SKYWORKS®

5G in Perspective

A Pragmatic Guide to What's Next

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Executive Summary

Six years after the advent of Long Term Evolution (LTE), it is helpful to look back at the truly transformational effect it has had on people's lives around the world. One can argue that the arrival of LTE has had a larger impact than any other single technology to further both developed and emerging economies, as its benefits extend to all types of end users.

With increased smartphone adoption and access to data through LTE services, the mobile industry is now the world's largest innovation engine. Billions of new users have gained access to information through the Internet, which has driven more new economic opportunities than could have ever been imagined. Regardless of geography, socioeconomic class, education level or ethnicity, the fruits of access are evident across the globe. Today, approximately 4.8 billion people worldwide subscribe to a mobile service – almost two-thirds of the world's population – with that number expected to reach 5.6 billion unique subscribers by 2020.

In most parts of the world, mobile is the leading platform for Internet access, particularly when you consider the lack of alternative infrastructure in some regions. By the end of this decade, close to 60 percent of the global population will have access to mobile Internet; however, this still leaves 40 percent of the world without access[1].

Future growth will be fueled by extending network coverage to rural areas, improving affordability of mobile services, delivering locally relevant content and increasing digital skills and literacy.

The future is not just about connectivity, however. It is about the opportunities enabled by this connectivity (see Figure 1). It is about connecting everyone and everything to a more efficient way of doing things. Society has an opportunity to leverage mobile networks and services to help achieve a "mobilized economy" globally.

LTE is the best global, scalable and secure communications network capable of providing individuals, communities, corporations and governments with tools to grow their own innovative platforms and initiatives.

This paper examines the current state of LTE networks and the ways it could evolve to deliver a gigabit-per-second user experience. To accomplish this, the ecosystem will need to deliver 100x data throughput improvement. As a premier provider of RF front-end solutions, Skyworks believes we have the capability to enable this evolution using tools and techniques provided in the LTE specification leading up to the release of 5G. Additionally, this paper explores the impact of new 5G services from the mobile and fixed wireless perspective.

Figure 1. The 5G Ecosystem: Enabling a Mobilized Economy

[1] GSMA. 2016 Mobile Industry Impact Report: Sustainable Development Goals. September 19, 2016.

Introduction

Wireless connectivity has expanded far beyond smartphones and WLAN routers, but we are still in the early stages of expanding beyond person-to-person communications as device-to-device connectivity in connected homes, machine-to-machine, industrial and automotive segments become more commonplace.

New and exciting applications are bringing together deep learning, artificial intelligence and "ambient awareness." As a consequence, we are interacting with the world in new and more beneficial ways. In the near future, we believe these technology advancements will enable people to lead fuller and richer lives based on today's innovations (see Figure 2).

While these segments all share the LTE backbone, there are different requirements driving unique solutions, and therefore broadening the LTE content space.

Given that much has transpired with a few generations of cellular standards, you may ask what the future will bring. Skyworks believes we are in the early stages of even greater evolution as we progress to 5G. The way we do business and interact with each other may be scarcely recognizable to many of us in 20 years, yet entirely ordinary to our children.

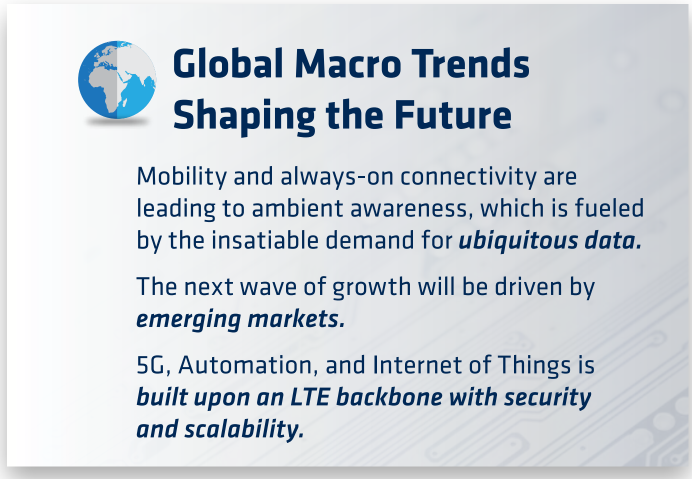


Figure 2. Global Macro Trends

Insatiable Demand for Ubiquitous LTE Data

Numerous studies from Cisco, Ericsson, Huawei and the GSMA have well documented the exponential growth of data consumption. It is truly a virtuous cycle starting with the availability of LTE data. When you combine mobility (smartphones), good network performance, and desirable content, you create ***a data flywheel effect*** (see Figure 3) whereby more and more data is consumed as the user experience improves. This 'data demand' has been the goal of the mobile industry since the inception of LTE. With every new release of the Third Generation Partnership Program (3GPP) standard, techniques to improve the data throughput of modern smartphones have been proposed, validated, then implemented in both networks and user equipment (UE).

