Forum, *Market drivers for multi-operator small cells*, Jan. 2016. Report available at scf.io/docs/017. This report defines multi-operator small cells as, "A single small cell which can support coverage for multiple operators' networks in the spectrum of just one, and a neutral host as, "A small cell network deployed and run by an independent third party, paying fees for an MNO's spectrum (or in future, other types of spectrum). MNOs and other providers then pay fees to connect to the network."

Figure 20: Global Small-Cell Forecast in 2020 with and without Access to Multi-Operator Platforms[48]



A candidate band for neutral-host small cells is 3.5 GHz, using LTE TDD and MulteFire as potential technologies. Wi-Fi technology also addresses neutral-host configurations at the access level, but it has roaming and authentication challenges. HotSpot 2.0 (covered in the appendix) addresses roaming and authentication but is not yet widely used.

ACG Research reported last year that the worldwide small-cell market grew by 17.5% over the previous year and predicted it will grow five-fold by 2019.[49]

Unlicensed Spectrum Integration

Unlicensed spectrum is becoming ever-more important to mobile broadband networks. Initial use was rudimentary offload onto Wi-Fi networks, but now, Wi-Fi networks are becoming more tightly integrated into cellular networks. Efforts are also underway to use LTE in unlicensed spectrum.

Unlicensed spectrum adds to capacity in two ways. First, a large amount of spectrum (approximately 500 MHz) is available across the 2.4 GHz and 5 GHz bands, with the 3.5 GHz band adding further spectrum in the future. Second, unlicensed spectrum is mostly used in small coverage areas, resulting in high-frequency reuse and much higher throughput rates per square meter of coverage versus typical cellular deployments.

The IEEE 802.11 family of technologies has experienced rapid growth, mainly in private deployments. The latest 802.11 standard, 802.11ac, offers peak theoretical throughputs in

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48 Ibid.

49 ACG Research Blog, "Worldwide Small Cell Market to Grow Five-fold by 2019," June 8, 2015.

excess of 1 Gbps and improved range through use of higher-order MIMO. 802.11ac Wave 2 products include a multi-user MIMO capability that further increases capacity and throughput. IEEE is developing a subsequent version, 802.11ax, which could have throughputs as high as 10 Gbps. In the mmWave frequencies, IEEE has developed 802.11ad, which operates at 60 GHz, and is currently working on a successor technology, 802.11ay.

Integration between mobile broadband and Wi-Fi networks can be either 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 thereof, may traverse the operator core network. Wi-Fi calling using IMS, for example, relies on tight integration.

Although offloading onto Wi-Fi can reduce traffic on the core network, the Wi-Fi network does not necessarily always have greater spare capacity than the cellular network. The goal of future integrated cellular/Wi-Fi networks is to intelligently load balance between the two. Simultaneous cellular/Wi-Fi connections will also become possible. For example, in Release 13, 3GPP introduces link aggregation of Wi-Fi and LTE through LWA and LWIP.

Successfully offloading data and providing users a good experience 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. Many stakeholders are working toward tighter integration between Wi-Fi and cellular networks.

Another approach for using unlicensed spectrum employs LTE as the radio technology, initially in a version referred to as LTE-Unlicensed, which will work with Releases 10-12 of LTE, as defined in the LTE-U Forum. In Release 13, 3GPP specified LAA, which implements listen-before-talk capability, a requirement for unlicensed operation in Europe and Japan. Initially, carrier aggregation combines a licensed carrier with an unlicensed 20 MHz carrier in the 5 GHz band as a supplemental channel, with the aggregation of multiple unlicensed channels an eventual possibility. Operating LTE in unlicensed bands could decrease the need for handoffs to Wi-Fi. LAA may also be deployed in 3.5 GHz bands. Enhanced LAA (eLAA), to be specified in Release 14, adds uplink use of unlicensed spectrum.

LTE will not displace Wi-Fi. Besides being an inherently simpler technology, Wi-Fi will remain suited good choice for ad hoc, small business, enterprise, and consumer deployments. Wi-Fi is also well-suited for neutral-host deployments.

A concern with using LTE in unlicensed bands is whether it will be a fair neighbor to Wi-Fi users. LTE-U based on Release 10-12 attempts to address this concern by methods such as selecting clear channels to use and measuring the channel activity of Wi-Fi users, then using an appropriate duty cycle for fair sharing. License-Assisted Access in Release 13 adds listen-before-talk (LBT) and also implements other regulatory requirements that exist in some countries. 3GPP conducted a study and concluded that, "A majority of sources providing evaluation results showed at least one LBT scheme for LAA that does not impact Wi-Fi more than another Wi-Fi network."[50]

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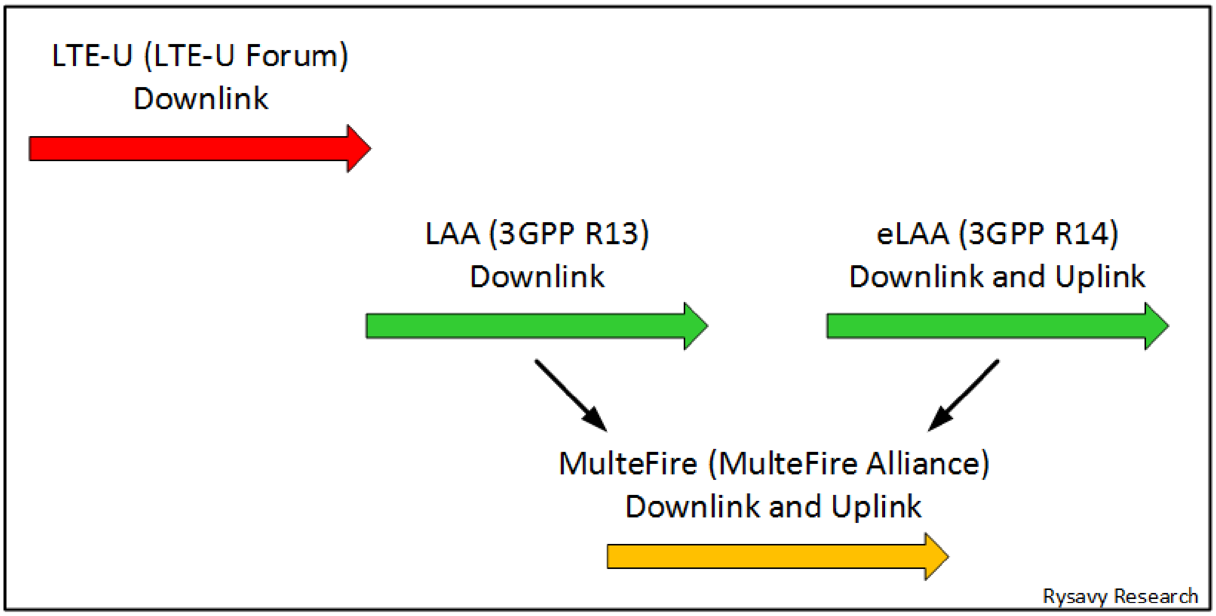
[50] 3GPP, *Technical Specification Group Radio Access Network; Study on Licensed-Assisted Access to Unlicensed Spectrum; (Release 13). 36.889.* See section 9, "Conclusions."

To address co-existence, the cellular industry is working closely with the Wi-Fi Alliance, which in 2016 is developing a test plan for LTE-U. The testing goal is to verify that, in a laboratory environment, an LTE-U base station does not impact a Wi-Fi network any more than another Wi-Fi access point.[51]

MulteFire, specified by the MulteFire Alliance, is an application of LTE in unlicensed bands that does not require an anchor in licensed spectrum, opening up the possibility of deployments by non-operator entities, including internet service providers, venue operators, and enterprises. Under a roaming arrangement with cellular operators, LTE customers could roam into MulteFire networks. Figure 21 shows the evolution of the different versions of LTE for unlicensed bands.

Figure 21: Timeline Relationship of LTE-U, LAA, eLAA, and MulteFire



An alternative approach for integrating Wi-Fi is LWA. LTE handles the control plane, but connections occur over separate LTE base stations and Wi-Fi access points. LWA benefits operators that wish to emphasize Wi-Fi technology for harnessing capacity in unlicensed spectrum. LWIP is a variation of LWA that also integrates LTE and Wi-Fi, but by integrating at a higher level of the protocol stack (IP instead of PDCP), it facilitates use of existing Wi-Fi equipment and devices, with integration typically occurring at the eNodeB.

Figure 22 shows how the different technologies exploit licensed and unlicensed spectrum.

[51] See Wi-Fi Alliance, "Unlicensed Spectrum," http://www.wi-fi.org/discover-wi-fi/unlicensed-spectrum.

Figure 22: How Different Technologies Harness Spectrum

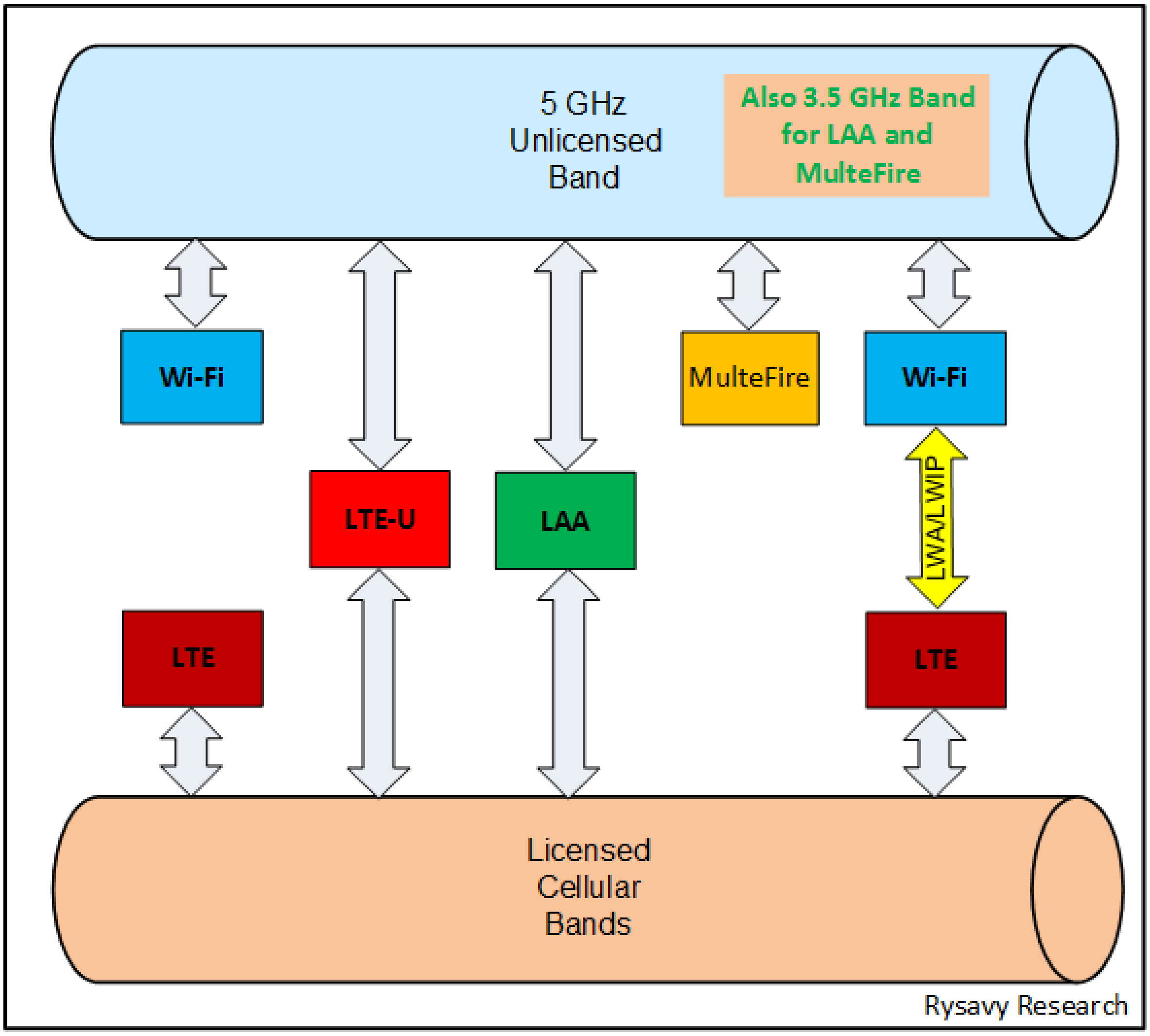


Table 9 summarizes the different uses of unlicensed spectrum for public mobile-broadband networks.

Table 9: Approaches for Using Unlicensed Spectrum.

	Technology	Attributes
Wi-Fi	Ever-more-sophisticated means to integrate Wi-Fi in successive 3GPP Releases.	Combining Wi-Fi with cellular increases capacity.
Release 10-12 LTE-U Based on LTE-U Forum Specifications	LTE-U Forum-specified approach for operating LTE in unlicensed spectrum.	Available in 2016. More seamless than Wi-Fi. Cannot be used in some regions (e.g., Europe, Japan). The impact on Wi-Fi networks is under study.

Release 13 Licensed-Assisted Access	3GPP-specified approach for operating LTE in unlicensed spectrum. Downlink only.	Available in late 2017 or 2018 timeframe. Designed to address global regulatory requirements.
Release 14 Enhanced Licensed-Assisted Access	Addition of uplink operation.	Available in 2019-2020 timeframe.
MulteFire	Does not require a licensed anchor.	Potentially creates a neutral-host small cell solution.
LWA	Aggregation of LTE and Wi-Fi connections at PDCP layer.	Part of Release 13. Available in late 2017 or 2018 timeframe.
LWIP	Aggregation of LTE and Wi-Fi connections at IP layer.	Part of Release 13. Available in late 2017 or 2018 timeframe.

Refer to the appendix section "Unlicensed Spectrum Integration" for further technical details.

Internet of Things and Machine-to-Machine

Machine-to-machine communications, now evolving into the Internet of Things, is a vast opportunity for wireless communications, with all 3GPP technologies potentially playing roles.

The lowest-cost cellular devices enabling M2M communications today are GPRS modems, which may become obsolete as operators sunset their GSM systems. HSPA is also used for M2M communications, as is LTE, which has been optimized to efficiently communicate small bursts of information, making it particularly well suited for M2M.

Low-cost GSM (through Enhanced Coverage GSM IoT [EC-GSM-IoT]) and LTE modem options in 3GPP releases 10 through 13 reduce cost, improve communications range, and extend battery life. See the appendix section "Internet of Things and Machine-to-Machine" for details.

3GPP has a Release 14 study item on how LTE technologies can operate for vehicle communications, including vehicle-to-vehicle and vehicle-to-infrastructure, leveraging device-to-device communications capabilities already specified for LTE in Releases 12 and 13.[52]

Developers will use 3GPP wireless technologies for a large number of IoT applications. In other instances, developers will use local-area technologies, such as Wi-Fi, Bluetooth Low Energy, and ZigBee. New Low-Power Wide-Area (LPWA) wireless technologies emerging specifically to support IoT include Ingenu, LoRa, and Sigfox. The low-power operation of

[52] 3GPP, *3GPP TR 36.885, Technical Specification Group Radio Access Network; Study on LTE-based V2X Services; (Release 14).*

some of these technologies, including LTE, will permit battery operation over multiple years. Table 10 summarizes the various technologies.

Table 10: Wireless Networks for IoT

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

Smart Antennas and MIMO

Smart antennas, defined with progressively greater capabilities in successive 3GPP releases, provide significant gains in throughput and capacity. By employing multiple antennas at the base station and the subscriber unit, the technology either exploits signals traveling through multiple paths in the environment or does beam-steering, in which multiple antennas coordinate their transmissions to focus radio energy in a particular direction.

Initial low-band LTE deployments used 2X2 MIMO on the downlink (two base station transmit antennas, two mobile receive antennas) and 1X2 on the uplink (one mobile transmit antenna, two base station receive antennas). In the higher bands, 2X2 downlink MIMO has been deployed, but it is more common to employ four antennas for uplink reception in a 1X4 configuration. Some LTE deployments are now using 4X2 MIMO on the downlink (four base station transmit antennas). LTE specifications encompass higher-order configurations, such as 4X4 MIMO, 8X2 MIMO, and MU-MIMO on the downlink and 1X4 on the uplink. Practical considerations, such as antenna sizes that are proportional to wavelength, dictate MIMO options for different bands.

Engineers are now experimenting with what are called massive MIMO systems, which employ a far larger number of antenna elements at the base station—64, 128, and eventually even more. Use in 5G of cmWave and mmWave bands, with their short wavelengths, will facilitate massive MIMO, but even before then, 3GPP is developing specifications for massive MIMO for 4G systems in what it calls full-dimension MIMO (FD-MIMO). Two-dimensional antenna arrays may use up to 64 antennas. At 2.5 GHz, an 8X8 array using half wavelength spacing would produce a form factor of 50 cm X 50 cm. Applications of such arrays include beamforming along a horizontal direction as well as beamforming in a vertical direction, such as to serve different levels of high-rise buildings.

See the appendix section "LTE Smart Antennas" and "LTE-Advanced Antenna Technologies" for further details.

Virtualization

Virtualization refers to implementing the functions of infrastructure nodes in software on commercial "off-the-shelf" computing equipment. The approach promises lower capital expenditures, lower operating costs, faster deployment of new services, energy savings, and improved network efficiency. With NFV, multiple tenants will be able to share the same infrastructure, facilitating, for example, mobile virtual network operator (MVNO) and multi-operator virtualized RAN arrangements. NFV, however, also constitutes an entirely new way of building and managing networks, so widespread adoption will occur over a long period.[53]

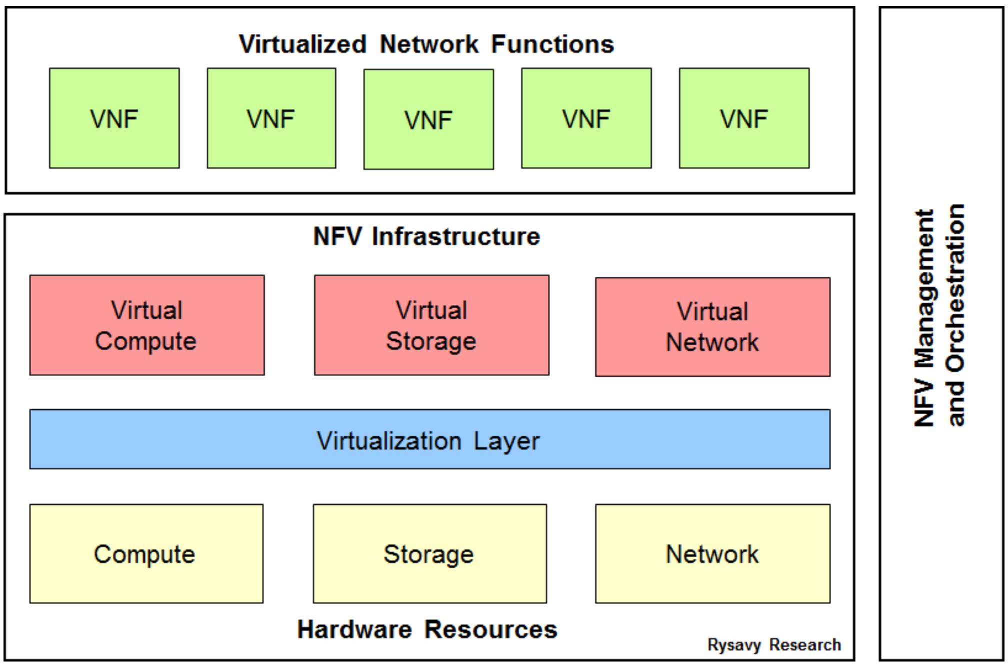
Both the core network and portions of the radio-access network can be virtualized. The core network, consisting of fewer nodes, is an easier starting point. Virtualizing RAN elements, although more complex, could eventually provide the greatest network efficiency gains, particularly for small-cell deployments where it can facilitate coordination among cells and use of methods such as CoMP and interference coordination. Unlike the core, virtualizing the entire RAN is not possible because a physical network function must terminate the radio interface. As operators virtualize their core networks, they put in place the systems and know-how to extend virtualization to the RAN.

[53] For an example of an NFV deployment, see AT&T, *AT&T Domain 2.0 Vision White Paper*, November 2013.

The European Telecommunications Standards Institute (ETSI) is standardizing a framework, including interfaces and reference architectures for virtualization. Other standards and industry groups involved include 3GPP, The Open Network Foundation, OpenStack, Open Daylight, and OPNFV. 3GPP specifications do not currently incorporate NFV.[54]

Figure 23 shows the ETSI framework, in which virtualized network functions are the nodes or applications by which operators build services.

Figure 23: ETSI NFV High-Level Framework



Some specific use cases for NFV include:

- **IMS and VoLTE.** IMS is necessary for VoLTE, but an NFV approach could reduce the complexity associated with the multiple nodes and interfaces in the IMS architecture.
- **Virtualized EPC (VEPC).** The Evolved Packet Core, consisting of the Serving Gateway (SGW), the Packet Gateway (PGW), and Mobile Management Entity (MME), can be virtualized, but doing so will require meeting operator bandwidth, latency, and control-plane service requirements.
- **New VEPC Services.** With a virtualized EPC, an operator can more easily create MVNO services, each with its own virtualized MME, SGW, and PGW. An M2M virtualized service is another example of offering a more finely tuned service for the target application. Because the PGW connects to external networks, further opportunities exist for virtualized services to augment networking functions,

[54] 3GPP, "Network Functions Virtualisation," http://www.3gpp.org/technologies/keywords-acronyms/1584-nfv, accessed June 24, 2015.

including video caching, video optimization, parental controls, ad insertion, and firewalls.

- **Cloud RAN.** Pooling of baseband processing in a cloud RAN can, but does not necessarily, use virtualization techniques. Separating the radio function from baseband processing typically requires transporting digitized radio signals across high-bandwidth (multi-Gbps) fiber connections, sometimes referred to as front-hauling. Refer to the appendix section "Cloud Radio-Access Network (RAN) and Network Virtualization" for a more detailed technical discussion.[55]

Because of higher investment demands, RAN virtualization will take longer to deploy than core network virtualization and likely will occur selectively for small-cell deployments.

For additional details, refer to the 5G Americas white paper, *Bringing Network Function Virtualization to LTE*.[56]

Mobile-Edge Computing

ETSI is standardizing Mobile-Edge Computing, a technology that empowers a programmable application environment at the edge of the network, within the RAN.[57] Goals include reduced latency, more efficient network operation for certain applications, and an improved user experience. Although MEC emphasizes 5G, it can also be applied to 4G LTE networks.

Applications that will benefit are ones that require server-side processing but are location specific. Examples include:

- Augmented reality.
- Intelligent video processing, such as transcoding, caching, and acceleration.
- Connected cars.
- Premise-based IoT gateways.

Fixed Mobile Convergence and IMS

Not only do 3GPP technologies provide continual improvements in capacity and data performance, they also expand available services, either through operator-provided services, such as IP-based voice or video calling, or via interfaces that enable third-party services, such as WebRTC. This section provides an overview of these topics, and the appendix goes into greater detail.

Fixed Mobile Convergence (FMC) refers to the integration of fixed services (such as telephony provided by wireline or Wi-Fi) with mobile cellular-based services. For users, FMC simplifies how these services communicate, making it possible for them to use one device at work, where it connects with a Wi-Fi or macrocellular network, and at home,

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[55] For further details of NFV use cases, refer to ETSI, *ETSI GS NFV 001 v.1.1.1 (2013-10), Network Functions Virtualisation (NFV); Use Cases*.

[56] Available at http://www.4gamericas.org/files/1014/1653/1309/4G_Americas_-_NFV_to_LTE_-_November_2014_-_FINAL.pdf.

[57] See ETSI, *Mobile Edge Computing, A key technology towards 5G*, ETSI White Paper No. 11, Sep. 2015.

where it might connect with a Wi-Fi network or femtocell. Users can also benefit from single voice mailboxes and single phone numbers and gain greater control over how and with whom they communicate.

For operators, FMC can consolidate core services across multiple-access networks. For instance, an operator can offer complete VoIP-based services that operate over Digital Subscriber Line (DSL), Wi-Fi, or mobile broadband. FMC can also offload data-intensive applications, such as video streaming, from the macro network.

IMS is the most important convergence technology, offering access to core services and applications across multiple-access networks. IMS allows for creative blending of different types of communications and information, including voice, video, instant messaging (IM), presence information, location, and documents. Developers can create applications never before possible, and users can communicate in entirely new and dynamic ways. For example, during an interactive text-based chat session, a user could launch a voice call. Or during a voice call, a user could suddenly add a simultaneous video connection, or start transferring files. While browsing the Web, a user could decide to speak to a customer-service representative.

IMS will be a key platform for all-IP architectures for both HSPA and LTE. Although IMS adoption by cellular operators was initially slow, deployment is accelerating as operators make packet voice service available for LTE. Operators will keep using VoLTE, enabled by IMS, even as they roll out 5G.

Multicast and Broadcast

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

VoLTE, RCS, WebRTC, and Wi-Fi Calling

Voice is evolving from a separate circuit-switched service in 2G and 3G networks to a packet-switched-service in 4G LTE networks that can integrate with other services and applications, such as messaging and video calling. Elements that make these capabilities possible include the quality-of-service mechanisms in LTE, the IMS platform discussed above, implementation of Rich Communications Suite, compliance with GSMA IR.92 guidelines, and optional support for WebRTC.

Voice Support and VoLTE

While 2G and 3G technologies were deployed from the beginning with both voice and data capabilities, LTE networks can be deployed with or without voice support. Moreover, there are two methods available: circuit-switched fallback (CSFB) to 2G/3G and VoIP. Most operators deploying LTE used CSFB initially but are now migrating to VoIP methods with VoLTE that uses IMS. Initial VoLTE deployments occurred in 2012. Because VoLTE needs new software in phones, the transition from circuit-switched voice to VoLTE on a large scale will occur over a number of years as users upgrade their devices.

For the time being, 3GPP operators with UMTS/HSPA networks will continue to use circuit-switched voice for their 3G connections, although packet voice over HSPA (VoHSPA) methods have been defined.[58]

Using VoLTE, operators are planning high-definition (HD) voice using the new Adaptive Multi-Rate Wideband (AMR-WB) voice codec. HD voice not only improves voice clarity and intelligibility, it also suppresses background noise. AMR-WB extends audio bandwidth to 50-7000 Hz compared with the narrowband codec that provides audio bandwidth of 80-3700 Hz. HD voice will initially function only between callers on the same network. 3GPP has also developed a new voice codec, called “Enhanced Voice Services” (EVS), which will be the successor to AMR and AMR-WB codecs.

Other advantages of LTE’s packetized voice include being able to combine it with other services, such as video calling and presence; half the call setup time of a 3G connection; and high voice spectral efficiency. Some operators, such as in Canada, are deploying only LTE networks, making voice support essential. With VoLTE’s HD voice quality, lower delay, and higher capacity, operators can compete against OTT VoIP providers. Due to traffic prioritization, VoLTE voice quality remains high even under heavy loads that cause OTT voice service to deteriorate.

Applications based on WebRTC will also increasingly carry voice sessions. See the section “VoLTE and RCS” in the appendix for more details on LTE voice support.

Rich Communications Suite

An initiative called “Rich Communications Suite” (RCS), supported by many operators and vendors, builds on IMS technology to provide a consistent feature set as well as implementation guidelines, use cases, and reference implementations. RCS uses existing

[58] For further details, see 4G Americas, *Delivering Voice Using HSPA*, February 2012. Available at http://www.4gamericas.org/documents/4G%20Americas%20VoHSPA%20paper_final%202%2022%2012.pdf.

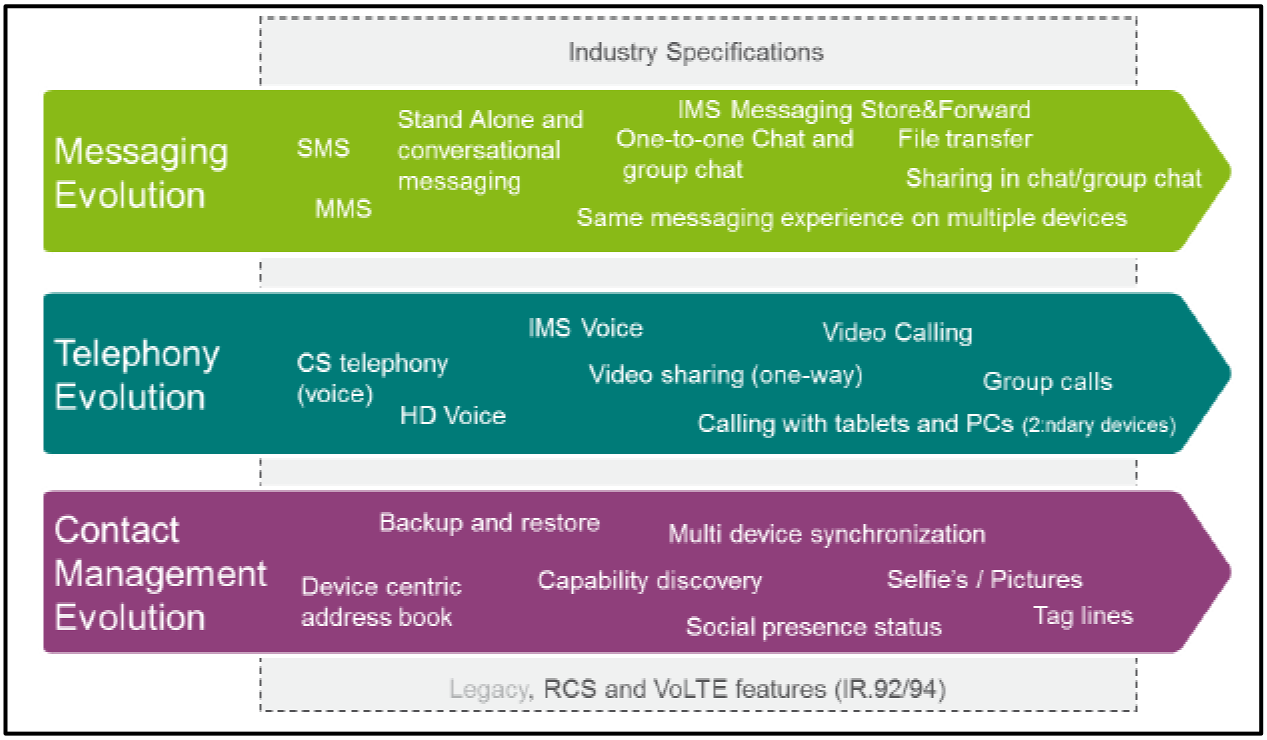
standards and specifications from 3GPP, Open Mobile Alliance (OMA), and GSMA and enables interoperability of supported features across operators that support the suite. RCS supports both circuit-switched and packet-switched voice and can interoperate with LTE packet voice.

Core features include:

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

The primary drivers for RCS adoption are the ability to deploy VoLTE in a well-defined manner and to support messaging in the IP domain. RCS addresses the market trend of users moving away from traditional text-based messaging and provides a platform for operator-based services that compete with OTT messaging applications. Figure 24 shows the evolution of RCS capability, including the addition of such features as messaging across multiple devices, video calling, video sharing, and synchronized contact information across multiple devices.

Figure 24: Evolution of RCS Capability.[59]



[59] 4G Americas, *VoLTE and RCS Technology - Evolution and Ecosystem*, Nov. 2014.

WebRTC

WebRTC is an open project supported by Google, Mozilla, and Opera within the Internet Engineering Taskforce (IETF) that enables real-time communications in Web browsers via JavaScript APIs. 3GPP Release 12 specifications define how WebRTC clients can access IMS services, including packet voice and video communication. WebRTC operating over IMS gains the additional benefit of seamless transition across transport networks, for example, LTE to Wi-Fi.

Operators can integrate WebRTC with RTC, facilitating development of vertical applications such as telemedicine and customer service. WebRTC and RCS are more complementary than competitive. Both, through application interfaces, can provide access to underlying network functions.

Wi-Fi Calling

Another advantage of the VoLTE/IMS/RCS architecture is that it is agnostic to the user connection, meaning voice and video service can extend to Wi-Fi connections as easily as LTE connections. Wi-Fi calling can be advantageous in coverage areas were the Wi-Fi signal has better quality than an LTE signal. For video calling, use of Wi-Fi will also reduce data consumption over the cellular connection. By implementing a standards-based approach, as opposed to OTT-voice approaches, called parties see the same phone number regardless of network and can reach the subscriber using that phone number.

Previous technical approaches, such as Generic Access Network (GAN, initially called Unlicensed Mobile Access [UMA]), did not include as robust a handover mechanism as is provided by VoLTE/IMS.

For the best-quality voice in a Wi-Fi network, the device and Wi-Fi network should implement Wi-Fi Multimedia (WMM), which gives voice packets higher priority than other data traffic. WMM is especially necessary in congested networks. In addition, the Access Network Discovery and Selection Function (ANDSF) and cellular-WLAN enhancement features in 3GPP Release 12 introduce policies for enabling voice handover between LTE and Wi-Fi.

Roaming with Wi-Fi calling will need to address whether the visited network’s IMS infrastructure handles the Wi-Fi call or whether the home network’s IMS does.

Public Safety

An important LTE application is for public safety, initially as a broadband data service and eventually for mission-critical voice service. Current public safety networks use technologies, such as Terrestrial Trunked Radio (TETRA) in Europe and Project 25 (P25) in the United States, that provide mission-critical voice but only narrowband data.

In the United States, the government has made 20 MHz of spectrum available at 700 MHz in band 14 and created the First Responder Network Authority (FirstNet), an independent authority within the National Telecommunications and Information Administration (NTIA) to provide a nationwide public-safety broadband network. Proposals by entities to develop FirstNet were due May 31, 2016.[60] FirstNet says it will issue the award by November 1, 2016.[61]

Another country driving the use of LTE for public safety is the United Kingdom, where the UK Home Office has a program for the Emergency Service Network.

Using LTE for public safety is a complex undertaking because public-safety needs differ from those of consumers. Addressing these needs requires both different features, which 3GPP is incorporating in multiple releases of LTE specifications, and different network deployment approaches. Public safety also has different device-level needs than consumers.

LTE Features for Public Safety

Some broadband applications for public safety can use standard LTE capability. For example, sending email, accessing a database, or streaming a video may not require any special features. Other applications, however, require new capabilities from 3GPP standards, including:

Group Communication

Available in Release 12, the Group Communication Service (GCS) application server, using one-to-one (unicast) and one-to-many communications (broadcast), will be able to send voice, video, or data traffic to multiple public-safety devices. The broadcast mode will use eMBMS to use radio resources efficiently, but if coverage is weak, a unicast approach may deliver data more reliably. The system will be able to dynamically switch between broadcast and unicast modes.

A Release 13 study item is investigating single-cell point-to-multipoint transmission that would use radio resources more efficiently than with eMBMS.

Proximity-Based Services (Device-to-Device)

With proximity-based services, defined in Release 12, user devices will be able to communicate directly, a capability that will benefit both consumers and public safety. This type of communication is called sidelink communication. Consumer devices can find other

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[60] Department of the Interior, *FirstNet Nationwide Public Safety Broadband Network (NPSBN), Solicitation Number: D15PS00295E*, May 16, 2016. Available at https://www.fbo.gov/index?id=711e7a2a8b944e2f53352758558c6e56.

[61] FirstNet Press Release, "FirstNet Extends Proposal Deadline to May 31," Apr. 11, 2016. http://www.firstnet.gov/news/firstnet-extends-proposal-deadline-may-31.

devices only with assistance from the network, but for public safety, devices will be able to communicate directly with other devices independently of the network.

In Release 13, devices will be able to act as relays for out-of-coverage devices, such as inside a building.

The appendix section "Proximity Services (Device-to-Device)" discusses this feature in greater detail.

Mission-Critical Push-to-Talk

MCPTT, being defined in Release 13, will provide one-to-one and one-to-many push-to-talk communications services. With this feature, available in the 2018 timeframe, public-safety organizations will be able to consider retiring legacy voice-based systems.

Prioritization

To prevent interference with public-safety operations in emergency situations experiencing high load, the network can prioritize at multiple levels. First, the network can bar consumer devices from attempting to access the network, thus reducing signaling load. Second, the network can prioritize radio resources, giving public-safety users higher priority. Third, using a new capability called "Multimedia Priority Service" (MPS), the network can prioritize a connection between an emergency worker and a regular subscriber. Finally, the network can assign specific quality-of-service (QoS) parameters to specific traffic flows, including guaranteed bit rate. 3GPP has defined specific QoS quality-class identifiers for public safety.

High power

Release 11 defines higher-power devices for the public safety band that can operate at 1.25 Watts, improving coverage and reducing network deployment costs.

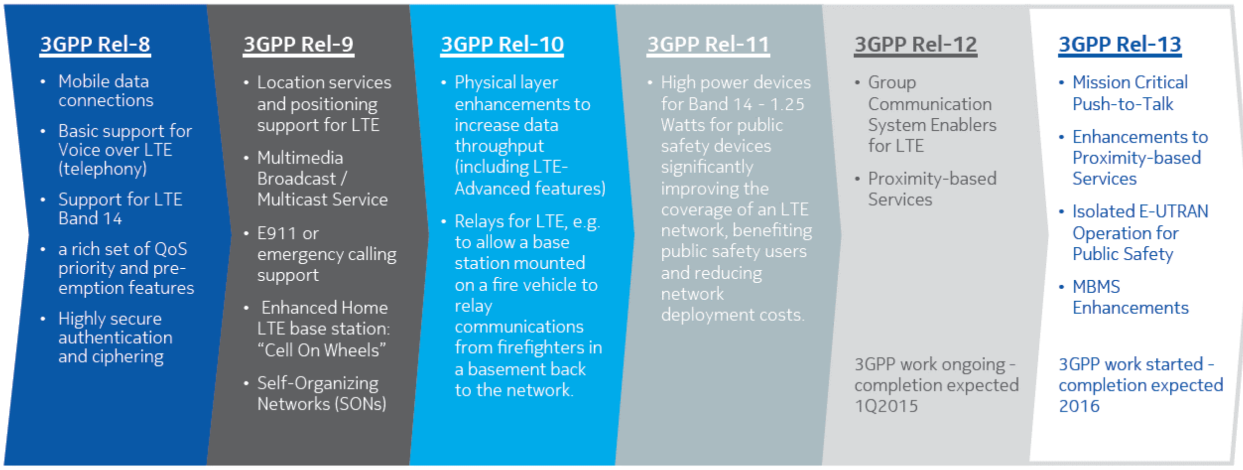
Isolated operation

In Release 13, 3GPP is expected to specify how a base station can continue offering service even with the loss of backhaul, a capability that will benefit disaster situations.

Relays

Figure 25 summarizes the more than eighteen features in 3GPP relays that apply to public safety.

Figure 25: Summary of 3GPP LTE Features to Support Public Safety[62]



Deployment Schedule and Approaches

In the United States, FirstNet is expected to issue an official RFP in late 2015, followed by the possibility of an award in 2016. Deployments could begin in the 2017-2018 timeframe.

Because huge investment in infrastructure would be required for a network dedicated only to public safety, industry and government are evaluating approaches with which public safety can leverage existing commercial network deployments. Public-safety networks also have resilience and security requirements that differ from commercial networks.

Shared Network

As depicted in Figure 26, multiple sharing approaches are possible:

1. In this scenario, public safety owns and operates the entire network, an approach that gives public-safety organizations the greatest control over the network but at the highest cost.
2. A commercial operator shares its radio-access network, including cell sites and backhaul, but the public-safety entity manages core network functions including gateways, the Mobile Management Entity, the Home Subscriber Server (HSS), and public-safety application servers. Because the radio-access network is the most costly part of the network, this approach significantly reduces the amount public safety has to invest in the network. Even though the RAN is shared, public safety still can use its dedicated spectrum.
3. In an MVNO approach, the operator shares its cell sites and backhaul as well as some core network functions, such as the MME and Serving Gateway. Public safety manages a small number of network functions, such as the Packet Gateway, HSS, and its application servers.

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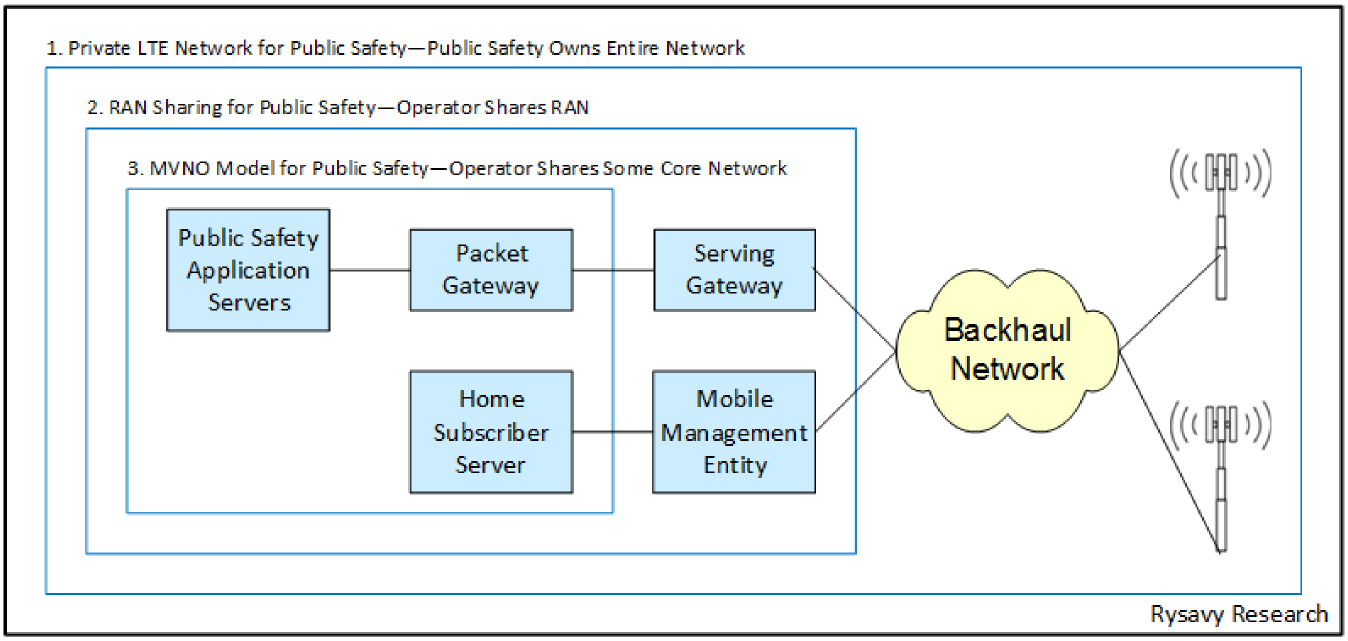
[62] Nokia, *LTE networks for public safety services*, 2014. Available at http://networks.nokia.com/sites/default/files/document/nokia_lte_for_public_safety_white_paper.pdf.

4. A final approach, not shown in the figure, is one in which the mobile operator hosts all of the elements shown in the figure and public safety manages only its application servers.

Figure 26: Sharing Approaches for Public Safety Networks



Resilience

Public safety may need greater resilience than found in commercial networks, including hardware redundancy, geographic redundancy, load balancing, fast re-routing in IP networks, interface protection, outage detection, self-healing, and automatic reconfiguration.

Security

Public-safety networks may have higher security requirements than commercial networks, including physical security of data centers, core sites, and cell sites. Whereas LTE networks do not have to encrypt traffic in backhaul and core networks, public-safety applications may choose to encrypt all IP traffic using virtual private networking approaches.

Coverage

A number of approaches can ensure the broadest possible coverage for public-safety networks. First, public-safety frequencies at 700 MHz already propagate and penetrate well. Next, public-safety devices will be able to transmit at higher power. In addition, base stations can employ four-way receiver diversity and higher-order sectorization. For disaster situations, public safety can also use rapidly deployable small cells, such as on trailers. Finally, proximity-based services operating in a relay mode, as discussed above, can extend coverage.

Device Considerations for Public Safety

Public-safety devices will have unique requirements, including guaranteed network access under all conditions and guidelines for how devices are shared among users.

Access to Commercial Networks

Public-safety devices could be designed to also to communicate on commercial LTE networks, providing an alternate communications avenue when the device cannot connect to a public-safety network. Subscriptions to all major commercial networks would make this approach the most effective. Wi-Fi capability further extends this concept.

Device Sharing

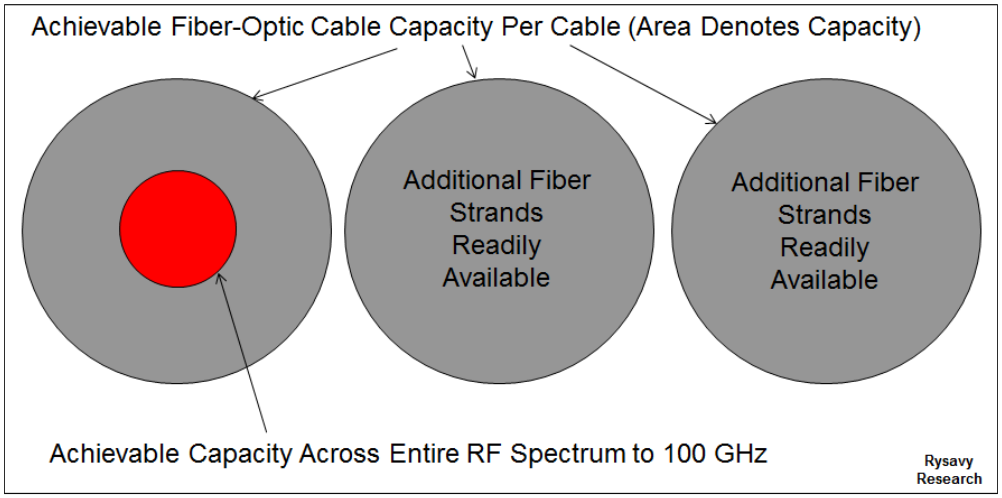
Because public-safety devices may be shared among personnel, user profiles cannot be stored on USIM cards stored in the devices. Bluetooth-based remote SIMs are one approach to address this problem.

Expanding Capacity

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

Over time, wireless networks will gain substantial additional capacity through the methods discussed in the next section. While they will compete with copper twisted pair and coax, they will never catch up to fiber. The infra-red frequencies used in fiber-optic communications have far greater bandwidth than radio. As a result, one fiber-optic strand has greater bandwidth than the entire usable radio spectrum to 100 GHz, as illustrated in Figure 27.[63]

Figure 27: RF Capacity vs. Fiber-Optic Cable Capacity

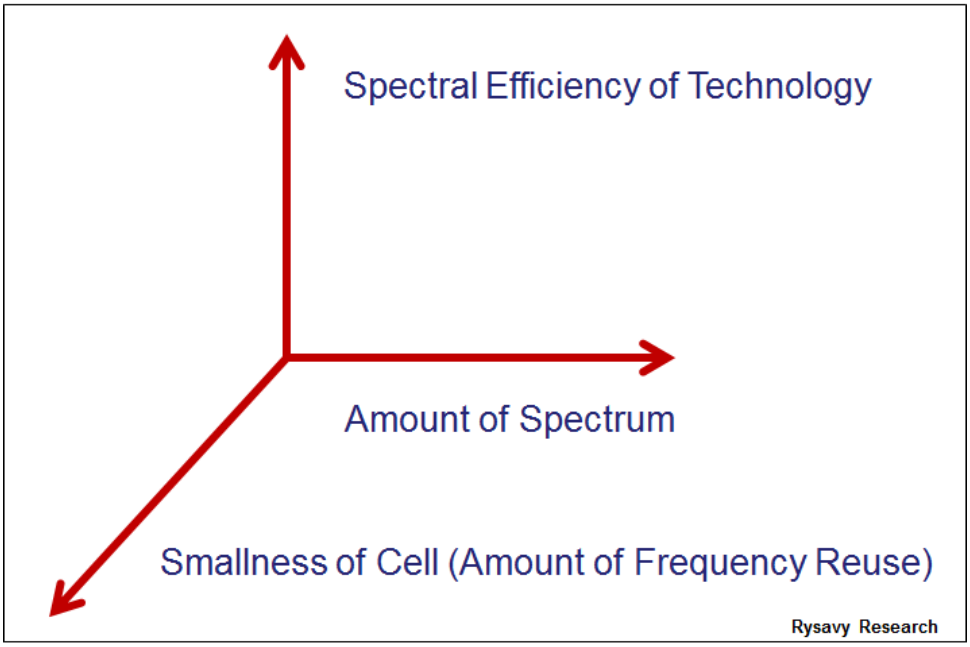


A dilemma of 4G mobile broadband is that it *can* provide a broadband experience similar to wireline, but it *cannot* do so for all subscribers in a coverage area at the same time. Hence, operators must carefully manage capacity, demand, policies, pricing plans, and user expectations. Similarly, application developers must become more conscious of the inherent constraints of wireless networks.

Three factors determine wireless network capacity, as shown in Figure 28: the amount of spectrum, the spectral efficiency of the technology, and the size of the cell. Because smaller cells serve fewer people in each cell and because there are more of them, small cells are a major contributor to increased capacity.

[63] One fiber-optic cable can transmit over 10,000 Gbps compared with all wireless spectrum to 100 GHz that, even at an extremely high 10 bps/Hz, would have only 1,000 Gbps of capacity.

Figure 28: Dimensions of Capacity



Given the relentless growth in usage, mobile operators are combining multiple approaches to increase capacity and managing congestion:

- **More spectrum.** Spectrum correlates almost directly to capacity, and more spectrum is becoming available globally for mobile broadband. In the U.S. market, the FCC National Broadband Plan seeks to make an additional 500 MHz of spectrum available by 2020. mmWave band spectrum for 5G will provide far more spectrum, but propagation characteristics will restrict its use to small cells. Multiple papers by Rysavy Research and others[64] argue the critical need for additional spectrum.
- **Unpaired spectrum.** LTE TDD operates in unpaired spectrum. In addition, technologies such as HSPA+ and LTE permit the use of different amounts of spectrum between downlink and uplink. Additional unpaired downlink spectrum can be combined with paired spectrum to increase capacity and user throughputs.
- **Supplemental downlink.** With downlink traffic five to ten times greater than uplink traffic, operators often need to expand downlink capacity rather than uplink capacity. Using carrier aggregation, operators can augment downlink capacity by combining separate radio channels.
- **Spectrum sharing.** Policy makers are evaluating how spectrum might be shared between government and commercial entities. Although a potentially promising approach for the long term, sharing raises complex issues, as discussed further in the section "Spectrum Developments."
- **Increased spectral efficiency.** Newer technologies are spectrally more efficient, meaning greater aggregate throughput using the same amount of spectrum. Wireless technologies such as LTE, however, are reaching the theoretical limits of spectral

[64] See multiple papers on spectrum and capacity at http://www.rysavy.com/writing.

efficiency, and future gains will be quite modest, allowing for a possible doubling of LTE efficiency over currently deployed versions. See the section "Spectral Efficiency" for a further discussion.

- **Smart antennas.** Through higher-order MIMO and beamforming, smart antennas gain added sophistication in each 3GPP release and are the primary contributor to increased spectral efficiency (bps/Hz). Massive MIMO, beginning in Release 13, will support 16-antenna-element systems and in 5G, will expand to potentially hundreds of antenna elements.
- **Uplink gains combined with downlink carrier aggregation.** Operators can increase network capacity by applying new receive technologies at the base station (for example, large-scale antenna systems such as massive MIMO) that do not necessarily require standards support. Combined with carrier aggregation on the downlink, these receive technologies produce a high-capacity balanced network, suggesting that regulators should in some cases consider licensing just downlink spectrum.
- **Small cells and heterogeneous networks.** Selective addition of picocells to macrocells to address localized demand can significantly boost overall capacity, with a linear increase in capacity relative to the number of small cells. HetNets, which also can include femtocells, hold the promise of increasing capacity gains by a factor of four and even higher with the introduction of interference cancellation in devices. Distributed antenna systems (DAS), used principally for improved indoor coverage, can also function like small cells and increase capacity. Actual gain will depend on a number of factors, including number and placement of small cells,[65] user distribution, and any small-cell selection bias that might be applied.
- **Offload to unlicensed spectrum.** Using unlicensed spectrum with Wi-Fi or LTE operation in unlicensed spectrum offers another means of offloading heavy traffic. Unlicensed spectrum favors smaller coverage areas because interference can be better managed, so spectral re-use is high, resulting in significant capacity gains.
- **Higher-level sectorization.** For some base stations, despite the more complex configuration involved, six sectors can prove advantageous versus the more traditional three sectors, deployed either in a 6X1 horizontal plane or 3X2 vertical plane.[66]

Strategies to manage demand include:

- **Quality of service (QoS) management.** Through prioritization, certain traffic, such as non-time-critical downloads, could occur with lower priority, thus not affecting other active users. New network-neutrality rules, however, may constrain use of traffic prioritization.[67]
- **Off-peak hours.** Operators could offer user incentives or perhaps fewer restrictions on large data transfers during off-peak hours.

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[65] With small-cell range expansion using a large selection bias, small cells can be distributed uniformly.

[66] An example of vertical layering would be a 3X1 layer at ground level and a separate 3X1 layer for higher levels of surrounding buildings.

[67] For a discussion of this issue, see Rysavy Research, *LTE Congestion Management – Enabling Innovation and Improving the Consumer Experience*, January 2015. Available at http://www.rysavy.com/Articles/2015-01-Rysavy-LTE-Congestion-Management.pdf.

Given a goal of increasing capacity by a factor of 1,000, 50X could roughly be achieved through network densification; 10X through more spectrum, including higher frequencies such as mmWave; and 2X by increases in spectral efficiency.

Based on historical increases in the availability of new spectrum, technologies delivering better spectral efficiency, and increases in the number of cell sites, Rysavy Research has calculated that, over the last thirty-year period, aggregate network capacity has doubled every three years. Rysavy Research expects this trend to continue into the future.

Rysavy Research Analysis:

Aggregate Wireless Network Capacity
Doubles Every Three Years.

Spectrum Developments

Licensed spectrum scarcity continues to challenge the industry. Tactics to make the best use of this limited resource include deploying technologies that have higher spectral efficiency; adapting specifications to enable operation of UMTS-HSPA and LTE in all available bands; designing both FDD and TDD versions of technology to take advantage of both paired and unpaired bands; designing carrier aggregation techniques in HSPA+ and LTE-Advanced; and deploying as many new cells, large and small, as is economically and technically feasible. Although all of these industry initiatives greatly expand capacity, they do not obviate the need for additional spectrum. 5G technology will be able to employ frequencies not previously used in cellular systems, spanning 6 GHz to 100 GHz.

The FCC released a report in October 2010 that projected U.S. spectrum requirements[68] and concluded that 275 MHz of additional spectrum would be needed within five years and 500 MHz of additional spectrum within 10 years. This forecast assumes ongoing increases in spectral efficiency from improving technologies.

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

3GPP has specified LTE for operation in many different bands, and initial use will be more fragmented than the four bands (850 MHz, 900 MHz, 1.8 GHz, 1.9 GHz) that enable global roaming on 2G and the additional two bands (1.7 GHz and 2.1 GHz) that enable 3G roaming. In the Americas, LTE roaming may occur in the 1.7/2.1 GHz (AWS) bands, and globally, LTE roaming may occur in the 1.8 and 2.6 GHz bands. Longer term, operators will refarm spectrum used for 2G and 3G and apply it to LTE. Unfortunately, the process of identifying new spectrum and making it available for the industry is a lengthy one, as shown in Figure 29.

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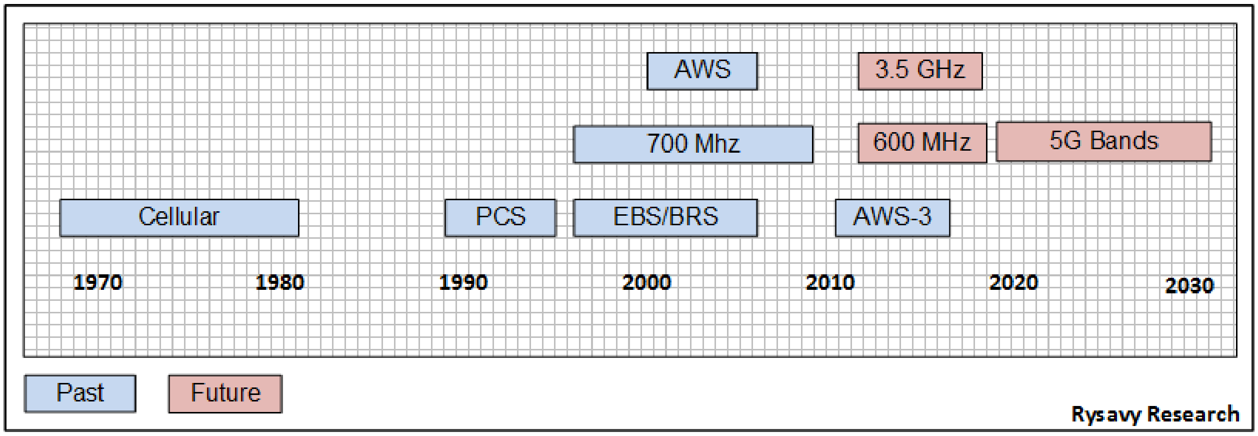
[68] FCC, *Mobile Broadband: The Benefits of Additional Spectrum*, October 2010.

Figure 29: Spectrum Acquisition Time[69]



New short-term spectrum opportunities in the United States currently are incentive auctions of TV-broadcasting spectrum at 600 MHz and the "small-cell" band from 3550 to 3700 MHz.

Table 11 summarizes current and future spectrum allocations in the United States.[70]

Table 11: United States Current and Future Spectrum Allocations

Frequency Band	Amount of Spectrum	Comments
700 MHz	70 MHz	Ultra-High Frequency (UHF).
850 MHz	64 MHz	Cellular and Specialized Mobile Radio.
1.7/2.1 GHz	90 MHz	Advanced Wireless Services (AWS)-1.
1695-1710 MHz, 1755 to 1780 MHz, 2155 to 2180 MHz	65 MHz	AWS-3. Uses spectrum sharing.
1.9 GHz	140 MHz	Personal Communications Service (PCS).
2000 to 2020, 2180 to 2200 MHz	40 MHz	AWS-4 (Previously Mobile Satellite Service).
2.3 GHz	20 MHz	Wireless Communications Service (WCS).

69 Source for historical data, FCC, *National Broadband Plan*, Chapter 5. Available at http://www.broadband.gov/plan/5-spectrum/, accessed June 20, 2014. Future based on Rysavy Research analysis.

70 For international allocations, refer to Wik-Consult, Study for the European Commission, *Inventory and review of spectrum use: Assessment of the EU potential for improving spectrum efficiency*, September 2012. Available at http://ec.europa.eu/digital-agenda/sites/digital-agenda/files/cion_spectrum_inventory_executive_summary_en.pdf.

2.5 GHz	194 MHz	Broadband Radio Service. Closer to 160 MHz deployable.
	FUTURE	
600 MHz	Up to 120 MHz	Incentive auctions underway in 2016.
3.55 to 3.70 GHz	150 MHz	Small-cell band with spectrum sharing and unlicensed use.
Above 6 GHz	Multi GHz	Anticipated for 5G systems in 2020 timeframe. Based on wavelengths, 3 GHz to 30 GHz is referred to as the cmWave band and 30 GHz to 300 GHz is referred to as the mmWave band.

Today's licensed-spectrum networks operate most efficiently and are deployed most cost-effectively using a combination of low-band spectrum, below 1 GHz, for coverage and 1 GHz to 3 GHz for capacity. As technology improves, bands in 3 GHz to 100 GHz, and eventually higher, will supplement capacity.

The subsections below provide additional information about the recently completed AWS-3 auction, incentive auctions, the 3.5 GHz, 5G, spectrum harmonization, unlicensed spectrum, and spectrum sharing.

AWS-3

In early 2015, the FCC received close to $45 billion for the U.S. Treasury in the AWS-3 auction, more than twice the amount of any previous auction, demonstrating the value of higher-band spectrum.[71] The auction adds 65 MHz of desirable spectrum to the mobile-broadband industry. The plan is to employ spectrum sharing among commercial networks and select government systems. Eventually, most of these government systems will migrate to other spectrum. 3GPP has specified use of both AWS-3 and AWS-4 spectrum in what it refers to as "Band 66." Operators have indicated they could begin deploying in this band in the 2017-2018 timeframe.[72]

This band is asymmetrical, with a downlink of 90 MHz and an uplink of 70 MHz. An operator can use the upper-most 20 MHz of the downlink only with carrier aggregation.

[71] For further details, see Rysavy Research, "Latest FCC auction shatters spectrum myths," January 2015. Available at https://gigaom.com/2015/01/17/latest-fcc-auction-shatters-spectrum-myths/.

[72] For example, see http://www.fiercewireless.com/story/analysts-aws-3-auction-helps-att-catch-verizon-spectrum-ownership-major-mar/2015-02-02 and http://www.wirelessweek.com/news/2015/01/t-will-begin-deploying-its-new-aws-3-spectrum-2017.

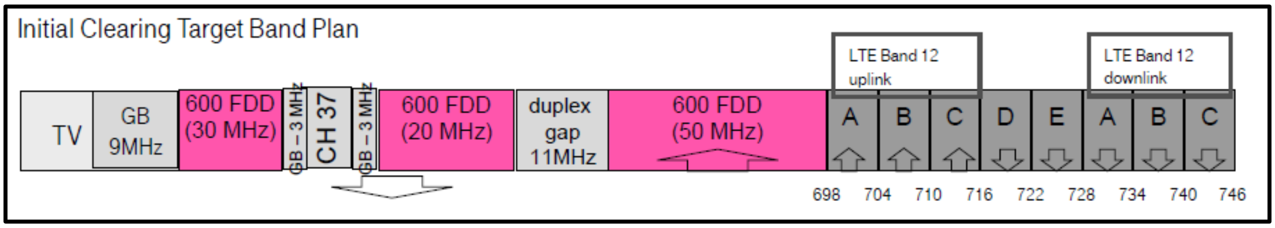
Broadcast Incentive Auction (600 MHz)

The broadcast incentive auction underway in 2016 will reallocate up to 120 MHz of UHF channels in the 600 MHz band that are currently used by TV broadcasters.[73] The auction will be more complicated than past spectrum auctions, when the FCC simply reassigned or designated spectrum for commercial mobile use and then conducted an auction.

In the first stage, the FCC is conducting a reverse auction to determine how much spectrum broadcasters might wish to relinquish in exchange for how much compensation. In the second stage, mobile operators will bid for spectrum in a forward auction, similar to past spectrum auctions.

At the beginning of the auction process in 2016, the FCC announced an initial clearing target of 126 MHz, with Figure 30 showing the clearing target band plan.

Figure 30: 600 MHz Target Band Plan[74]



Part of the auction process will be to reorganize and repack relinquished channels, as well as channels needed for broadcasters that want to keep broadcasting, to make useful blocks of spectrum for mobile broadband. The FCC's goal is to design an auction that will result in a uniform nationwide band plan, but in some markets, there may be deviations from that plan. The final amount of spectrum that becomes available will depend on an interplay between the financial interests of both the broadcasters selling their spectrum licenses and companies purchasing spectrum licenses.

With a 39-month schedule for winning bidders to move into their new spectrum, the 600 MHz band could come online in the 2020 timeframe. Operators could use the band for LTE or for 5G.

3550 to 3700 MHz "Small-Cell" Band

In the United States, the FCC is in the process of opening the 3550 to 3650 MHz band, with a recent extension of 3650 to 3700 MHz. The best use of this band will be small cells and backhaul. The FCC has proposed a three-tier model with incumbent access, priority access with priority access licenses (PALs), and general authorized access (GAA) for unlicensed users.[75] Incumbent access will include government radar systems.

[73] For further details, see FCC, Learn Program, "A Groundbreaking Event for the Broadcast Television, Mobile Wireless, and Technology Sectors of the U.S. Economy," http://wireless.fcc.gov/incentiveauctions/learn-program/ .

[74] 5G Americas member contribution.

[75] For further details, see Official FCC Blog, "Innovation in the 3.5 GHz Band: Creating a New Citizens Broadband Radio Service," March 2015, available at http://www.fcc.gov/blog/innovation-35-ghz-band-

The mobile broadband industry will mostly use LTE TDD in small-cell configurations, in either a licensed mode or unlicensed mode using LAA.

Although this band represents a significant amount of new spectrum, potential adopters of the band have expressed concern about proposed rules for use of the band. For example:

- IEEE has stated it will not pursue a version of 802.11 for this band because exclusion zones are so large that the percentage of the U.S. population that could be served is below what is required for a successful market.[76]

- Licensed users will only be able to obtain three-year licenses with no automatic renewal.[77]

See the section "Spectrum Sharing" for further details of this band.

2.5 GHz Band

In the United States, the primary operator at 2.5 GHz is Sprint. Having an average of 160 MHz of spectrum at 2.5 GHz in its top 100 markets, Sprint is in the process of deploying LTE-Advanced. In addition, Sprint is in a deployment mode that includes the following features:

- Carrier aggregation capability between 2.5 GHz and lower bands (800MHz and 1900 MHz) and aggregating three carriers in a single band.

- TDD operation at 2.5 GHz and FDD operation in lower bands.

- 8 transmit and 8 receive radios at the base station that enables 4X2 MIMO in combination with beamforming.[78]

5G Bands

As radio technology progresses, it can handle higher frequencies, and it occupies greater bandwidth. 1G systems used 30 kHz radio carriers, 2G in GSM uses 200 kHz carriers, 3G in UMTS uses 5 MHz carriers, and 4G in LTE uses carriers of up to 100 MHz through carrier aggregation.

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creating-new-citizens-broadband-radio-service. See also FCC, *Further Notice of Proposed Rulemaking--Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550- 3650 MHz Band*, April 23, 2014.

[76] IEEE 802.11, *Comments of IEEE 802.11, In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band,"* Jul, 2015. Available at http://apps.fcc.gov/ecfs/document/view?id=60001115064.

[77] See Rysavy article about this band, "Scary Experimentation at 3.5 GHz," Jun. 2016, available at http://www.rysavy.com/Articles/2016-06-Scary-Experimentation-3-5-GHz.pdf. See also AT&T ex-parte FCC communication, http://apps.fcc.gov/ecfs/document/view?id=60001569272.

[78] For more details, see Sprint article at: http://newsroom.sprint.com/blogs/sprint-perspectives/introducing-the-sprint-lte-plus-network--faster-stronger-more-reliable-than-ever-before.htm

Although 5G research and development is in its infancy, to achieve the 20 Gbps or higher throughput rates envisioned for 5G will require radio carriers of at least 1 GHz, bandwidths available only at frequencies above 5 GHz. Researchers globally are studying high-frequency spectrum options including both cmWave frequencies (3 GHz to 30 GHz) and mmWave (30 GHz to 300 GHz). Ten times as much spectrum, or more, could be available in these higher frequencies than in all current cellular spectrum.

During the World Radiocommunication Conference (WRC) 15, the ITU proposed a set of global frequencies for 5G[79], which it intends to finalize at the next conference in 2019 (WRC 19):

- 24.25–27.5GHz
- 31.8–33.4GHz
- 37–40.5GHz
- 40.5–42.5GHz
- 45.5–50.2GHz
- 50.4–52.6GHz
- 66–76GHz
- 81–86GHz

In 2014, the FCC published a Notice of Inquiry into use of spectrum bands above 24 GHz for Mobile Radio Services,[80] followed by a Notice of Proposed Rulemaking in October 2015, which listed the following potential bands for 5G in the United States.[81]

- 27.5-28.35 GHz (28 GHz band)
- 37.0-38.6 GHz (37 GHz band)
- 38.6-40 GHz (39 GHz band)
- 64-71 GHz (unlicensed use)
- 70/80 GHz Bands: 71-76 GHz, 81-86 GHz

The FCC issued adopted rules to identify and open up 5G spectrum allocation in July 2016 that identify 3.85 GHz of licensed spectrum and 7 GHz of unlicensed spectrum: licensed use in 28 GHz, 37 GHz, and 39 GHz bands; unlicensed use in 64-71 GHz; and shared access in the 37-37.6 GHz band.[82]

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[79] 5G Americas Webcast, "LTE-Steps to 5G," Feb 12, 2016.

[80] FCC, *Notice of Inquiry, Use of Spectrum Bands above 24 GHz for Mobile Radio Services*, Oct. 17, 2014.

[81] FCC, *Notice of Proposed Rulemaking, Use of Spectrum Bands Above 24 GHz for Mobile Radio Services, GN Docket No. 14-177,* Oct 23, 2015.

[82] FCC, "Fact Sheet: Spectrum Frontiers Rules Identify, Open up Vast Amounts of New High-Band Spectrum for Next Generation (5G) Wireless Broadband," July 2016, available at http://transition.fcc.gov/Daily_Releases/Daily_Business/2016/db0714/DOC-340310A1.pdf.

The complex ITU harmonization process may mean that some regions, or even countries, pursue 5G bands that are not globally harmonized. For example, U.S. operators, along with operators in Korea and Japan, are planning 5G trials in the 28 GHz band, even though it is not one of the ITU bands.

Harmonization

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

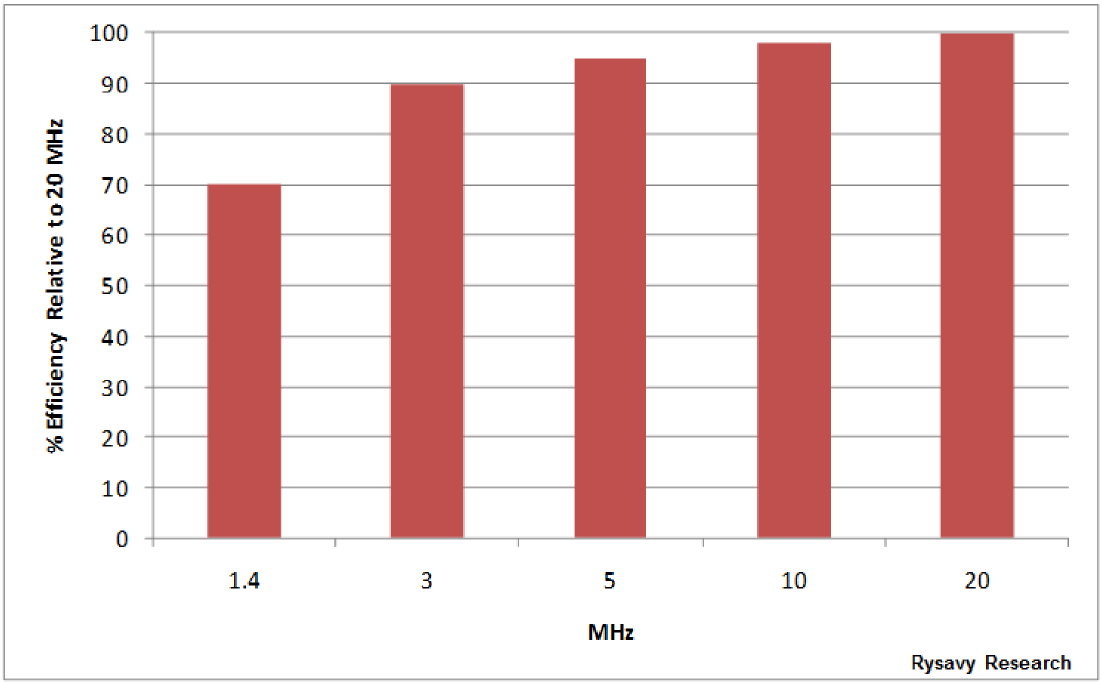
As regulators make more spectrum available, it is important that they follow guidelines such as those espoused by 5G Americas:[83]

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

Emerging technologies such as LTE benefit from wider radio channels. These wider channels are not only spectrally more efficient, they also offer greater capacity. Figure 31 shows increasing LTE spectral efficiency obtained with wider radio channels, with 20 MHz on the downlink and 20 MHz (20+20 MHz) on the uplink comprising the most efficient configuration.

[83] 4G Americas, *Sustaining the Mobile Miracle – A 4G Americas Blueprint for Securing Mobile Broadband Spectrum in this Decade*, March 2011.

Figure 31: LTE Spectral Efficiency as Function of Radio Channel Size[84]



The organization tasked with global spectrum harmonization, the International Telecommunication Union, periodically holds World Radiocommunication Conferences.[85]

Harmonization occurs at multiple levels:

- Allocation of radio frequencies to a mobile service in the ITU frequency allocation table.
- Establishment of global or regional frequency arrangements, including channel blocks and specific duplexing modes.
- Development of detailed technical specifications and standards, including system performance, RF performance, and coexistence with other systems in neighboring bands.
- Assignment for frequency blocks with associated technical conditions and specifications to appropriate operators and service providers.[86]

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[84] 5G Americas member company analysis.

[85] International Telecommunication Union, "World Radiocommunication Conferences (WRC)," http://www.itu.int/ITU-R/index.asp?category=conferences&rlink=wrc&lang=en, accessed June 20, 2014.

[86] International Telecommunication Union Radiocommunication Study Groups, *Technical Perspective On Benefits Of Spectrum Harmonization for Mobile Services and IMT*, Document 5D/246-E, January 2013.

Unlicensed Spectrum

Wi-Fi, an unlicensed wireless technology, has experienced huge success due to high throughput rates, ease of use for consumers, extensive deployment by businesses, widespread availability in public places, and large amounts of available spectrum. Now, 3GPP is preparing a version of LTE that can also operate in unlicensed spectrum, which will provide an alternate means for operators to harness unlicensed spectrum, as discussed above in the section "Unlicensed Spectrum Integration."

Wi-Fi uses spectrum efficiently because its small coverage areas result in high-frequency reuse and high data density (bps per square meter). Less efficient are white-space unlicensed networks, sometimes called "super Wi-Fi," that, because of large coverage areas, have much lower throughput per square meter. While white-space networks may be a practical broadband solution in rural or undeveloped areas, they face significant challenges in urban areas that already have mobile and fixed broadband available.[87] See the section on "White Space Networks" in the appendix for further details.

Advocates argue that unlicensed spectrum unleashes innovation and that government should allocate greater amounts of unlicensed spectrum. Although Wi-Fi has been successful, the core elements that make unlicensed spectrum extremely successful are also the source of inherent disadvantages: local coverage and its unlicensed status. Local coverage enables high data density and high frequency reuse but makes widespread continuous coverage almost impossible. Similarly, unlicensed operation facilitates deployment by millions of entities but results in overlapping coverage and interference.

Networks built using unlicensed spectrum cannot replace networks built using licensed spectrum, and vice versa. The two are complementary and helpful to each other, as summarized in Table 12.[88]

Table 12: Pros and Cons of Unlicensed and Licensed Spectrum

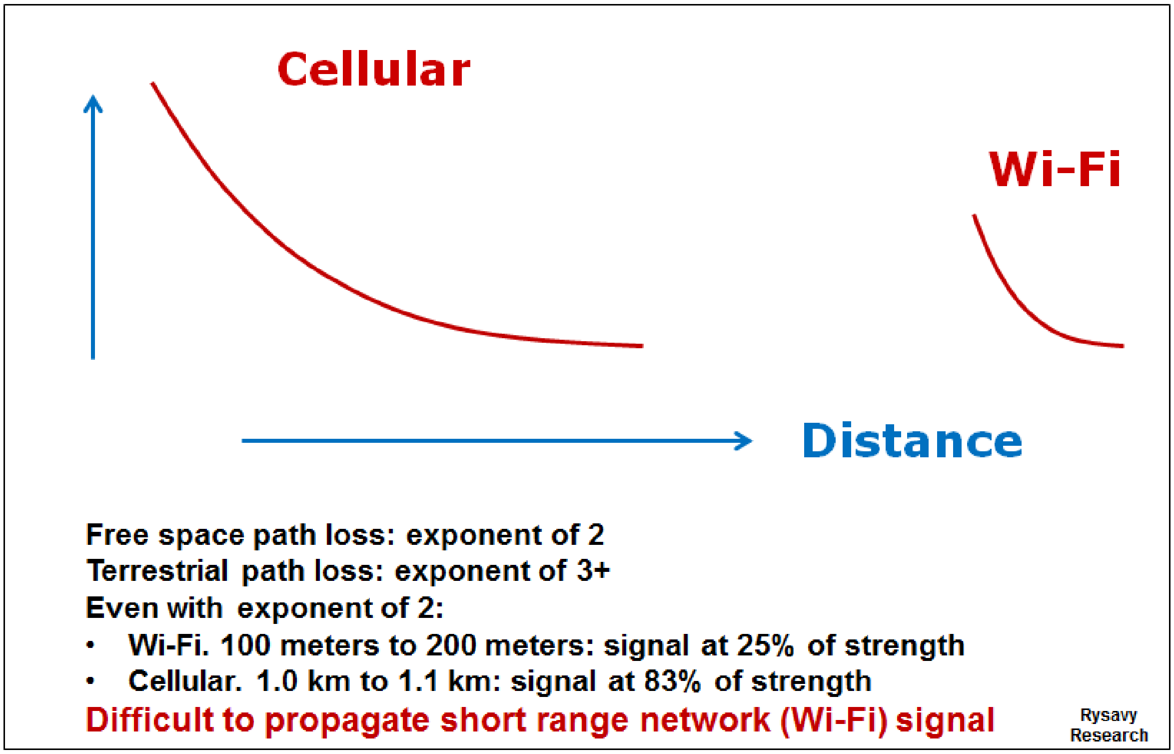
Unlicensed Spectrum			Licensed Spectrum	
Pros	**Cons**		**Pros**	**Cons**
Easy and quick to deploy	Potential of other entities using same frequencies		Huge coverage areas	Expensive infrastructure
Low-cost hardware	Difficult to impossible to provide wide-scale coverage		Able to manage quality of service	Each operator has access to only a small amount of spectrum

[87] For further analysis, see Rysavy Research, "White spaces networks are not 'super' nor even Wi-Fi," Gigaom, March 2013. Available at http://gigaom.com/2013/03/17/white-spaces-networks-are-not-super-nor-even-wi-fi/.

[88] For further analysis, see Rysavy Research, "It's Time for a Rational Perspective on Wi-Fi," Gigaom, April, 2014. Available at http://gigaom.com/2014/04/27/its-time-for-a-rational-perspective-on-wi-fi/.

Some operators offer a "Wi-Fi first" capability with which devices always attempt to use a Wi-Fi connection and fall back to a cellular connection only if no Wi-Fi is available. Such cellular backup is essential because Wi-Fi, due to low-power operation in many bands, is inherently unsuited for providing continuous coverage. The sharp drop-off in signal strength due to low transmit power makes coverage gaps over large areas inevitable, especially outdoors.

Figure 32: Propagation Losses of Cellular vs. Wi-Fi[89]



Spectrum Sharing

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

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

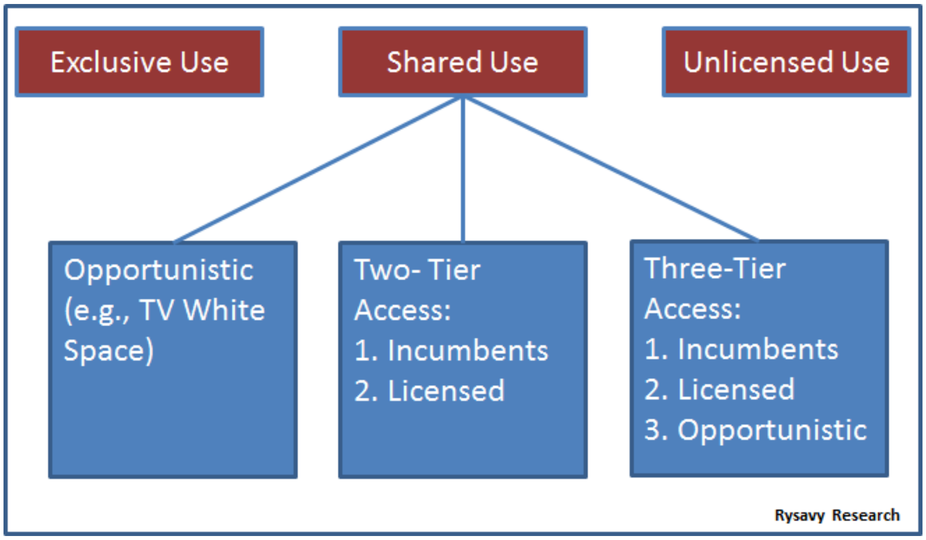
The U.S. government can designate spectrum for exclusive, shared, or unlicensed use, as shown in Figure 33. Shared use can be opportunistic, as with TV white spaces; two-tier with incumbents and licensed users; or three tier, which adds opportunistic access. The

[89] Assumes 1.0 km radius for cellular and 100 meter radius for Wi-Fi.

bands initially targeted for spectrum sharing include AWS-3 (two tiers on a temporary basis) and the 3.5 GHz band (three tiers).

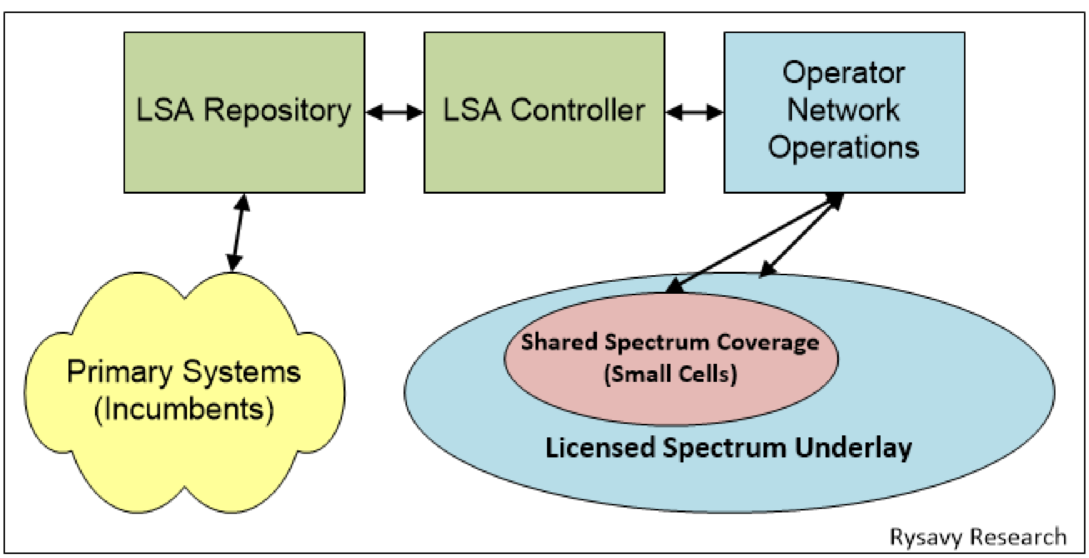
The three-tier plan envisioned by the U.S. government for the 3.5 GHz band gives more entities access to the spectrum but at the cost of increased complexity.

Figure 33: Spectrum Use and Sharing Approaches



The European Telecommunications Standards Institute (ETSI) is the leading organization standardizing cognitive radios. The most relevant effort is called "Licensed Shared Access" (LSA), a two-tier spectrum sharing system that includes incumbents and licensed secondary users that access shared spectrum via a database, as depicted in Figure 34.

Figure 34: Licensed Shared Access (LSA)



The three-tier system expected for the 3.5 GHz band in the United States will be complex, necessitating a real-time Spectrum Access System, the SAS, the design and development of which will encompass:

- Algorithms and methods;
- Methods of nesting hierarchical SAS entities (federal secure SAS versus commercial SASs);
- Coordination among multiple, competing commercial SAS managing entities;
- Interface definitions;
- Communication protocol definitions;
- Database and protocol security;
- Policy enforcement;
- Speed of channel allocation/reallocation;
- Time intervals for spectrum allocation;
- Effectively managing large numbers of Tier 3 users; and
- Data ownership, fees, rules, fairness, and conflict resolutions, all of which have policy, regulatory, and business implications.

TVWS databases available today address only a tiny subset of these requirements.[90]

Figure 35 shows the proposed architecture of the 3.5 GHz system. The system consists of incumbents (government systems), Priority Access Licenses, and General Authorized Access. Government systems include military ship-borne radar, military ground-based radar, fixed-satellite service earth stations (receive only), and government broadband services (3650 to 3700 MHz). PAL licenses will be used by entities such as cellular operators and will be available for three-year periods. GAA users are licensed by rule and must protect both incumbents and PALs. Some examples of GAA use cases are small-business hotspots, campus hotspots, and backhaul.

Citizens Broadband Radio Service Devices (CBSDs) are the base stations operating under this service; they can operate only under the authority and management of the SAS, either by direct communications or a proxy node.

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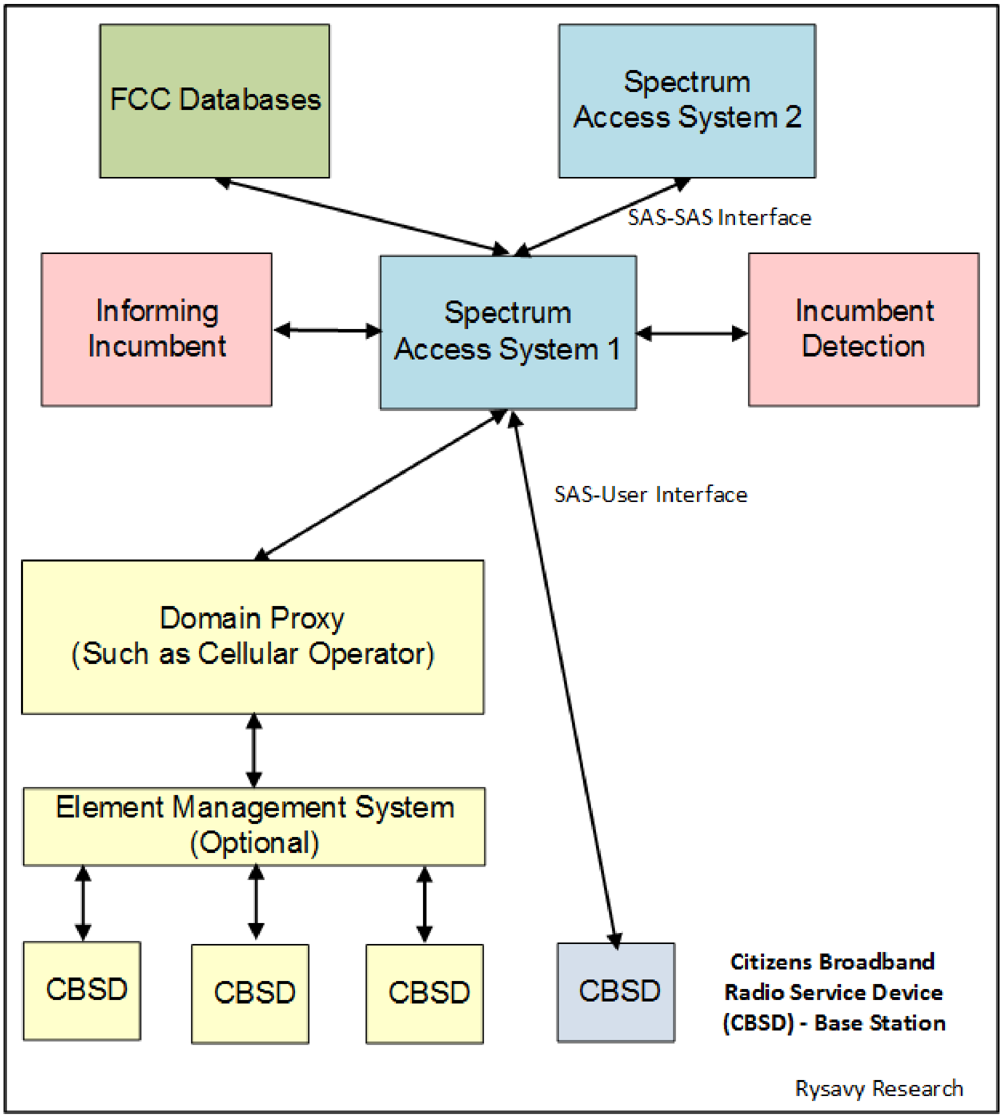
[90] For further analysis, see Rysavy Research and Mobile Future, *Complexities of Spectrum Sharing: How to Move Forward*, April 2014. Available at http://www.rysavy.com/Articles/2014-04-Spectrum-Sharing-Complexities.pdf.

Figure 35: United States 3.5 GHz System Currently Being Developed



Conclusion

Mobile broadband remains at the forefront of innovation and development in computing, networking, and application development. As users, and now machines, consume ever more wireless data, the industry is responding with more efficient, faster, and higher-capacity networks. Even as excitement builds about 5G, the key technology remains LTE, which has become a global wireless foundation, supporting continual enhancements.

LTE-Advanced and LTE-Advanced Pro innovations include carrier aggregation, already in use, and LAA/LWA/LWIP, NB-IoT, eICIC, SON, dual connectivity, and CoMP, all capabilities in the process of being unleashed that will improve performance, efficiency, capacity, and enable support for new vertical segments. Carriers are implementing NFV and SDN to reduce network costs, improve service velocity, and simplify deployment of new services. Such improvements also facilitate cloud RANs that promise further efficiency gains.

5G research and development efforts have accelerated, and deployment could commence close to 2020 and continue through 2030. Operators have even announced pre-standard deployments for fixed wireless. 3GPP has implemented a 5G standardization process that begins in Release 14 with a study of the new 5G radio, continues with a first phase of specifications in Release 15, then moves ahead with a second phase of specifications in Release 16, scheduled to complete in time for deployments around 2020. By harnessing new spectrum, such as mmWave bands above 24 GHz, 5G will eventually be able to access ten times as much spectrum as is currently available for cellular operation. Using radio bands 200 MHz or wider will result in multi-Gbps throughput capabilities. 5G will be designed to integrate with LTE networks, and many 5G features may be implemented as LTE-Advanced Pro extensions prior to full 5G availability.

Small cells will play an ever-more-important role in boosting capacity, benefiting from a number of technologies and developments, including SON, eICIC, Dual Connectivity, LWA/LWIP, LTE-U, LTE-LAA, MulteFire, improved backhaul options, and spectrum intended for small cells, such as 3.5 GHz. Improved Wi-Fi integration techniques provide another avenue to increase capacity. Obtaining more spectrum remains a critical priority globally. In U.S. markets, a number of initiatives hold promise—television incentive auctions for 600 MHz spectrum, the 3.5 GHz small-cell band, more unlicensed spectrum at 5GHz, and the proposed 5G spectrum bands.

The future of mobile broadband, including both LTE-Advanced and 5G, is bright, with no end in sight for continued growth in capability, nor for the limitless application innovation that mobile broadband enables.

Appendix: Technology Details

The 3GPP family of data technologies provides ever increasing capabilities that support ever more demanding applications. Services obviously need to provide broad coverage and high data throughput. Less obvious for users, but as critical for effective application performance, are the need for low latency, QoS control, and spectral efficiency. Higher spectral efficiency translates to higher average throughputs (and thus more responsive applications) for more active users in a coverage area. The discussion below details the progression of capability for each technology, including throughput, security, latency, QoS, and spectral efficiency.

This appendix provides details on UMTS/WCDMA, HSPA+, LTE, LTE-Advanced, HetNets, EPC, Wi-Fi integration, IMS, broadcast/multicast services, backhaul, UMTS TDD, Time-Division Synchronous Code Division Multiple Access (TD-SCDMA), EDGE, and TV white spaces.