Each technique applied moves the flywheel successively faster, opening up new and more data-intensive applications, which serve as catalysts for growth of the mobile networks. Consequently, mobile data rates are on track to surpass wired network data rates and push global initiatives that accelerate mobilized economies and spur

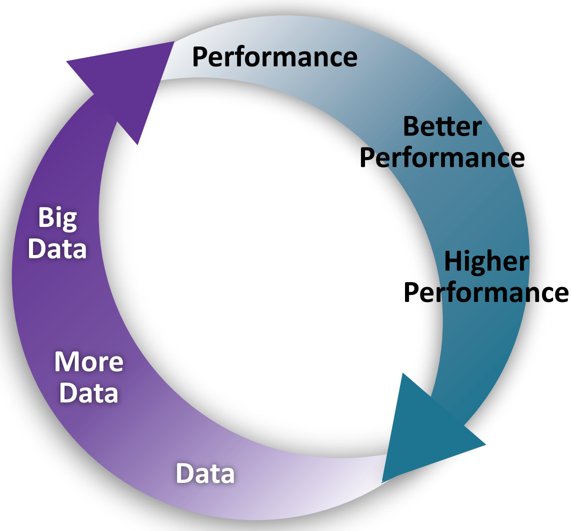


Figure 3. Data Flywheel Effect

innovation.

These studies show the direct correlation between increased use of LTE data with more advanced smartphones, faster processors, larger display sizes, and networks with higher peak speeds.

New applications are being created daily thanks to revolutionary advances made in devices and networks. Social networking with a mobile app is driving large content demand as profile updates, pictures, and videos of day-to-day activities get uploaded to the World Wide Web. According to some research reports, streaming audio services are estimated to grow 45% from 2015 to 2020. In that same time, streaming video will be the number one driver of mobile traffic with estimated growth from 55% to 72% of the total mobile data traffic. These applications are just the beginning. Improvements in data throughput will allow augmented and virtual reality applications to become common. In addition, we foresee large growth in connected vehicles as we move toward augmented and autonomous driving.

The transition to more experiential activities such as augmented and virtual reality will place higher demand on networks and devices requiring greater bandwidth and lower latency. A quick scan of the YouTube video sharing website reveals that uploads are migrating from low fidelity to HD and even ultra HD 4K video, commensurate with device and network upgrades.

The 'Buffering Wheel' is the New Dropped Call

Results from the *Ericsson Mobility Report* (Ericsson, 2016) indicate there is a new LTE satisfaction index, similar to the dropped call scenarios that bothered consumers in the past. In order to quantify a consumer's need for speed, Ericsson polled consumers and determined a time-to-content key performance indicator (KPI). The time-to-content KPI is a measure of whether users have a positive or negative experience when they are downloading or using smartphones. Instantaneous data access translates to superior consumer satisfaction and, as the time to download content increases, the experience will be more disappointing. Ericsson's report demonstrates that most consumers need to see reaction times below six seconds in order to report a positive experience (see Figure 4).

There are a number of network factors that affect the user experience: the network condition, whether the call is initiated inside or outside a building, the distance to a base station, and how many simultaneous users are requesting support at the particular base station they are using to access the network. Frankly, consumers do not care about what goes on behind the scenes. They want instantaneous access