3GPP Releases

- **Release 99**: Completed. First deployable version of UMTS. Enhancements to GSM data (EDGE). Provides support for GSM/EDGE/GPRS/WCDMA radio-access networks.
- **Release 4**: Completed. Multimedia messaging support. First steps toward using IP transport in the core network.
- **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 6**: Completed. HSUPA. Enhanced multimedia support through Multimedia Broadcast/Multicast Services (MBMS). Performance specifications for advanced receivers. Wireless Local Area Network (WLAN) integration option. IMS enhancements. Initial VoIP capability.
- **Release 7**: Completed. Provides enhanced GSM data functionality with Evolved EDGE. Specifies HSPA+, which includes higher order modulation and MIMO. Performance enhancements, improved spectral efficiency, increased capacity, and better resistance to interference. Continuous Packet Connectivity (CPC) enables efficient "always-on" service and enhanced uplink UL VoIP capacity, as well as reductions in call set-up delay for Push-to-Talk Over Cellular (PoC). Radio enhancements to HSPA include 64 Quadrature Amplitude Modulation (QAM) in the downlink and 16 QAM in the uplink. Also includes optimization of MBMS capabilities through the multicast/broadcast, single-frequency network (MBSFN) function.
- **Release 8**: Completed. Comprises further HSPA Evolution features such as simultaneous use of MIMO and 64 QAM. Includes dual-carrier HSDPA (DC-HSDPA) wherein two downlink carriers can be combined for a doubling of throughput performance. Specifies OFDMA-based 3GPP LTE. Defines EPC and EPS.
- **Release 9**: Completed. HSPA and LTE enhancements including HSPA dual-carrier downlink operation in combination with MIMO, Multimedia Broadcast Multicast Services (MBMS), HSDPA dual-band operation, HSPA dual-carrier uplink operation, EPC enhancements, femtocell support, support for regulatory features such as emergency user-equipment positioning and Commercial Mobile Alert System (CMAS), and evolution of IMS architecture.

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

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

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

- **Release 13**: Completed. LTE features include Active Antenna Systems (AAS) with support for as many as 16 antenna elements and beamforming, Network-Assisted Interference Cancellation and Suppression (NAICS), radio-access network sharing, carrier aggregation supporting 32 component carriers,[91] carrier aggregation of up to four carriers on the downlink and two carriers on the uplink, License Assisted Access (LAA) for operation in unlicensed bands, LTE Wi-Fi Aggregation, isolated operation and mission-critical voice communications for public safety, application-specific congestion management, user-plane congestion management, enhancement to WebRTC interoperability, architecture enhancement for dedicated core networks, enhancement to proximity-based services, mission-critical push-to-talk, group communications, CoMP enhancements, small cell enhancements, machine-type communications enhancements including NB-IoT and Extended Coverage GSM (EC-GSM), VoLTE enhancements, SON enhancements, shared network enhancements, and enhanced

[91] This level of aggregation refers to signaling capabilities. The number of carriers that can be combined in an actual deployment is smaller and depends on RAN co-existence studies. Refer to the appendix section on "Carrier Aggregation" for additional details.

circuit-switched fallback. HSPA+ features include support for dual-band uplink carrier aggregation.

- **Release 14**: Expected completion June 2017. Contemplated features include uplink operation for LAA (enhanced LAA), massive MIMO with more than 16 antenna elements, dual-connectivity of licensed and unlicensed carriers across non-collocated nodes, vehicle-to-vehicle and vehicle-to-infrastructure (V2X) communications built on Release 12 Proximity Services, shared LTE broadcast in which different operators broadcast the same content on the same frequency, non-IP operation for IoT, Downlink Multiuser Superposition Transmission (MUST), enhanced LWA, and LTE latency reduction.

- **Release 15**: Expected completion H2 of 2018. Specifies phase 1 of 5G. Likely to emphasize enhanced-mobile-broadband use case and sub-40 GHz operation. Further LTE and HSPA+ enhancements.

- **Release 16**: Expected completion end of 2019. Specifies phase 2 of 5G. Likely to add >40 GHz operation, core network functions, and additional use cases for massive IoT and ultra-reliable and low-latency communications. Further LTE and HSPA+ enhancements.

Data Throughput Comparison

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

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

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

Some operators, primarily in the United States, also quote typical throughput rates, which are based on throughput tests the operators have done across their operating networks and incorporate a higher level of network load. Although the operators do not disclose the precise methodologies they use to establish these figures, the values provide a good indication of what users can realistically expect.

Table 13 presents the technologies in terms of peak network throughput rates, peak user rates (under favorable conditions), and typical rates. It omits values that are not yet known, such as for future technologies.

The projected typical rates for HSPA+ and LTE show a wide range because these technologies exploit favorable radio conditions to achieve high throughput rates, but under poor radio conditions, throughput rates are lower.

Table 13: Throughput Performance of Different Wireless Technologies (Blue Indicates Theoretical Peak Rates, Green Typical)

	Downlink		Uplink	
	Peak Network Speed	Peak and/or Typical User Rate	Peak Network Speed	Peak and/or Typical User Rate
EDGE (type 2 MS)	473.6 Kbps	Not Applicable (N/A)	473.6 Kbps	N/A
EDGE (type 1 MS) (Practical Terminal)	236.8 Kbps	200 Kbps peak 160 to 200 Kbps typical[92]	236.8 Kbps	200 Kbps peak 80 to 160 Kbps typical[93]
HSDPA Initial Devices (2006)	1.8 Mbps	> 1 Mbps peak	384 Kbps	350 Kbps peak
HSDPA	14.4 Mbps	N/A	384 Kbps	N/A
HSPA[94] Initial Implementation	7.2 Mbps	> 5 Mbps peak 700 Kbps to 1.7 Mbps typical[95]	2 Mbps	> 1.5 Mbps peak 500 Kbps to 1.2 Mbps typical
HSPA	14.4 Mbps	N/A	5.76 Mbps	N/A

[92] Assumes four-to-five downlink timeslot devices (each timeslot capable of 40 Kbps).

[93] Assumes two-to-four uplink timeslot devices (each timeslot capable of 40 Kbps).

[94] High Speed Packet Access (HSPA) consists of systems supporting both High Speed Downlink Packet Access (HSDPA) and High Speed Uplink Packet Access (HSUPA).

[95] Typical downlink and uplink throughput rates based on AT&T press release, June 4, 2008

	Downlink		Uplink	
	Peak Network Speed	**Peak and/or Typical User Rate**	**Peak Network Speed**	**Peak and/or Typical User Rate**
HSPA+ (DL 64 QAM, UL 16 QAM, 5+5 MHz)	21.6 Mbps	1.9 Mbps to 8.8 Mbps typical[96]	11.5 Mbps	1 Mbps to 4 Mbps typical
HSPA+ (2X2 MIMO, DL 16 QAM, UL 16 QAM, 5+5 MHz)	28 Mbps	N/A	11.5 Mbps	N/A
HSPA+ (2X2 MIMO, DL 64 QAM, UL 16 QAM, 5+5 MHz)	42 Mbps	N/A	11.5 Mbps	N/A
HSPA+ (DL 64 QAM, UL 16 QAM, Dual Carrier, 10+5 MHz)	42 Mbps	Approximate doubling of 5+5 MHz rates - 3.8 to 17.6 Mbps.	11.5 Mbps	1 Mbps to 4 Mbps typical
HSPA+ (2X2 MIMO DL, DL 64 QAM, UL 16 QAM, Dual Carrier, 10+10 MHz)	84 Mbps	N/A	23 Mbps	N/A
HSPA+ (2X2 MIMO DL, DL 64 QAM, UL 16 QAM, Quad Carrier,[97] 20+10 MHz)	168 Mbps	N/A	23 Mbps	N/A
HSPA+ (2X2 MIMO DL and UL, DL 64 QAM, UL 16 QAM, Eight Carrier, 40+10 MHz)	336 Mbps	N/A	69 Mbps	N/A
HSPA+ (4X2 MIMO DL, 2X2 MIMO UL, DL 64 QAM, UL 16 QAM, 8 carrier, 40+10 MHz)	672 Mbps	N/A	69 Mbps	N/A

[96] 5G 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.

[97] No operators have announced plans to deploy HSPA in a quad (or greater) carrier configuration. Three carrier configurations, however, have been deployed.

	Downlink		Uplink	
	Peak Network Speed	Peak and/or Typical User Rate	Peak Network Speed	Peak and/or Typical User Rate
LTE (2X2 MIMO, 10+10 MHz, DL 64 QAM, UL 16 QAM)	70 Mbps	6.5 to 26.3 Mbps[98]	35 Mbps[99]	6.0 to 13.0 Mbps
LTE Advanced (2X2 or 4X4 MIMO, 20+20 MHz or 40+20 MHz with Carrier Aggregation [CA], DL 64 QAM, UL 16 QAM)	300 Mbps	N/A	71 Mbps[100]	N/A
LTE Advanced (4X4 MIMO, 60+20MHz, CA, 256 QAM DL, 64 QAM UL	600 Mbps		150 Mbps	
LTE Advanced (4X4 MIMO, 80+20 MHz, CA, 256 QAM DL, 64 QAM UL	> 1 Gbps		150 Mbps	
LTE Advanced (8X8 MIMO, 20+20 MHz, DL 64 QAM, UL 64 QAM)	1.2 Gbps	N/A	568 Mbps	N/A
LTE Advanced, 100 MHz + 100 MHz	3 Gbps		1.5 Gbps	
LTE Advanced 32 Carriers	>> 3 Gbps			
CDMA2000 EV-DO Rel. 0	2.4 Mbps	> 1 Mbps peak	153 Kbps	150 Kbps peak

[98] 5G 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. See additional LTE throughput information in the section below, "LTE Throughput."

[99] Assumes 64 QAM. Otherwise 22 Mbps with 16 QAM.

[100] Assumes 64 QAM. Otherwise 45 Mbps with 16 QAM.

	Downlink		Uplink	
	Peak Network Speed	**Peak and/or Typical User Rate**	**Peak Network Speed**	**Peak and/or Typical User Rate**
CDMA2000 EV-DO Rev. A	3.1 Mbps	> 1.5 Mbps peak 600 Kbps to 1.4 Mbps typical[101]	1.8 Mbps	> 1 Mbps peak 300 to 500 Kbps typical
CDMA2000 EV-DO Rev. B (3 radio channels 5+5 MHz)	14.7[102] Mbps	Proportional increase of Rev A typical rates based on number of carriers.	5.4 Mbps	N/A
CDMA2000 EV-DO Rev B Theoretical (15 radio channels 20+20 MHz)	73.5 Mbps	N/A	27 Mbps	N/A

Additional information about LTE throughput appears below in the section "LTE Throughput."

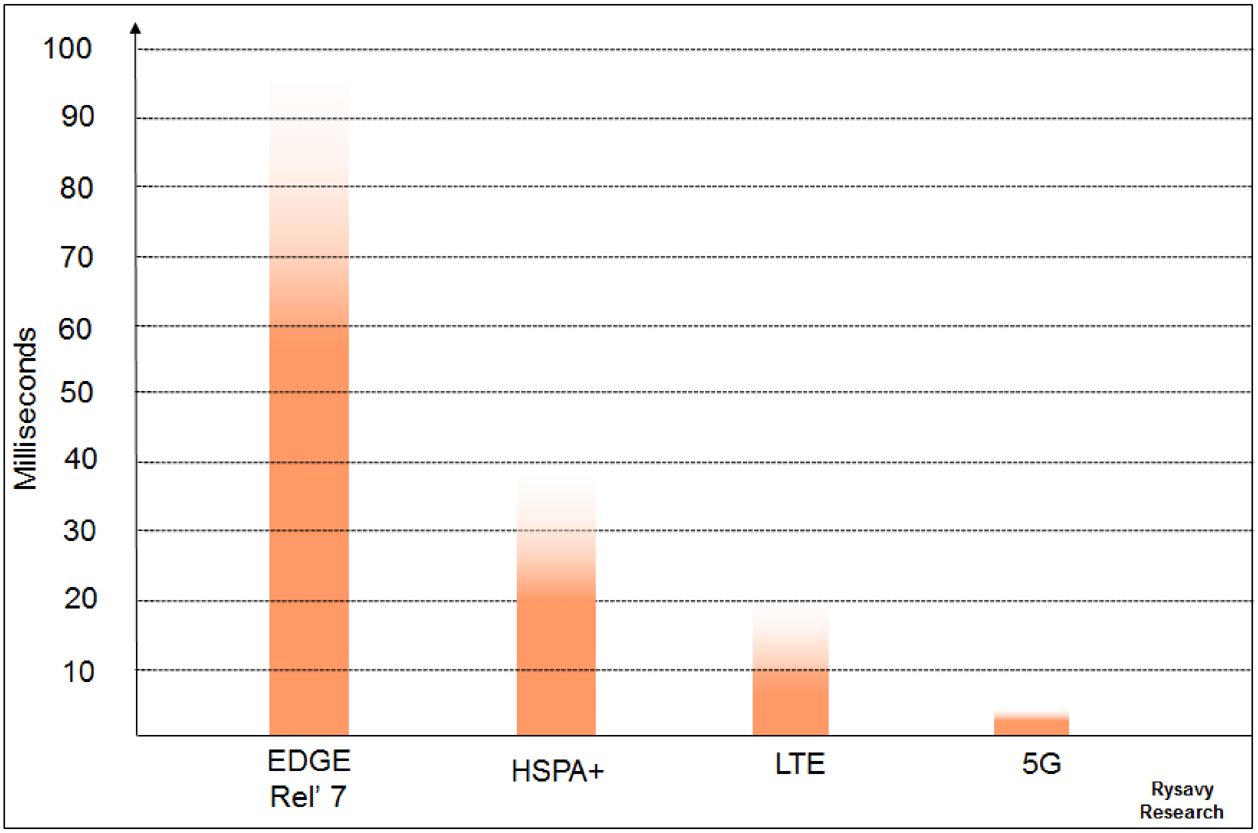
Latency Comparison

As important as throughput is network latency, defined as the round-trip time it takes data to traverse the network. Each successive data technology from GPRS forward reduces latency, with LTE networks having latency as low as 15 msec. Ongoing improvements in each technology mean that all of these values will go down as vendors and operators fine-tune their systems. Figure 36 shows the latency of different 3GPP technologies.

[101] Typical downlink and uplink throughput rates based on Sprint press release Jan. 30, 2007.

[102] Assuming use of 64 QAM.

Figure 36: Latency of Different Technologies[103]



The values shown in Figure 36 reflect measurements of commercially deployed technologies, with EDGE Release 7 achieving 70 to 95 msec, HSPA+ 25 to 30 msec, and LTE 15 to 20 msec. A goal for 5G is less than 1 msec latency.

Spectral Efficiency

The evolution of data services is characterized by an increasing number of users with ever-higher bandwidth demands. As the wireless data market grows, deploying wireless technologies with high spectral efficiency is of paramount importance. Keeping all other things equal, including frequency band, amount of spectrum, and cell site spacing, an increase in spectral efficiency translates to a proportional increase in the number of users supported at the same load per user—or, for the same number of users, an increase in throughput available to each user.

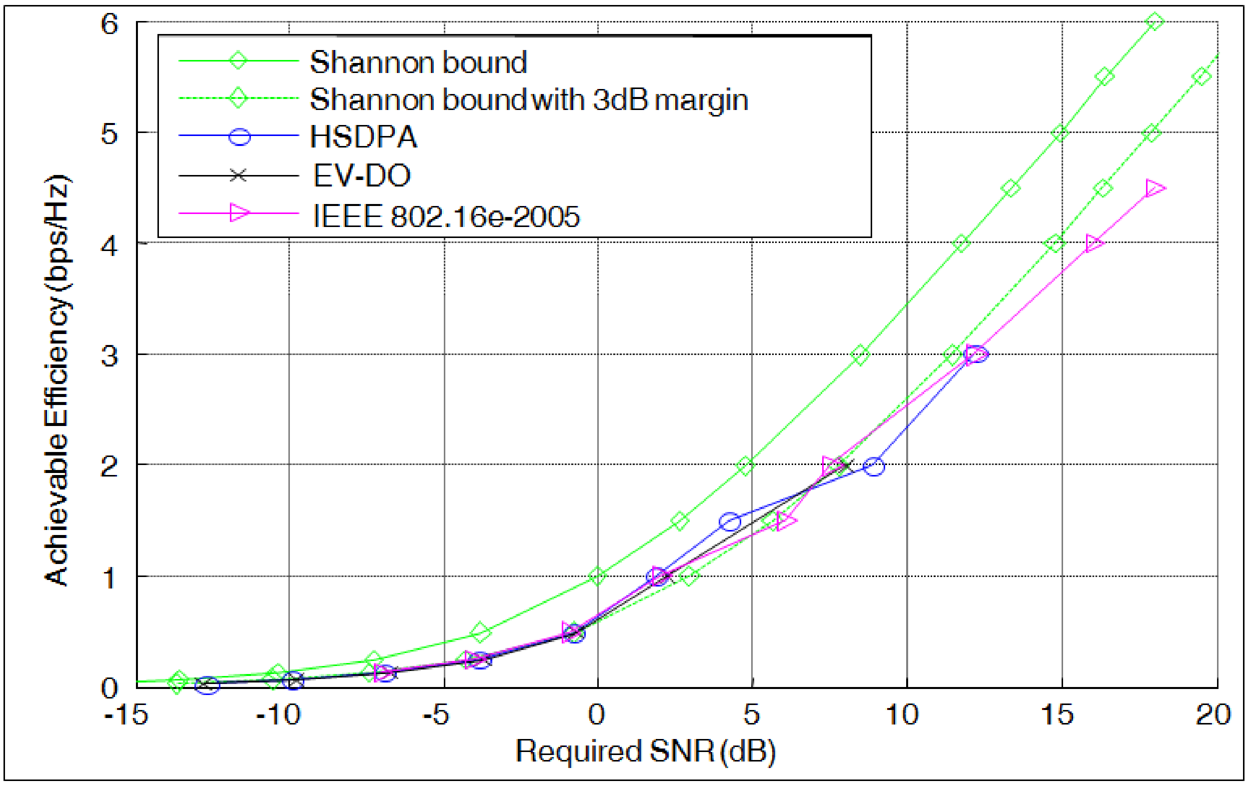
Increased spectral efficiency, however, comes at a price because it generally involves greater complexity for both user and base station equipment. Complexity can arise from the increased number of calculations performed to process signals or from additional radio components. Hence, operators and vendors must balance market needs against network

[103] 5G 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.

and equipment costs. OFDMA technologies, such as LTE and planned 5G approaches, achieve higher spectral efficiency with lower overall complexity, especially in larger bandwidths.

As shown in Figure 37, the link layer performance of modern wireless 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 SNRs of the communications link.) Figure 37 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.

Figure 37: Performance Relative to Theoretical Limits for HSDPA, EV-DO, and WiMAX (IEEE 802.16e-2005)[104]



The curves in Figure 37 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

[104] 5G Americas member contribution.

of the traffic in a cellular system is at slow speeds (for example, 3 km/hr. or less) rather than at higher speeds. The Shannon bound is consequently also relevant for a realistic deployment environment.

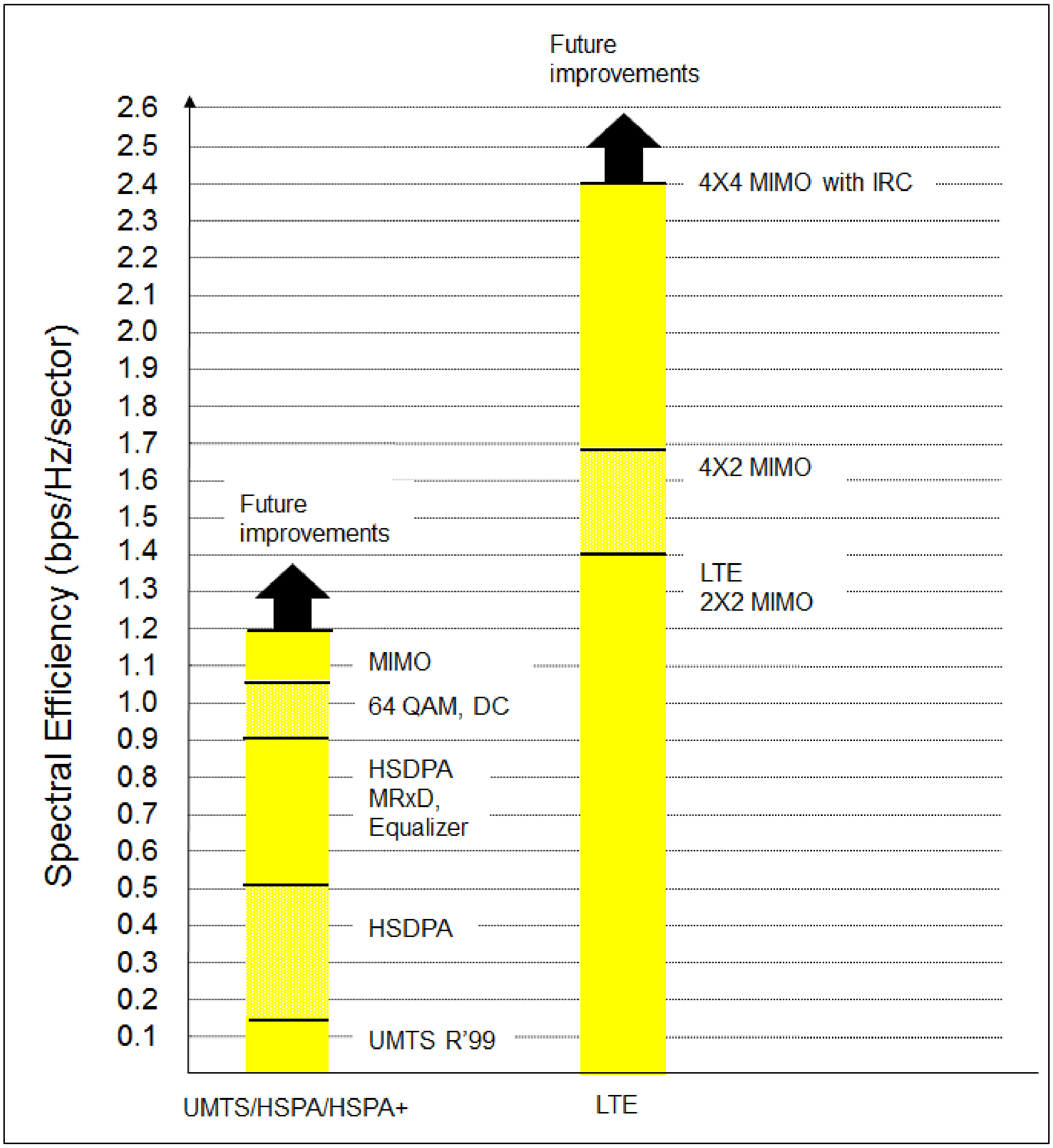
As the speed of the mobile station increases and the channel estimation becomes less accurate, additional margin is needed. This additional margin, however, would impact the different standards fairly equally.

The focus of future technology enhancements is on improving system performance aspects that reduce interference to maximize the experienced SNRs in the system and antenna techniques (such as MIMO) that exploit multiple links or steer the beam rather than on investigating new air interfaces that attempt to improve link-layer performance.

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

Figure 38 compares the spectral efficiency of different wireless technologies based on a consensus view of 5G 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 HSPA and LTE spectral efficiencies. Nevertheless, there are practical considerations in implementing technologies that can prevent actual deployments from reaching calculated values. Consequently, initial versions of technology may operate at lower levels but then improve over time as designs are optimized. Therefore, readers should interpret the values shown as achievable, but not as the actual values that might be measured in any specific deployed network.

Figure 38: Comparison of Downlink Spectral Efficiency[105]



The values shown in Figure 38 are not all possible combinations of available features. Rather, they are representative milestones in ongoing improvements in spectral efficiency. For instance, terminals may employ mobile-receive diversity but not equalization.

The figure does not include EDGE, but EDGE itself is spectrally efficient at 0.6 bps/Hz using mobile receive diversity and, potentially, 0.7 bps/Hz with MIMO. Relative to WCDMA Release 99, HSDPA increases capacity by almost a factor of three. Type 3 receivers that

[105] Joint analysis by 5G Americas members. 5+5 MHz FDD for UMTS-HSPA/LTE. Mix of mobile and stationary users.

include MMSE equalization and Mobile Receive Diversity (MRxD) effectively double HSDPA spectral efficiency. The addition of dual-carrier operation and 64 QAM increases spectral efficiency by about 15%, and MIMO can increase spectral efficiency by another 15%, reaching 1.2 bps/Hz. Dual-carrier HSPA+ offers a gain in spectral efficiency from cross-carrier scheduling with possible gains of about 10%.[106]

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

Beyond HSPA, 3GPP LTE results in further spectral efficiency gains, initially with 2X2 MIMO, then 4X2 MIMO, and then 4X4 MIMO. The gain for 4X2 MIMO will be 20% more than LTE with 2X2 MIMO; the gain for 4X4 MIMO in combination with interference rejection combining (IRC) will be 70% greater than 2X2 MIMO, reaching 2.4 bps/Hz. This value represents a practical deployment of 4X4 MIMO, with random phase and some timing-alignment error included in each of the four transmit paths. CoMP, discussed below in the appendix, provides a minimal contribution to spectral efficiency.

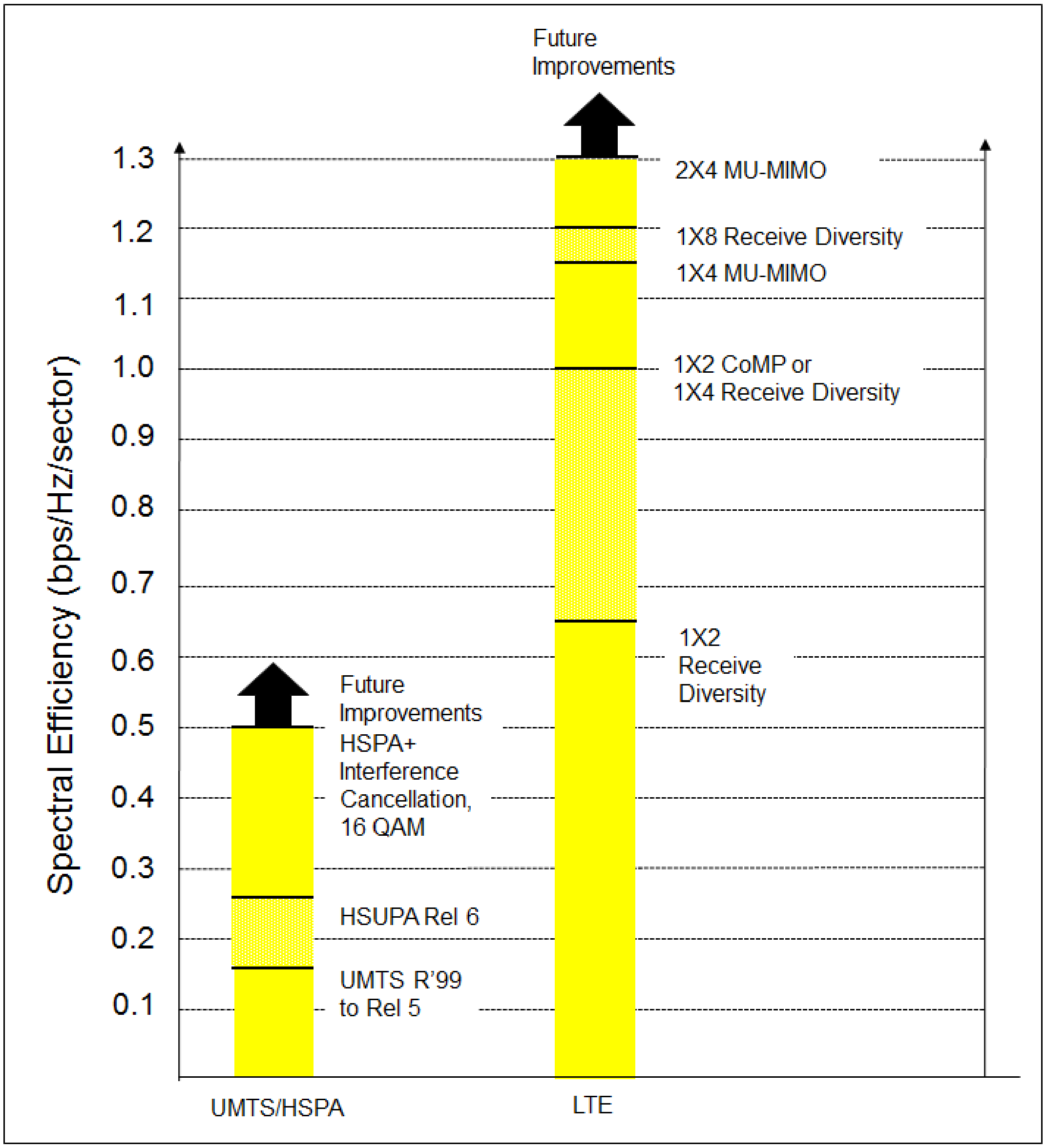
LTE is even more spectrally efficient when deployed using wider radio channels of 10+10 MHz and 20+20 MHz, although most of the gain is realized at 10+10 MHz. LTE TDD has spectral efficiency that is within 1% or 2% of LTE FDD.[107]

Figure 39 compares the uplink spectral efficiency of the different systems.

[106] 5G 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.

[107] Assumes best-effort traffic. Performance between LTE-TDD and FDD differs 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.

Figure 39: Comparison of Uplink Spectral Efficiency[108]



The implementation of HSUPA in HSPA significantly increases uplink capacity.

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.

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

[108] Joint analysis by 5G Americas members. 5+5 MHz for UMTS-HSPA/LTE. Mix of mobile and stationary users.

increases depending on how well link adaptation is implemented. The figure uses a conservative 15% gain, showing MU-MIMO with a 1X4 antenna configuration increasing spectral efficiency by 15%, to 1.15 bps/Hz, and 2X4 MU-MIMO a further 15%, to 1.3 bps/Hz.

In Release 11, uplink CoMP using 1X2 increases efficiency from .65 bps/Hz to 1.0 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 40 compares voice spectral efficiency.

Figure 40: Comparison of Voice Spectral Efficiency[109]

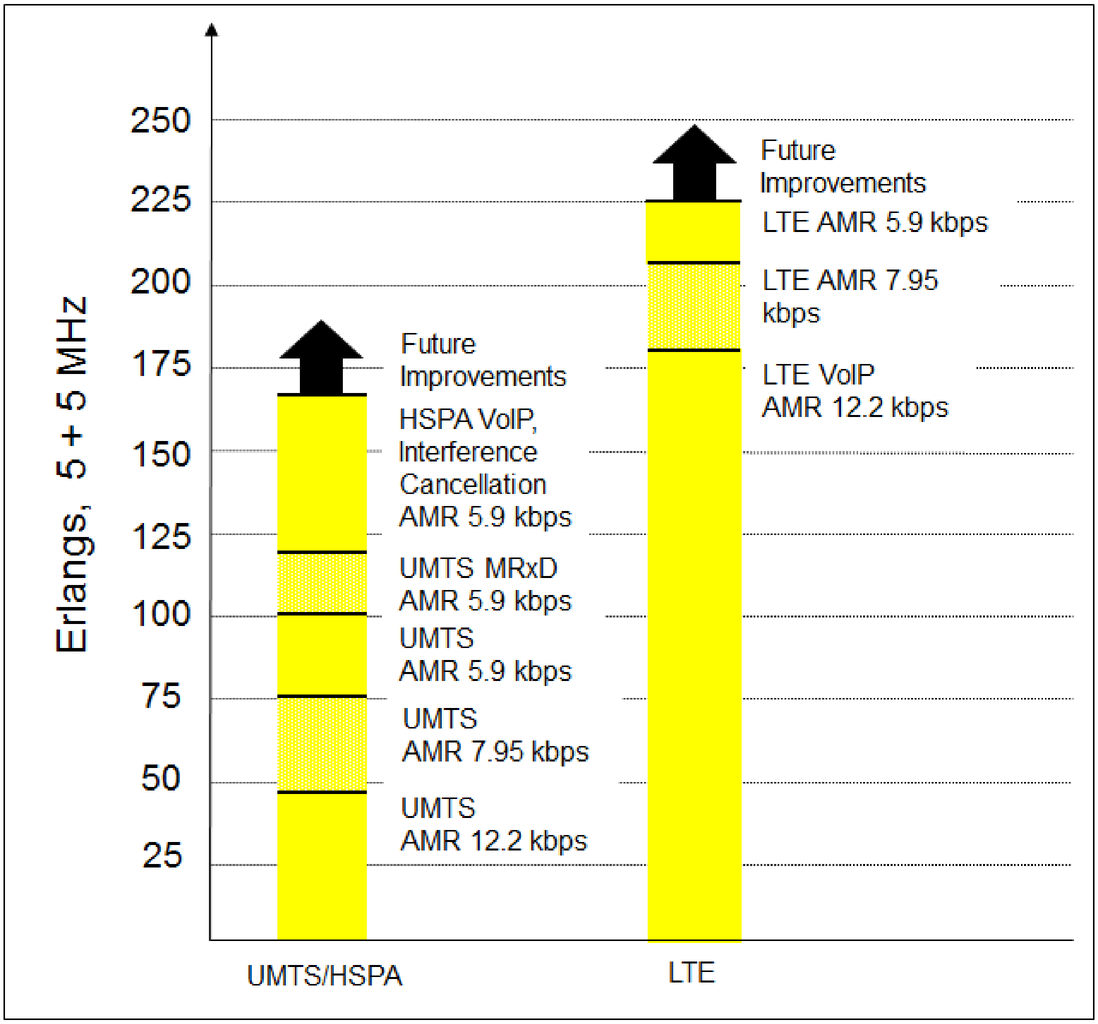


Figure 40 shows UMTS Release 99 with AMR 12.2 Kbps, 7.95 Kbps, and 5.9 Kbps vocoders. The AMR 12.2 Kbps vocoder provides superior voice quality in good (for example, static and indoor) channel conditions.

[109] Joint analysis by 5G Americas members. 5 + 5 MHz for UMTS-HSPA/LTE. Mix of mobile and stationary users.

UMTS has dynamic adaptation between vocoder rates, enabling enhanced voice quality compared with EVRC at the expense of capacity in situations that are not capacity limited. With the addition of mobile receive diversity, UMTS circuit-switched voice capacity could reach 120 Erlangs in 5+5 MHz.

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. These gains do not derive through use of VoIP, but rather from advances in radio techniques applied to the data channels. Many of these same advances may also be applied to current circuit-switched modes.

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

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

The voice efficiency of the wideband AMR voice codec, operating at 12.65 Kbps, is similar to the AMR codec at 12.2 Kbps, with a value of 180 Erlangs for both since both codecs operate at approximately the same bit rate. 1xRTT has voice capacity of 85 Erlangs in 5+5 MHz with EVRC-A and reaches voice capacity of 120 Erlangs with the use of Quasi-Linear Interference Cancellation (QLIC) and EVRC-B at 6 Kbps.

Data Consumed by Video

Table 14 quantifies usage based on advanced video compression schemes such as H.264 and H.265, the type of application, and usage per day.

Table 14: Data Consumed by Different Streaming Applications[110]

Application	Throughput (Mbps)	MByte/hour	Hrs./day	GB/month
Audio or Music	0.1	58	0.5	0.9
			1.0	1.7
			2.0	3.5
			4.0	6.9
Small Screen Video (e.g., Feature Phone)	0.2	90	0.5	1.4
			1.0	2.7
			2.0	5.4
			4.0	10.8
Medium Screen Video (e.g., Smartphone, Tablet, Laptop)	1.0	450	0.5	6.8
			1.0	13.5
			2.0	27.0
			4.0	54.0
Larger Screen Video (e.g., 720p medium definition)	3.0	1350	0.5	20.3
			1.0	40.5
			2.0	81.0
			4.0	162.0
High Definition (e.g., 1080p Netflix HD)	5.0	2250	0.5	33.8
			1.0	67.5
			2.0	135.0
			4.0	270.0
4K Ultra-High Definition (Rates will range 12 to 30 Mbps)	20.0	9000	0.5	135.0
			1.0	270.0
			2.0	540.0
			4.0	1080.0

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

Spectrum Bands

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

Table 15 shows the UMTS FDD bands.

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110 Rysavy Research analysis. See also Netflix discussion of usage, "How can I control how much data Netflix uses?" https://help.netflix.com/en/node/87. Viewed May 3, 2016.

Table 15: UMTS FDD Bands[111]

Operating Band	UL Frequencies UE transmit, Node B receive	DL frequencies UE receive, Node B transmit
I	1920 - 1980 MHz	2110 -2170 MHz
II	1850 -1910 MHz	1930 -1990 MHz
III	1710-1785 MHz	1805-1880 MHz
IV	1710-1755 MHz	2110-2155 MHz
V	824 - 849MHz	869-894MHz
VI	830-840 MHz	875-885 MHz
VII	2500 - 2570 MHz	2620 - 2690 MHz
VIII	880 - 915 MHz	925 - 960 MHz
IX	1749.9 - 1784.9 MHz	1844.9 - 1879.9 MHz
X	1710-1770 MHz	2110-2170 MHz
XI	1427.9 - 1447.9 MHz	1475.9 - 1495.9 MHz
XII	699 - 716 MHz	729 - 746 MHz
XIII	777 - 787 MHz	746 - 756 MHz
XIV	788 - 798 MHz	758 - 768 MHz
XV	Reserved	Reserved
XVI	Reserved	Reserved
XVII	Reserved	Reserved
XVIII	Reserved	Reserved
XIX	830 – 845 MHz	875 -890 MHz
XX	832 - 862 MHz	791 - 821 MHz
XXI	1447.9 - 1462.9 MHz	1495.9 - 1510.9 MHz
XXII	3410 – 3490 MHz	3510 – 3590 MHz
XXV	1850 -1915 MHz	1930 -1995 MHz
XXVI	814-849 MHz	859-894 MHz
XXXII (NOTE 1)	N/A	1452 – 1496 MHz
NOTE 1: Restricted to UTRA operation when dual band is configured (e.g., DB-DC-HSDPA or dual band 4C-HSDPA). The down link frequenc(ies) of this band are paired with the uplink frequenc(ies) of the other FDD band (external) of the dual band configuration.		

Universal Mobile Telecommunications System (UMTS) Time Division Duplex (TDD) bands are the same as the LTE TDD bands. Table 16 details the LTE Frequency Division Duplex (FDD) and TDD bands.

[111] 3GPP, *Base Station (BS) radio transmission and reception (FDD) (Release 13),* January 2016, Technical Specification 25.104, V13.1.0.

Table 16: LTE FDD and TDD bands[112]

E-UTRA Operating Band	Uplink (UL) operating band BS receive UE transmit F_{UL_low} – F_{UL_high}	Downlink (DL) operating band BS transmit UE receive F_{DL_low} – F_{DL_high}	Duplex Mode
1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	FDD
2	1850 MHz – 1910 MHz	1930 MHz – 1990 MHz	FDD
3	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	FDD
4	1710 MHz – 1755 MHz	2110 MHz – 2155 MHz	FDD
5	824 MHz – 849 MHz	869 MHz – 894MHz	FDD
6 (NOTE 1)	830 MHz – 840 MHz	875 MHz – 885 MHz	FDD
7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	FDD
8	880 MHz – 915 MHz	925 MHz – 960 MHz	FDD
9	1749.9 MHz – 1784.9 MHz	1844.9 MHz – 1879.9 MHz	FDD
10	1710 MHz – 1770 MHz	2110 MHz – 2170 MHz	FDD
11	1427.9 MHz – 1447.9 MHz	1475.9 MHz – 1495.9 MHz	FDD
12	699 MHz – 716 MHz	729 MHz – 746 MHz	FDD
13	777 MHz – 787 MHz	746 MHz – 756 MHz	FDD
14	788 MHz – 798 MHz	758 MHz – 768 MHz	FDD
15	Reserved	Reserved	FDD
16	Reserved	Reserved	FDD
17	704 MHz – 716 MHz	734 MHz – 746 MHz	FDD
18	815 MHz – 830 MHz	860 MHz – 875 MHz	FDD
19	830 MHz – 845 MHz	875 MHz – 890 MHz	FDD
20	832 MHz – 862 MHz	791 MHz – 821 MHz	
21	1447.9 MHz – 1462.9 MHz	1495.9 MHz – 1510.9 MHz	FDD
22	3410 MHz – 3490 MHz	3510 MHz – 3590 MHz	FDD
23	2000 MHz – 2020 MHz	2180 MHz – 2200 MHz	FDD
24	1626.5 MHz – 1660.5 MHz	1525 MHz – 1559 MHz	FDD
25	1850 MHz – 1915 MHz	1930 MHz – 1995 MHz	FDD
26	814 MHz – 849 MHz	859 MHz – 894 MHz	FDD
27	807 MHz – 824 MHz	852 MHz – 869 MHz	FDD
28	703 MHz – 748 MHz	758 MHz – 803 MHz	FDD
29	N/A	717 MHz – 728 MHz	FDD (NOTE 2)
30	2305 MHz – 2315 MHz	2350 MHz – 2360 MHz	FDD
31	452.5 MHz – 457.5 MHz	462.5 MHz – 467.5 MHz	FDD
32	N/A	1452 MHz – 1496 MHz	FDD (NOTE 2)
33	1900 MHz – 1920 MHz	1900 MHz – 1920 MHz	TDD
34	2010 MHz – 2025 MHz	2010 MHz – 2025 MHz	TDD
35	1850 MHz – 1910 MHz	1850 MHz – 1910 MHz	TDD
36	1930 MHz – 1990 MHz	1930 MHz – 1990 MHz	TDD
37	1910 MHz – 1930 MHz	1910 MHz – 1930 MHz	TDD
38	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz	TDD
39	1880 MHz – 1920 MHz	1880 MHz – 1920 MHz	TDD
40	2300 MHz – 2400 MHz	2300 MHz – 2400 MHz	TDD
41	2496 MHz – 2690 MHz	2496 MHz – 2690 MHz	TDD
42	3400 MHz – 3600 MHz	3400 MHz – 3600 MHz	TDD
43	3600 MHz – 3800 MHz	3600 MHz – 3800 MHz	TDD
44	703 MHz – 803 MHz	703 MHz – 803 MHz	TDD
45	1447 MHz – 1467 MHz	1447 MHz – 1467 MHz	TDD
46	5150 MHz – 5925 MHz	5150 MHz – 5925 MHz	TDD (NOTE 3, NOTE 4)
65	1920 MHz – 2010 MHz	2110 MHz – 2200 MHz	FDD
66	1710 MHz – 1780 MHz	2110 MHz – 2200 MHz	FDD (NOTE 5)
67	N/A	738 MHz – 758 MHz	FDD (NOTE 2)

NOTE 1: Band 6 is not applicable.
NOTE 2: Restricted to E-UTRA operation when carrier aggregation is configured. The downlink operating band is paired with the uplink operating band (external) of the carrier aggregation configuration that is supporting the configured Pcell.
NOTE 3: This band is an unlicensed band restricted to licensed-assisted operation using Frame Structure Type 3.
NOTE 4: In this version of the specification, restricted to E-UTRA DL operation when carrier aggregation is configured. Band 46 is divided into four sub-bands as in Table 5.5-1A.
NOTE 5: The range 2180 – 2200 MHz of the DL operating band is restricted to E-UTRA operation when carrier aggregation is configured.

112 3GPP, *Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception (Release 13),* Jan. 2016, Technical Specification 36.104, V13.2.0.

LTE and LTE-Advanced

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

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

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

LTE capabilities include:

- Downlink peak data rates up to 300 Mbps with 20+20 MHz bandwidth in initial versions, increasing to over 1 Gbps in subsequent versions through carrier aggregation, higher-order modulation, and 4X4 MIMO.
- Uplink peak data rates up to 71 Mbps with 20+20 MHz bandwidth in initial versions, increasing to over 1 Gbps in subsequent versions.
- Operation in both TDD and FDD modes.
- Scalable bandwidth up to 20+20 MHz covering 1.4, 3, 5, 10, 15, and 20 MHz radio carriers.
- Increased spectral efficiency over HSPA by a factor of two to four.
- Reduced latency, to 15 msec round-trip times between user equipment and the base station, and to less than 100 msec transition times from inactive to active.
- Self-organizing capabilities under operator control and preferences that will automate network planning and will result in lower operator costs.

LTE-Advanced Terminology

LTE-Advanced, as specified in Release 10, is a term used for the version of LTE that addresses IMT-Advanced requirements. The ITU ratified LTE-Advanced as IMT-Advanced in November 2010. LTE-Advanced is both backward- and forward-compatible with LTE, meaning LTE devices operate in newer LTE-Advanced networks, and LTE-Advanced devices operate in older, pre Release 10 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 (HetNet) support including enhanced Inter-Cell Interference Coordination (eICIC).
- Relays.