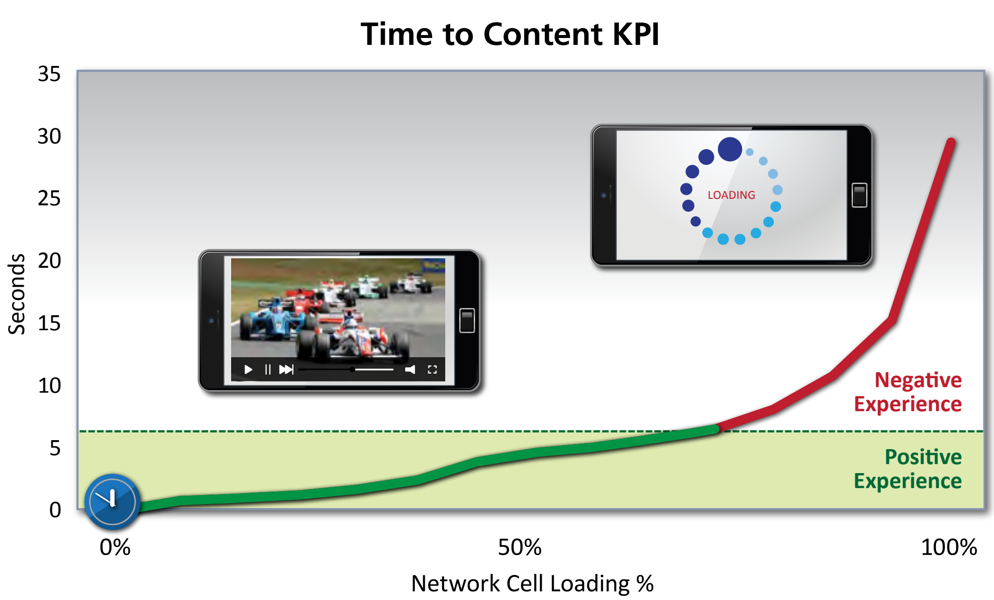


Figure 4. Target Time-to-Content User Experience

Satisfaction Index by Data Rate

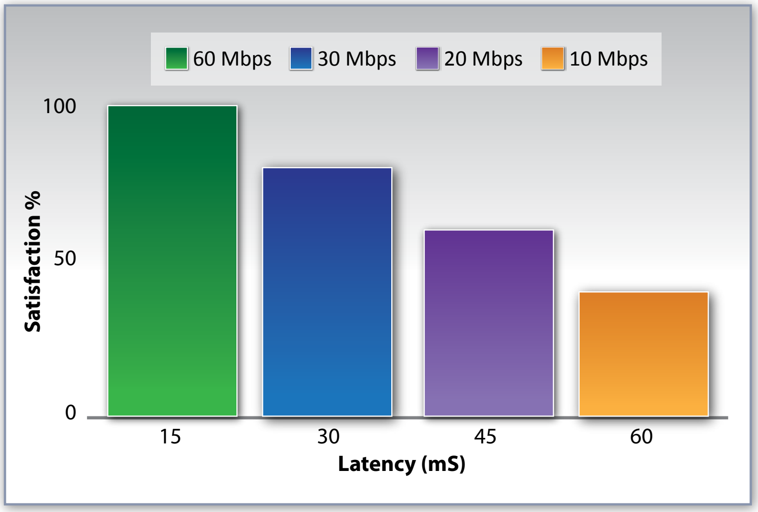


Figure 5. Time to Content KPI – Date Rate and Latency

to information and they want the same experience no matter the time of the day, where they're located in the world, or whatever the circumstances.

Huawei, a leading Chinese provider of mobile communications platforms, performed a similar investigation looking at consumer behavior related to mobile video experience in an attempt to quantify user perception.

The results were reported in the *'Mobile Video Report - a Key Driver of Mobile Market Value'* white paper (Huawei Technologies Co., Ltd., 2016). In Figure 5, customer satisfaction is measured based on a U-vMOS score and the impact of data rates and end-to-end round-trip time or latency on those scores. U-vMOS is a video mean opinion score–a subjective opinion of relative quality of video experience. From this chart, it is apparent that higher data

The Direct Correlation Between Mobile Advertising and Improved Mobile Networks Globally

> *So if you think about what is enabling video to become huge right now, it's that fundamentally the mobile networks are getting to a point where a large enough (number of) people around the world can have a good experience watching a video. If you go back a few years and you tried to load a video in News Feed, it might have to buffer for 30 seconds before you watched it, which wasn't a good enough experience for that to be the primary way that people shared. But now it loads instantly. You can take a video and upload it without having to take five minutes to do that, so it's a good experience.*
>
> *-Mark Zuckerberg, Facebook CEO (Gibbs, 2016)*

rates and lower latency generated a more positive consumer experience. That, concisely, is the goal for all the mobile operators and device manufacturers–improving consumer experience on their network.

Key Factors Impacting LTE Data Rates

Previously, we mentioned that there are many factors affecting the mobile user's experience. First, we will frame these factors through the embodiment of 3GPP standards, as implemented on the mobile operator network. Then we will discuss some of the device implications by reviewing both theoretical peak data rates (as defined in standards) and the typical user experience on today's mobile networks.

To understand issues around data rates, one useful analogy in visualizing LTE data is to think of it as water traveling through a hose. 3GPP and network operators are employing as many techniques as possible to carry as much water as possible, and as quickly as possible, to get more data to and from the user. We will cover these concepts in more technical detail later, but suffice it to say that increased network capacity can be obtained in two ways:

1) Widening the 'hose' for more capacity; and
2) Turning the water pressure higher, turning the 'spigot' on to make data go faster.

Also, we cannot forget that we need to supply high capacity pumps and drains for the system to work, so there should be higher capacity fronthaul / backhaul networks in place as well.

3GPP standards use a system to enumerate data speed capacity, referred to as device category to denote the maximum peak speed achievable under a set of conditions. Device Category, or CAT as it is commonly known, indicates the theoretical maximum download or upload data rates that can be supported in the device using existing network. As seen in Table 1 and Table 2, the LTE category peak data rate (Mbps) is mainly defined by channel bandwidth, modulation order, the number of component carriers (also known as Carrier Aggregation, or 'CA') and the number of multiple-input, multiple-output (MIMO) layers. Peak data rates are configured using multiple variables, and the category is typically quantified by the highest theoretical data rate that can be achieved with the maximal allowable configuration supported by the device and network.