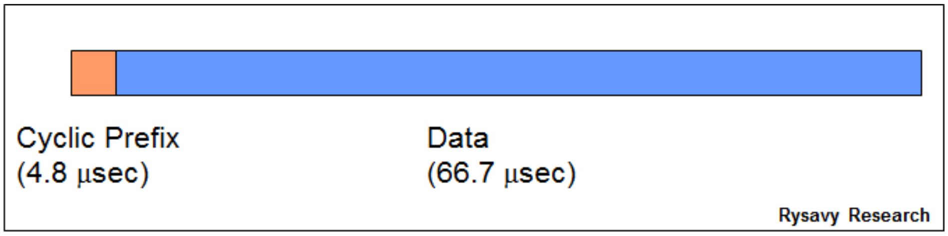
OFDMA and Scheduling

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

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

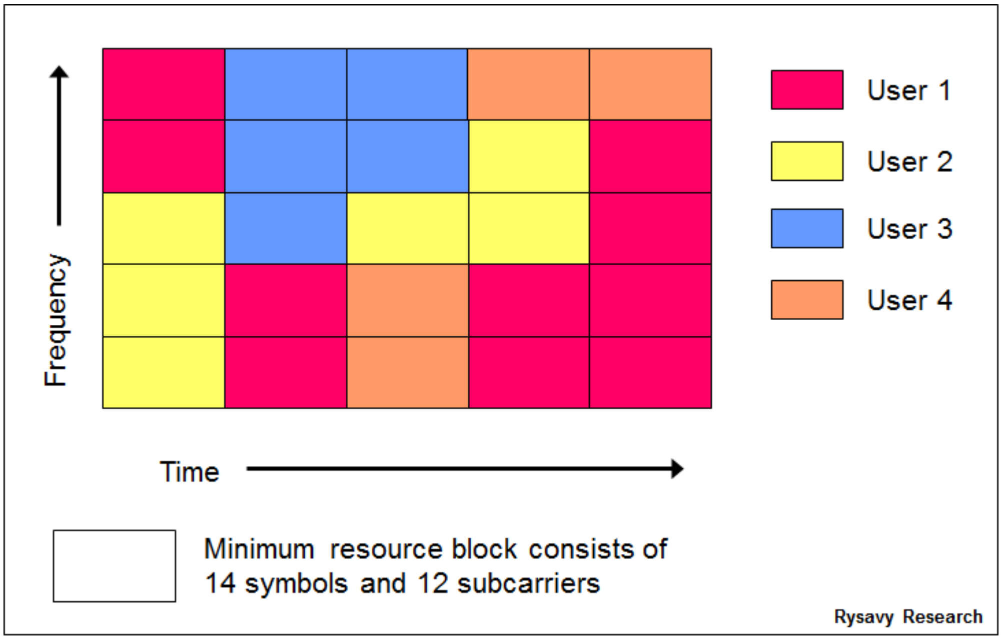
OFDM systems may lose their orthogonal nature as a result of the Doppler shift induced by the speed of the transmitter or the receiver. 3GPP specifically selected the subcarrier spacing of 15 kHz to avoid any performance degradation in high-speed conditions. WiMAX systems that use a lower subcarrier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

Figure 41: OFDM Symbol with Cyclic Prefix



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 42 shows how the system can assign these resource blocks to different users over both time and frequency.

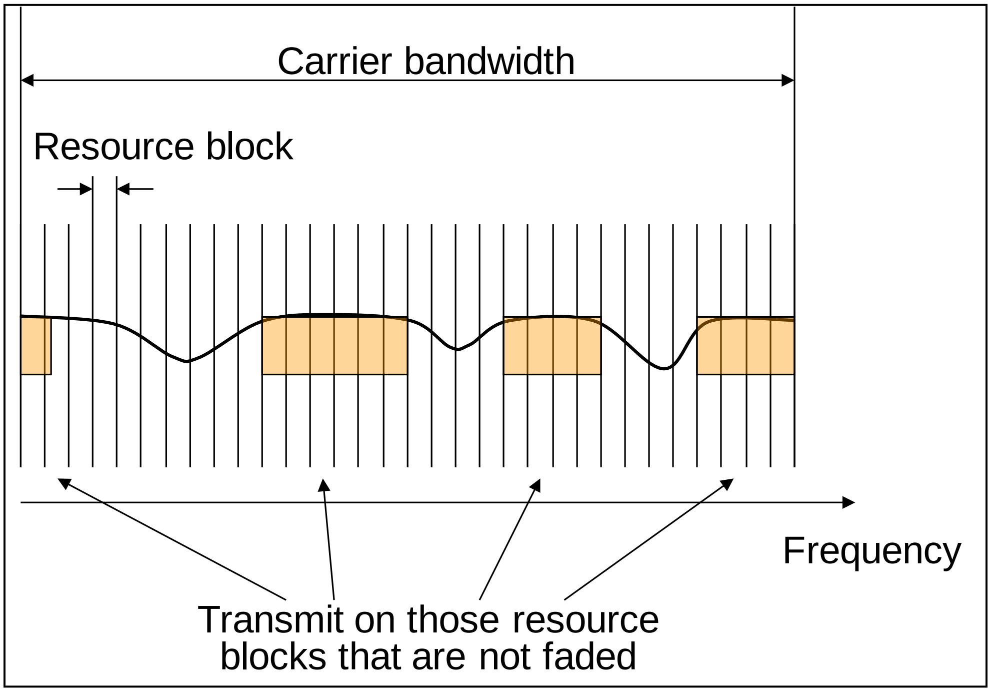
Figure 42: LTE OFDMA Downlink Resource Assignment in Time and Frequency



By controlling which subcarriers are assigned in which sectors, LTE can easily control frequency reuse. Using all the subcarriers in each sector, the system would operate at a frequency reuse of 1; but by using a different one third of the subcarriers in each sector, the system can achieve a looser frequency reuse of 1/3. The looser frequency reduces overall spectral efficiency but delivers high peak rates to users.

Beyond controlling frequency reuse, frequency domain scheduling, as shown in Figure 43 can use those resource blocks that are not faded, not possible in CDMA-based systems. Since different frequencies may fade differently for different users, the system can allocate those frequencies for each user that result in the greatest throughput. This results in up to a 40% gain in average cell throughput for low user speed (3 km/hour), assuming a large number of users and no MIMO. The benefit decreases at higher user speeds.

Figure 43: Frequency-Domain Scheduling in LTE[113]



LTE Smart Antennas

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

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

Table 17 shows the varous antenna transmission modes.

[113] 5G Americas member contribution.

Table 17: LTE Transmission Modes[114]

Transmission Mode	Description
1	Single-antenna transmission.
2	Transmit diversity.
3	Transmit diversity for one layer, open-loop codebook-based precoding if more than one layer.
4	Closed-loop codebook-based precoding.
5	Multi-user MIMO version of transmission mode 4.
6	Special case of closed-loop codebook-based precoding limited to single-layer transmission.
7	Beamforming. (Non-codebook-based precoding supporting one layer.)
8	Dual-layer beamforming. (Release 9. Non-codebook-based precoding supporting up to two layers.)
9	8-layer transmission. (Release 10. Non-codebook-based precoding supporting up to eight layers.)
10	8-layer transmission with support for CoMP. (Release 11.)

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

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

Fundamental variables distinguish the different antenna modes:

- **Single base-station antenna versus multiple antennas.** Single antennas provide for Single Input Single Output (SISO), 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.

[114] Erik Dahlman, Stefan Parkvall, Johan Skold, *4G - LTE/LTE Advanced for Mobile Broadband*, Academic Press, 2011.

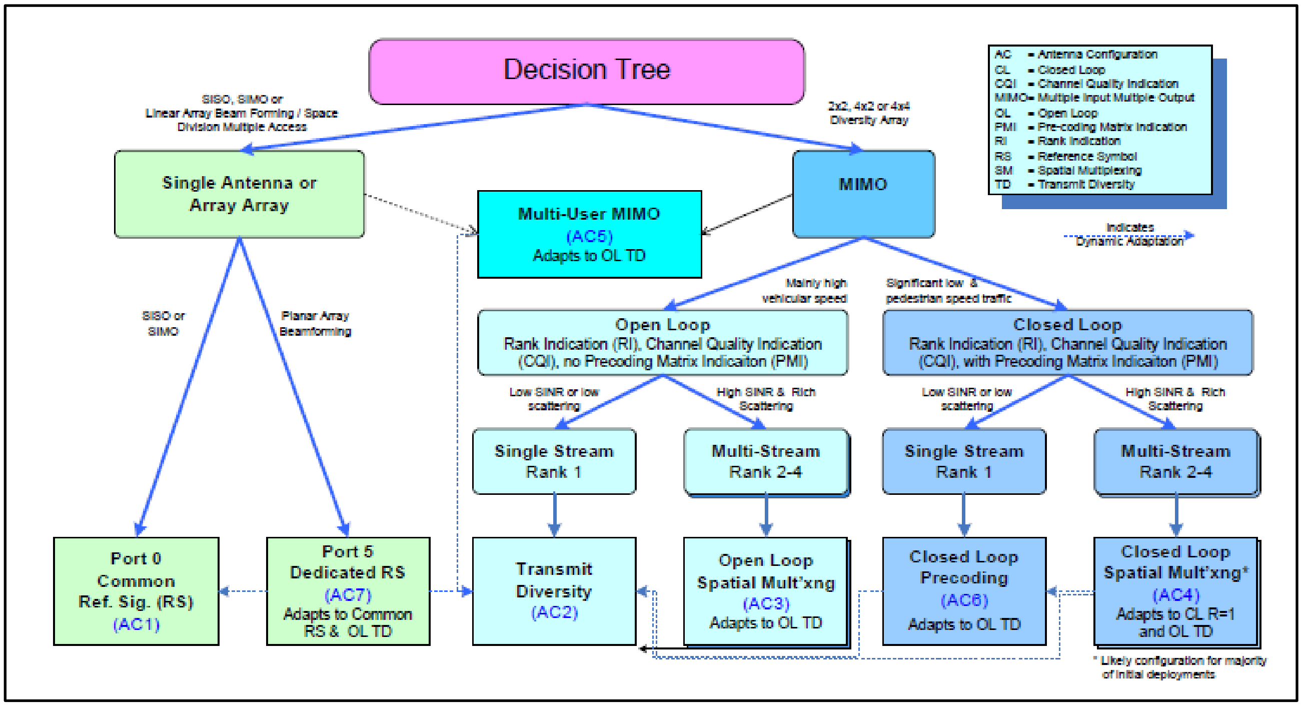
- **Single-user MIMO versus multi-user MIMO.** Release 8 only provides for single-user MIMO on the downlink. Release 10 includes multi-user MIMO.

- **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 44 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 44: Decision Tree for Different Antenna Schemes[115]



The simplest mode is AC2, referred to as Transmit Diversity (TD) or sometimes Space Frequency Block Code (SFBC) or even Open Loop Transmit Diversity. TD can operate under all conditions, meaning it works under low SINR, high mobility, and low channel rank (rank = 1). This rank means that the channel is not sufficiently scattered or 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), also referred to as large-delay Cyclic Delay Diversity (CDD). This mode supports two spatial streams or two codewords. This mode, also called multiple codeword (MCW) operation, increases throughput over SCW transmission.

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

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

[115] 4G Americas *MIMO and Smart Antennas for 3G and 4G Wireless Systems – Practical Aspects and Deployment Considerations*, May 2010.

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

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

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

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

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

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

For a more detailed discussion of 3GPP antenna technologies, refer to the 5G Americas white paper "MIMO and Smart Antennas for 3G and 4G Wireless Systems – Practical Aspects and Deployment Considerations," May 2010.

For advancements in LTE smart antennas, see the next section.

LTE-Advanced Antenna Technologies

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

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

Release 10 supports a maximum 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 eight layers), as well as the ability to dynamically switch between SU-MIMO and MU-MIMO.

Figure 45 shows the different forms of single-user MIMO in Releases 8, 9, and 10. Release 8 supports only a single layer, whereas two-layer beamforming is possible in Release 9, and eight layers are possible in Release 10 with eight antennas at the base station.

Figure 45: Single-User MIMO[116]

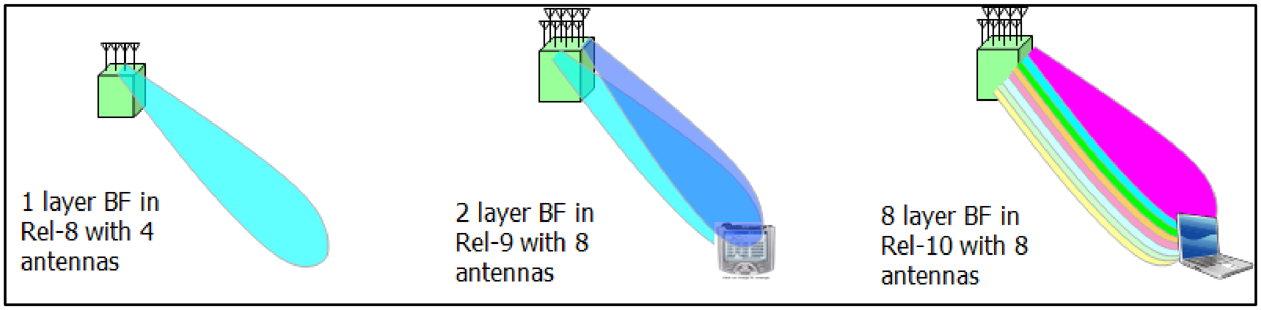
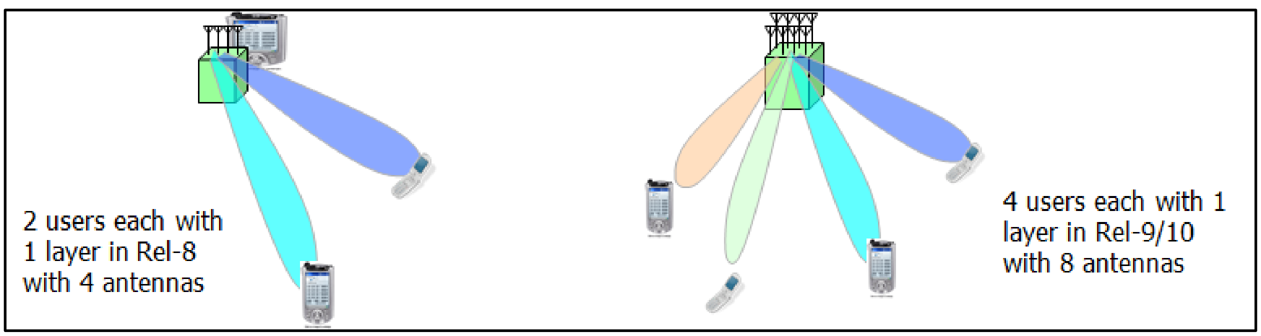


Figure 46 shows multi-user MIMO options across different releases. Release 8 supports two simultaneous users, each with one layer using four antennas, while Releases 9 and 10 support four simultaneous users, each with one layer.

Figure 46: Multi-User MIMO[117]



For four-antenna configurations at the base station, Release 12 improves throughput by adding a feedback mode, called mode 3-2, in which sub-band precoders and sub-band

116 5G Americas member contribution.

117 5G Americas member contribution.

channel quality indicators (CQIs) are included in the UE's feedback to the eNodeB. Release 12 also adds a new codebook that further improves throughput.

As depicted in Figure 47 and Figure 48, compared with the Release 8 codebook, the new Release 12 codebook provides a 10% gain for both median and cell-edge throughputs. Compared with feedback mode 3-1, feedback mode 3-2 provides an 18% to 20% gain in median and cell-edge throughput. Jointly, the two methods provide a 28% to 30% gain.

Figure 47: Median Throughput of Feedback Mode 3-2 and New Codebook.[118]

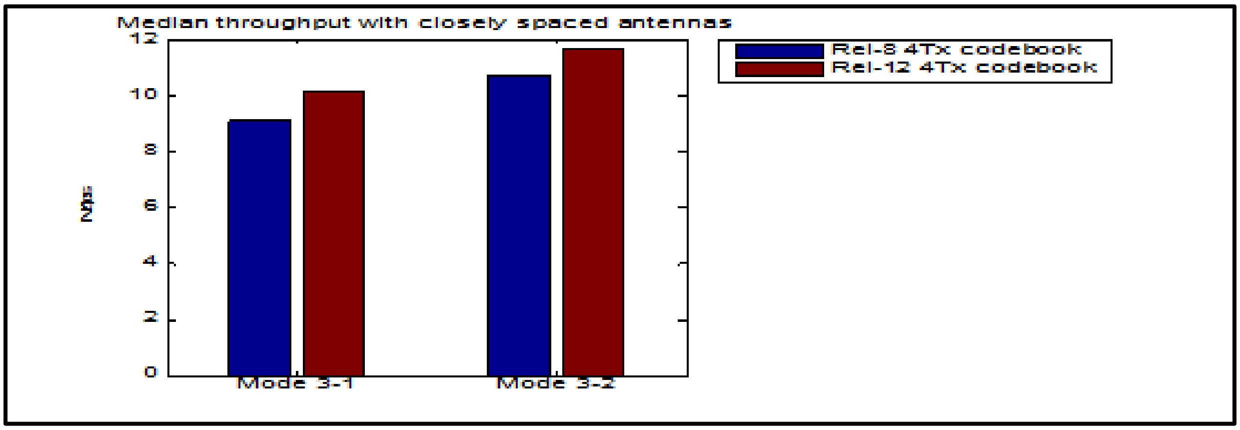
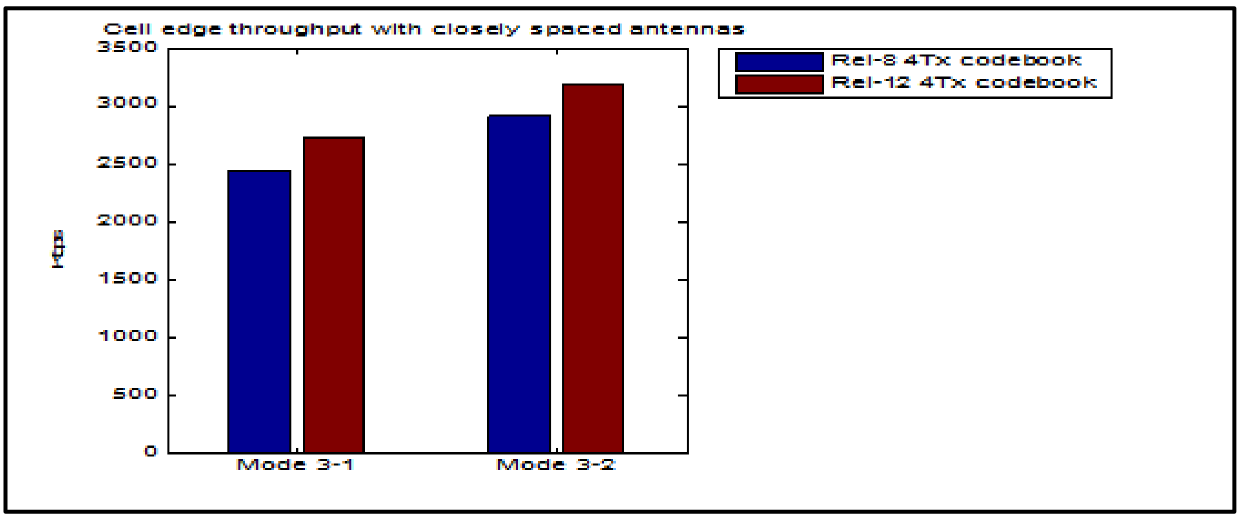


Figure 48: Cell-Edge Throughput of Feedback Mode 3-2 and New Codebook[119]



Release 12 also defines how Active Antenna Systems can use multiple transceivers on an antenna array to dynamically adjust a radiation pattern.

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[118] 5G Americas member contribution. Assumptions include: cellular layout of 19 sites hexagonal grid with three sectors per site and 500 meter inter-site distance; simulation case ITU uMa for macro; carrier frequency 2 GHz, deployment scenario A homogenous macro; SU-MIMO with maximum two layers per UE; proportional fair scheduler; and bursty traffic model.

[119] 5G Americas member contribution. Same assumptions as previous figure.

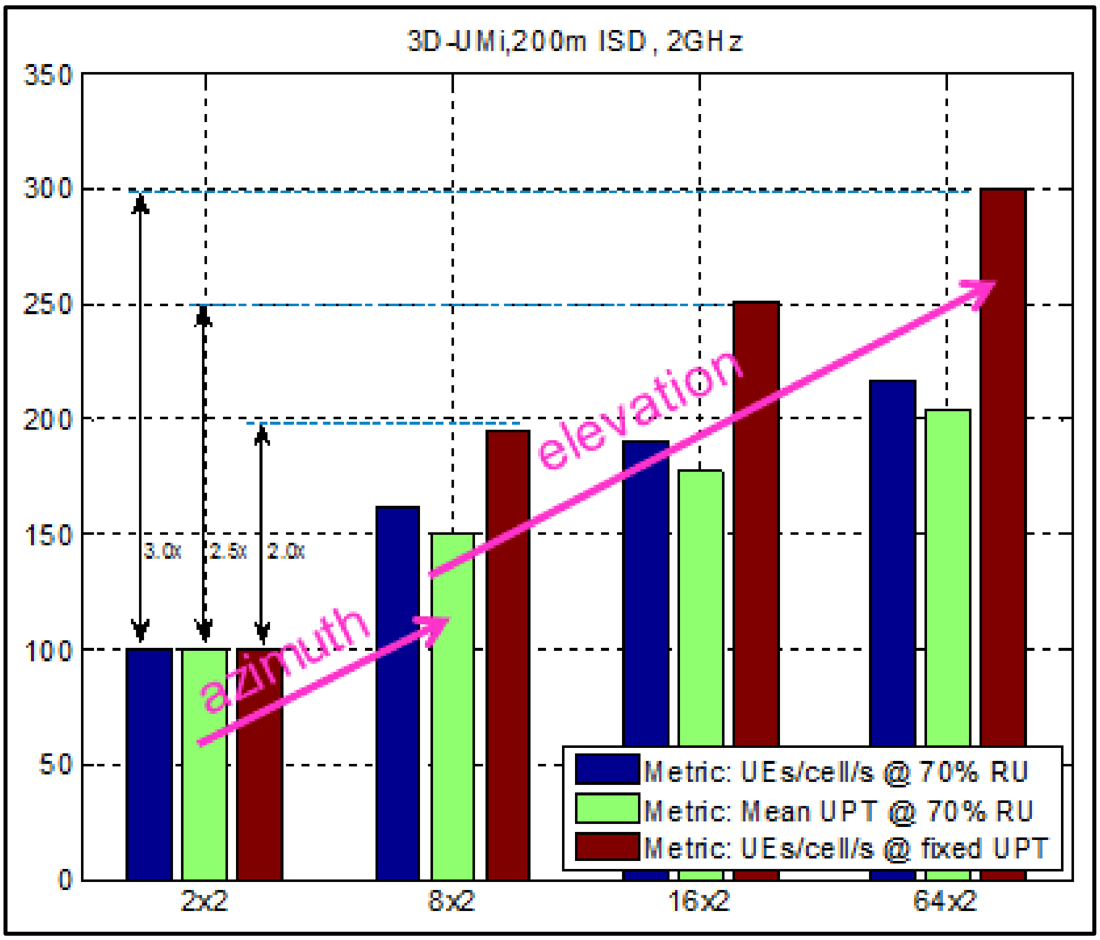
Release 13 is likely to define full-dimension MIMO, which adds a large number of antenna elements, potentially as many as 64 elements.

A practical consideration with antennas is that many towers today already support multiple operators, with tower companies having to manage interference placement, spectrum allocations, and wind and snow load. At higher frequencies, a single radome (antenna enclosure) can support 4X2 MIMO, but higher-order MIMO may prove impractical for many deployments.

5G systems operating at much higher frequencies will have an advantage since the antenna arrays will be much smaller due to the much smaller wavelengths.

Initial massive-MIMO techniques applied to LTE, such as full-dimension MIMO using 8, 16, and 64 transmit antennas, can provide dramatic performance gains, particularly in dense deployments, as shown in Figure 49.

Figure 49: Performance Gains with FD-MIMO Using 200 Meter ISD[120]



This figure compares 8X2, 16X2, and 64X2 MIMO performance relative to 2X2 MIMO (normalized to value 100). The blue bars (case 1) show the supported number of users per sector (referred to as "cell" in the figure) at a fixed resource utilization (RU) of 70%; the

[120] 5G Americas member contribution.

green bars (case 2) show mean user throughput (UPT) at a fixed RU of 70%; and the red bars (case 3) show system capacity in terms of supported number of users for a given user throughput. Resulting gains are:

- Case 2 (green bars): 1.5X with 8X2, 1.75X with 16X2, and 2X with 64X2 MIMO.
- Case 3 (red bars): 2X with 8X2, 2.5X with 16X2, and 3X with 64X2 MIMO.

The primary gains are from azimuth (horizontal dimension) in going from 2X2 to 8X2, and from elevation in going to 16X2 and 64X2. FD-MIMO gains are lower with larger ISD values, such as 500 meters.

3GPP has also studied FD-MIMO and conducted a field trial showing impressive throughput gains, particularly in a high-rise scenario.[121]

Carrier Aggregation

Carrier aggregation, first available in Release 10, plays 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 (for example, different amounts of spectrum used on the downlink versus the uplink) provides further flexibility and addresses the greater demand on downlink traffic.

Specific types of aggregation include:

- Intra-band on adjacent channels.
- Intra-band on non-adjacent channels.
- Inter-band (700 MHz, 1.9 GHz).
- Inter-technology (for example, LTE on one channel, HSPA+ on another). This approach is not currently specified nor being developed. While theoretically promising, a considerable number of technical issues would have to be addressed.[122] See Figure 50.

[121] 3GPP, *3D-MIMO Prototyping and Initial Field Trial Results*, TSG RAN WG1 Meeting #80, Agenda Item: 7.2.4.4, Document R1-150451.

[122] For further details, see 4G Americas, *HSPA+ LTE Carrier Aggregation*, June 2012.

Figure 50: Inter-Technology Carrier Aggregation[123]

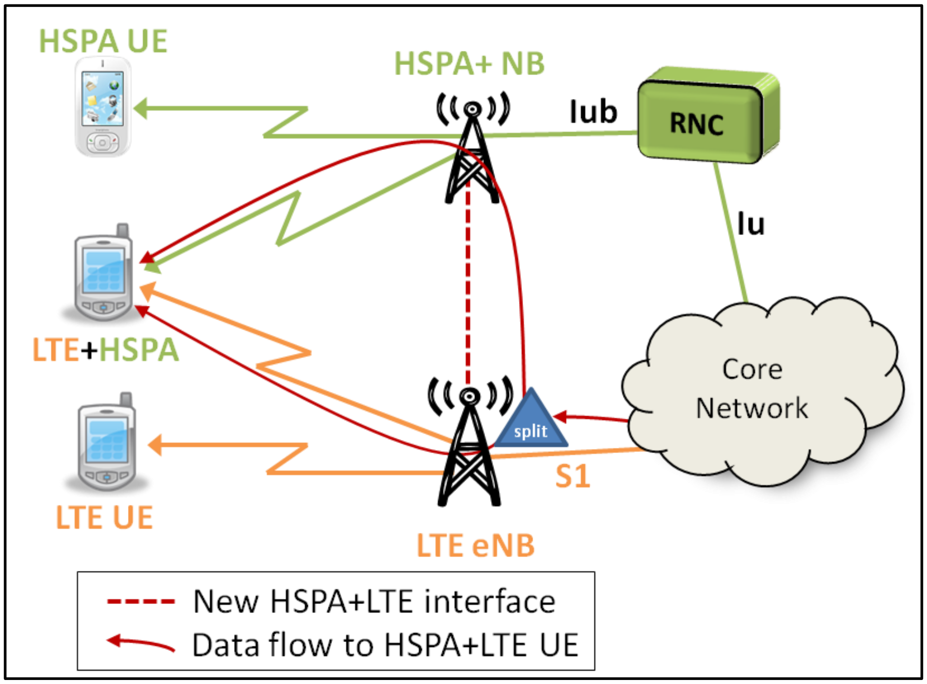
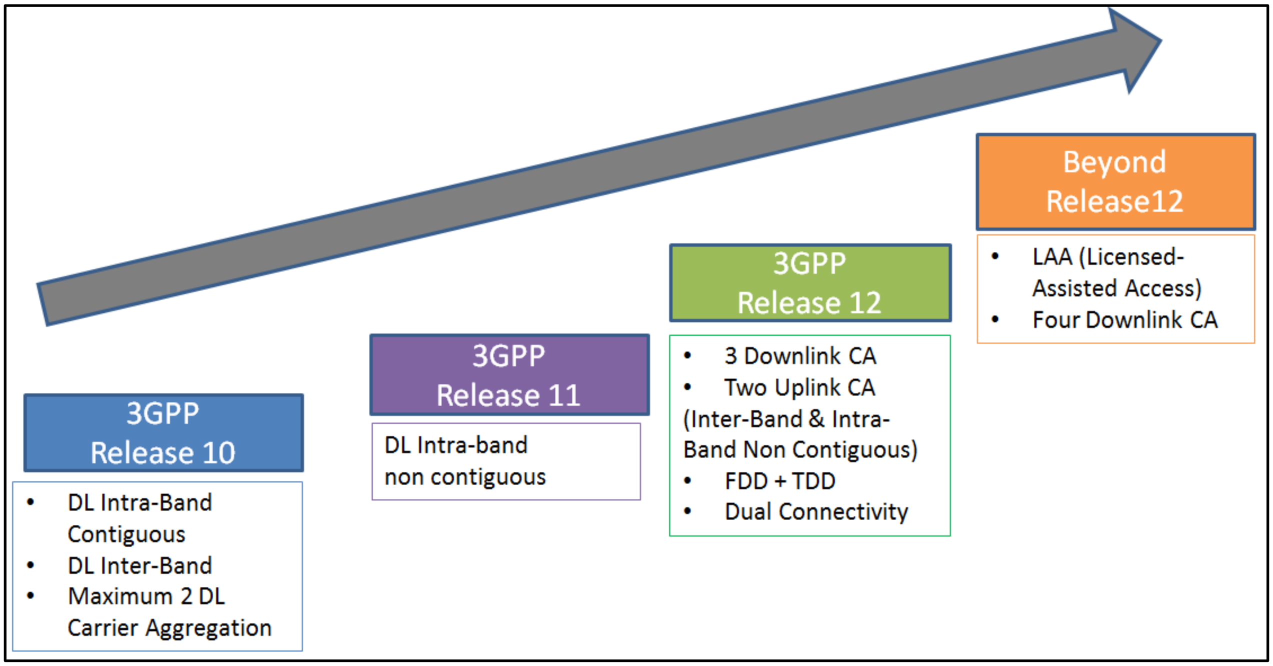


Figure 51 depicts the carrier-aggregation capabilities of different 3GPP releases.

[123] 5G Americas member contribution.

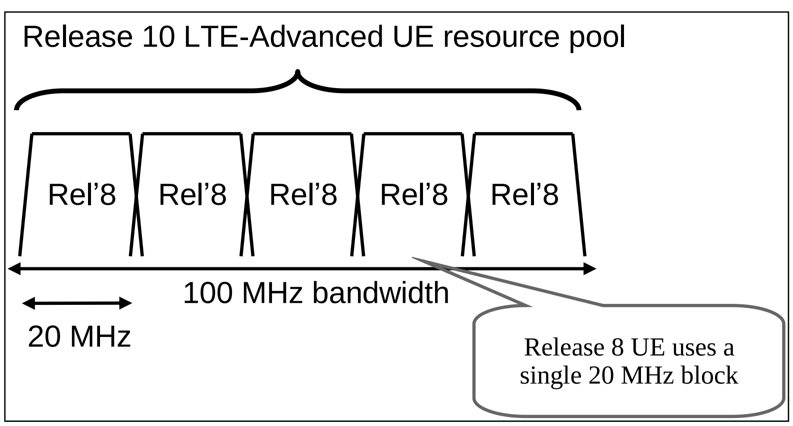
Figure 51: Carrier Aggregation Capabilities across 3GPP Releases[124]



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

Figure 52 shows an example of intra-band carrier aggregation using adjacent channels with up to 100+100 MHz of bandwidth supported. Radio-access network specifications, however, limit the number of carriers to two in Release 10 and Release 11.

Figure 52: Release 10 LTE-Advanced Carrier Aggregation[125]



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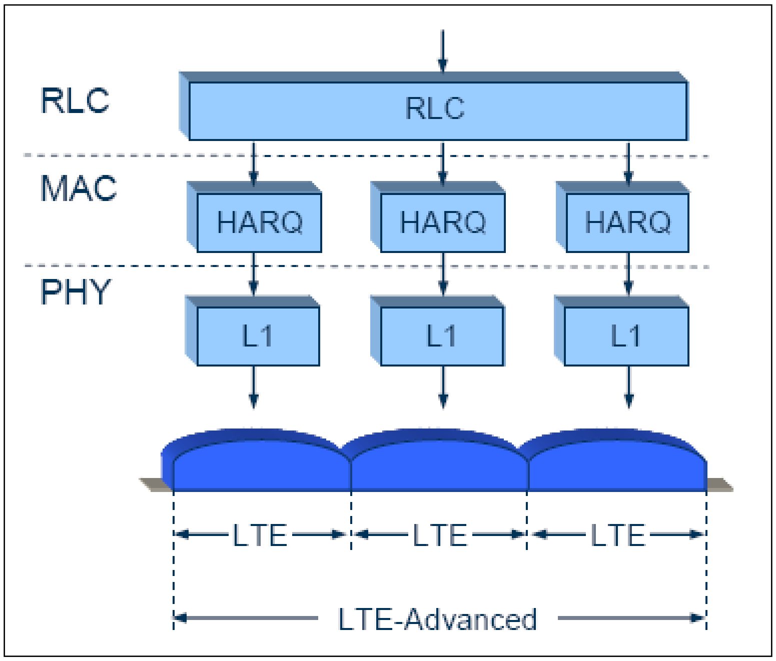
[124] 4G Americas, *Mobile Broadband Evolution: Rel-12 & Rel-13 and Beyond*, 2015.

[125] Harri Holma and Antti Toskala, *LTE for UMTS, OFDMA and SC-FDMA Based Radio Access*, Wiley, 2009.

Figure 53 shows the carrier aggregation operating at different protocol layers.

Figure 53: Carrier Aggregation at Different Protocol Layers[126]



Intra-band CA combinations being defined in the Release 11 timeframe include:

Table 18: Intra-Band Carrier Aggregation

Case No.	Band No.	Common Names	Carrier Examples
1	7	Intra-Band 2600	China Unicom
2	38	Intra-Band MBS of 2.6 GHz	China Mobile
3	40	Intra-Band IMT 2000	
4	41	Intra-Band 2600 BRS/EBS	Clearwire

Inter-Band CA combinations defined in the Release 11 timeframe include:

Table 19: Inter-Band Carrier Aggregation

Case No.	Band No.	Common Names	Carrier Examples

126 Stefan Parkvall and David Astely, Ericsson Research, "The Evolution of LTE towards IMT-Advanced," Journal of Communications, Vol. 4, No. 3, April 2009. Available at http://www.academypublisher.com/jcm/vol04/no03/jcm0403146154.pdf.

1	1+5	2100+cellular	
2	1+18	2100+ESMR	KDDI
3	1+19	2100+880	NTT DoCoMo
4	1+21	2100+1.5G	NTT DoCoMo
5	2+17	PCS+B&C	AT&T
6	3+5	1800+cellular	SK Telecom
7	3+7	1800+2.6	TeliaSonera
8	3+8	1800+900	KT
9	3+20	1800+Digital Dividend	Vodafone
10	4+5	AWS+Cellular	AT&T
11	4+7	AWS+2.6	Rogers Wireless
12	4+12	AWS+ABC	Leap
13	4+13	AWS+Upper C	Ericsson VZW
14	4+17	AWS+B&C	AT&T
15	5+12	Cellular+ABC	US Cellular
16	5+17	Cellular+B&C	AT&T
17	7+20	2.6+Digital Dividend	Orange
18	8+20	900+Digital Dividend	Vodafone
19	11+18	PDC+ESMR	KDDI

For Release 12, 3GPP has defined a significant number of additional band combinations.[127]

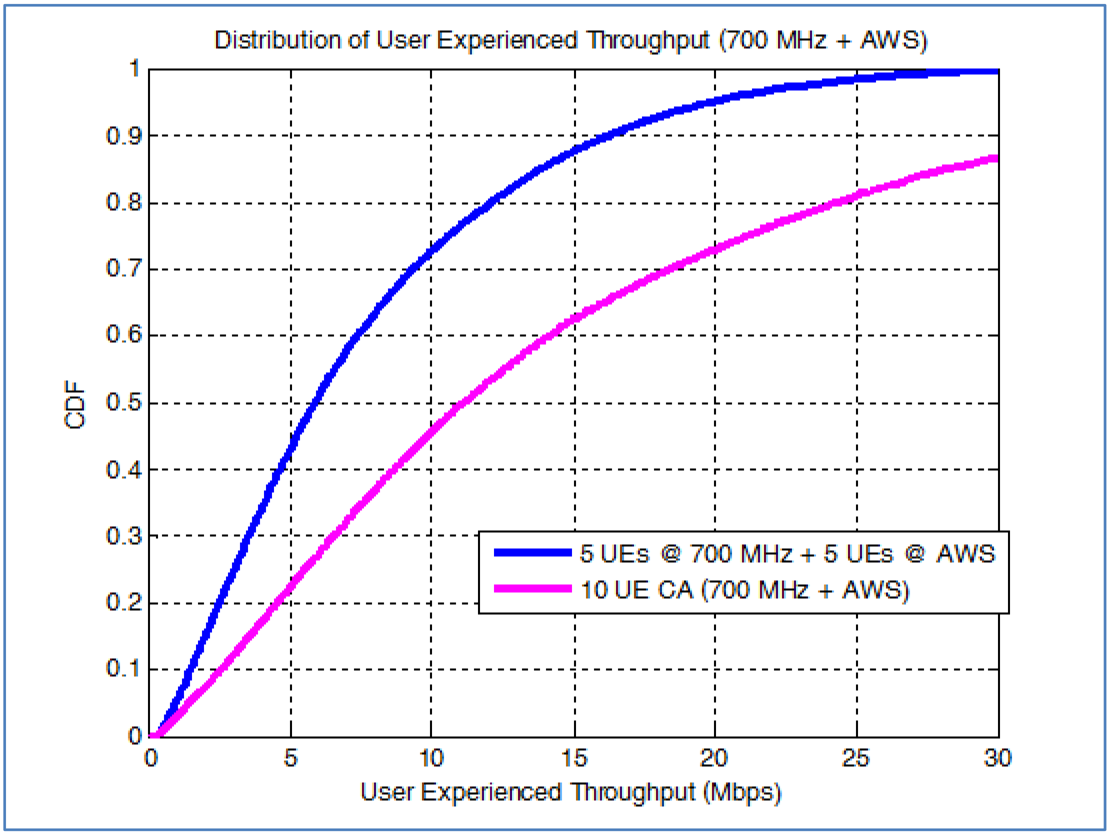
Carrier aggregation improves performance not only by combining the capacity of two or more different radio channels, but also through trunking efficiency, which refers to packets being able to traverse through either of the channels and solving the problem of one being congested while the other is idle.

Figure 54 shows the result of one simulation study that compares download throughput rates between the blue line, which shows five user devices in 700 MHz and five user devices in AWS not using CA, and the pink line, which shows ten user devices that have access to

[127] 4G Americas, *4G Mobile Broadband – 3GPP Release 11 & Release 12 and Beyond*, Appendix A, "Table 5.2, EUTRA Inter-Band Carrier Aggregation cases through current working view of Rel-12." Available at http://www.4gamericas.org/documents/4G%20Mobile%20Broadband%20Evolution%20Rel-11%20%20Rel%2012%20and%20Beyond%20Feb%202014%20-%20FINAL.pdf.

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 54: Gains from Carrier Aggregation[128]



Work in Release 12 is investigating aggregation of joint TDD and FDD carriers.

Coordinated Multi Point (CoMP)

Coordinated Multi Point (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 Release 10 and was standardized in Release 11.

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

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

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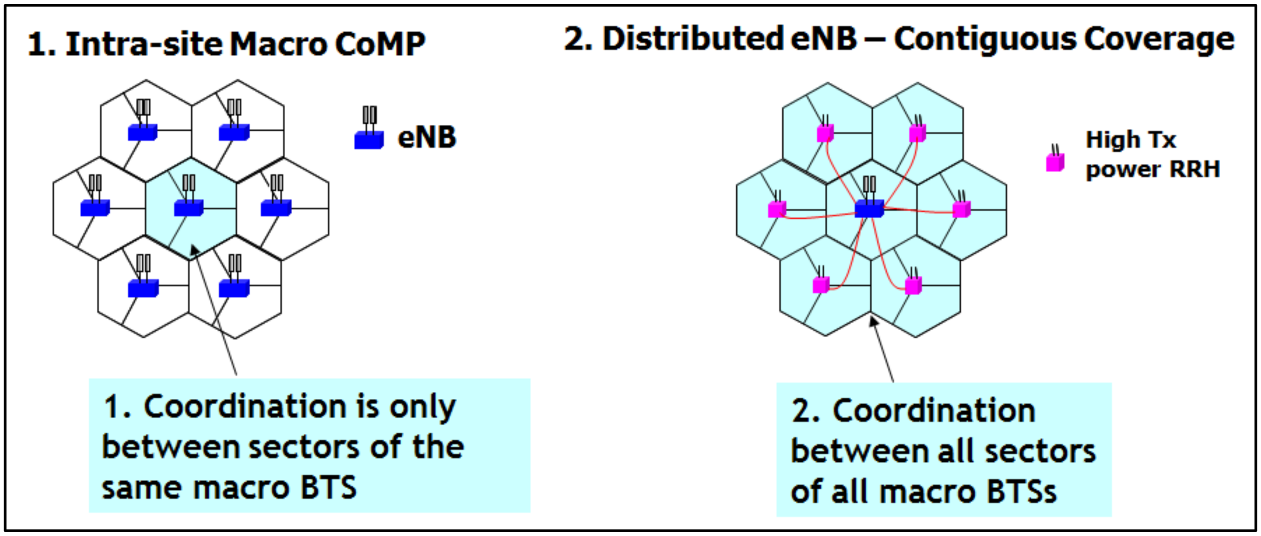
128 5G Americas member contribution. Assumptions: lightly-loaded network, 2.0 site-to-site distance, file size is 750 Kbytes, traffic model bursty with mean inter-arrival time of five seconds.

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

CoMP architectures include inter-site CoMP, intra-site CoMP, as well as CoMP with distributed eNBs (i.e., an eNB with distributed remote radio heads). Figure 55 shows two possible levels of coordination.

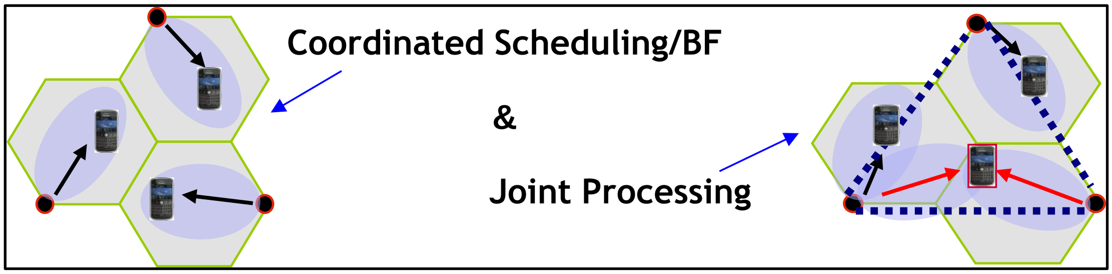
Figure 55: Different Coordination Levels for CoMP[129]



In one CoMP approach, called coordinated scheduling and shown in Figure 56, 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 56, multiple sites transmit simultaneously to a single user. This approach can achieve higher performance than coordinated scheduling, but it 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.

[129] 5G Americas member contribution.

Figure 56: Coordinated Scheduling/BF and Joint Processing CoMP Approaches[130]



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

The performance gains expected from CoMP are under discussion in the industry. According to 3GPP document TR 36.819, for the case of resource utilization below 35%, CoMP may provide a 5.8% performance gain on the downlink for the mean user and a 17% gain for cell-edge users relative to HetNets without eICIC. For resource utilization of more than 35%, CoMP may provide a 17% mean gain and a 40% cell-edge gain.[131] CoMP can also be used in combination with eICIC for additional gains.

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

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

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

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

The gains for UL CoMP based on Joint Reception (JR) are greater than the DL gains. For intra-eNodeB CoMP, the average and cell-edge throughputs are increased to 22% and 40%, assuming two receive antenna paths with SU-MIMO. These respective gains increase to 31% and 66% for inter-eNodeB CoMP. In addition, UL CoMP does not require standardization and thus facilitates vendor implementation.

[130] 5G Americas member contribution.

[131] 3GPP, *Coordinated Multi-Point Operation for LTE Physical Layer Aspects, TR 36.819 v11.1.0,* Tables 7.3.1.2-3 and 7.3.1.2-4, September 2011.

Uplink CoMP assists VoLTE because it improves cell-edge performance, making voice handover more reliable when traversing between cells. The benefit is analogous to CDMA soft handover; in both cases, the mobile device communicates with two sites simultaneously.

User-Plane Congestion Management (UPCON)

With User-Plane Congestion Management, specified in Release 13, operators have additional tools to mitigate network congestion in specific coverage areas. Mechanisms include traffic prioritization by adjusting QoS for specific services; reducing traffic by, for example, compression; and limiting traffic, such as by prohibiting or deferring certain traffic.

3GPP specifications add a new architectural entity, called the "RAN Congestion Awareness Function" (RCAF), that determines whether a cell is congested, determines the UEs supported by that cell, and informs the Policy Control and Charging Rules Function (PCRF), which can subsequently apply different policies to mitigate the congestion.[132]

Network-Assisted Interference Cancellation and Suppression (NAICS)

NAICS, a Release 13 capability, enhances the interference cancellation and suppression capability of UEs by using more information from the network. The fundamental goal of NAICS is to identify and cancel the dominant interferer, not an easy task when the dominant interferer can be on or off and can change in time and frequency. One analysis estimates an average performance gain of 7.4% relative to Release 11 Interference Rejection Combining and 11.7% at the cell edge.[133] 5G Americas members expect even higher performance gains, for example 20%, with implementation-specific scheduling and as NAICS methods are refined.

Multi-User Superposition Transmission (MUST)

MUST, a study item in Release 13 and tentatively planned for Release 14 uses simultaneous transmissions of data for more than one UE within a cell without time, frequency, or spatial layer separation. The concept relies on a UE close to the base station having low propagation loss and a UE far from the base station having high propagation loss. The far UE is not aware of, nor interfered by the near UE transmission. The near UE cancels the far UE interference. The capacity gain grows with the SNR/SINR difference between the close and far UEs.

IPv4/IPv6

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

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[132] For further details, see 3GPP TR 23.705, "Study on system enhancements for user plane congestion management (Release 13)."

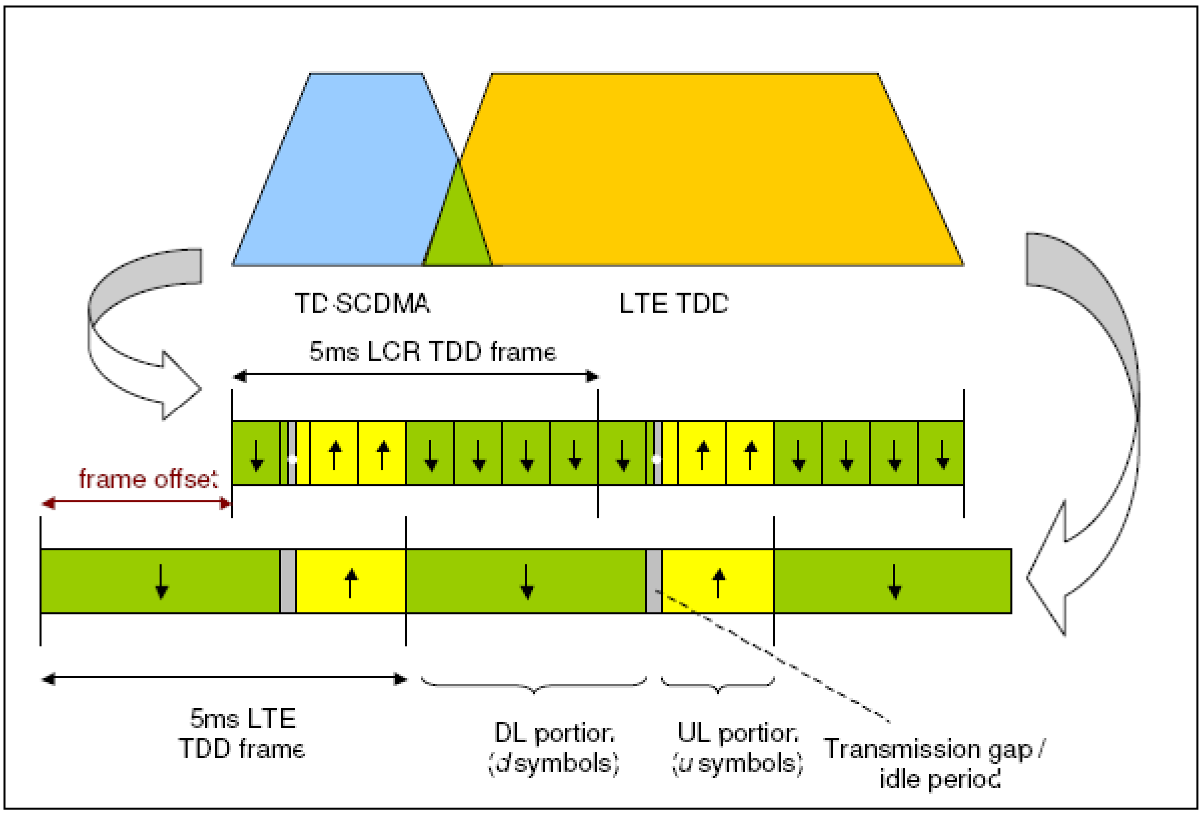
[133] Harri Holma, Antti Toskala, Jussi Reunanen, *LTE Small Cell Optimization: 3GPP Evolution to Release 13*, Jan 2016, Wiley, ISBN: 978-1-118-91257-7.

Communicating between IPv6-only devices and IPv4 endpoints will require protocol-conversion or proxies. For further details, refer to the 5G Americas white paper, "IPv6 – Transition Considerations for LTE and Evolved Packet Core," February 2009.

TDD Harmonization

3GPP developed LTE TDD to be fully harmonized with LTE FDD including alignment of frame structures, identical symbol-level numerology, the possibility of using similar reference signal patterns, and similar synchronization and control channels. Also, there is only one TDD variant. Furthermore, LTE TDD has been designed to co-exist with TD-SCDMA and TD-CDMA/UTRA (both low-chip rate and high-chip rate versions). LTE TDD achieves compatibility and co-existence with TD-SCDMA by defining frame structures in which the DL and UL time periods can be time aligned to prevent BTS to BTS and UE to UE interference to support operation in adjacent carriers without the need for large guardbands between the technologies. This will simplify deployment of LTE TDD in countries such as China that are deploying TD-SCDMA. Figure 57 demonstrates the synchronization between TC-SCDMA and LTE-TDD in adjacent channels.

Figure 57: TDD Frame Co-Existence between TD-SCDMA and LTE TDD[134]



For LTE FDD and TDD to coexist, large guardbands will be needed to prevent interference.

[134] 5G Americas member company contribution.

SMS in LTE

Even if an LTE network uses CSFB for voice, LTE devices will be able to send and receive SMS messages while on the LTE network. In this case, the 2G/3G core network will handle SMS messaging, but will tunnel the message to the MME in the EPC via the SGs interface. Once an LTE network uses IMS and VoLTE for packet voice service, SMS will be handled as SMS over IP and will use IMS infrastructure.[135]

User Equipment Categories

LTE specifications define categories of UE, which mainly determine the maximum throughputs of devices but also govern the number of downlink MIMO layers, as shown in Table 20.

Higher throughput capabilities are possible with 64 QAM and 256 QAM modulation. 3GPP is also defining Category 0 and Category M devices for M2M, as discussed in the section "Internet of Things and Machine-to-Machines."

Table 20: UE Categories[136]

UE Category	Max DL Throughput	Maximum DL MIMO Layers	Maximum UL Throughput
1	10.3 Mbps	1	5.2 Mbps
2	51.0 Mbps	2	25.5 Mbps
3	102.0 Mbps	2	51.0 Mbps
4	150.8 Mbps	2	51.0 Mbps
5	299.6 Mbps	4	75.4 Mbps
6	301.5 Mbps	2 or 4	51.0 Mbps
7	301.5 Mbps	2 or 4	102.0 Mbps
8	2998.6 Mbps	8	1497.8 Mbps
9	452.3 Mbps	2 or 4	51.0 Mbps
10	452.3 Mbps	2 or 4	102.0 Mbps
11	603.0 Mbps	2 or 4	51.0 Mbps
12	603.0 Mbps	2 or 4	102.0 Mbps

[135] For further details, see 4G Americas, *Coexistence of GSM, HSPA and LTE*, May 2011, 35.

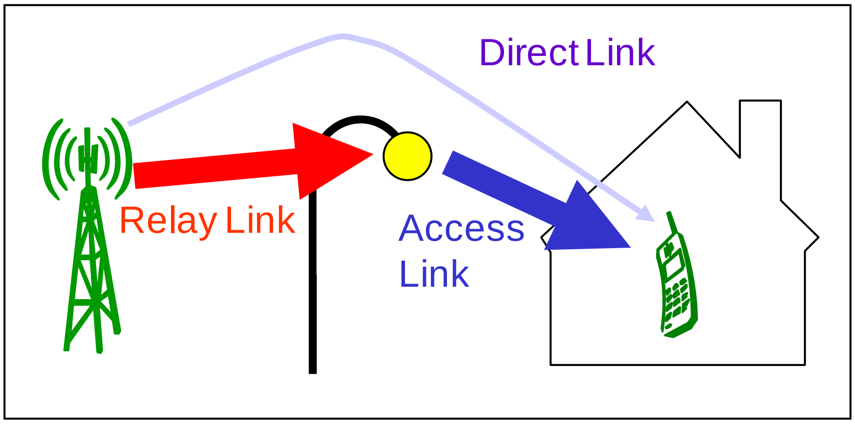
[136] 3GPP, E*volved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio access capabilities,* Technical Specification 36.306 V13.1.0, March 2016.

LTE-Advanced Relays

Another capability being planned for LTE-Advanced is relays, as shown in Figure 58. The idea is to relay frames at an intermediate node, resulting in much better in-building penetration, and with better signal quality, user rates will improve. Relay nodes can also improve cell-edge performance by making it easier to add picocells at strategic locations.

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

Figure 58: LTE-Advanced Relay[137]



Proximity Services (Device-to-Device)

Release 12 defined a capability for devices to communicate directly with one another using LTE spectrum, a feature also called "operator-enabled proximity services." With this capability, devices can autonomously discover nearby relevant devices and services in a battery-efficient manner. Devices broadcast their needs and services and can also passively identify services without user intervention. The communication between devices is called "sidelink communications" and uses an interface called "PC5." Release 12, emphasizing public-safety applications, supports only one-to-many sidelink communications, whereas Release 13 supports one-to-one sidelink communications between two group member UEs and between a remote UE and a relay UE.

Initial emphasis of this capability, in both Release 12 and Release 13, is on public safety. Examples of potential consumer or commercial applications include discovering friends and family (social matching), push advertising for relevant notifications, tourist bulletins, venue services, crime alerts, home automation, vehicle-to-vehicle communication, and detecting children leaving the vicinity of their homes. The service is designed to work during infrastructure failures, even in emergencies and natural disasters. As a new means of communicating, proximity services could result in innovative types of applications.

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

[137] 5G Americas member contribution.

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

LTE Throughput

The section "4G LTE Advances" above in the main section of the paper and "Data Throughput Comparison" in the appendix provide an overview of LTE throughputs. This section provides additional details.

Table 21 shows initial (Release 8) LTE peak data rates based on different downlink and uplink designs.

Table 21: LTE Peak Throughput Rates

LTE Configuration	Downlink (Mbps) Peak Data Rate	Uplink (Mbps) Peak Data Rate
Using 2X2 MIMO in the Downlink and 16 QAM in the Uplink, 10+10 MHz	70.0	22.0
Using 4X4 MIMO in the Downlink and 64 QAM in the Uplink, 20+20 MHz	300.0	71.0

LTE is not only efficient for data but, because of a highly efficient uplink, is extremely efficient for VoIP traffic. As discussed in the "Spectral Efficiency" section above, in 10+10 MHz of spectrum, LTE VoIP capacity will reach 500 users.[138]

Table 22 analyzes LTE median and average throughput values in greater detail for different LTE configurations.

[138] 3GPP Multi-member analysis.

Table 22: LTE FDD User Throughputs Based on Simulation Analysis[139]

Configuration	User Throughput, Mbps			
	Downlink (DL)		Uplink (UL)	
	Median	Average	Median	Average
LTE FDD: Low Band, 2x2 MIMO-DL, 1x2 SIMO-UL, 10+10 MHz, R8	8.6	10.9	4.5	5.0
LTE FDD: High Band, 4x2 MIMO-DL, 1x4 SIMO-UL, 10+10 MHz, R8	10.6	12.2	5.4	6.4
LTE FDD: High Band, 2x2 MIMO-DL, 1x2 SIMO UL, 20+20 MHz, R8	15.2	17.9	5.4	7.0
LTE FDD: High Band, 4x4 MIMO-DL, 1x4 SIMO UL, 20+20 MHz, R12	25.4	29.2	6.9	9.1

The simulation results represent a consensus view of 5G Americas members working on this white paper project. The goal of the analysis was to quantify LTE throughputs in realistic deployments. Simulation assumptions include:

- Traffic is FTP-like at a 50% load with a 75/25 mix of indoor/outdoor users.
- Throughput is at the medium-access control (MAC) protocol layer. (Application-layer throughputs may be 5 to 8 percent lower due to protocol overhead.)
- The 3GPP specification release numbers shown correspond to the infrastructure capability.
- The configuration in the first row corresponds to low-frequency band operation, representative of 700 MHz or cellular, while the remaining configurations assume high-frequency band operation, representative of PCS, AWS, or WCS. (Higher frequencies facilitate higher-order MIMO configurations and have wider radio channels available.)
- The downlink value for the first row corresponds to Release 8 device-receive capability (Minimum Mean Square Error [MMSE]), while the values in the other rows correspond to Release 11 device-receive capability (MMSE – Interference Rejection Combining [IRC]).
- The uplink value for the first row corresponds to a Maximal Ratio Combining (MRC) receiver at the eNodeB, while the remaining values correspond to an IRC receiver.
- Low-band operation assumes 1732 meter inter-site distance (ISD), while high-band operation assumes 500 meter ISD. The remaining simulation assumptions are listed in Table 23.

[139] 5G Americas member contribution. SIMO refers to Single Input Multiple Output antenna configuration, which in the uplink means one transmit antenna at the UE and multiple receive antennas at the eNodeB.

Table 23: LTE FDD User Throughput Simulation Assumptions[140]

Parameter	Value
Frequency	Low Band (LB): B17; High Band (HB): B30
Channel bandwidth	10 MHz, 20 MHz
System configuration	DL: 2x2, 4x2, and 4x4 Closed-Loop (CL) MIMO UL: 1x2 and 1x4 SIMO
Traffic type	FTP model 2: File size = 0.15 Mbyte, 1 second inter-arrival time, Load varied by changing number of users
Inter-Site Distance (ISD)	LB: 1732 m; HB: 500 m
Pathloss model	LB: HATA; HB: COST231 with correction
eNodeB transmit power	LB: 60 watts total; HB: 80 watts total
eNodeB antenna type	2 Tx = +-45 degrees cross-pol (DIV-1X); 4 Tx = Closely separated pair of cross-pols (CLA-2X)
eNodeB antenna gain	LB: 14.8 dBi; HB: 17.5 dBi
eNodeB antenna pattern	Actual antenna patterns as used in RF planning tool
eNodeB Rx type	LB: MRC; HB: IRC
Downtilt	LB: 7 degrees; HB: 9 degrees
Penetration loss	75/25 mix of indoor/outdoor users LB: 12 dB for indoor users; HB: 22 dB for indoor users
Device speed	3 km/h all users
Channel model	Modified SCME-WINNER+, LB: Suburban Macro (SMa) scenario; HB: Urban Macro (UMa)
Device antenna type	+-45 degrees cross-pol with built in correlation of 0.5
Device antenna gain and mismatch	LB: - 5 dBi and 3 dB; HB: -3 dBi and 3 dB
Device body loss	3 dB for both bands
Device Rx type	MMSE, MMSE-IRC
Uplink power control	LB: alpha = 1, Po = -100 dBm; HB: alpha = 0.9, Po = -100 dBm
Scheduler	Proportional fair, frequency selective

The assumptions, emphasizing realistic deployments, do not necessarily match assumptions used by other organizations, such as 3GPP, so results may differ.

Additional insight into LTE performance under different configuration comes from a test performed on a cluster of cells in an LTE operator's network, comparing downlink performance of 4X2 MIMO against 2X2 MIMO, and uplink performance of 1X4 SIMO against 1X2 SIMO. The test employed LTE category 4 devices.[141]

[140] 5G Americas member contribution.

[141] 5G Americas member contribution.

These tests, which were performed in a 20+20 MHz cluster, show significant improvements in cell edge uplink and downlink throughput, in addition to an overall increase in uplink and downlink throughputs. Specific results include:

- A 100% increase in uplink throughput at the cell edge with 1X4 SIMO compared to 1x2 SIMO.
- A 40% increase in downlink throughput at the cell edge with 4x2 closed-loop MIMO compared to 2x2 open-loop MIMO
- A 50 to 75% increase in downlink throughput with closed loop MIMO compared to transmit diversity modes.
- Up to 6dB gains in uplink transmit power with 1X4 SIMO, which directly translates into UE battery savings.
- Peak speeds of 144 Mbps with 4X2 MIMO in the downlink and 47 Mbps with 1X4 SIMO in the uplink.

Another LTE operator's testing results for LTE in a TDD configuration, using 20 MHz channels, 3:2 DL to UL ratio, and category 3 devices, showed:

- Peak speeds of 55 Mbps.
- Typical speeds of 6 to 15 Mbps.[142]

Figure 59 shows the result of a drive test in a commercial LTE network with a 10 MHz downlink carrier demonstrating 20 Mbps to 50 Mbps throughput rates across much of the coverage area. Throughput rates would double with a 20+20 MHz configuration.

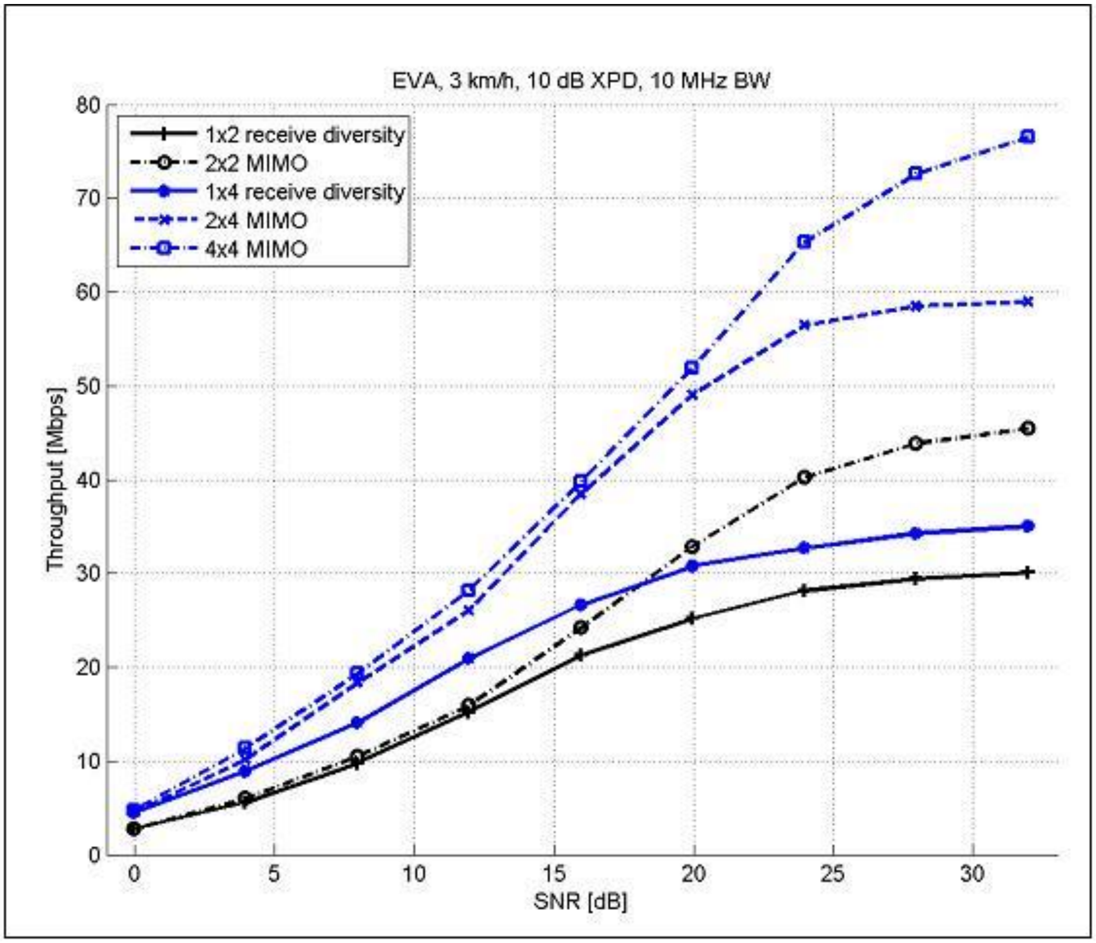
[142] 5G Americas member contribution.

Figure 59: Drive Test of Commercial European LTE Network (10+10 MHz)[143]

[143] Ericsson contribution.

Figure 60 provides additional insight into LTE downlink throughput, showing Layer 1 throughput simulated at 10 MHz bandwidth using the Extended Vehicular A 3 km/hour channel model. The figure shows the increased performance obtained with the addition of different orders of MIMO. Note how throughput improves based on higher signal-to-noise ratio (SNR).

Figure 60: LTE Throughput in Various Modes[144]



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

- **RF Conditions and User Speed.** Peak rates depend on optimal conditions. Suboptimal conditions include being at the edge of the cell or moving at high speed, resulting in lower throughput.
- **Network Loading.** Like all wireless systems, throughput rates go down as more devices simultaneously use the network. Throughput degradation is linear.

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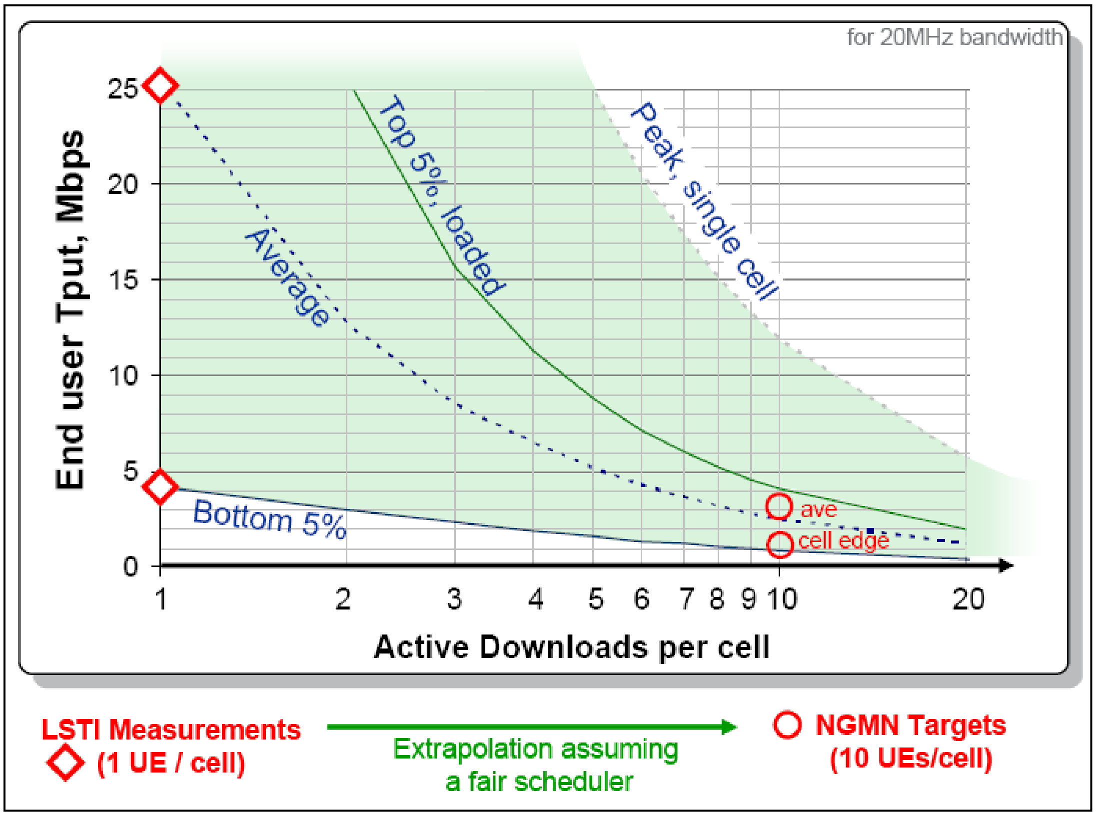
144 Jonas Karlsson, Mathias Riback, "Initial Field Performance Measurements of LTE," *Ericsson Review*, No. 3, 2008.

Figure 61 shows how dramatically throughput rates can vary by number of active users and radio conditions. The higher curves are for better radio conditions.

Figure 61: LTE Actual Throughput Rates Based on Conditions[145]



[145] LTE/SAE Trial Initiative, "Latest Results from the LSTI, Feb 2009," http://www.lstiforum.org.

VoLTE and RCS

This paper introduced VoLTE and voice support in the earlier section, "VoLTE, RCS, WebRTC, and Wi-Fi Calling." This section in the appendix provides additional technical detail about the operation of VoLTE and RCS.

Voice in LTE can encompass: no voice support, voice implemented in a circuit-switched fallback (CSFB) mode using 2G or 3G, and VoIP implemented with IMS.

Initial network deployments used CSFB, with which the LTE network carries circuit-switched signaling over LTE interfaces, allowing the subscriber to be registered with the 2G/3G MSC even while on the LTE network. When there is a CS event, such as an incoming voice call, the MSC sends the page to the LTE core network, which delivers it to the subscriber device. The device then switches to 2G/3G operation to answer the call.

Voice over LTE using VoIP requires IMS infrastructure. To facilitate IMS-based voice, vendors and operators created the One Voice initiative to define required baseline functionality for user equipment, the LTE access network, the Evolved Packet Core, and the IMS. GSMA adopted the One Voice initiative in what it calls VoLTE, specified in GSMA reference document IR.92.[146] GSMA specifies interconnection and international roaming among LTE networks through the IR.88[147] specification. Another specification, IR.94, provides the IMS Profile for Conversational Video Service, a service referred to as "Video over LTE" (ViLTE).[148]

For a phone to support VoLTE, it needs software implementing the IMS protocol stack. For example, the iPhone 6 was the first iPhone to implement such software. Additional software implementing RCS application programming interfaces can provide applications with access to IMS-based services, such as voice, messaging, and video. The Open Mobile Alliance has defined RESTful network APIs for RCS that support the following functions: notification channel, chat, file transfer, third-party calls, call notification, video sharing, image sharing, and capability discovery. As shown in Figure 62, over time, new profile releases will broaden the scope of these APIs.

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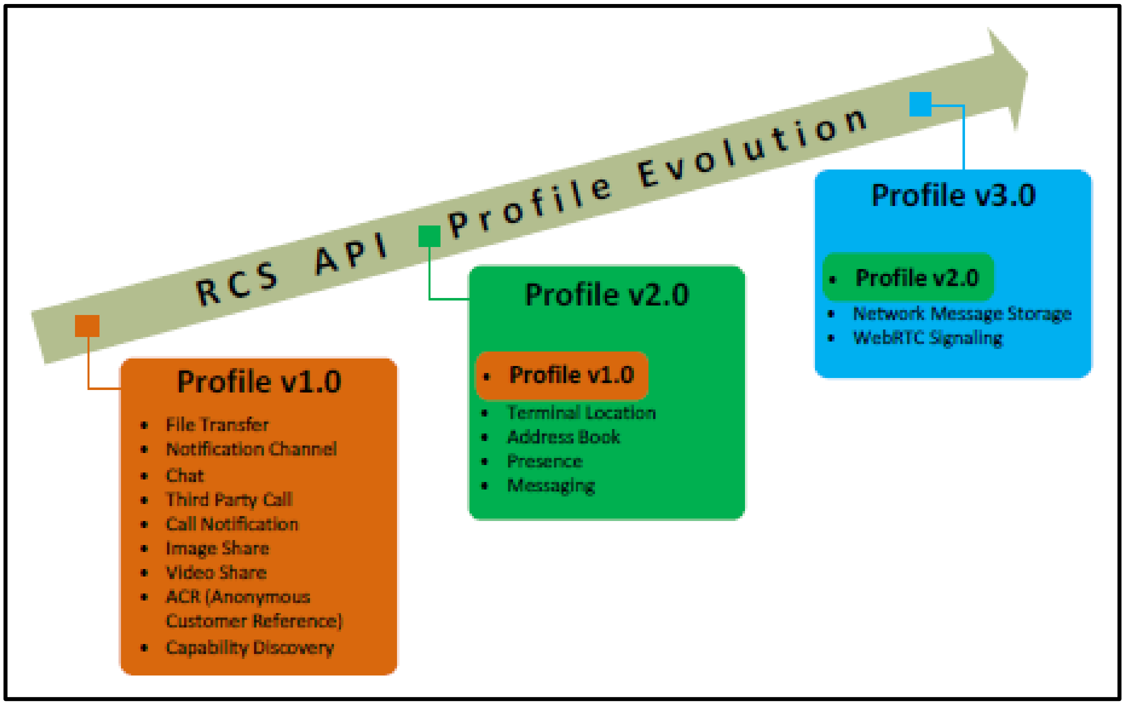
[146] GSMA, "IMS Profile for Voice and SMS," Document IR.92. Available at http://www.gsma.com/newsroom/wp-content/uploads/2013/04/IR.92-v7.0.pdf.

[147] GSMA, "LTE Roaming Guidelines," GSMA Document IR.88. Available at http://www.gsma.com/newsroom/wp-content/uploads/2013/04/IR.88-v9.0.pdf.

[148] GSMA, "IMS Profile for Conversational Video Service," Document IR.94. Available at http://www.gsma.com/newsroom/all-documents/ir-94-ims-profile-for-conversational-video-service/.

Figure 62: Evolution of RCS API Profiles[149]



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

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

VoLTE roaming across operators will require network-to-network interfaces between their respective IMS networks. Such roaming and interconnect will follow initial VoLTE deployments. Different IMS stack implementations between vendors will also complicate roaming.

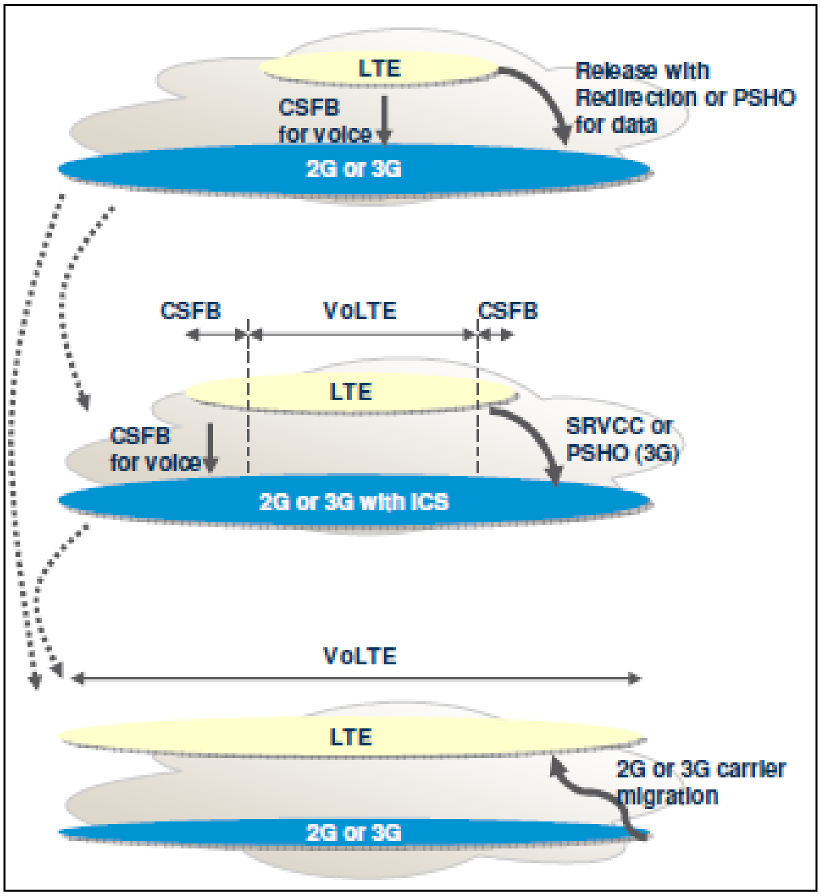
One roaming consideration is how operators handle data roaming. LTE roaming can send all visited network traffic back to the home network, which for a voice call, increases voice latency. For voice calls, the local-breakout option would mitigate this latency.

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

[149] 4G Americas, *VoLTE and RCS Technology – Evolution and Ecosystem,* Nov. 2014.

Figure 63 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 63: Evolution of Voice in an LTE Network[150]



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

3GPP has developed a new codec, called "Enhanced Voice Services" (EVS), which will include super-wideband voice capability. For the same bit rate, EVS provides higher voice quality than the other codecs.[151] Table 24 summarizes the features and parameters of the three 3GPP codecs used in LTE.

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[150] 5G Americas member contribution.

[151] See Figure 9.2. 3GPP, *TR 26.952 V12.1.0, Codec for Enhanced Voice Services (EVS); Performance Characterization*, March 2015.

Table 24: Comparison of AMR, AMR-WB and EVS Codecs[152]

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

Figure 64 shows mean opinion scores (MOS) for different codecs at different bit rates, illustrating the advantage of EVS, particularly for bit rates below 32 kbps that cellular networks use.

[152] 4G Americas, *Mobile Broadband Evolution: Rel-12 & Rel-13 and Beyond*, 2015. See also T-Mobile 2016 EVS announcement: https://newsroom.t-mobile.com/news-and-blogs/volte-enhanced-voice-services.htm.

Figure 64: Combined Mean Opinion Score Values[153]

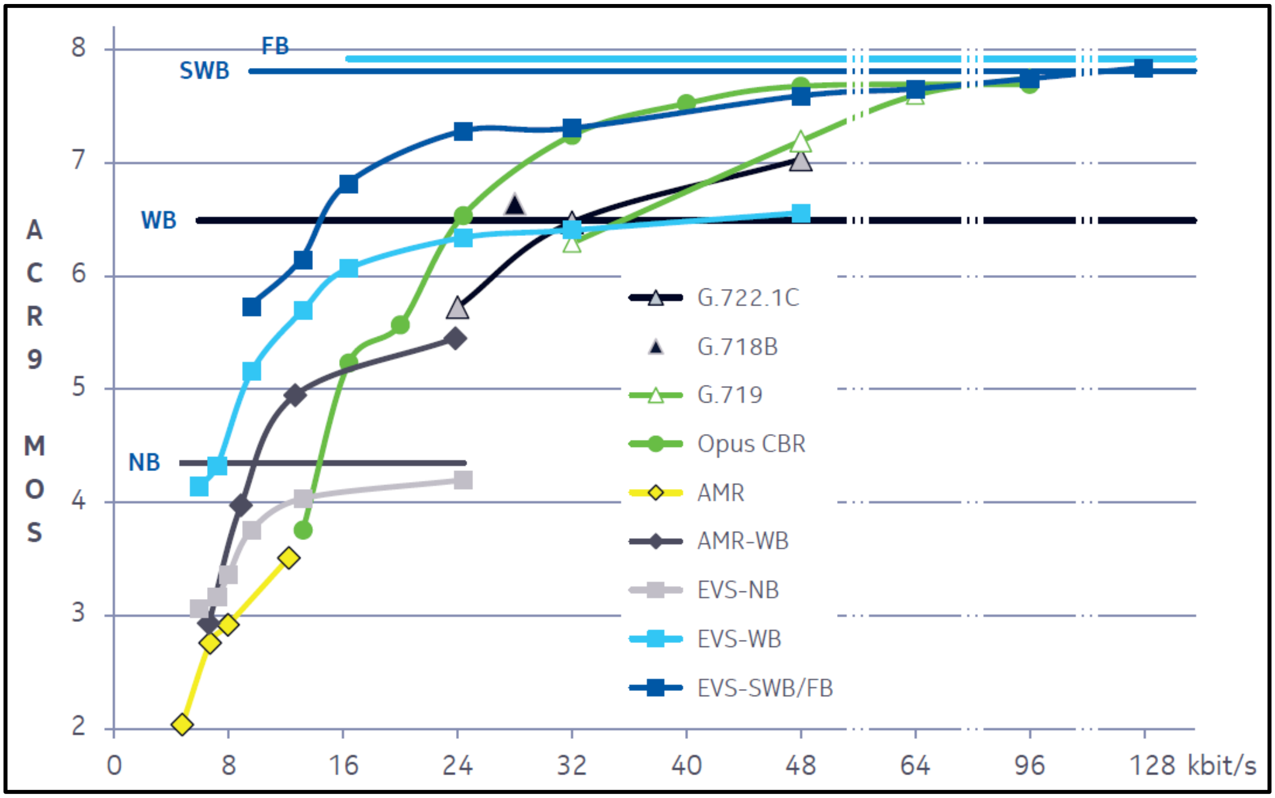


Table 25 shows EVS (narrowband, wideband, super-wideband) audio bandwidths and bitrates that create subjective quality equal to or better than AMR or AMR-WB for typical conversational voice scenarios.

Table 25: EVS Compared to AMR and AMR-WB[154]

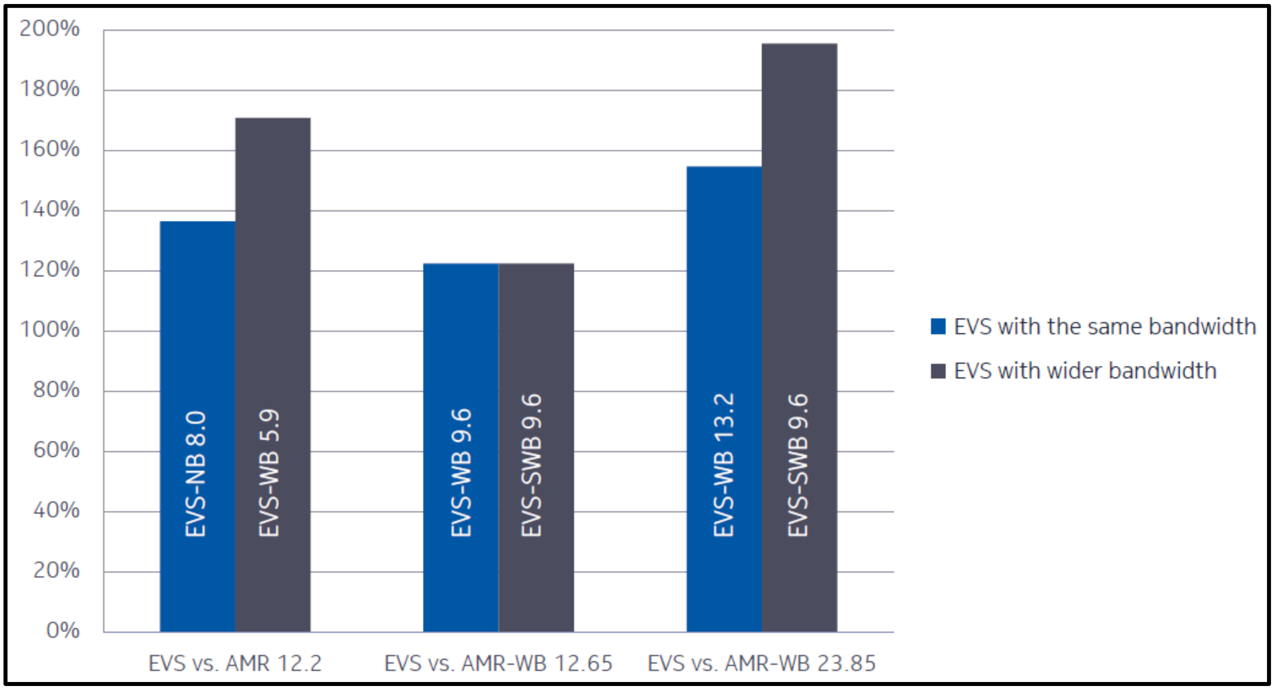
Reference	Equal bandwidth	Wider bandwidth
AMR 12.2 kbit/s	EVS-NB 8.0 kbit/s	EVS-WB 5.9 kbit/s
AMR-WB 12.65 kbit/s	EVS-WB 9.6 kbit/s	EVS-SWB 9.6 kbit/s
AMR-WB 23.85 kbits/s	EVS-WB 13.2 kbit/s	EVS-SWB 9.6 kbit/s

Figure 65 compares EVS capacity gains over AMR and AMR-WB for the references cases shown in Table 25. EVS-SWB at 9.6 kbps almost doubles voice capacity compared to AMW-WB at 23.85 kbps.

[153] Nokia, *The 3GPP Enhanced Voice Services (EVS) codec*, 2015. Available at http://networks.nokia.com/file/41551/the-3gpp-enhanced-voice-services-evs-codec.

[154] Ibid.

Figure 65: EVS Voice Capacity Compared to AMR and AMR-WB[155]



Internet of Things and Machine-to-Machine

Anticipating huge growth in machine-to-machine communications, Release 11 added a Machine Type Communications (MTC) Interworking Function and Service Capability Server. Release 12 defines a category 0 device designed for low cost through a single antenna design and other simplifications.[156] Release 13 goes even further with a category M architecture that further reduces cost, improves range, and extends battery life. Category 13 also adds Narrowband-IoT capability with Category NB-1 and an IoT solution for GSM, called "EC-GSM-IoT," that extends coverage by 20 dB. Category M and NB-IoT devices could achieve battery life as high as 10 years.

Figure 66 depicts the methods used to reduce cost in a Category M device compared with a Category 4 device.

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155 Ibid.

156 3GPP, *Access System for Ultra Low Complexity and Low Throughput Internet of Things based on Cellular,* GP-140301, May 2014.

Figure 66: Means of Achieving Lower Cost in IoT Devices[157]

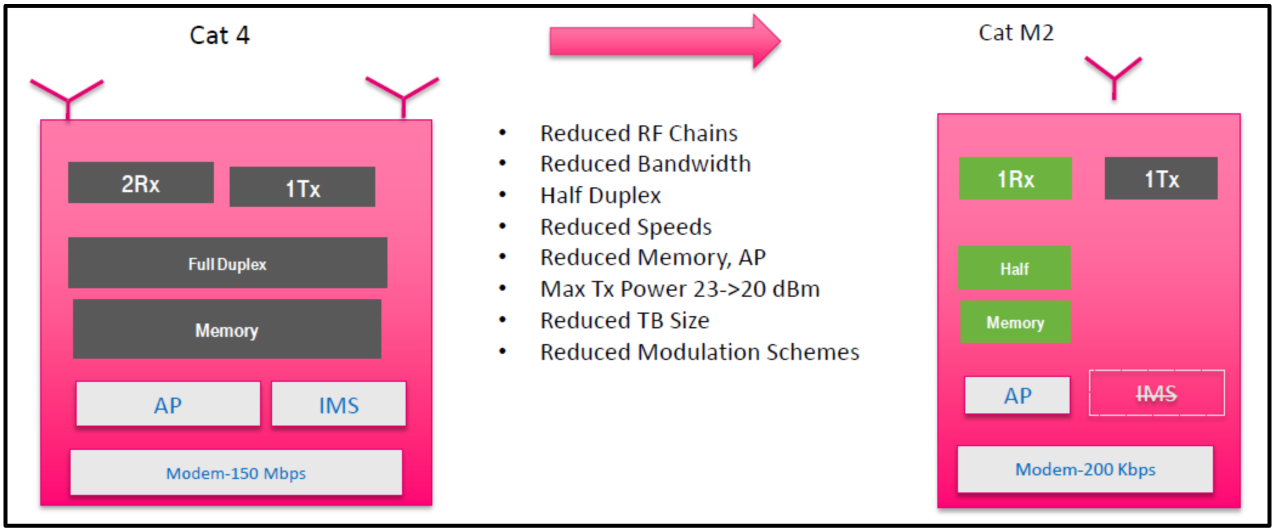


Table 26 summarizes the features of different LTE IoT devices based on 3GPP Release.

Table 26: Summary of IoT Features in LTE Devices

Device Category	Category 3	Category 1	Category 0	Category M-1	Category NB-1	EC-GSM-IoT
3GPP Release	10	11	12	13	13	13
Max. Data Rate Downlink	100 Mbps	10 Mbps	1 Mbps	1 Mbps	200 Kbps	74 Kbps
Max. Data Rate Uplink	50 Mbps	5 Mbps	1 Mbps	1 Mbps	200 Kbps	74 Kbps
Max. Bandwidth	20 MHz	20 MHz	20 MHz	1.4 MHz	0.18 MHz	0.2 MHz
Duplex	Full	Full	Optional half-duplex	Optional half-duplex	Half	Half
Max. Receive Antennas	Two	Two	One	One	One	One

[157] 5G Americas member contribution.

Device Category	Category 3	Category 1	Category 0	Category M-1	Category NB-1	EC-GSM-IoT
Power		Power Save Mode[158]	Power Save Mode	Power Save Mode		
Sleep				Longer sleep cycles using Idle Discontinuous Reception (DRX)		
Coverage				Extended through redundant transmissions and Single Frequency Multicast		

Heterogeneous Networks and Small Cells

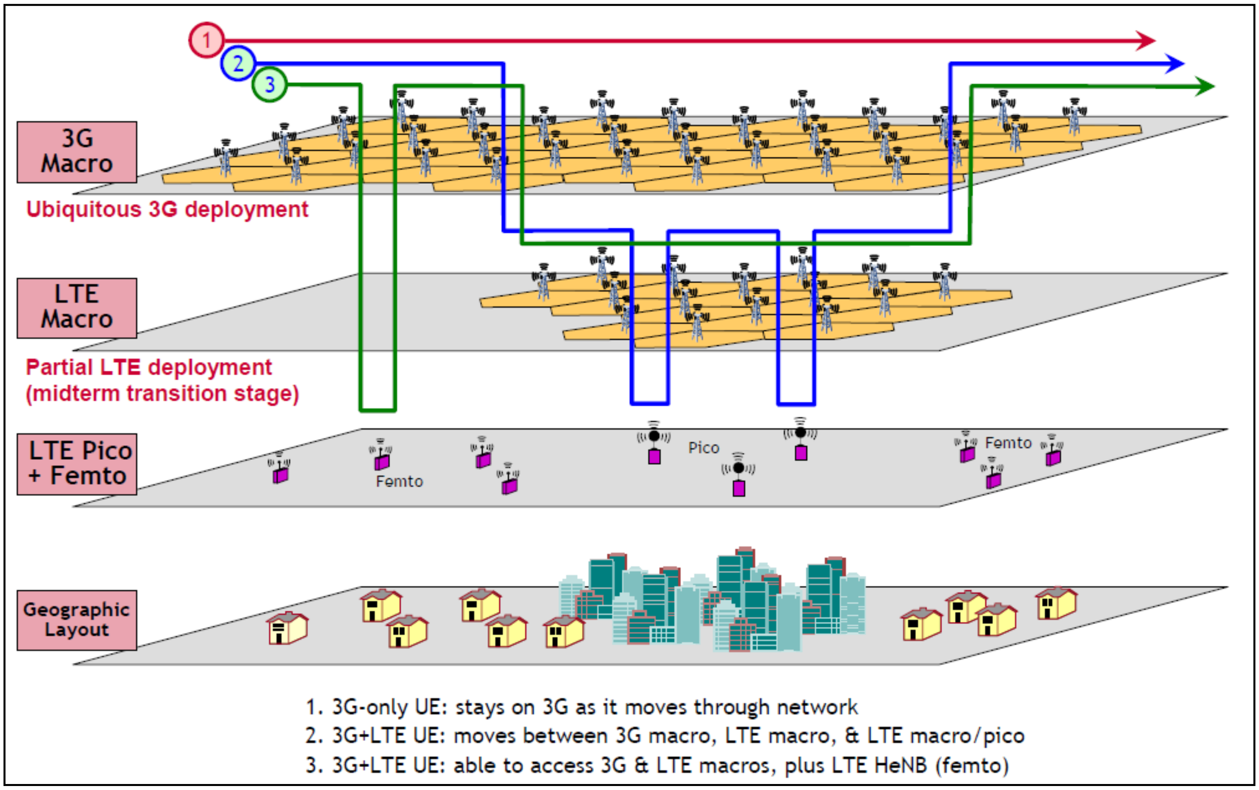
A fundamental concept in the evolution of next-generation networks is the blending of multiple types of networks to create a "network of networks" characterized by:

- Variations in coverage areas, including femtocells (either enterprise femtos or home femtos, called HeNBs), picocells (also referred to as metro cells), and 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 in which wireless links can serve as backhaul.