Network operators and device manufacturers will sometimes refer to the 3GPP device category when discussing the peak data rates of their networks or devices, respectively.

We can make some observations of the Device Category information in Table 1 and Table 2:

- Downlink and uplink data rates are asymmetrical, with downlink (network to device) streams typically faster than uplink

Downlink

	Category	Data Rate Mbit/s	Carrier Aggregation (# of CC)	Max. Bandwidth (MHz)	Modulation (QAM)	MIMO Order
5G	19	1600	3 or more	100 *	64 or **256**	2 or **4**
	18	1200	4 or more	100 *	64 or 256	2 or **4**
	16	1000	5	100	64 or 256	2 or 4
Class Leading	11, 12	600	3 or more	60	64 or 256	2 or 4
	9, 10	450	3	60	64	2
CA Starts	6, 7	300	2	40	64	2
Legacy	4	150	1	20	64	2
	1	10	1	20	64	1
IoT	0, M1	1	1	1.4	16	1
	NB1	0.144	1	0.18	16	1
		Measure of how fast data can be transferred	Data streams applies to MIMO layer, here it is more number of aggregated channels.	Channel bandwidth allocated to data stream	higher modulation = higher data rate (256 QAM > 64 QAM	1, 2, 4, 8 number of Tx, Rx antennas Higher number means higher data rate

* Maximum 5CC CA combinations specified today: **bold** combination possible only

Table 1. Device Category - Downlink

Uplink

	Category	Data Rate Mbit/s	Carrier Aggregation (# of CC)	Max. Bandwidth (MHz)	Modulation (QAM)	MIMO Order
5G	20*	300	3	60	256	1
	18*	200	2	40	256	1
	16*	100	1	20	256	1
	15*	225	3	60	64	1
Class Leading	13	150	2	40	64	1
	5	75	1	20	64	1
Legacy	4	50	1	20	16	1
	1	5	1	20	16	1
IoT	0, M1	1	1	1.4	16	1
	NB1	0.144	1	0.18	QPSK	1
		Measure of how fast data can be transferred	Data streams applies to MIMO layer, here it is more number of aggregated channels.	Channel bandwidth allocated to data stream	higher modulation = higher data rate (256 QAM > 64 QAM	1, 2, 4, 8 number of Tx, Rx antennas Higher number means higher data rate

*Rel 14 category proposal

Table 2. Device Category - Uplink

- Peak data rates are strongly affected by and will increase with wider bandwidth (more component carriers), higher-order modulation, and an increase in the number of Transmit (Tx)/Receive (Rx) antennas (MIMO order)

Movement towards more cloud-based computing and some new applications such as autonomous co-pilot, will drive towards a more symmetrical network where upload and download ratios are closer to 2:1, down from their asymmetrical 5:1 to 10:1 range (downlink:uplink).

We will first look at the state of current LTE networks and then examine the myriad of different approaches to increase consumer data rates on existing and future networks.

Current State of LTE

The July 2016 report *'Evolution to LTE'* from the Global mobile Suppliers Association (*GSA*, 2016) reviewed and categorized the highest peak rates supported on commercially available LTE networks. Of the 708 networks (see Figure 6), GSA reported that 147 of those networks (21%) supported LTE Advanced features including CA and MIMO (greater than 3GPP Release 10). There were 374 potential LTE networks to upgrade with advanced features such as CA.

Of the 147 LTE Advanced data networks, 102 supported Category 6, or 300 Mbps downlink speeds. In the same report, GSA stated that 52% of the commercially available LTE devices could support up through Category 4, or 150 Mbps downlink. These facts indicate a movement towards higher data throughput networks and devices to support users in their quest for faster mobile data.

Speed Thrills

Theoretical peak speed in the network is only part of the story. Real-life experience indicates that users typically experience one to two orders of magnitude below "peak" in day-to-day usage. This discrepancy was reported in a Cisco VNI report, where global averages in 2015 were just below 3 Mbps and the forecast expected to reach 10 Mbps in 2020. That is very different from peak LTE data rates that are currently supported on the network.

By utilizing some of the data on Ookla, the leading web-based service that provides data analytics on Internet access performance metrics of fixed and mobile networks, Skyworks plotted the average download and upload data by country then sorted for iPhone 6 generation devices. Obviously, many factors come into play when trying to estimate average data rates for entire countries comprised of disparate economic profiles, unique network providers within the same country, various devices operating on any given network, and different rural, urban and geographical makeup. However, some high level observations can still be drawn from this data (see Figure 7). In all real-world cases, data throughput is approximately ten times below the maximum theoretical peak throughput. While any distinct user's experience can change by device type, time of day, location distance from a base station, and even data plan – this information still proves that maximum peak data rates are not being achieved in current networks.

We will address regional differences in data rates in the next section.