Figure 67 shows how user equipment might access different network layers.

[158] Power Save Mode specified in Release 12, but applicable to Category 1 device configured as Release 12.

Figure 67: Load Balancing with Heterogeneous Networks[159]



HetNets will allow significant capacity expansion in configurations in which operators can add picocells to coverage areas served by macrocells, particularly if there are hot spots with higher user densities.

Small cells differentiate themselves from macrocells according to the parameters shown in Table 27.

Table 27: Small Cell Vs. Macro Cell Parameters: Typical Values

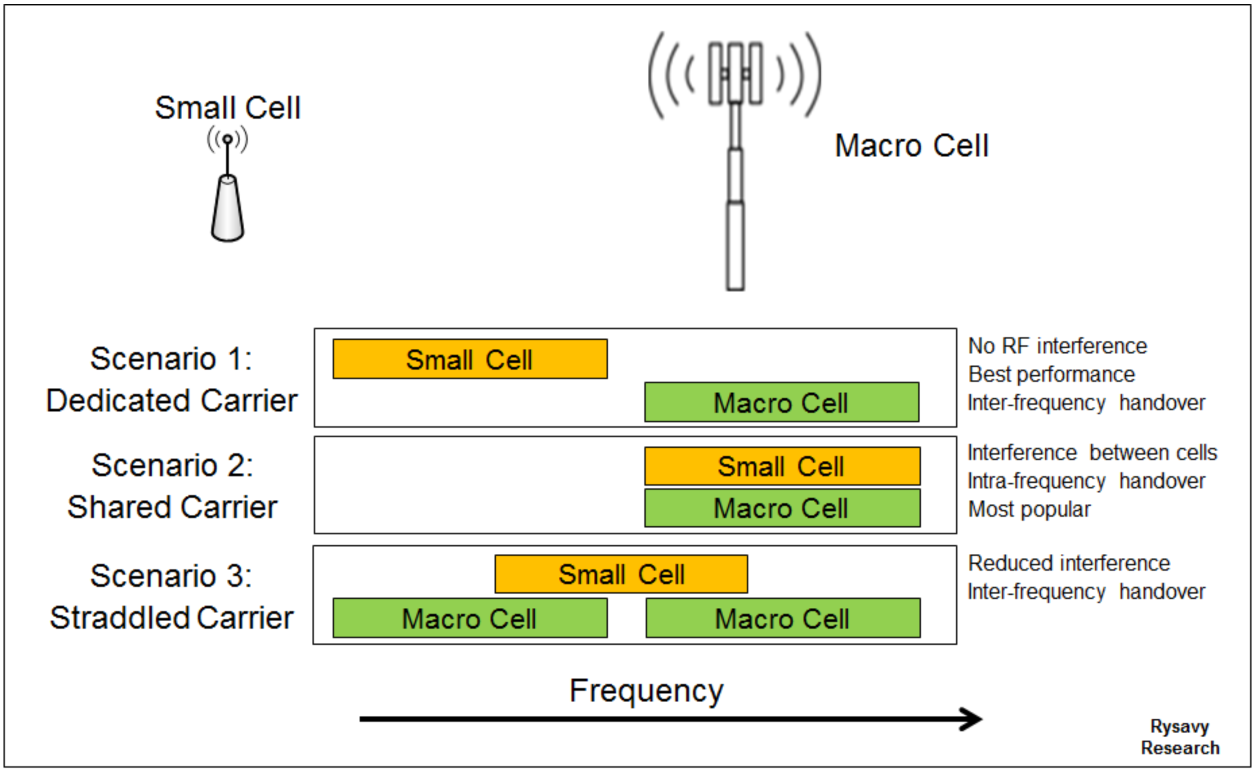
Parameter	Small Cell	Macro Cell
Transmission Power	24 dBm (0.25 W)	43 dBm (20 W)
Antenna Gain	2 dBi	15 dBi
Users	Tens	Hundreds
Mobility	30 km/hr.	350 km/hr.

[159] 5G Americas member contribution.

Whether or not the small cell uses the same radio carriers as the macro cell involves multiple tradeoffs. In Figure 68 Scenario 1, the small cells and macro cell use different radio carriers, the two not interfering with each other. Although this configuration requires more spectrum, the small cells are able to cover larger areas than if they were deployed using the same radio carrier as the macro. This configuration supports medium-to-high penetration levels of small cells, allowing the network to reach huge capacity.

In Scenario 2, the small cells and macro cells use the same radio carrier, accommodating operators with more limited spectrum, but the network must manage interference using the techniques discussed below. Operators must carefully manage small-cell transmission power in this configuration.

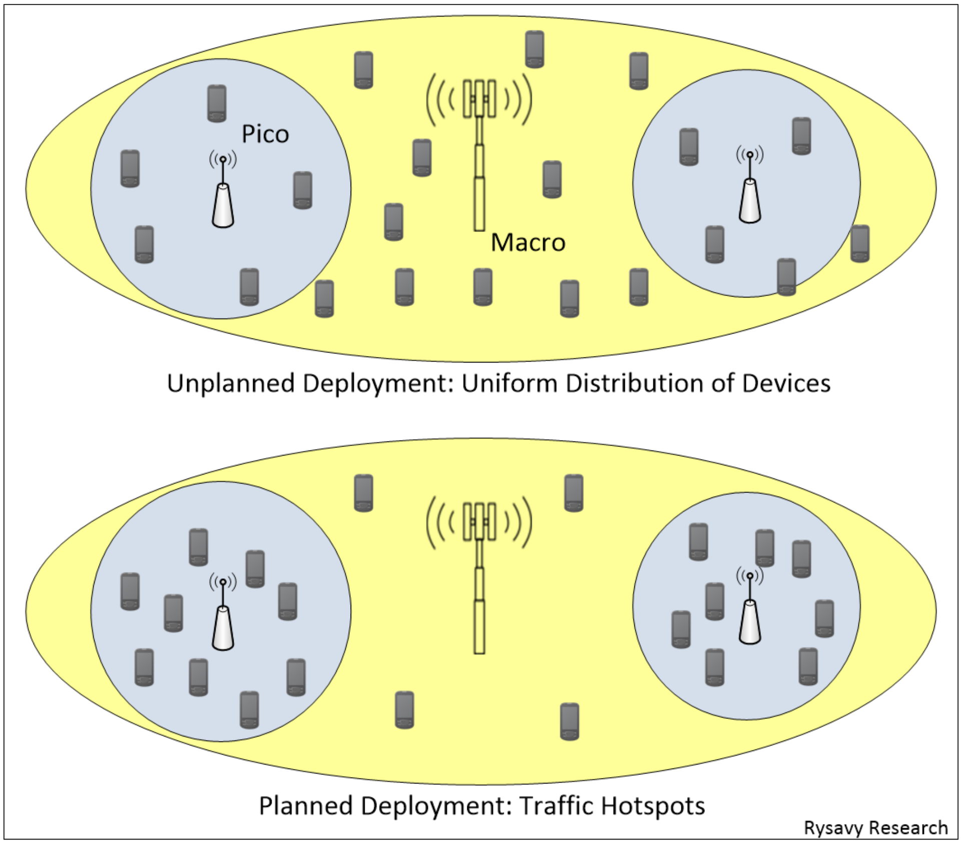
Figure 68: Scenarios for Radio Carriers in Small Cells



In Scenario 3, the small cells use a straddled radio carrier, accommodating operators with more spectrum, but the network still needs to manage interference using techniques discussed below. Compared with a shared carrier configuration, this configuration has benefits similar to dedicated carriers in terms of radio-parameter planning and reduced interference.

Figure 69 shows two different traffic distribution scenarios, with a uniform distribution of devices in the first and higher densities serviced by picocells in the second. The second scenario can result in significant capacity gains as well as improved user throughput.

Figure 69: Different Traffic Distributions Scenarios



One vendor calculated expected HetNet gains assuming no eICIC, no picocell range extension, and no eICIC. For the case of four picocells without picocell range extension and uniform user distribution, the median-user-throughput gain compared with a macro-only configuration was 85%. For a similar case of four picocells but using a hotspot user distribution, the gain was much higher, 467%.[160] Additional gains will occur with picocell range extension.

Expected picocell gains rise proportionally to the 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 HetNet scenario in the time domain with Enhanced Intercell Interference Coordination (eICIC) and Further Enhanced Intercell Interference Coordination (feICIC), as well as in the frequency domain with carrier-aggregation-based ICIC.

HetNet capability keeps becoming more sophisticated through successive 3GPP releases as summarized in Table 28.

[160] 5G 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.

Table 28: 3GPP HetNet Evolution

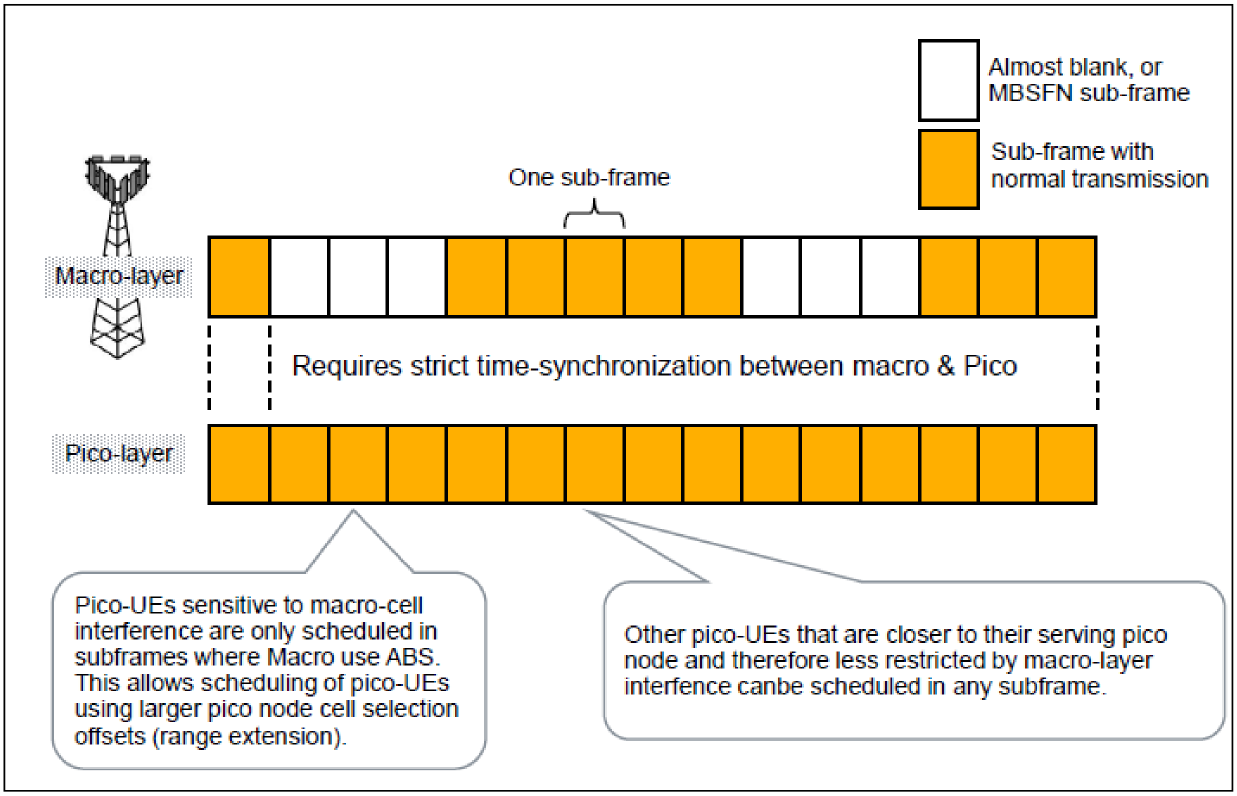
3GPP Release	HetNet Feature
8	Initial SON capabilities, most for auto configuration. Initial intercell interference coordination (ICIC) available.
9	More mobility options (for example, handover between HeNBs), operator customer subscriber group (SCG) lists, load-balancing, coverage and capacity improvements.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

Enhanced Intercell Interference Coordination

Significant challenges must be addressed in these heterogeneous networks. One is near-far effects, in which local small-cell signals can easily interfere with macro cells if they are using the same radio carriers.

Interference management is of particular concern in HetNets since, by design, coverage areas of small-coverage cells overlap with the macro cell. Beginning with Release 10, eICIC introduces an approach of almost-blank subframes by which subframe transmission can be muted to prevent interference. Figure 70 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.

Figure 70: Example of Enhanced Intercell Interference Coordination[161]

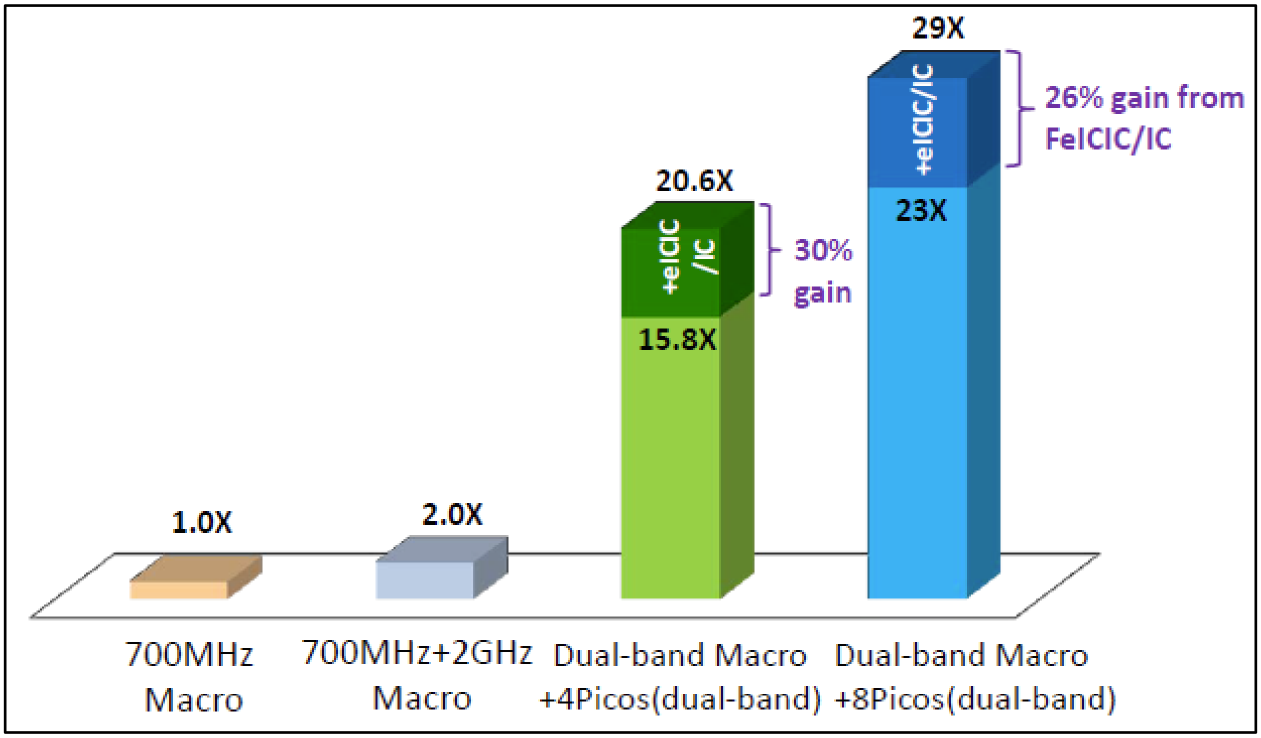


LTE can also combine eICIC with interference-cancellation-based devices to minimize the harmful effects of interference between picocells and macro cells.

Figure 71 shows one 4G America member's analysis of anticipated median throughput gains using picocells and Release 11 Further Enhanced ICIC.

[161] 5G Americas member contribution.

Figure 71: Median Throughput Gains in Hotspot Scenarios[162]



FeICIC is also beneficial in non-hotspot scenarios. In the case of a uniform distribution of picocells, this same 5G Americas member estimates a 130% gain from FeICIC for an eight picocell per macrocell scenario, increasing capacity from a factor of 3.3 for the picocells alone to a factor of 7.6 with the addition of FeICIC.[163]

Further insight is available from Figure 72, which shows 5 percentile and 50 percentile throughput with and without eICIC under different conditions of range extension and almost blanked subframes.

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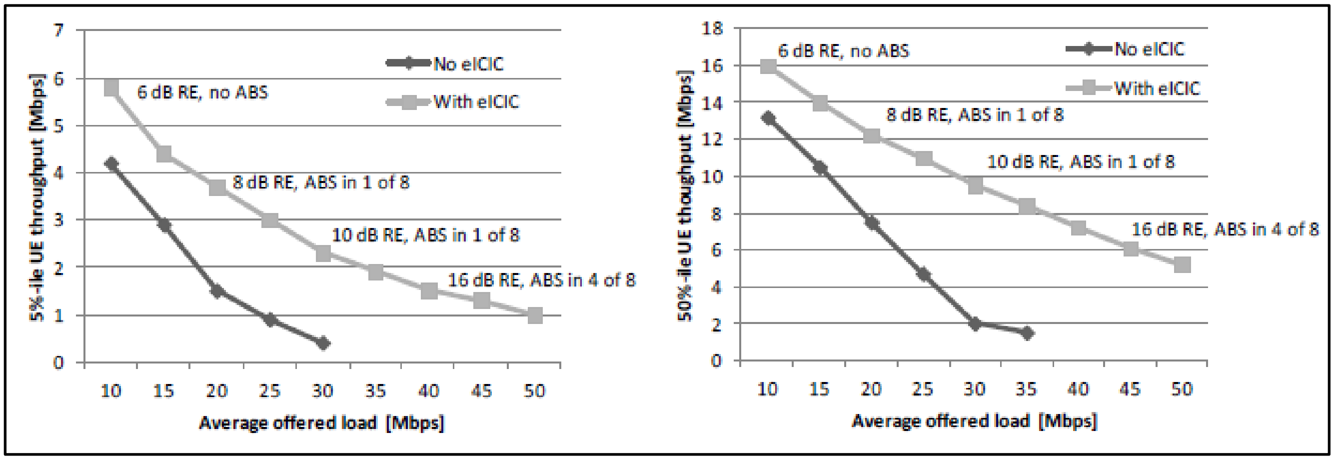
[162] 5G Americas member contribution. Assumes 3GPP evaluation methodology TR 36.814, carrier-aggregation UEs, macro ISD = 1732m, 700 MHz and 2GHz carrier frequency, full-buffer traffic, FDD 10+10 MHz per carrier, 6 degree antenna downtilt, 4 or 8 Picos and 30 UEs per Macro cell, hotspot distribution with 20 of 30 UEs near picos, PF scheduler, 2x2 MIMO, TU3 channel, NLOS, local partitioning algorithm.

[163] Assumes 3GPP evaluation methodology TR 36.814, macro ISD = 1732m, 700 MHz and 2GHz carrier frequency, full-buffer traffic, 6 degree antenna downtilt, 30 carrier-aggregation UEs per Macro cell, uniform random layout, PF scheduler, FDD, 10+10 MHz per carrier, 2x2 MIMO, TU3 channel, NLOS, local partitioning algorithm. Additional information is available at ftp://ftp.3gpp.org/tsg_ran/WG1_RL1/TSGR1_66b/Docs/R1-113383.zip.

Figure 72: User Throughput Performance With/Without eICIC for Dynamic Traffic vs. Average Offered Load per Macro-Cell Area[164]



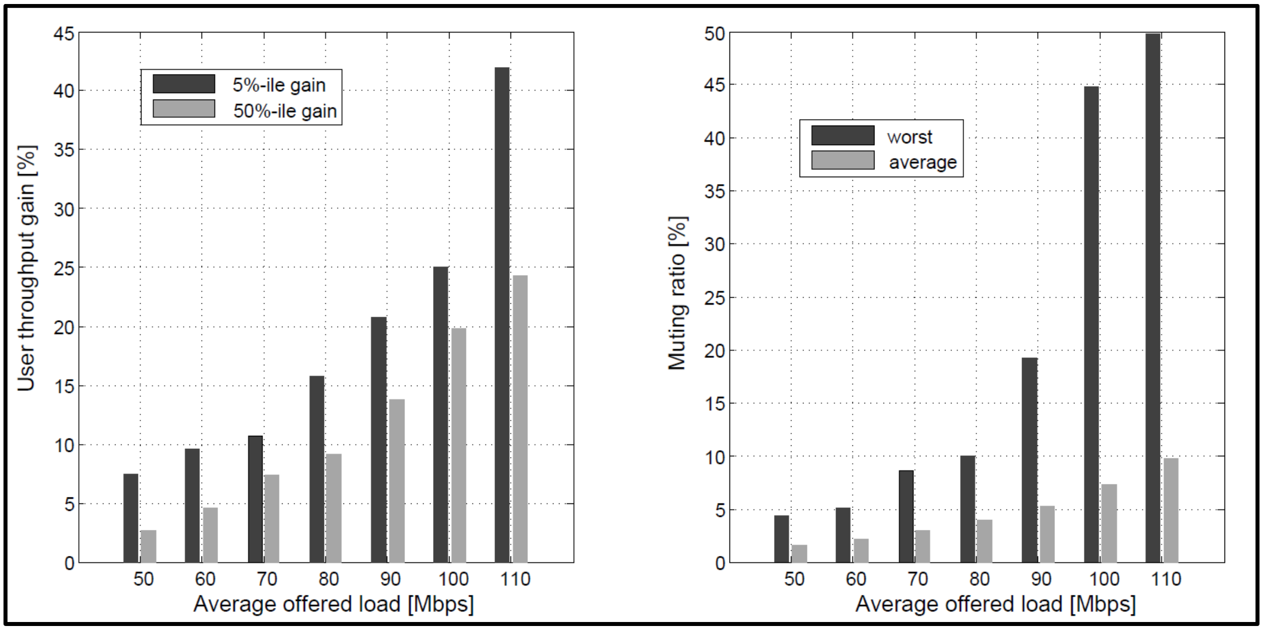
The muting of certain subframes in eICIC is dynamic and depends on identifying, on a per-user basis, whether an interfering cell's signal exceeds a threshold relative to the serving cell signal. Coordinating muting among small cells can be complicated because a small cell can simultaneously be an interferer while serving a UE that is a victim of another cell. The network must therefore coordinate muting among multiple small cells.

Figure 73 below at left shows user throughput gains of time-domain interference relative to network load. Throughput gains are higher at higher network loads because of more active users and the higher likelihood of interference between the small cells.

Figure 73 below at right shows the maximum muting ratio, which increases with higher network load.

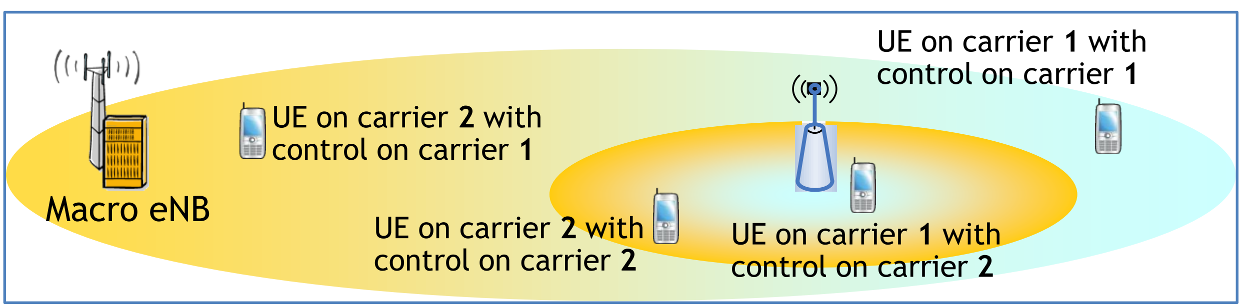
[164] 5G Americas member contribution. Assumes 3GPP evaluation methodology TR 36.814, 500 meter ISD, 4 picos per macro-cell area, Poisson call arrival, finite payload for each call, and termination of call upon successful delivery.

Figure 73: Throughput Gain of Time-Domain Interference Coordination[165]



Another approach for addressing inter-layer interference cancellation in HetNets can come from carrier aggregation with no further additions or requirements and realizable with Release 10 LTE networks. Consider the scenario in Figure 74, in which both the macro eNB and the pico eNB are allocated two component carriers (namely CC1 and CC2). The idea is to create a "protected" component carrier for downlink control signals and critical information (Physical Downlink Control Channel, system information, and other control channels) while data can be conveniently scheduled on both component carriers through cross-carrier scheduling.

Figure 74: Carrier-Aggregation Based ICIC[166]



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

165 5G Americas member contribution. Simulations based on 12 densely deployed small cells at 3.5 GHz and 3GPP Release 12 simulation assumptions in TR 36.842.

166 5G Americas member contribution.

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

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

Dual Connectivity

A major enhancement in Release 12 is a UE being served at the same time by both a macro cell and a small cell operating at different carrier frequencies, a capability called dual connectivity and illustrated in Figure 75. Data first reaches the macro eNodeB and is split, with part of it transmitted from the macro and the balance sent via an X2 interface to the small cell for transmission to the UE.

Figure 75: Dual Connectivity[167]

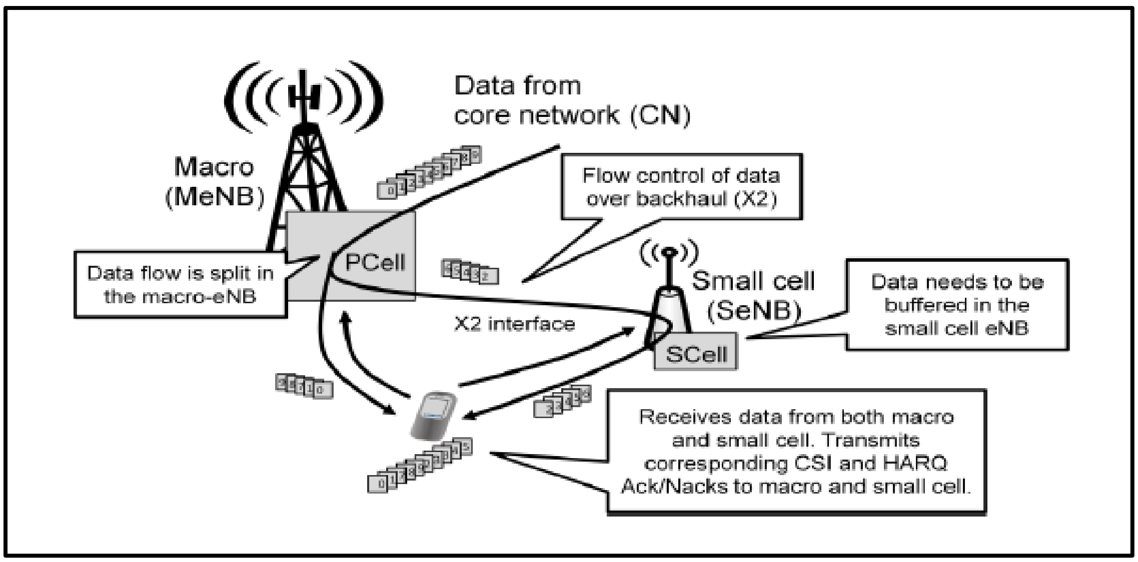
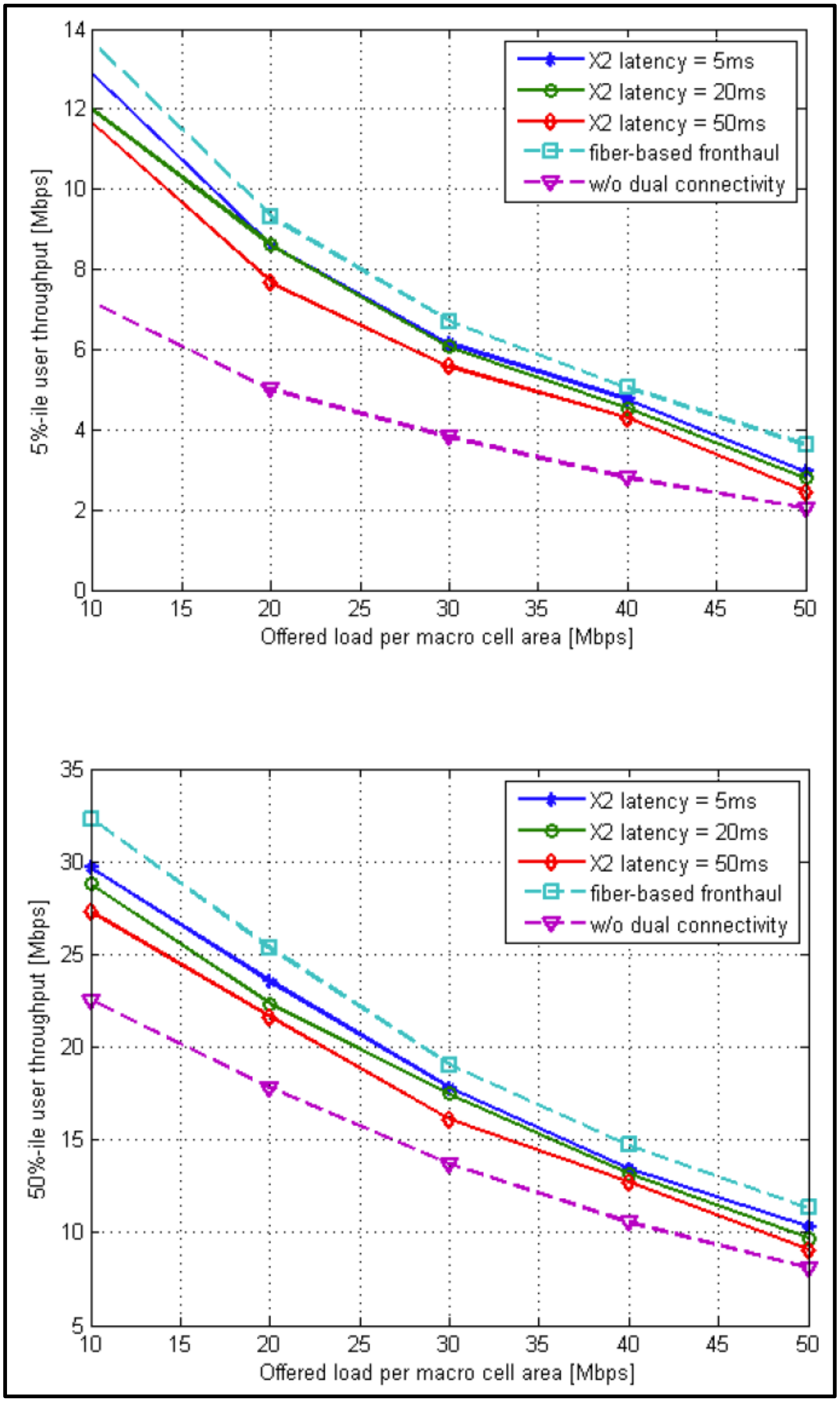


Figure 76 shows throughput gains of dual connectivity at 5 percentile and 50 percentile (median) levels relative to the load on the network and different degrees of latency in the X2 interface. Benefits are higher with lower network load and with lower X2 latency.

[167] Source: 5G Americas member contribution.

Figure 76: Dual Connectivity User Throughput[168]



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[168] 5G Americas member contribution.

Cloud Radio-Access Network (RAN) and Network Virtualization

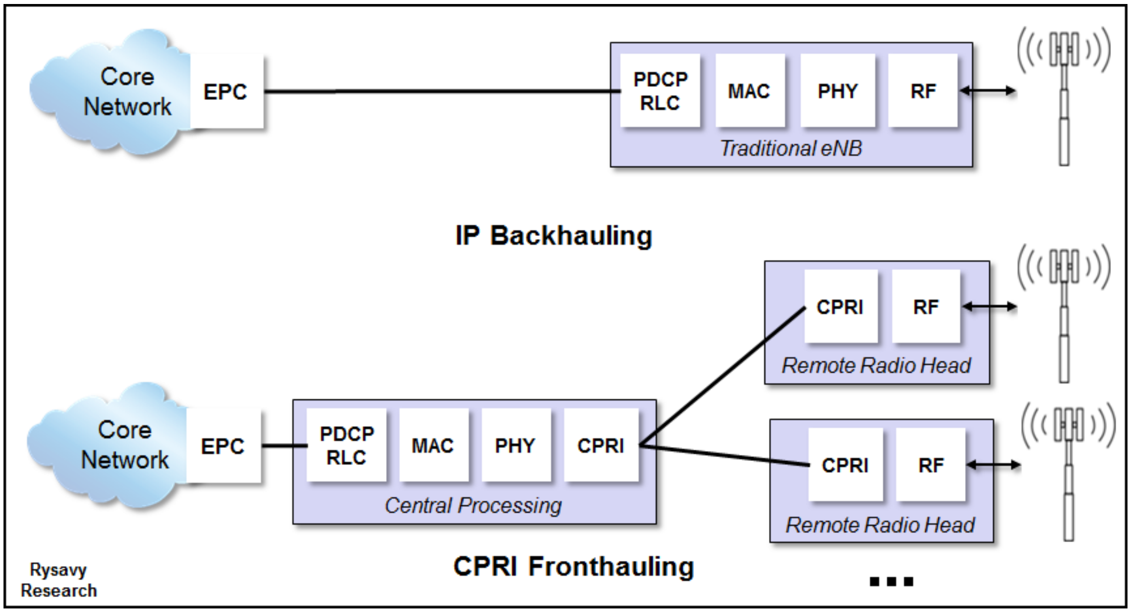
Still in the early stages of development, cloud RAN (C-RAN) is a distributed architecture in which multiple remote radio heads connect to a "cloud" that consists of a farm of baseband processing nodes. This approach can improve centralized processing, as is needed for CoMP, centralized scheduling, and multiflow, without the need to exchange information among many access nodes. The performance of both LTE and HSPA technologies could be enhanced by the application of cloud RAN architectures. The term "fronthauling" has been used to describe the transport of "raw" radio signals to central processing locations, such as between the Physical Network Function (PNF) and a Virtual Network Function (VNF).

This architecture, shown in Figure 77, comes at the cost of requiring high-speed, low-latency backhaul links between these radio heads and the central controller. One vendor states that carrying 10+10 MHz of LTE with 2X2 MIMO requires 2.5 Gbps of bandwidth and imposes less than 0.1 msec of delay.[169] A standard called "Common Public Radio Interface" (CPRI) addresses generic formats and protocols for such a high-speed link. ETSI has also developed the Open Radio Equipment Interface (ORI). The feasibility of cloud RAN depends to a large extent on the cost and availability of fiber links between the remote radio heads and the centralized baseband processing location.

Unlike virtualizing the EPC, in which the entirety of the function can be virtualized, cloud RAN needs a PNF that terminates the RF interface. Cloud RAN therefore requires a split to be defined within the RAN. As a consequence, initial deployments of cloud RAN have looked to ruse the CPRI interface between the RRH and the baseband unit.

[169] Dudu Bercovich, Ran Avital, "Holistic HetNet Hauling (3H)," Ceragon, February 2013. Available at http://www.ceragon.com/images/Reasource_Center/White_Papers/Ceragon_Holistic_Hetnet_Hauling_White_Paper.pdf.

Figure 77: Potential Cloud RAN Approach



The next evolutionary step after centralizing baseband processing is to virtualize the processing by implementing the functions in software on commodity computing platforms, thus abstracting the functions from any specific hardware implementation.

C-RANs can vary by the extent of coverage, ranging from being highly localized and operating across a small number of sites to metropolitan-wide solutions. Other variables include existing deployments versus greenfield situations, new LTE and 5G technologies versus integrating legacy 2G and 3G technologies, and integrating Wi-Fi. Greater scope increases complexity but yields benefits including better load-balancing and greater flexibility in spectrum refarming.

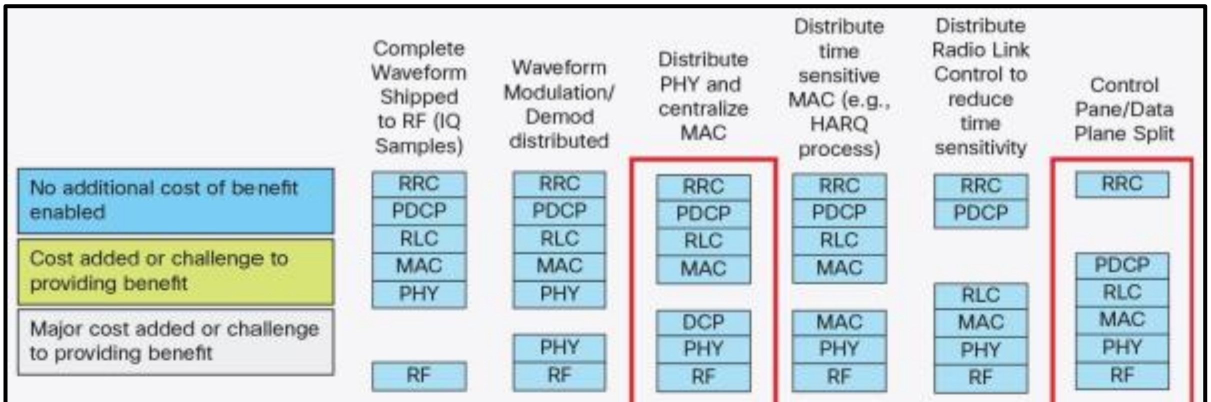
Another design choice, as detailed in Table 29, is whether to centralize Layer 1 and Layer 2 functions (an RF-PHY split), or whether to keep Layer 1 at the base stations and centralize only Layer 2 (a PHY-MAC split).

Table 29: Partially Centralized Versus Fully Centralized C-RAN

	Fully Centralized	Partially Centralized
Transport Requirements	Multi-Gbps, usually using fiber	20 to 50 times less
Fronthaul Latency Requirement	Less than 100 microseconds	Greater than 5 milliseconds.
Applications	Supports eICIC and CoMP	Supports centralized scheduling
Complexity	High	Lower
Benefit	Capacity gain	Lower capacity gain

Figure 78 analyzes the different possible RAN decompositions in greater detail.

Figure 78: Costs and Benefits of Various RAN Decompositions[170]



	CPRI	Split PHY	MAC-PHY	Split MAC	PDCP-RLC	RRC-PDCP Split
Fronthaul delay requirements	100 us transport latency	<6 ms latency for interleaved HARQ	<6 ms latency for interleaved HARQ	RLC ACK Windowing latency only	Same as legacy backhaul	Same as legacy backhaul
Fronthaul bandwidth requirements	30 x BW expansion	UL BW expansion due to soft bits	Same as legacy backhaul	Same as legacy backhaul	Same as legacy backhaul	Same as legacy backhaul
Multi-vendor alignment	Limited multi-vendor ORI Support	Proprietary	Small Cell Ecosystem defining	Proprietary	Challenging	Challenging
Virtualization Support	Specialized HW required	Some functions virtualized	Some functions virtualized	Virtualized central functions	Maximal virtualization	Maximal virtualization
Performance Improvements	Inter-cell gains possible	Inter-cell gains possible	Some inter-cell gains possible	Limited inter-cells gains	Limited inter-cells gains	Some handover optimization

Although some operators in dense deployments with rich fiber assets may centralize all functions, Figure 78 uses the red rectangles to show the two most likely functional splits for LTE-Advanced and 5G:

1. **Distributed PHY and Centralized MAC.** This approach relaxes the fronthaul delay requirement to 6 msec, compared with the CPRI requirement of 250 microseconds. Fronthaul bandwidth requirement is only 10-20% greater than conventional backhaul.

2. **Control Plane/Data Plane Split.** This approach further relaxes fronthaul requirements to 30 msec and is the approach used for dual-connectivity, such as a macro and small cell simultaneously connecting to a user.

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170 Cisco, *Cisco 5G Vision Series: Small Cell Evolution*, 2016.

Next Generation Mobile Networks studied the pros and cons of different fronthauling interfaces and published the results in March 2015.[171]

One application of C-RAN, proposed by NTT DOCOMO for 5G, uses C-RAN to coordinate small cells and macro cells, with the macro cell managing the control plane, and small cells operating in different bands than the macro, but being aggregated with the macro bands for higher capacity.[172]

Longer-term, perhaps in the 5G context, virtualized C-RANs may take away the very concept of cells. With methods such as beamforming and device-to-device communication, coverage may extend dynamically from a multitude of sources based on instantaneous load notifications and the radio resources available at different nodes.

In the past, RAN and core networks have been distinct entities, but over the next decade, the two may merge with more centralized, virtualized, and cloud-driven approaches.

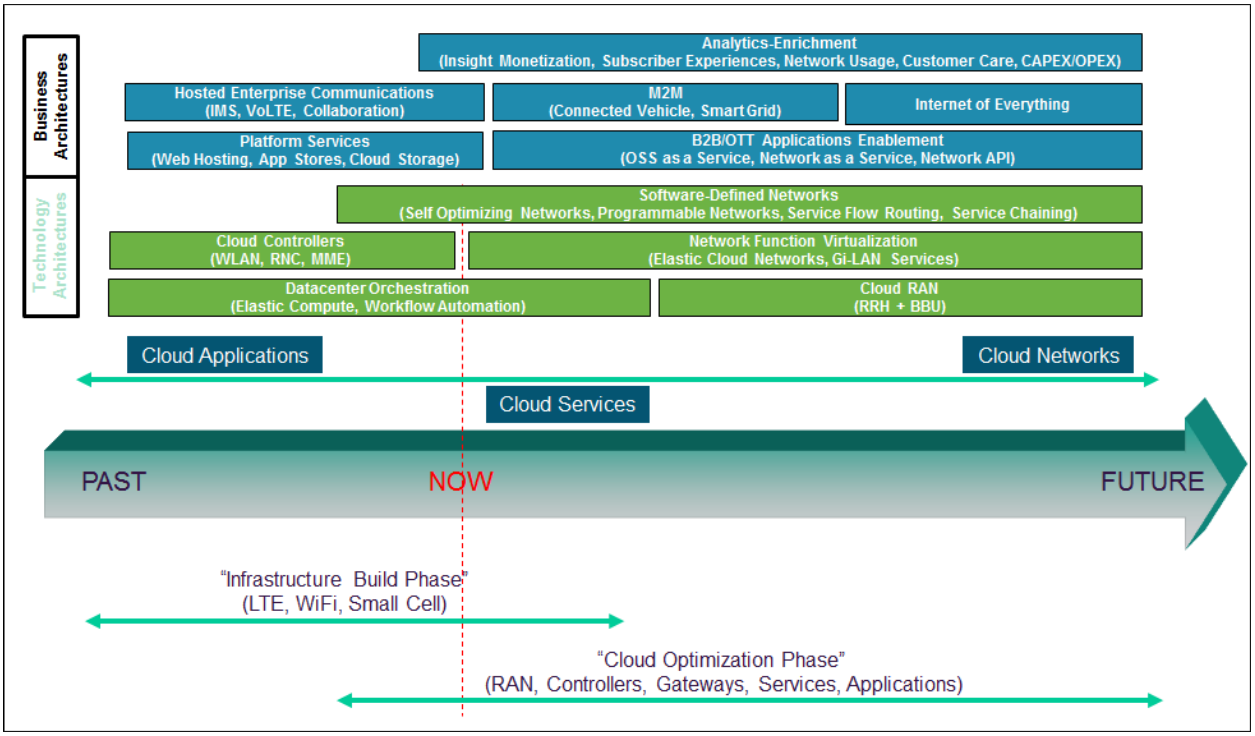
Another form of virtualization is software-defined networking, an emerging trend in both wired and wireless networks. For cellular, SDN promises to reduce OPEX costs, simplify the introduction of new services, and improve scalability; all major infrastructure vendors are involved. The Open Networking Foundation explains that an SDN decouples the control and data planes, centralizing network state and intelligence, while abstracting the underlying network infrastructure from applications.[173] Virtualization of network functions will be a complex, multiyear undertaking and will occur in stages, as shown in Figure 79.

[171] Next Generation Mobile Networks, *Further Study on Critical C-RAN Technologies, Version 1.0*, March 2015. See sections 2.2 and 2.3. Available at https://www.ngmn.org/uploads/media/NGMN_RANEV_D2_Further_Study_on_Critical_C-RAN_Technologes_v1.0.pdf.