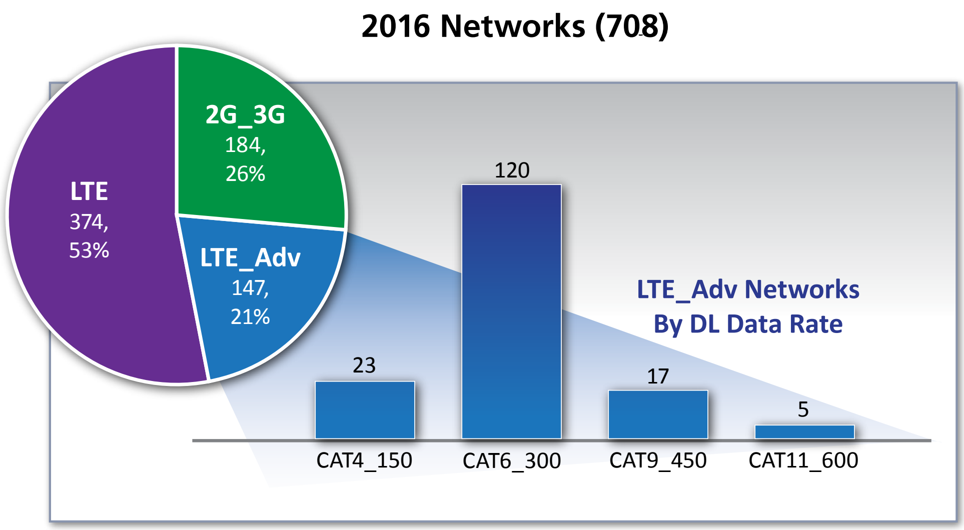


Figure 6. LTE Advanced (CA) Networks

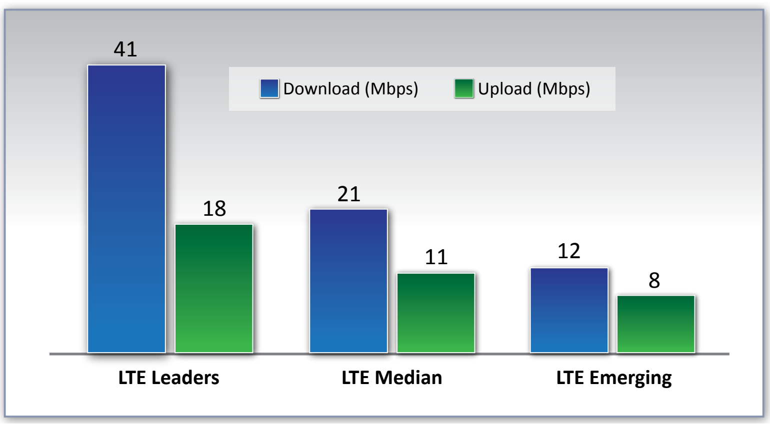


Figure 7. Average Data Rates of Same High Tier/Performance Phone in Varied Global Networks

Key Insights

- *Mobile Data and Video are Global Catalysts*
- *Increased User Satisfaction (Phones / Networks) Creates More Demand*
- *LTE Improvements Will Be Delivered Across All Tiers in All Geographies*

Developing Markets are Fueling LTE Growth and Will Require Optimized Solutions

Globally, we have witnessed the successful rollout of LTE and strong adoption by consumers. The strongest evidence is the experience in greater China. LTE was introduced in this country in 2014, and now supports more than 650 million LTE connections according to GSMA Intelligence as of the third quarter of 2016. This is the fastest adoption of any mobile technology since inception. In Figure 8, we look at further evidence of LTE growth as reported by GSMA in *"The Mobile Economy"* (GSMA, 2016). This shows 4G LTE connections reached approximately 1.3 billion at the end of 2016 and are expected to reach 3.5 billion by the end of 2020. That would represent approximately 40% of the 8.8 billion total connections. The LTE standard is growing by 24% compound annual growth rate (CAGR), whereas 2G and 3G technologies are on the decline.