[172] Presented at the Wireless Technology Association workshop, "Can Mobile Broadband Realize Its Full Potential? The Technology and Policy Paths to Massive Capacity Enhancement," Washington D.C., October 29, 2014.

173 Open Networking Foundation, "Software-Defined Networking: The New Norm for Networks," http://www.opennetworking.org/sdn-resources/sdn-library/whitepapers, accessed June 20, 2014.

Figure 79: Software-Defined Networking and Cloud Architectures[174]



Unlicensed Spectrum Integration

See the earlier section in this report on unlicensed spectrum integration, which includes a discussion of LTE-U, LTE-LAA, and MulteFire. This section covers integration approaches other than these.

3GPP has evolved its thinking on how best to integrate Wi-Fi with 3GPP networks. At the same time, the Wi-Fi Alliance and other groups have also addressed hotspot roaming, namely the ability to enable an account with one public Wi-Fi network provider 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 confusing landscape of integration methods, which this section attempts to clarify. Most integration today is fairly loose, meaning that either a device communicates data via the cellular connection or via Wi-Fi. If via Wi-Fi, the connection is directly to the internet and bypasses the operator core network. In addition, any automatic handover to hotspots occurs only between the operator cellular network and operator-controlled hotspots. The goals moving forward are to:

- Support roaming relationships so that users can automatically access Wi-Fi hotspots operated by other entities.
- 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.

[174] 5G Americas member contribution.

- Provide secure communications on the radio link as provided by the IEEE 802.11i standard.
- Allow policy-based mechanisms that define the rules by which devices connect to various Wi-Fi networks.
- Enable simultaneous connections to both cellular and Wi-Fi, with control over which applications use which connections.
- Support different types of Wi-Fi deployments, including third-party access points and carrier access points.

Release 6 I-WLAN

3GPP Release 6 was the first release to offer the option of integrating Wi-Fi in a feature called "Interworking WLAN" (I-WLAN), using a separate IP address for each network type.

Release 8 Dual Stack Mobile IPv6 and Proxy Mobile IPv6

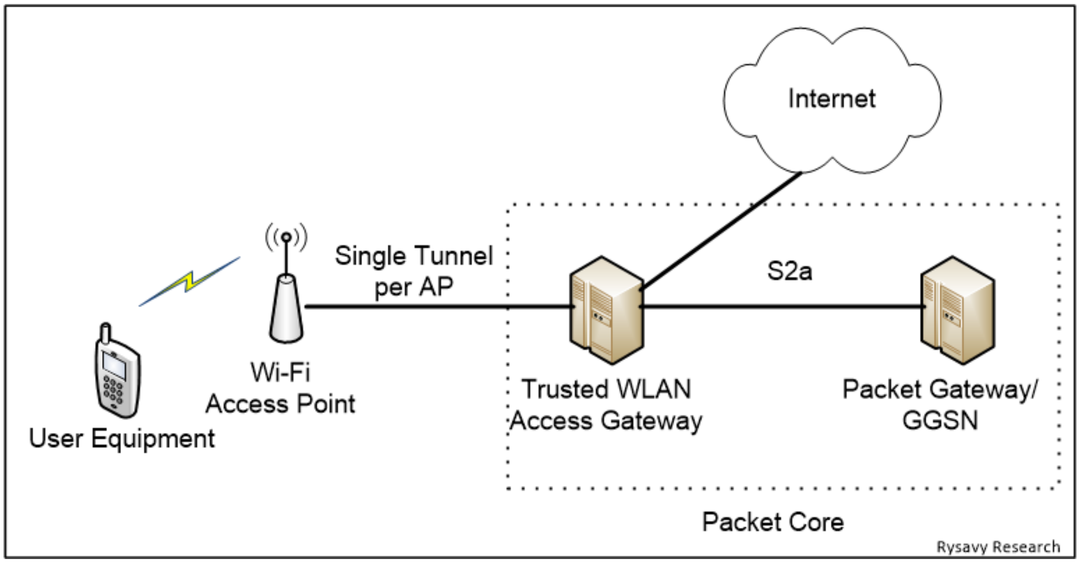
3GPP Release 8 specified Wi-Fi integration with the EPC using two different approaches: host-based mobility with Dual Stack Mobile IPv6 (DSMIPv6) in the client, and network-based mobility with Proxy Mobile IPv6 (PMIPv6) using an intermediary node called an "Enhanced Packet Data Gateway" (ePDG).[175] This method is intended for untrusted (non-carrier-controlled) Wi-Fi networks.

Release 11 S2a-based Mobility over GTP

Release 11, however, implements a new and advantageous approach as shown in Figure 80, one that eliminates the ePDG. Called "S2a-based Mobility over GTP" (SaMOG), a trusted WLAN access gateway connects to multiple 3GPP-compliant access points. Traffic can route directly to the internet or traverse the packet core. This method is intended for trusted (carrier-controlled) Wi-Fi networks.

[175] 3GPP, *System Architecture Evolution (SAE); Security aspects of non-3GPP accesses*. TS 33.402.

Figure 80: Release 11 SaMOG-based Wi-Fi Integration



Release 12 improves SaMOG capabilities in Enhanced SaMOG (eSaMOG), in which UEs can:

- Request the connectivity type
- Indicate the Access Point Name (APN) to establish PDN connectivity
- Request to hand over an existing PDN connection
- Establish multiple PDN connections in parallel over the WLAN
- Establish a non-seamless WLAN offload connection in parallel to a Packet Data Network connection over WLAN.

Multipath TCP

A new method for potentially integrating Wi-Fi and 3GPP networks is based on work by the Internet Engineering Taskforce (IETF). Called "Multipath TCP," the approach allows a TCP connection to occur simultaneously over two different paths. The advantages of this approach include higher speeds by aggregating links and not requiring any special provisions for link-layer handovers.

The IETF has published an experimental specification, *Request for Comments 6824: CP Extensions for Multipath Operation with Multiple Addresses*, which explains this approach. The IETF is also specifying Multipath QUIC.

ANDSF

Another relevant specification is 3GPP Access Network Discovery and Selection Function (ANDSF), which provides mechanisms by which mobile devices can know where, when, and how to connect to non-3GPP access networks, such as Wi-Fi.[176] ANDSF operates independently of SaMOG or other ways that Wi-Fi networks might be connected.

[176] 3GPP, *Architecture enhancements for non-3GPP accesses, Technical Specification 23.402*.

ANDSF functionality increases with successive 3GPP versions, as summarized in Table 30.

Table 30: ANDSF Policy Management Objects and 3GPP Releases[177]

ANDSF Policy Type	Policy Rule & Management Object	Release 8, 9	Release 10, 11	Release 12
Inter-System Mobility Policy (ISMP)	Policy, Rule priority, Prioritized Access, Validity Area (3G,4G, WI-FI, Geo), PLMN, Time-of-Day	X	X	X
Discovery Info	Access Network Type, Access Network Area (3G, 4G, Wi-Fi, Geo), Access Network Reference	X	X	X
UE Location	3GPP, 3GPP2, WiMAX, Wi-Fi network ID, Geo Location, PLMN	X	X	X
Inter-System Routing Policy (ISRP)	Flow Based routing, Service Based routing, Non-Seamless Offload, Roaming, PLMN, Routing Criteria, Time-of-Day, Routing rule		X	X
UE Profile	Device app/OS capability		X	X
Inter-APN Routing Policy (IARP)	Inter-APN routing over IP interface (in progress)			X
WLAN Selection Policy	Operator defined WLAN selection policy			X
Rule Selection Information	VPLMN with preferred WLAN roaming			X
Home Operator Preference	Home SP preference for S2a PDN session			X

Bidirectional Offloading Challenges

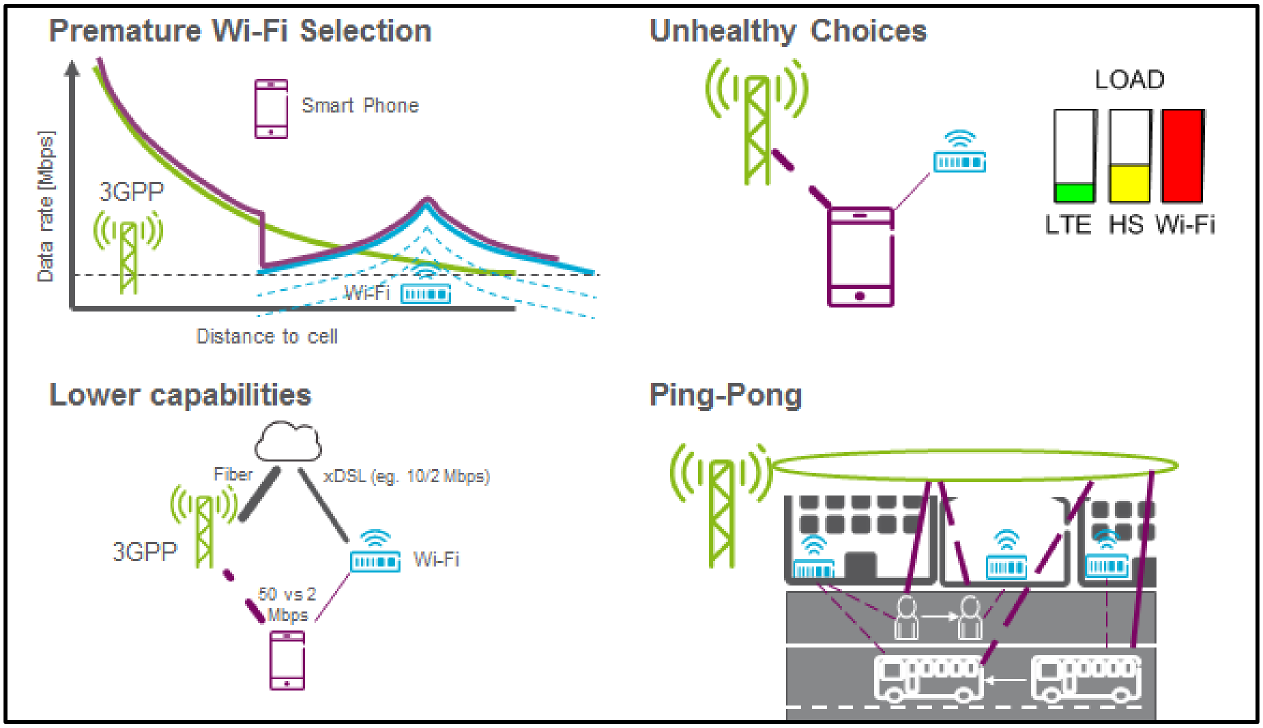
Eventually, operators will be able to closely manage user mobile broadband and Wi-Fi connections, dynamically selecting a particular network for a user based on real-time changes in loads and application requirements. Work is occurring in Release 12 to define parameters that would control switching from LTE to Wi-Fi or from Wi-Fi to LTE.[178]

Bidirectional offloading, however, creates various challenges, as shown in Figure 81 and discussed below.

[177] Courtesy Smith Micro Software, 2014. http://www.smithmicro.com.

[178] 3GPP, *Study on Wireless Local Area Network (WLAN) - 3GPP radio interworking (Release 12)*, TR 37.834.

Figure 81: Bidirectional-Offloading Challenges



1. **Premature Wi-Fi Selection.** As Wi-Fi-capable devices move into Wi-Fi coverage, they can prematurely reselect to Wi-Fi without comparative evaluation of existing cellular and incoming Wi-Fi capabilities, possibly resulting in the degradation of the end user experience. Real-time throughput-based traffic steering can mitigate this effect.

2. **Unhealthy choices.** In a mixed network of LTE, HSPA, and Wi-Fi, reselection can occur due to a strong Wi-Fi network signal even though the network is under heavy load. The resulting "unhealthy" choice degrades the end user experience because the performance on the cell edge of a lightly loaded cellular network may be superior to that of the heavily loaded Wi-Fi network. Real-time load-based traffic steering can be beneficial in this scenario.

3. **Lower capabilities.** In some cases, selection to a Wi-Fi network may result in reduced performance even if it offers a strong signal because of other factors, such as lower-bandwidth backhaul. Evaluation of criteria beyond wireless capabilities prior to access selection can improve this circumstance.

4. **Ping-Pong.** Ping-ponging between Wi-Fi and cellular, especially if both offer similar signal strengths, can also degrade the user experience. Hysteresis approaches, similar to those used in cellular inter-radio transfer, can better manage transfer between Wi-Fi and cellular accesses.

3GPP RAN2 is discussing real-time or near-real-time methods to address the challenges discussed above.

Other Integration Technologies (SIPTO, LIPA, IFOM, MAPCON)

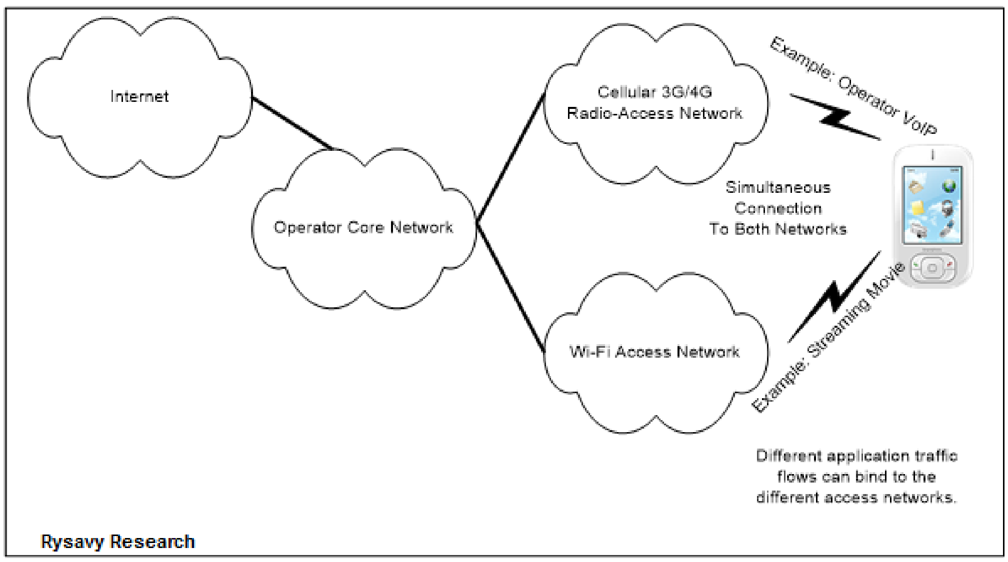
Release 10 defines additional options for Wi-Fi integration, including Selected IP Traffic Offload (SIPTO), Local IP Access (LIPA), Multi-Access PDN Connectivity (MAPCON), and IP Flow and Seamless Offload (IFOM).

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, or it can operate in the macro network.

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

IFOM, as shown in Figure 82, enables simultaneous cellular and Wi-Fi connections, with different traffic flowing 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).

Figure 82: 3GPP IP Flow and Seamless Mobility

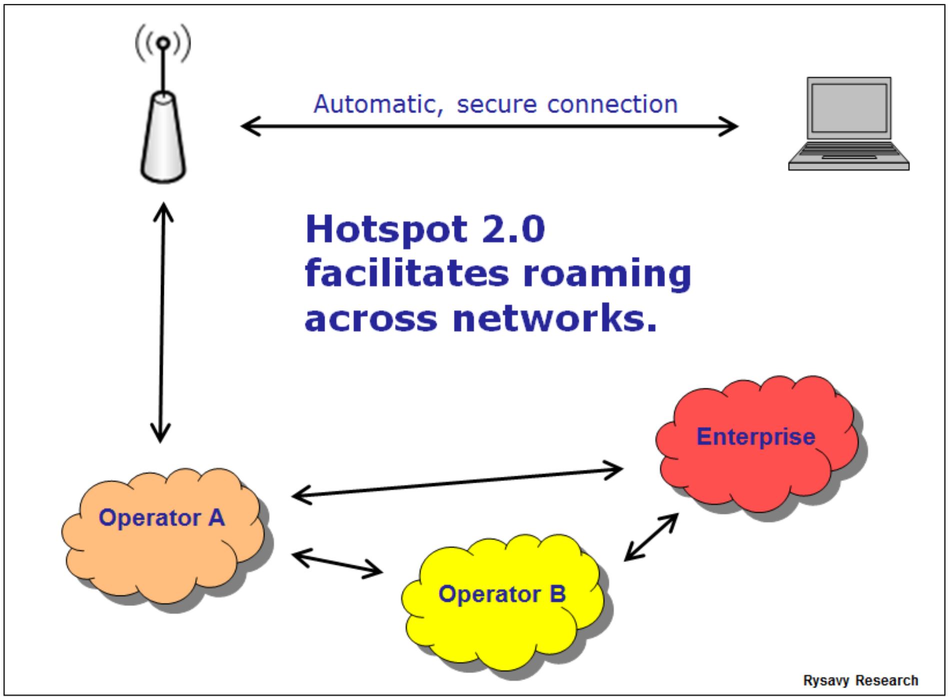


Similar to IFOM, Release 10 feature MAPCON allows multiple simultaneous PDN connections (each with a separate APN), such as Wi-Fi and 3GPP radio access. The UE uses separate IP addresses for each connection but does not need Dual Stack Mobile IPv6 (DSMIPv6).

Hotspot 2.0

Developed by the Wi-Fi Alliance, Hotspot 2.0 specifications, also called "Next Generation Hotspot," facilitate Wi-Fi roaming. 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, as shown in Figure 83.[179] It also provides for encrypted communications over the radio link.[180]

Figure 83: Roaming Using Hotspot 2.0



Using IEEE 802.11u, devices can determine what roaming relationships an access point supports and can then securely connect to the Wi-Fi network using one of these roaming arrangements, as shown in Figure 84. Hotspot 2.0 authentication is based on the Extended Authentication Protocol (EAP) using SIM credentials. There are plans to enhance the Hotspot 2.0 protocols in Phase 2, which will define online signup to enable non-SIM-based devices to easily and securely register for services. The Wi-Fi alliance began a Hotspot 2.0 certification process for devices and access points in June 2012 and uses the designation "Wi-Fi Certified Passpoint" for compliant devices.

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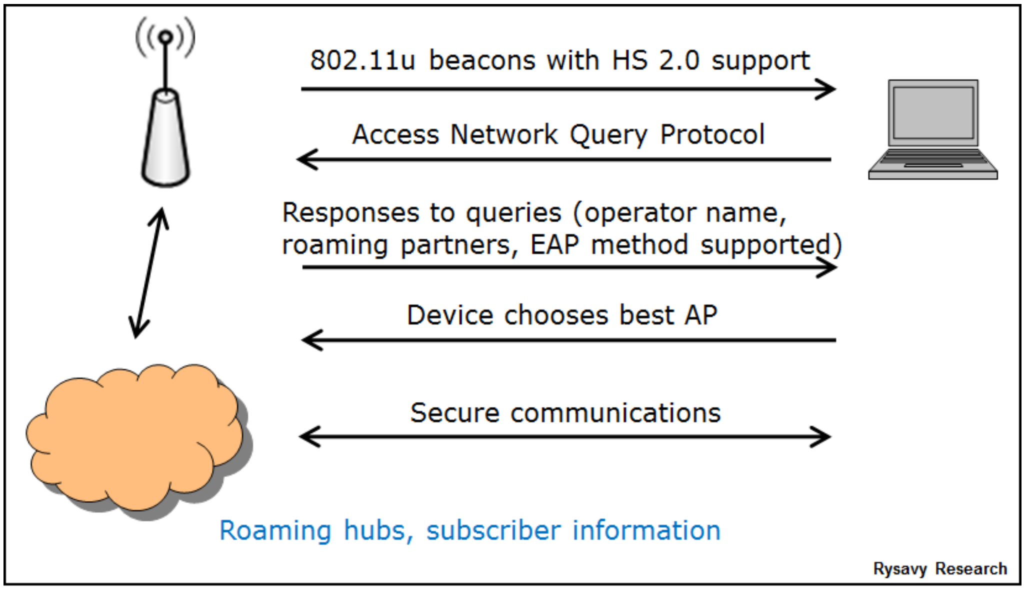
[179] For example, user devices can be authenticated based on their SIM credentials. Or, users can register or click through an agreement and then not need to redo that with future associations.

[180] 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.

Figure 84: Hotspot 2.0 Connection Procedure



Release 2 of Passpoint, available in 2014, added immediate account provisioning, which facilitates a user establishing an account at the point of access. The new version also provides for policies to be downloaded from the network operator; these policies control network selection priorities when multiple networks are available.

Evolved Packet Core (EPC)

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

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

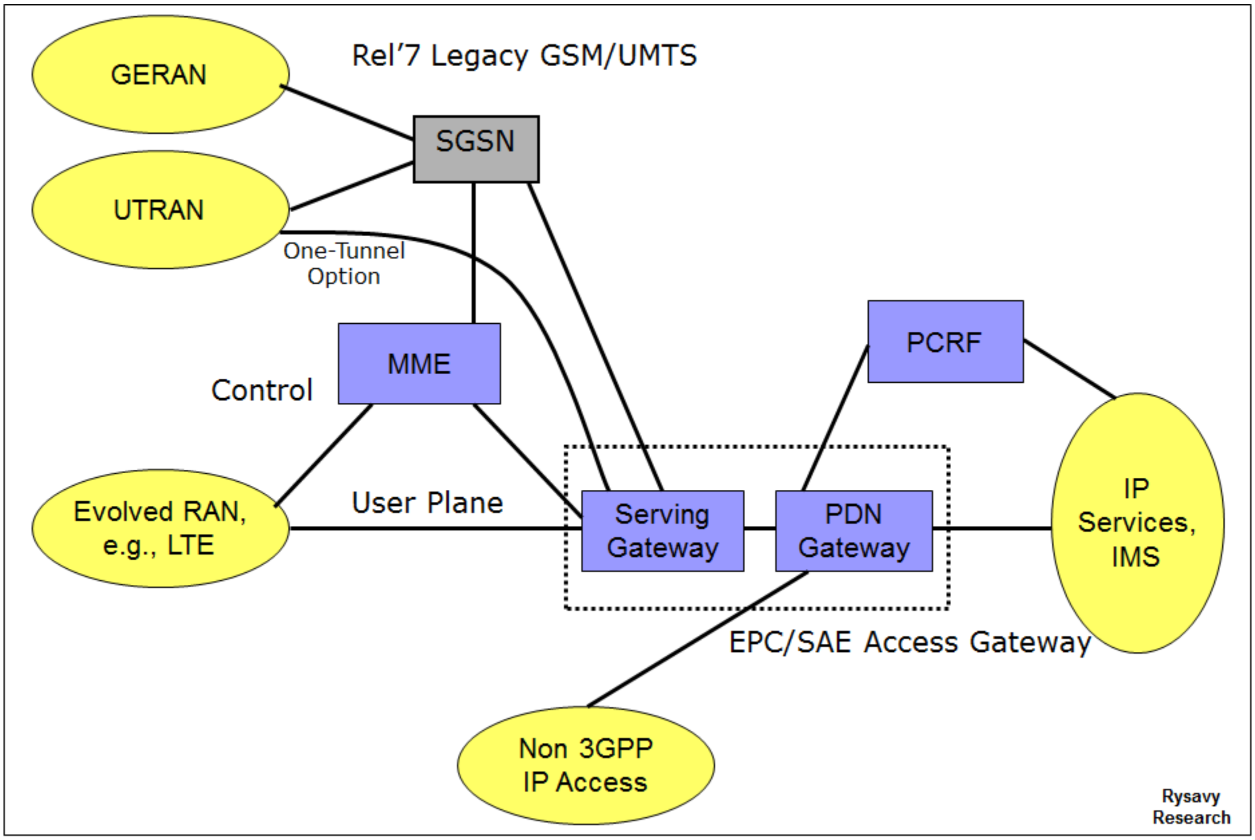
One important performance-enhancing aspect of EPC is a flatter architecture. For packet flow, EPC includes two network elements, called "Evolved Node B" (eNodeB) and the Access Gateway (AGW). The eNodeB (base station) integrates the functions traditionally performed by the radio-network controller, which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

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

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

Figure 85 shows the EPC architecture.

Figure 85: 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 that manages QoS aspects.

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

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

- **VoIP support with IMS.** QoS is a crucial element for providing LTE/IMS voice service. (See section below on IMS).
- **Enhanced application performance.** Applications such as gaming or video can operate more reliably.
- **More flexible business models.** With flexible, policy-based charging control, operators and third-parties will be able to offer content in creative new ways. For example, an enhanced video stream to a user could be paid for by an advertiser.
- **Congestion control.** In congestion situations, certain traffic flows (bulk transfers, abusive users) can be throttled down to provide a better user experience for others.

Table 31 shows the nine QCI used by LTE.

Table 31: LTE Quality of Service

QCI	Resource Type	Priority	Delay Budget	Packet Loss	Examples
1	GBR (Guaranteed Bit Rate)	2	100 msec.	10^{-2}	Conversational 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^{-6}	Non-conversational video (buffered streaming)
5	Non-GBR	1	100 msec.	10^{-6}	IMS signaling
6	Non-GBR	6	300 msec.	10^{-6}	Video (buffered streaming), TCP Web, e-mail, and FTP.

QCI	Resource Type	Priority	Delay Budget	Packet Loss	Examples
7	Non-GBR	7	100 msec.	10^{-3}	Voice, video (live streaming), interactive gaming
8	Non-GBR	8	300 msec.	10^{-6}	Premium bearer for video (buffered streaming), TCP Web, e-mail, and FTP
9	Non-GBR	9	300 msec.	10^{-6}	Default bearer for video, TCP for non-privileged users

Self-Organizing Networks (SON)

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 one another and with the core network. SONs can also self-heal in failure situations.

3GPP began standardization of self-optimization and self-organization in Releases 8 and 9, a key goal being support of multi-vendor environments. Successive releases have augmented SON capabilities.

Features being defined in SON include:

- Automatic inventory;
- Automatic software download;
- Automatic neighbor relation;
- Automatic physical Cell ID assignment;
- Mobility robustness/handover optimization;
- Random access channel optimization;
- Load-balancing optimization;
- Inter-cell interference coordination (ICIC) management;
- Enhanced inter-cell interference coordination (eICIC) management;
- Coverage and capacity optimization;
- Cell outage detection and compensation;
- Self-healing functions;

- Minimization of drive testing;
- Energy savings; and
- Coordination among various SON functions.

3GPP categorizes SON as centralized, distributed, or hybrid, which is a combination of centralized and distributed approaches.

In a centralized architecture, SON algorithms operate on a central network management system or central SON server. In contrast, in a distributed approach, the SON algorithms operate at the eNBs, which make autonomous decisions based on local measurements as well as from other nearby eNBs received via an X2 interface that interconnects eNBs.

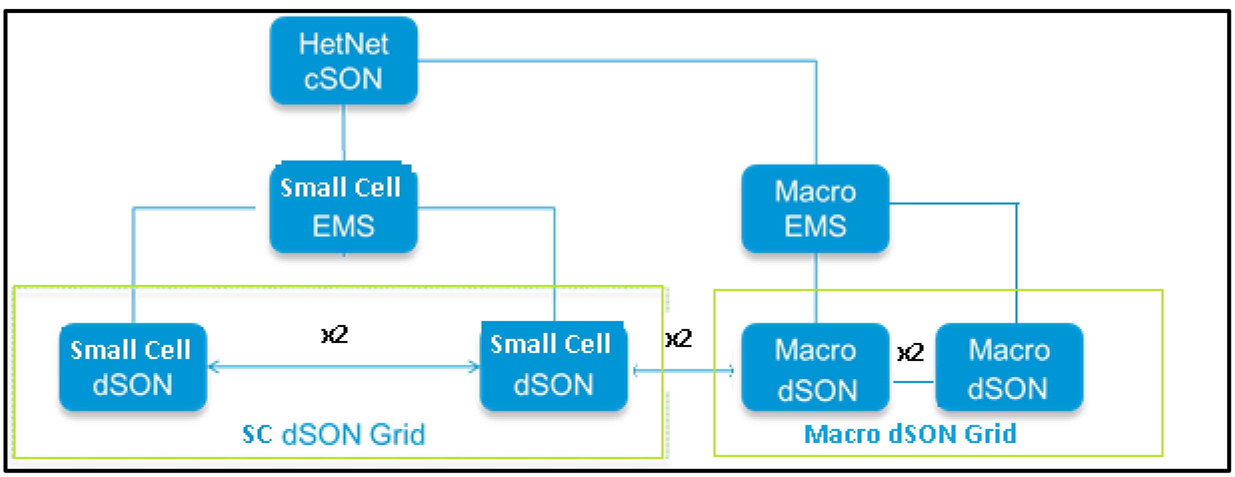
The distributed architecture permits faster and easier deployment but is not necessarily as efficient or as consistent in operation, especially in multi-vendor infrastructure deployments.

In a hybrid approach, shown in Figure 86, SON algorithms operate both at the eNB and at a central SON server, with the server supplying values of initial parameters, for example. The eNBs may then update and refine those parameters in response to local measurements.

The hybrid approach resolves deployment scenarios that cannot be resolved by dSON, for example, cases such as:

- No X2 interface between the eNBs.
- Multi-vendor deployment with different dSON algorithms.
- Multi-technology load balancing and user steering.

Figure 86: Hybrid SON Architecture[181]



With increasing numbers of macro cells and small cells, interference opportunities increase as well. Optimizing power settings through intelligent power management algorithms is crucial for maximum efficiency with the least amount of interference, including pilot

[181] 5G Americas member contribution.

pollution. Pilot pollution can result in low data rates and ping-pong handovers due to channel fading. A hybrid SON approach is well suited for optimized power management.

IP Multimedia Subsystem (IMS)

IP Multimedia Subsystem (IMS) is a service platform for IP multimedia applications: video sharing, PoC, VoIP, streaming video, interactive gaming, and others. IMS by itself does not provide all these applications. Rather, it provides a framework of application servers, subscriber databases, and gateways to make them possible. The exact services will depend on cellular operators and the application developers that make these applications available to operators. The primary application in 2016, however, is VoLTE.

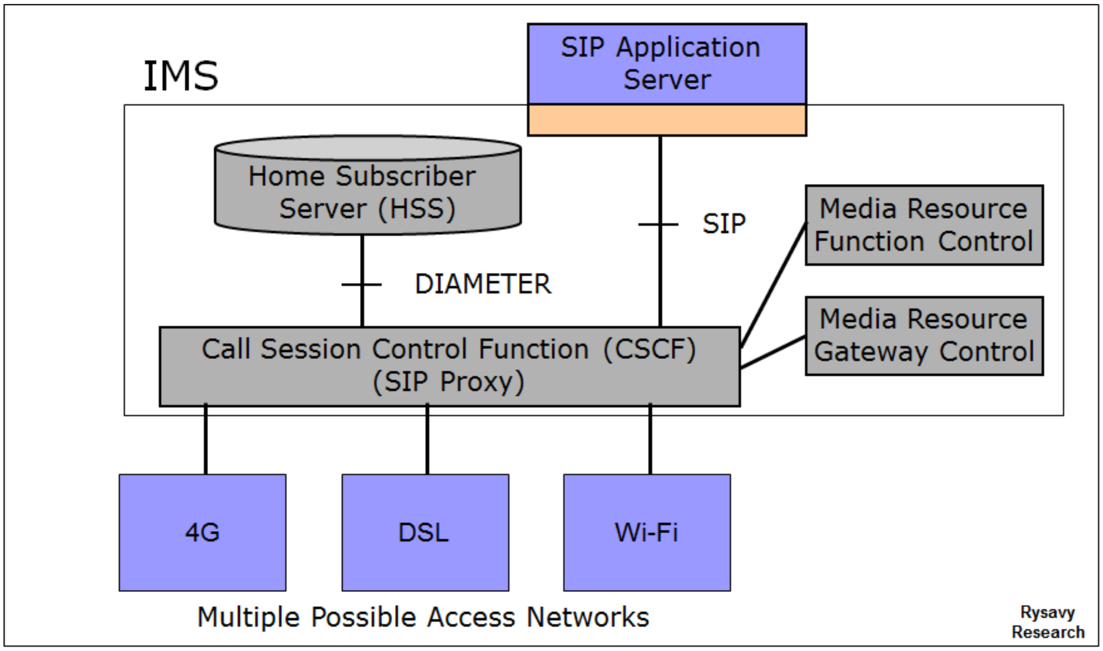
The core networking protocol used within IMS is Session Initiation Protocol (SIP), which includes the companion Session Description Protocol (SDP) used to convey configuration information such as supported voice codecs. Other protocols include Real Time Transport Protocol (RTP) and Real Time Streaming 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 IETF, which specifies key protocols such as SIP, and the Open Mobile Alliance, which specifies end-to-end, service-layer applications. Other organizations supporting IMS include the GSMA, ETSI, CableLabs, 3GPP2, The Parlay Group, the ITU, ANSI, the Telecoms and Internet Converged Services and Protocols for Advanced Networks (TISPAN), and the Java Community Process (JCP).

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

As shown in Figure 87, IMS operates just outside the packet core.

Figure 87: 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 based on IP building blocks for both voice and data services.

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

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

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

Given that LTE operators will integrate their 5G networks with their current LTE networks, operators are likely to keep using IMS in conjunction with LTE for their voice and other services that use IMS, even as they begin deploying 5G.

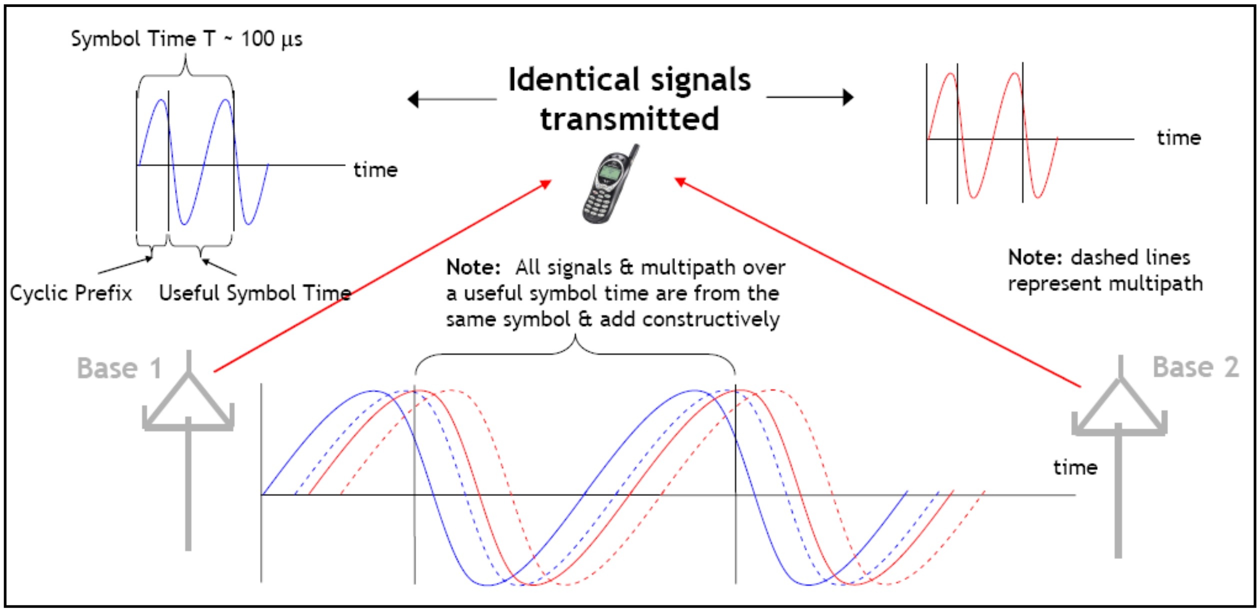
Broadcast/Multicast Services

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

3GPP defined highly efficient broadcast/multicast capabilities for UMTS in Release 6 with MBMS. Release 7 defined optimizations through a feature 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 MBMS Single Frequency Network (SFN), or MBSFN, cell transmissions. The result is highly efficient, WCDMA-based broadcast transmission technology that matches the benefits of OFDMA-based broadcast approaches.

LTE also has a broadcast/multicast capability called eMBMS. OFDM is particularly well-suited for efficient broadcasting, as shown in Figure 88, because the mobile system can combine the signal from multiple base stations, also an MBSFN approach, and because of the narrowband nature of OFDM. Normally, these signals would interfere with one another. The single frequency network is a cluster of cells that transmit the same content synchronously with a common carrier frequency.

Figure 88: OFDM Enables Efficient Broadcasting



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

Backhaul

Connecting sites to core networks remains a challenge, whether for small cells or macro cells, especially as networks need to deliver higher bandwidth. Fiber is the gold standard, but it is not available everywhere and can be expensive, so operators use a combination of wired and wireless links. Table 32 and Table 33 summarize the methods and capabilities of the various available approaches.

Table 32: Wired Backhaul Methods and Capabilities[182]

Technology	Distance	Throughput Speed
Direct Fiber	80 km	Hundreds of Mbps to Gbps
Bonded VDSL2	To 5,000 feet	75 Mbps down, 12 Mbps up
FTTX	Most urban areas	Up to 2.5 Gbps down, 1.5 Gbps up
DOCSIS	Most urban areas	Up to 285 Mbps down, 105 Mbps up

Table 33: Wireless Backhaul Methods and Capabilities[183]

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

[182] Small Cell Forum, "Backhaul Technologies for Small Cells," February 2013.

[183] Small Cell Forum, "Backhaul Technologies for Small Cells," February 2013.

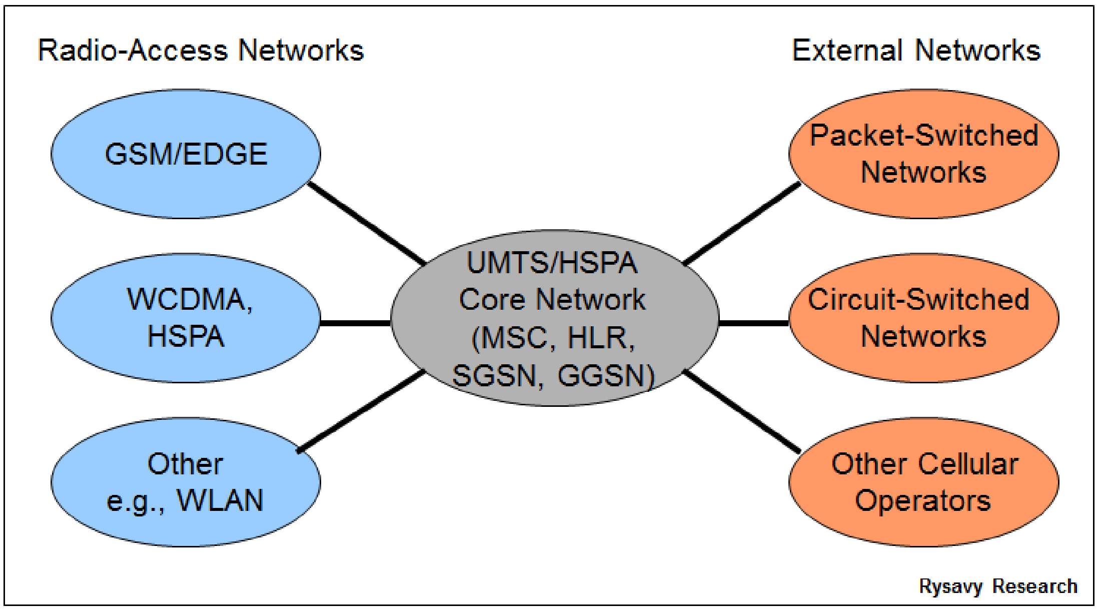
Technology	Distance	Line of Sight	Throughput Speed
Satellite	Available everywhere	Yes	Up to 50 Mbps downlink, 15 Mbps uplink

UMTS-HSPA

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

Additionally, operators can use a common core network, called the UMTS multi-radio network as shown in Figure 89, which supports multiple radio-access networks including GSM, EDGE, WCDMA, HSPA, and evolutions of these technologies.

Figure 89: UMTS Multi-radio Network



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

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

Whereas GSM can effectively operate like a spread-spectrum system[184], 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.

HSDPA

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

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

HSDPA achieves its performance gains from the following radio features:

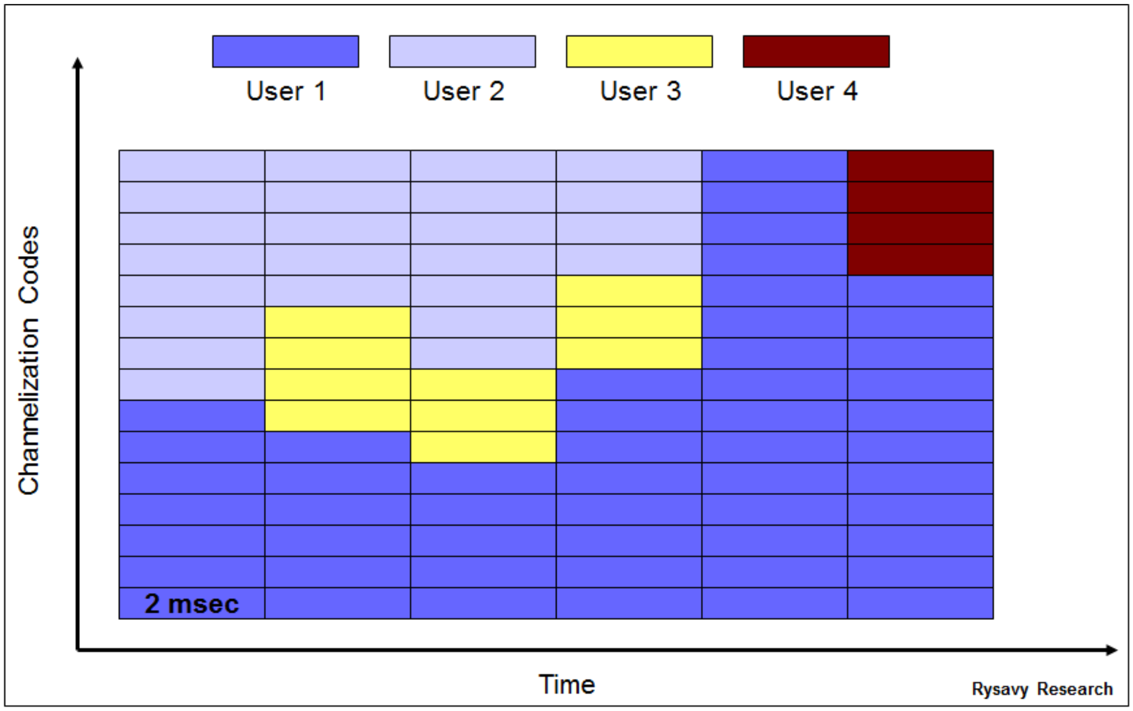
- High-speed channels shared in both code and time domains
- Short TTI
- Fast scheduling and user diversity
- Higher order modulation
- Fast link adaptation
- Fast HARQ

These features function as follows:

High-Speed Shared Channels and Short Transmission Time Interval: First, HSDPA uses high-speed data channels called "High Speed Physical Downlink Shared Channels" (HS-PDSCH). Up to 15 of these channels can operate in the 5 MHz WCDMA radio channel. Each uses a fixed spreading factor of 16. User transmissions are assigned to one or more of these channels for a short TTI of 2 msec. The network can then readjust how users are assigned to different HS-PDSCH every 2 msec. Resources are thus assigned in both time (the TTI interval) and code domains (the HS-PDSCH channels). Figure 90 illustrates different users obtaining different radio resources.

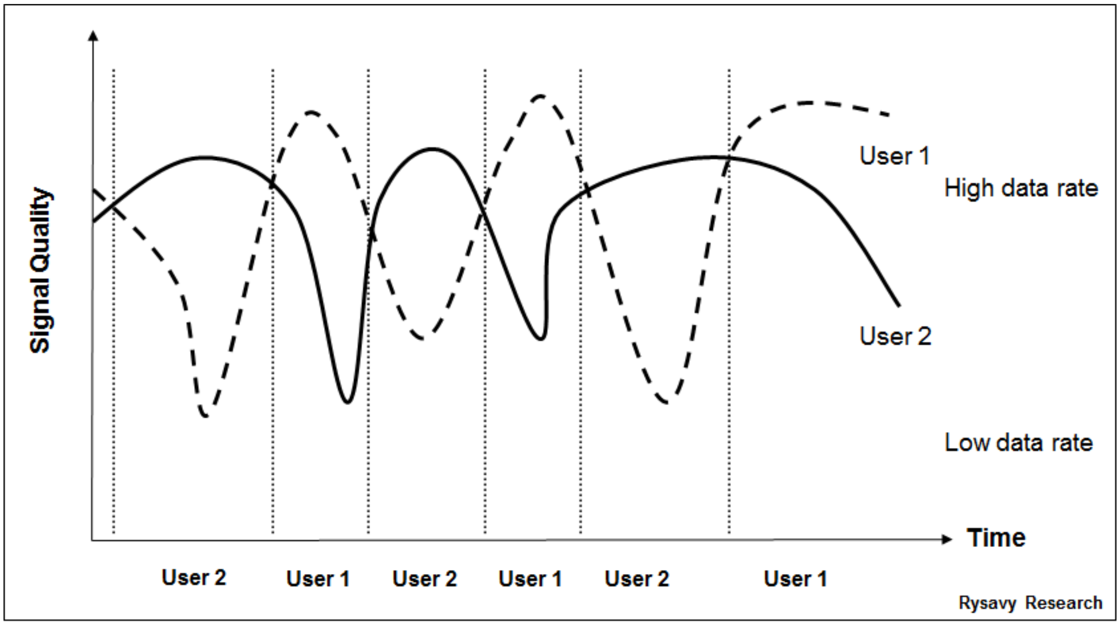
[184] Spread spectrum systems can either be direct sequence or frequency hopping.