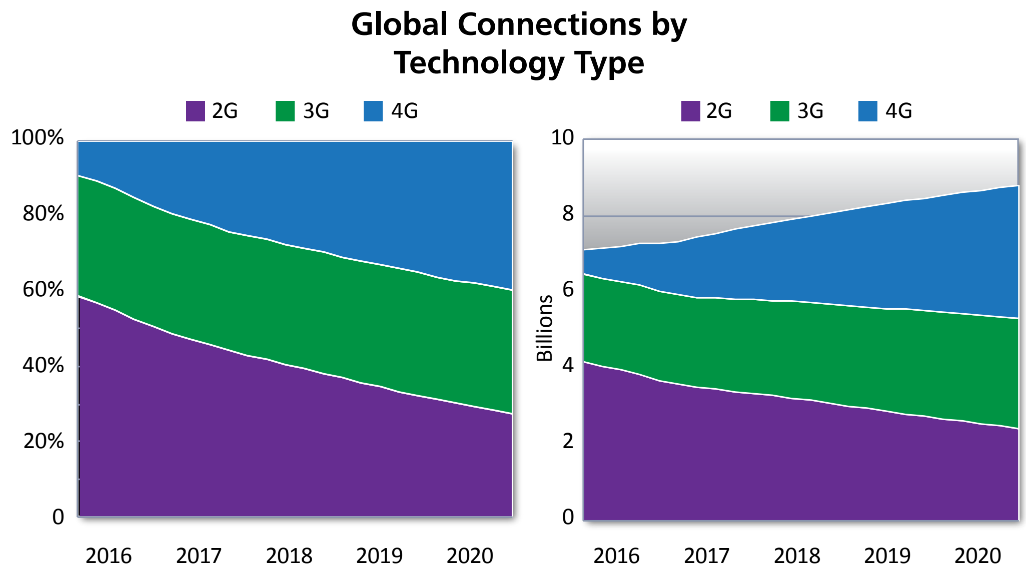


Figure 8. LTE Connections Growing

Plots of subscriber and connection data from the GSMA Intelligence database (GSMA, 2016) allow us to infer some dramatic changes ahead for LTE.

As shown in Figure 9, there is a 4% expected annual increase in subscribers from 2015 to 2020. That represents nearly one billion new subscriptions. If we dig a little deeper, we see that a majority of new subscribers will be from emerging economies. The projections show a 6% increase in emerging economy subscriptions versus 2–4% for developed or fast-growing economies of Asia. The third chart is even more insightful, as it indicates growth from one billion-plus connections to greater than 3.1 billion connections utilizing LTE. By 2030, LTE is set to be the dominant connection technology used globally.

It is clear that the majority of new LTE subscribers will come from emerging economies with much different characteristics than that of the developed markets that ushered in the LTE era.

We have recently witnessed this in China's experience with its recent conversion to LTE networks from 2G and TD-SCDMA. As first evidenced by China Mobile, the operator successfully bypassed the normal technical evolution of 2G to 3G to

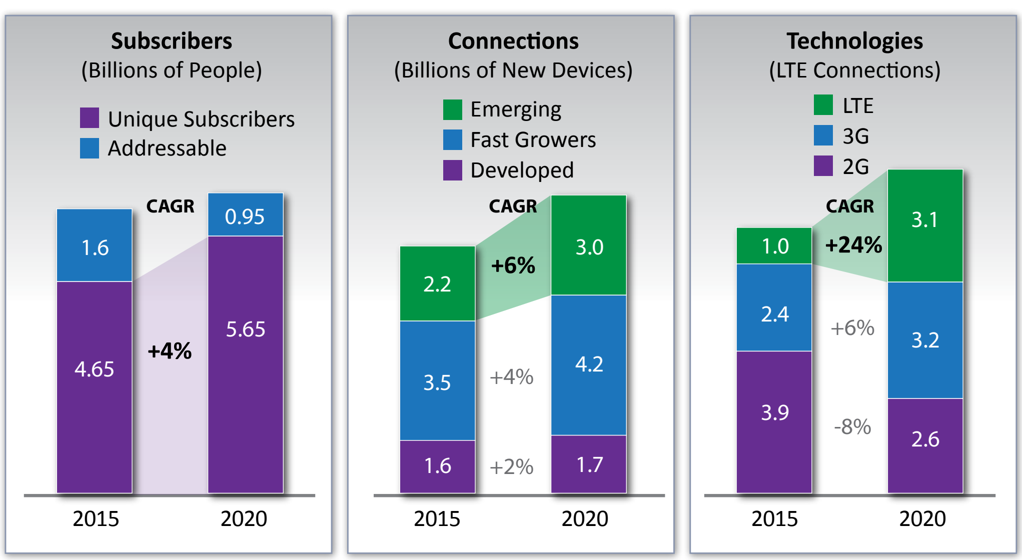


Figure 9. LTE is Mobile Growth

What will subscriber growth mean for device technologies being employed?

Will usage models change and how will that impact products from major smartphone manufacturers?

Majority of the new 1.1B subscribers will come from India, Asia-Pacific, China, and sub-Saharan Africa[2]

Implications: Expected Rise in Locally-Optimized Regional SKUs to Enable High Data Rate LTE

LTE, to an accelerated adoption of LTE technologies which benefited new users. In our opinion, the incentives provided by mobile operators along with the relative affordability of LTE devices will translate into rapid adoption in other emerging economies such as India, Latin America and sub-Saharan Africa.

Indications show that mobile video will continue to be the basic driver for data around the world and the trends for increased data consumption appear to be global. Adoption obstacles in the emerging economies can be attributed to a few key factors: affordability, video quality and content.

Affordability: Plans tailored for the region and the local socioeconomic conditions will play a key role in adoption. The rapid ascent of the Reliance Jio mobile network for LTE services in India is just one example of these regionally customized plans.

Video Quality: Improved quality as a result of capital investments in 4G network upgrades, along with faster data rate terminals.

Content: Relevant and localized content adapted for the cultural norms of the region will drive adoption of video.

Key Insights

Key Ecosystem Highlights

- *Global Usage Trends Validate Similar Requirements Regardless of GDP*
- *Mobile Broadband Penetration Rates Increase with Rising GDP*
- *LTE Adoption is a Rising Tide, Lifting All RF Content*
- *Emerging Economies are More Reliant on Wireless Devices and Networks to Establish Internet Connections*
- *RF Front-end Modules are Increasingly Complex; Band Counts are Stabilizing, but CA Combinations are Growing Exponentially*

[2] GSMA. 2016 Global Mobile Trends. October 2016.

The Gigabit Era – LTE Advanced Pro to 5G

We are bombarded everyday with new articles, announcements and proclamations telling us how great our lives will be when 5G arrives. However, what exactly are we waiting for – is it an evolution or a revolution? As this paper will describe, we won't have to wait that long to realize many of the benefits associated with 5G because it is simultaneously an evolutionary process (LTE evolution) with a dash of revolution (5G New Radio [NR]). The evolution of LTE Advanced Pro (Release 13/14) to 5G (Release 15/16/17) will show strong progressions in data throughput and be transformational in the way we live our lives.

As we have seen in previous sections, consumer satisfaction and the utility of mobile connected devices go hand-in-hand with increased data rate in the network and throughput via user equipment.

It is Skyworks' assertion that driving average data throughput ranges in the tens of gigabits per second will satisfy almost any definition of a 5G device. Fortunately, consumers do not have to wait until 5G rolls out in 2022 to experience improvements in data rates and performance. Using 3GPP-approved techniques that are standardized and included in Releases 13, 14 and 15, will ensure data rates increase 2 to 3 times using a combination of advanced 3GPP standardized methods.

3GPP Standards Leading Towards 5G

Much of our discussion will focus on the transition from LTE Advanced Pro (Release 13) to the next generation 5G networks. The International Telecommunication Union (ITU) Network 2020 initiative, along with many other concerned global groups, has set specific goals and objectives for 5G – in other words, key pillars of success.

Three main vectors will define success for the next generation system as illustrated in Figure 10.

eMBB – Enhanced mobile broadband – will deal with growing system capacity, with the goal of 1000x capacity, greater than 10 Gbps peak, and a minimum of 100 Mbps for every user. This will have aspects of sub-6 GHz 4G and 5G, and above 6 GHz 5G NR communications.

uRLLC – Ultra-reliable low latency communications – will deal with new applications that require mission-critical communications with almost no latency. The goals for these new market verticals are to ensure high reliability and availability with extremely low latency, or below two milliseconds.

mMTC – Massive machine-type communications – will be associated with extremely low cost and low data rate emerging market segments. This is most closely correlated with the Internet of Things and is embodied by a tremendous amount of new connections to the LTE network.