Figure 90: High Speed–Downlink Shared Channels (Example)



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 91 shows how a scheduler might choose between two users based on their varying radio conditions to emphasize the user with better instantaneous signal quality. With about 30 users active in a sector, the network achieves significant user diversity and much higher spectral efficiency. The system also ensures that each user receives a minimum level of throughput, an approach called proportional fair scheduling.

Figure 91: User Diversity



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

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

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

Using the approaches just described, HSDPA maximizes data throughputs and capacity and minimizes delays. For users, this translates to better network performance under loaded conditions, faster application performance, and a greater range of applications that function well.

Field results validate the theoretical throughput results. With initial 1.8 Mbps peak-rate devices, vendors measured consistent throughput rates in actual deployments of more than 1 Mbps. These rates rose to more than 2 Mbps for 3.6 Mbps devices and then close to 4 Mbps for 7.2 Mbps devices.

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

HSUPA

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

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

HSUPA achieves its performance gains through the following approaches:

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

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

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

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

Beyond throughput enhancements, HSUPA also significantly reduces latency.

Evolution of HSPA (HSPA+)

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

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

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

The goals of HSPA+ were to:

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

Advanced Receivers

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

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

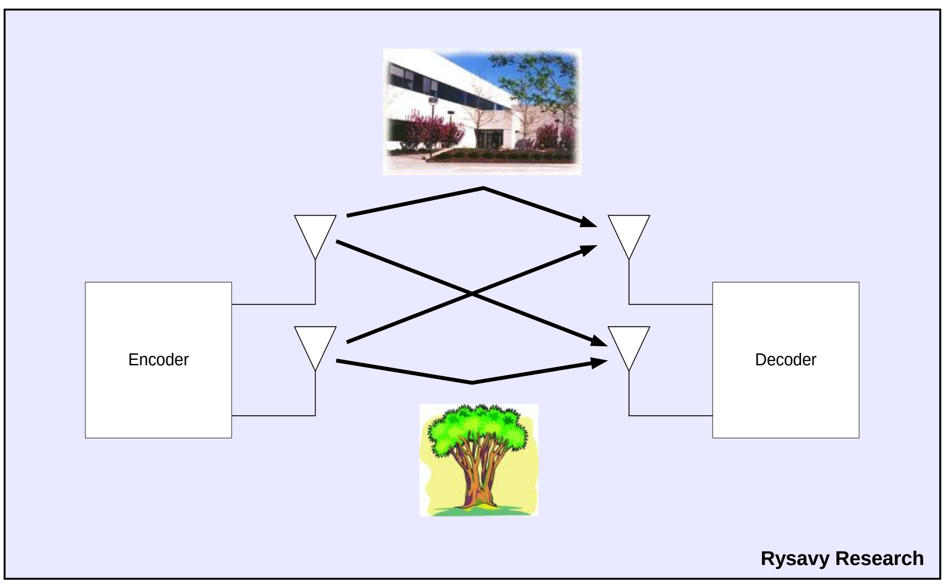
Current receiver architectures based on rake receivers are effective for speeds up to a few megabits per second. But at higher speeds, the combination of reduced symbol period and multipath interference results in inter-symbol interference and diminishes rake receiver performance. This problem can be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

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

MIMO

Another standardized capability is MIMO, a technique that employs multiple transmit antennas and multiple receive antennas, often in combination with multiple radios and multiple parallel data streams. The most common use of the term "MIMO" applies to spatial multiplexing. The transmitter sends different data streams over each antenna. Whereas multipath is an impediment for other radio systems, MIMO—as illustrated in Figure 92—actually exploits multipath, relying on signals to travel across different uncorrelated communications paths. The multiple data paths effectively operate in parallel and, with appropriate decoding, in a multiplicative gain in throughput.

Figure 92: MIMO Using Multiple Paths to Boost Throughput and Capacity



Tests of MIMO have proven effective in WLANs operating in relative isolation where interference is not a dominant factor. Spatial multiplexing MIMO can also benefit HSPA "hotspots" serving local areas including airports, campuses, and malls. In a fully loaded network with interference from adjacent cells, however, overall capacity gains will be more modest—in the range of 20% to 33% over mobile-receive diversity. Relative to a 1x1 antenna system, however, 2X2 MIMO can deliver cell throughput gains of about 80%. 3GPP has standardized spatial multiplexing MIMO in Release 7 using Double Transmit Adaptive Array (D-TxAA).

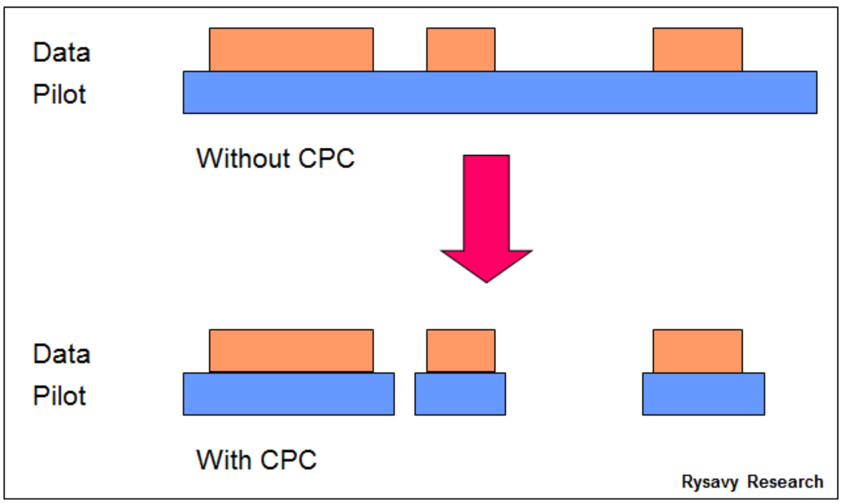
Release 9 provides for a means to leverage MIMO antennas at the base station when transmitting to user equipment that does not support MIMO. The two transmit antennas in the base station can transmit a single stream using beam forming. This is called "single-stream MIMO" or "MIMO with single-stream restriction" and results in higher throughput rates because of the improved signal received by the user equipment.

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

Continuous Packet Connectivity

Continuous Packet Connectivity (CPC) specified in Release 7 reduces the uplink interference created by the dedicated physical control channels of packet data users when those channels have no user data to transmit, which increases the number of simultaneously connected HSUPA users. CPC allows both discontinuous uplink transmission and discontinuous downlink reception, wherein the modem can turn off its receiver after a certain period of HSDPA inactivity. CPC is especially beneficial to VoIP on the uplink because the radio can turn off between VoIP packets, as shown in Figure 93.

Figure 93: Continuous Packet Connectivity



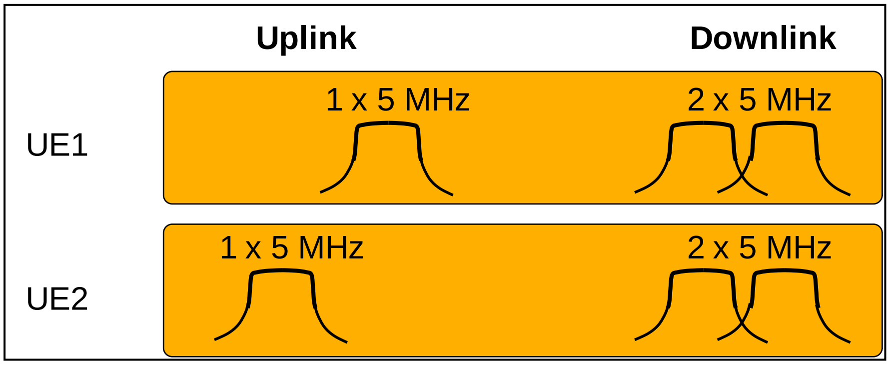
Higher Order Modulation

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

Multi-Carrier HSPA

3GPP defined dual-carrier HSPA operation in Release 8, which coordinates the operation of HSPA on two adjacent 5 MHz carriers so that data transmissions can achieve higher throughput rates, as shown in Figure 94. The work item assumed two adjacent carriers, downlink operation and no MIMO. This configuration achieves a doubling of the 21 Mbps maximum rate available on each channel to 42 Mbps.

Figure 94: Dual-Carrier Operation with One Uplink Carrier[185]



Benefits include:

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

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

Release 9 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. Release 11 supports eight radio channels on the downlink, resulting in a further doubling of theoretical throughput to 336 Mbps. On the uplink, devices can transmit using two antennas for either rank 1 (single stream beamforming) or rank 2 (dual-stream MIMO) transmission modes. Rank 1 beamforming helps with coverage (approximately 40%), while rank 2 MIMO helps with throughput speeds (approximately 20% median and 80% at cell edge). In addition, 64 QAM will be possible on the uplink, enabling uplink speeds to 69 Mbps in dual-carrier operation.

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 HetNet operation in which picocell coverage can be expanded within a macrocell coverage area, as shown in Figure 95.

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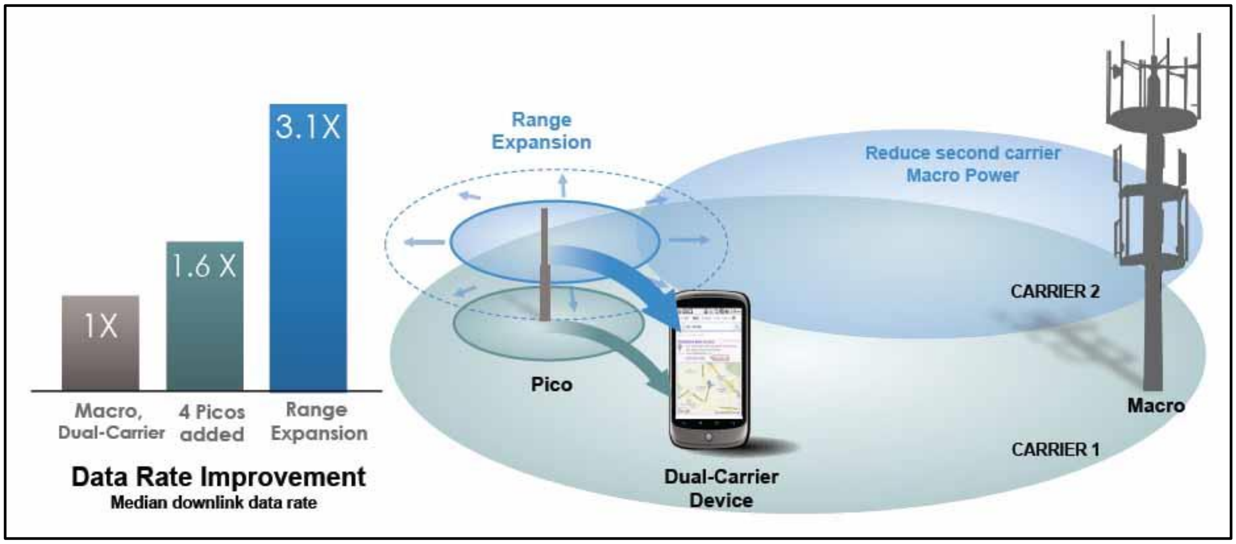
[185] Harri Holma and Antti Toskala, *LTE for UMTS, OFDMA and SC-FDMA Based Radio Access*, Wiley, April 2009.

Figure 95: HSPA+ HetNet Using Multipoint Transmission[186]



Multiflow enhances HSPA+ network operation using the following approaches:

- **Single Frequency Dual Cell.** The UE communicates with two different cells using the same frequency, improving cell-edge performance and providing network load balancing.
- **Dual Frequency Three Cell.** The UE communicates with two different cells using the same frequency. In addition, it communicates with one other cell on a different frequency.
- **Dual Frequency Four Cells.** The UE communicates using two instances of Single Frequency Dual Cell operation as described above.

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

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

HSPA+ Throughput Rates

Table 34 summarizes the capabilities of HSPA and HSPA+ based on the various methods discussed above.

Table 34: HSPA Throughput Evolution

Technology	Downlink (Mbps) Peak Data Rate	Uplink (Mbps) Peak Data Rate
HSPA as defined in Release 6	14.4	5.76

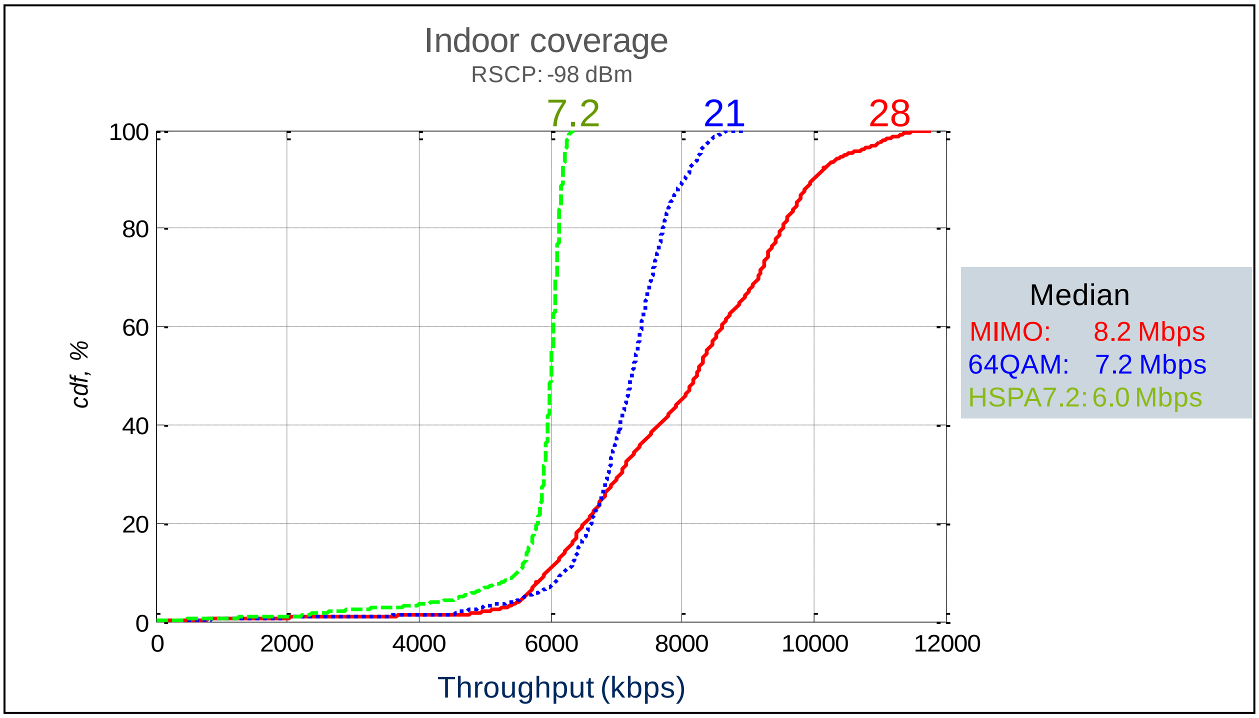
[186] Qualcomm, "HSPA+ Advanced: Taking HSPA+ to the Next Level," February 2012, http://www.qualcomm.com/media/documents/hspa-advanced-taking-hspa-next-level-whitepaper, accessed June 20, 2014.

Technology	Downlink (Mbps) Peak Data Rate	Uplink (Mbps) Peak Data Rate
Release 7 HSPA+ DL 64 QAM, UL 16 QAM, 5+5 MHz	21.1	11.5
Release 7 HSPA+ 2X2 MIMO, DL 16 QAM, UL 16 QAM, 5+5 MHz	28.0	11.5
Release 8 HSPA+ 2X2 MIMO DL 64 QAM, UL 16 QAM, 5+5 MHz	42.2	11.5
Release 8 HSPA+ (no MIMO) Dual Carrier, 10+5 MHz	42.2	11.5
Release 9 HSPA+ 2X2 MIMO, Dual Carrier DL and UL, 10+10 MHz	84.0	23.0
Release 10 HSPA+ 2X2 MIMO, Quad Carrier[187] DL, Dual Carrier UL, 20+10 MHz	168.0	23.0
Release 11 HSPA+ 2X2 MIMO DL and UL, 8 Carrier DL, Dual Carrier UL, 40+10 MHz	336.0	69.0

Figure 96 shows the cumulative distribution function of throughput values in a commercially deployed Release 8 HSPA+ network in an indoor-coverage scenario. The figure shows significant performance gains from higher-order modulation and MIMO.

[187] No operators have announced plans to deploy HSPA in a quad (or greater) carrier configuration. Three carrier configurations, however, have been deployed.

Figure 96: HSPA+ Performance Measurements Commercial Network (5+5 MHz)[188]

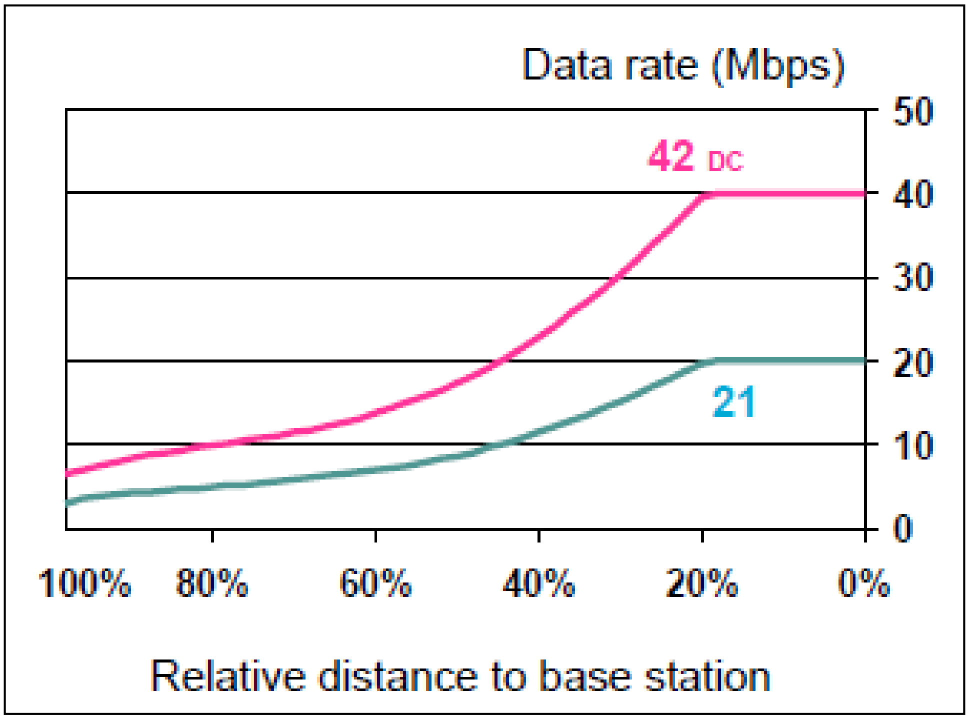


The figure shows a reasonably typical indoor scenario in a macro-cell deployment. Under better radio conditions, HSPA+ will achieve higher performance results.

Figure 97 shows the benefit of dual-carrier operation (no MIMO employed), which essentially doubles throughputs over single carrier operation.

[188] 5G Americas member company contribution.

Figure 97: Dual-Carrier HSPA+ Throughputs[189]

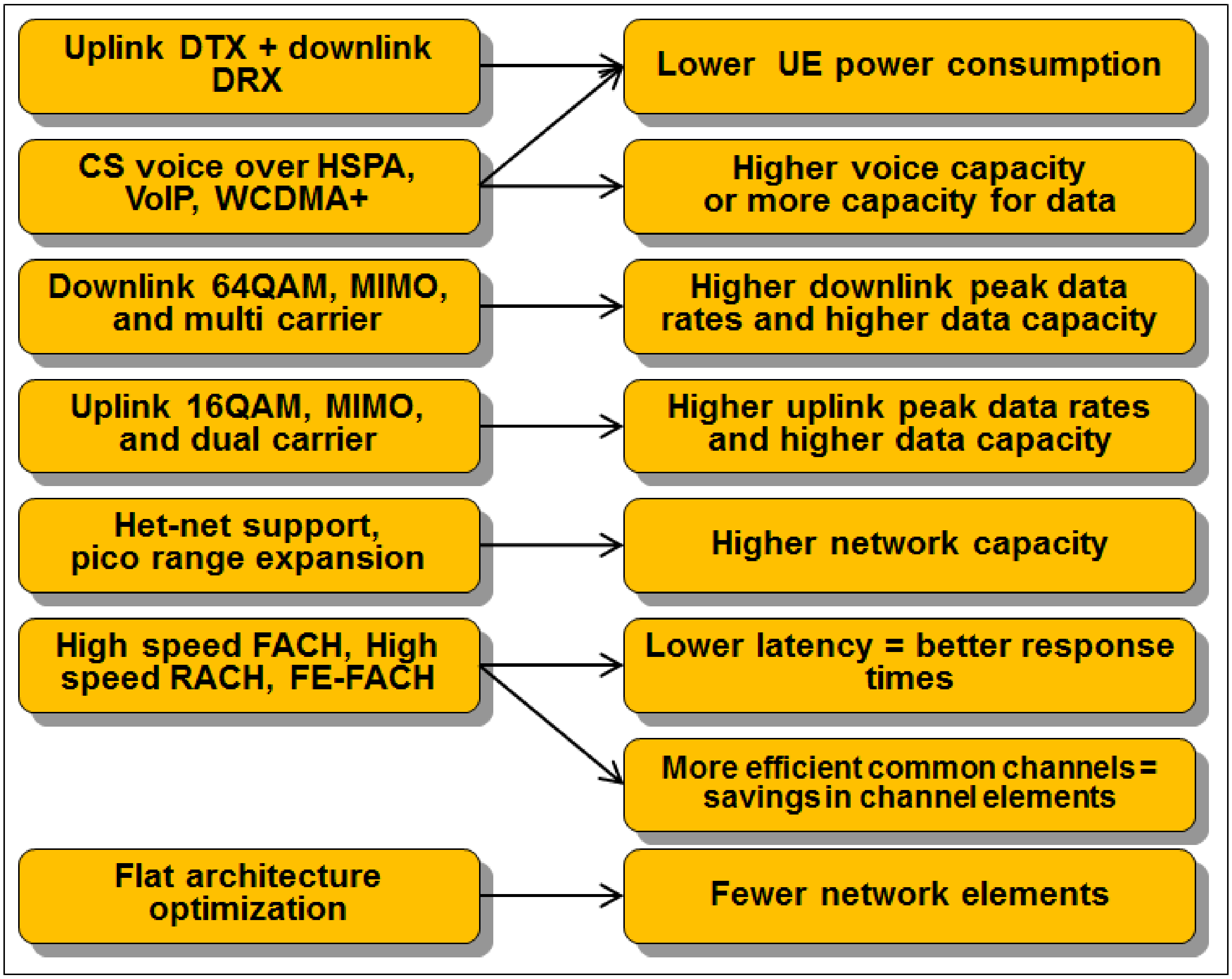


HSPA+ also has improved latency performance of as low as 25 msec and improved packet call setup time of below 500 msec.

Figure 98 summarizes the key capabilities and benefits of the features being deployed in HSPA+.

[189] 5G Americas member company contribution. 64 QAM.

Figure 98: Summary of HSPA Functions and Benefits[190]



UMTS-HSPA Voice

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

Improved Circuit-Switched Voice

Release 12 includes a feature called "DCH Enhancements for UMTS" that improves circuit-switched voice capacity through a combination of approaches, including:

- Reducing transmit-power overhead by eliminating the dedicated pilot and using the transmit-power control bits for channel estimation.

[190] 5G Americas member contribution.

- Implementing a new, more efficient frame format that multiplexes two voice calls by splitting the 20 msec frame into two 10 msec halves.
- Terminating frame transmissions early once they are successfully decoded.
- Using the new Enhanced Voice Services (EVS) codec.

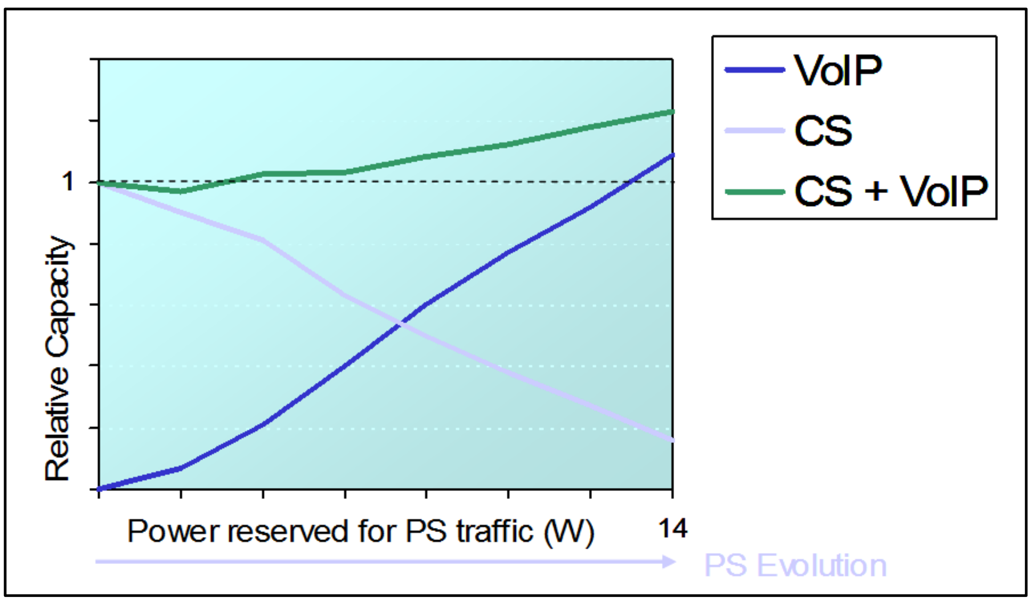
The motivation is not necessarily to support more voice calls, but to free up resources for data. The listed improvements result in only about half the radio resources needed to carry the same number of voice calls, with the remaining resources freed for data.

HSPA VoIP

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

Operators can smoothly migrate users from circuit-switched operation to packet-switched operation over time. Because the UMTS radio channel supports both circuit-switched voice and packet-switched data, some voice users can be on legacy circuit-switched voice and others can be on VoIP. Figure 99 shows a system's voice capacity with the joint operation of circuit-switched and IP-based voice services.

Figure 99: Ability for UMTS to Support Circuit and Packet Voice Users[191]



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

[191] 5G Americas member contribution.

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

UMTS TDD

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

TDD does not provide any inherent advantage for voice functions, which need balanced links—namely, the same amount of capacity in both the uplink and the downlink. Many data applications, however, are asymmetric, often with the downlink consuming more bandwidth than the uplink. A TDD radio interface can dynamically adjust the downlink-to-uplink ratio accordingly, hence balancing both forward-link and reverse-link capacity. Note that for UMTS FDD, the higher spectral efficiency achievable in the downlink versus the uplink addresses the asymmetrical nature of average data traffic.

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

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

In the United States, there is limited spectrum specifically allocated for TDD systems, the major band being BRS at 2.5 GHz used by Clearwire for WiMAX and now LTE TDD.[192] 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.

TDD systems require network synchronization and careful coordination between operators or guardbands, which may be problematic in certain bands.

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

TD-SCDMA

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

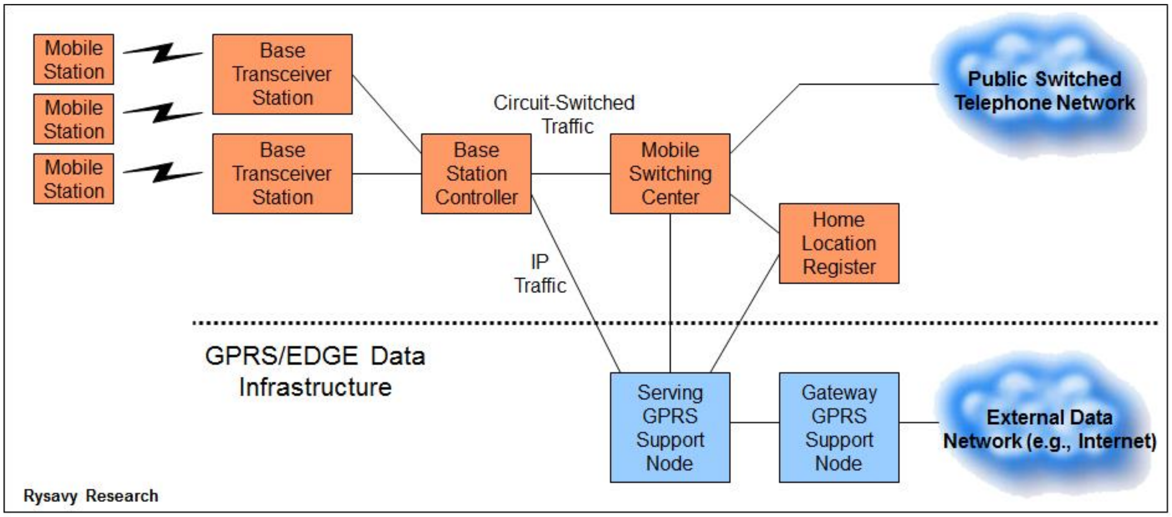
[192] The 1910-1920 MHz band targeted unlicensed TDD systems but has never been used.

Although there are no planned deployments in any country other than China, TD-SCDMA could theoretically be deployed anywhere unpaired spectrum is available—such as the bands licensed for UMTS TDD—assuming appropriate resolution of regulatory issues.

EDGE/EGPRS

Today, most GSM networks support EDGE, an enhancement to GPRS, which is the original packet data service for GSM networks.[193] GPRS provides a packet-based IP connectivity solution supporting a wide range of enterprise and consumer applications. GSM networks with EDGE operate as wireless extensions to the internet and give users internet access, as well as access to their organizations from anywhere. Peak EDGE user-achievable[194] throughput rates are up to 200 Kbps. Figure 100 depicts the system architecture.

Figure 100: GSM/GPRS/EDGE Architecture



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

- 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.
- 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.

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[193] GSM technology also provides circuit-switched data services, which are not described in this paper since they are seldom used.

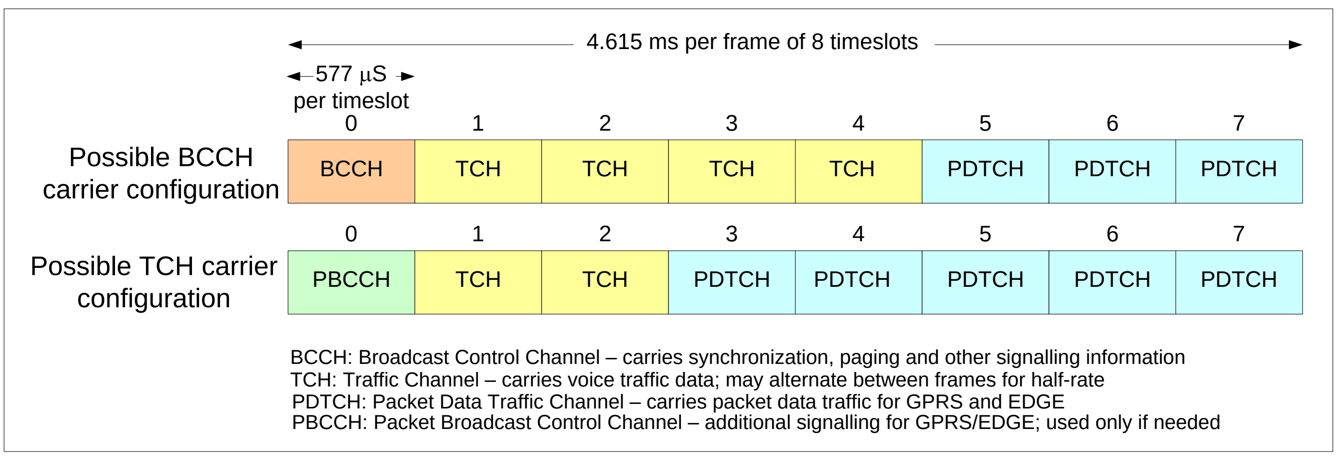
[194] "Peak user-achievable" means users, under favorable conditions of network loading and signal propagation, can achieve this rate as measured by applications such as file transfer. Average rates depend on many factors and will be lower than these rates.

- 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 101. The network can have multiple radio channels (referred to as transceivers) operating in each cell sector. The network assigns different functions to each timeslot such as the Broadcast Control Channel (BCCH), circuit-switched functions like voice calls or data calls, the optional Packet Broadcast Control Channel (PBCCH), and packet data channels. The network can dynamically adjust capacity between voice and data functions, and it can also reserve minimum resources for each service. This scheduling approach enables more data traffic when voice traffic is low or, likewise, more voice traffic when data traffic is low, thereby maximizing overall use of the network. For example, the PBCCH, which expands the capabilities of the normal BCCH, may be set up on an additional timeslot of a Time Division Multiple Access (TDMA) frame when justified by the volume of data traffic.

Figure 101: Example of GSM/EDGE Timeslot Structure[195]



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[196] while on a voice call, as described below.

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[195] 5G Americas member company contribution.

[196] Example: WAP notification message delivered via SMS.

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

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

EDGE is an official 3G cellular technology that can be deployed within an operator's existing 850, 900, 1800, and 1900 MHz spectrum bands. EDGE capability is now largely standard in new GSM deployments. A GPRS network using the EDGE radio interface is technically called an "Enhanced GPRS" (EGPRS) network, and a GSM network with EDGE capability is referred to as GSM Edge Radio Access Network (GERAN). EDGE has been an inherent part of GSM specifications since Release 99. It is fully backward-compatible with older GSM networks, meaning that GPRS devices work on EDGE networks and that GPRS and EDGE terminals can operate simultaneously on the same traffic channels.

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

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

TV White Spaces

The FCC in the United States has ruled that unlicensed devices that have mechanisms to eliminate interference with TV broadcast channels may use TV channels that are not in use.[197] 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.

The incentive auctions at 600 MHz will allocate new white-space frequencies, but the repacking process may also affect currently available frequencies.

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) and possess 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

[197] FCC, "Unlicensed Operation in the TV Broadcast Bands, Second Report and Order," FCC-08-260, November 2008. Available at https://apps.fcc.gov/edocs_public/attachmatch/FCC-08-260A1.pdf.

both TV broadcasting and wireless microphone signals. The rules include transmit power and emission limits.

These 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. Some in the industry refer to white-space technology as "Super Wi-Fi," which misrepresents the technology because no existing Wi-Fi device can use white spaces.[198]

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

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

[198] Rysavy Research, "White spaces networks are not "super" nor even Wi-Fi," *Gigaom*, Mar 2013. Available at http://gigaom.com/2013/03/17/white-spaces-networks-are-not-super-nor-even-wi-fi/.

Abbreviations and Acronyms

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

1G – First Generation

1xEV-DO – One Carrier Evolution, Data Optimized

1xEV-DV – One Carrier Evolution, Data Voice

1XRTT – One Carrier Radio Transmission Technology

2G – Second Generation

3G – Third Generation (meeting requirements set forth by the ITU-IMT project)

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

API – Application Programming Interface

APN – Access Point Name

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 Multi Point
cMTC – Critical Machine Type Communications
CP – Cyclic Prefix
CPC – Continuous Packet Connectivity
CPRI – Common Public Radio Interface
CQI - Channel Quality Indicators
C-RAN – Cloud Radio Access Network
CRM – Customer Relationship Management
CRS – Cell-specific Reference Signal
CS – Convergence Sublayer
CSFB – Circuit-Switched Fallback
CTIA – Cellular Telephone Industries Association
D-AMPS – Digital Advanced Mobile Phone Service
DAS – Distributed Antenna System
DAS – Downlink EGPRS2-A Level Scheme
dB – Decibel
DBS – Downlink EGPRS2-B Level Scheme
DC-HSPA – Dual Carrier HSPA
DFT – Discrete Fourier Transform
DL – Downlink
DNS – Domain Name Service
DPCCH – Dedicated Physical Control Channel
DPS – Dynamic Point Selection
DSL – Digital Subscriber Line
DSMIPv6 – Dual Stack Mobile IPv6
DTM – Dual Transfer Mode
DRX – Discontinuous Reception
D-TxAA – Double Transmit Adaptive Array
DVB-H – Digital Video Broadcasting Handheld
E–DCH – Enhanced Dedicated Channel
EBCMCS – Enhanced Broadcast Multicast Services
EC-GSM – Extended Coverage GSM
EDGE – Enhanced Data Rates for GSM Evolution

EFTA – Enhanced Flexible Timeslot Assignment
EGPRS – Enhanced General Packet Radio Service
eICIC – Enhanced Inter-Cell Interference Coordination
eMBMS – Enhanced Multimedia Broadcast Multicast Services
eNodeB – Evolved Node B
EAP – Extensible Authentication Protocol
eLAA – Enhanced Licensed-Assisted Access
eNB – Evolved Node B
EPC – Evolved Packet Core
EPDCCH – Enhanced Physical Downlink Control Channel
eMBB – Enhanced Mobile Broadband
ePDG – Enhanced Packet Data Gateway
EPS – Evolved Packet System
ERP – Enterprise Resource Planning
eSaMOG – Enhanced S2a-based Mobility over GTP
eSRVCC – Enhanced Single-Radio Voice Call Continuity
ETRI – Electronic and Telecommunications Research Institute
ETSI – European Telecommunications Standards Institute
E-UTRAN – Enhanced UMTS Terrestrial Radio Access Network
EVS – Enhanced Voice Services (codec)
FE-FACH – Further Enhanced Forward Access Channel
EV-DO –Evolution, Data Optimized
EV-DV –Evolution, Data Voice
EVRC – Enhanced Variable Rate Codec
FBMC – Filter-Bank Multi-Carrier
FCC – Federal Communications Commission
FDD – Frequency Division Duplex
feICIC – Further enhanced ICIC
FirstNet – First Responder Network Authority
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
GAA – General Authorized Access
GAN – Generic Access Network
GB – Gigabyte
Gbps – Gigabits Per Second
GBR – Guaranteed Bit Rate

GByte – Gigabyte
GCS – Group Communication Service
GERAN – GSM EDGE Radio Access Network
GFDM – Generalized Frequency-Division Multiplexing
GGSN – Gateway GPRS Support Node
GHz — Gigahertz
GMSK – Gaussian Minimum Shift Keying
GPRS – General Packet Radio Service
G-Rake – Generalized Rake Receiver
GSM – Global System for Mobile Communications
GSMA – GSM Association
HARQ – Hybrid Automatic Repeat Request
HD – High Definition
HetNet – heterogeneous network
HLR – Home Location Register
Hr – Hour
HSDPA – High Speed Downlink Packet Access
HS-FACH – High Speed Forward Access Channel
HS-PDSCH - High Speed Physical Downlink Shared Channels
HS-RACH – High Speed Reverse Access Channel
HSPA – High Speed Packet Access (HSDPA with HSUPA)
HSPA+ – HSPA Evolution
HSS – Home Subscriber Server
HSUPA – High Speed Uplink Packet Access
Hz – Hertz
ICIC – Inter-Cell Interference Coordination
ICN – Information-Centric Networking
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
IRC – Interference Rejection Combining
IoT – Internet of Things

IPR - Intellectual Property Rights
IP – Internet Protocol
IPTV – Internet Protocol Television
IR – Incremental Redundancy
ISI – Intersymbol Interference
ISP – Internet Service Provider
ITU – International Telecommunication Union
JCP – Java Community Process
JR – Joint Reception
JT – Joint Transmission
Kbps – Kilobits Per Second
kHz — Kilohertz
km – Kilometer
LAA – License-Assisted Access
LBT – Listen Before Talk
LIPA – Local IP Access
LMDS – Local Multipoint Distribution Service
LPWA – Low-Power Wide-Area
LTE – Long Term Evolution
LTE-A – LTE-Advanced
LTE-TDD – LTE Time Division Duplex
LTE-U – LTE Unlicensed
LSTI – LTE/SAE Trial Initiative
LWA – LTE Wi-Fi Aggregation
LWIP – LTE WLAN Radio Level Integration with IPsec Tunnel
M2M – Machine-to-machine
MAC – Medium-Access Control
MAPCON – Multi-Access PDN Connectivity
MB - Megabyte
MBMS - Multimedia Broadcast/Multicast Service
Mbps – Megabits Per Second
MBR – Maximum Bit Rate
MBSFN – Multicast/broadcast, Single Frequency
MCPA – Mobile Consumer Application Platform
Mcps – Megachips Per Second
MCPTT – Mission-Critical Push-to-Talk
MCS – Modulation and Coding Scheme
MCW – Multiple Codeword
MDT – Minimization of Drive Tests

MEAP – Mobile Enterprise Application Platforms

MEC – Mobile-Edge Computing

MediaFLO – Media Forward Link Only

METIS – Mobile and wireless communications Enablers for the Twenty-twenty Information Society

MHz – Megahertz

MID – Mobile Internet Devices

MIMO – Multiple Input Multiple Output

MMSE – Minimum Mean Square Error

mITF – Japan Mobile IT Forum

MMDS – Multichannel Multipoint Distribution Service

MME – Mobile Management Entity

mMTC – Massive Machine Type Communicactions

MOS – Mean Opinion Score

MP-QUIC – Multipath Quick UDP Internet Connections

MP-TCP – Multipath TCP

MRxD – Mobile Receive Diversity

ms – millisecond

MS – Mobile Station

MSA – Mobile Service Architecture

MSC – Mobile Switching Center

MTC – Machine Type Communications

MTC-IWF – Machine-Type Communications Interworking Function (MTC-IWF)

msec – millisecond

MU-MIMO – Multi-User MIMO

MUST – Downlink Multiuser Superposition Transmission

NAICS – Network-Assisted Interference Cancellation and Suppression

NB-IoT – Narrowband Internet of Things

NENA – National Emergency Number Association

NGMC – Next Generation Mobile Committee

NGMN – Next Generation Mobile Networks Alliance

NOMA – Non-Orthogonal Multiple Access

NR – New Radio

NTIA – National Telecommunications and Information Administration

OFDM – Orthogonal Frequency Division Multiplexing

OFDMA – Orthogonal Frequency Division Multiple Access

OL-SM – Open Loop Spatial Multiplexing

OMA – Open Mobile Alliance

ORI – Open Radio Equipment Interface

PA – Priority Access

PAL – Priority Access License
PAR – Peak to Average Ratio
PBCCH – Packet Broadcast Control Channel
PCH – Paging Channel
PCRF – Policy Control and Charging Rules Function
PCS – Personal Communications Service
PDCP – Packet Data Convergence Protocol
PDN – Packet Data Network
PGW – Packet Gateway
PHY – Physical Layer
PMI – Precoding Matrix Indication
PMIPv6 – Proxy Mobile IPv6
PNF – Physical Network Function
PoC – Push-to-talk over Cellular
PSH – Packet Switched Handover
PSK – Phase-Shift Keying
QAM – Quadrature Amplitude Modulation
QCI – Quality of Service Class Identifier
QLIC – Quasi-Linear Interference Cancellation
QoS – Quality of Service
QPSK – Quadrature Phase Shift Keying
QUIC – Quick UDP Internet Connections.
RAB – Radio Access Bearer
RAN – Radio Access Network
RCAF – RAN Congestion Awareness Function
RCS – Rich Communications Suite
REST – Representational State Transfer
RF – Radio Frequency
RNC – Radio Network Controller
ROHC – Robust Header Compression
RRC – Radio Resource Control
RRH – Remote Radio Head
RRU – Remote Radio Unit
RTP – Real Time Transport Protocol
RTSP – Real Time Streaming Protocol
SAE – System Architecture Evolution
SaMOG – S2a-based Mobility over GTP
SAS – Spectrum Access System
SC-FDMA – Single Carrier Frequency Division Multiple Access

SCMA – Sparse Coded Multiple Access
SCRI – Signaling Connection Release Indication
SCW – Single Codeword
SDMA – Space Division Multiple Access
SDN – Software Defined Networking
SDP – Session Description Protocol
sec – Second
SFBA – Space Frequency Block Code
SFN – Single Frequency Network
SGSN – Serving GPRS Support Node
SGW – Serving Gateway
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-Organizing Network
SPS – Semi-Persistent Scheduling
SRVCC – 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
TETRA – Terrestrial Trunked Radio
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
UFMC – Universal Filtered Multi-Carrier
UICC – Universal Integrated Circuit Card
UL – Uplink
UMA – Unlicensed Mobile Access
UMB – Ultra Mobile Broadband
UMTS – Universal Mobile Telecommunications System
UPCON – User-Plane Congestion Management
URA-PCH – UTRAN Registration Area Paging Channel
URI – Uniform Resource Identifier
URLLC – Ultra-Reliable and Low Latency Communications
us – Microsecond
USIM – UICC SIM
UTRAN – UMTS Terrestrial Radio Access Network
V2X – vehicle -to-infrastructure
VAMOS – Voice Services over Adaptive Multi-User Channels on One Slot
VDSL – Very-High-Bit-Rate DSL
VEPC – Virtualized EPC
ViLTE – Video Over LTE
VoIP – Voice over Internet Protocol
VoHSPA – Voice over HSPA
VOLGA – Voice over LTE Generic Access
VoLTE – Voice over LTE
VNF- Virtual Network Function
VPN – Virtual Private Network
WAP – Wireless Application Protocol
WBA – Wireless Broadband Alliance
WCDMA – Wideband Code Division Multiple Access
WCS – Wireless Communication Service
WebRTC – Web Real-Time Communication
Wi-Fi – Wireless Fidelity
WiMAX – Worldwide Interoperability for Microwave Access
WLAN – Wireless Local Area Network
WMAN – Wireless Metropolitan Area Network
WMM – Wi-Fi Multimedia
WRC – World Radiocommunication Conference

Additional Information

5G Americas maintains market information, LTE deployment lists, and numerous white papers, available for free download on its web site: http://www.5gamericas.org.

If there are any questions regarding the download of this information, please call +1 425 372 8922 or e-mail Anushka Bishen, Public Relations Coordinator at info@5gamericas.org.

This white paper was written for 5G Americas by Rysavy Research (http://www.rysavy.com) and utilized a composite of statistical information from multiple resources.

http://www.rysavy.com