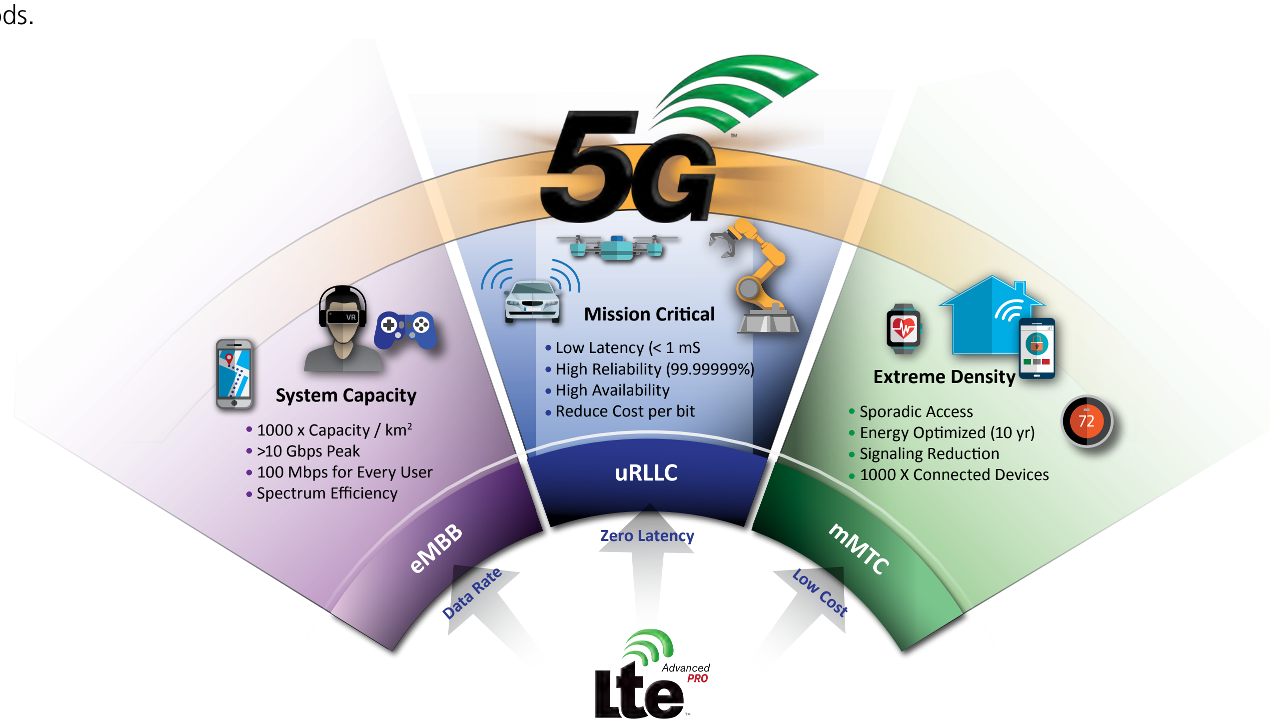


Figure 10. 5G Vision and Targets

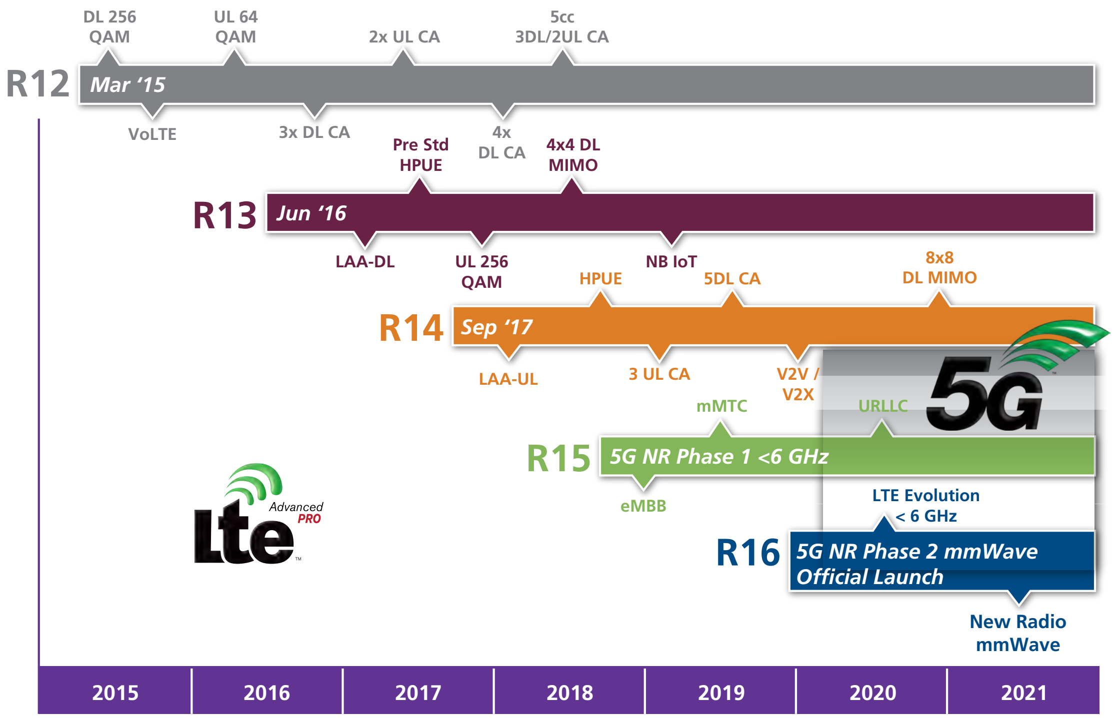


Figure 11. LTE Advanced Pro – UE Features Growing in Complexity

Figure 11 provides a high-level description of the release states for generation Release 12 through Release 16, with some of the key features listed. To understand the myriad of choices that device manufacturers have, it is important to understand that not every feature is rolled out into networks at the same time. The techniques must be ratified in the 3GPP standard, but also must be validated in network equipment deployed by the mobile operators. Then, user equipment must be available that can support these new features. As a result, the features are rolled out in each country and operator during the lag time between approval of the standards. Consequently, implementation in the field can take several months to several years.

3GPP LTE has seen a continuous development of the technology through its specification releases. Each release has a one to two year span and brings a breadth of new features and evolutions.

On the feature evolution side, for example, the CA feature, which was first introduced in Release 10 with two downlink carriers is now up to five downlink carriers and three uplink carriers in Release 14. Similarly, LTE was initially introduced with 64 QAM in downlink and 16 QAM in uplink. Since then, 256 QAM was introduced in downlink and 64 QAM in uplink, and both are now deployed in most advanced networks. Release 14 will now introduce 256 QAM in uplink too. Extensions have been implemented for up to 32 component carriers and enabling up to 8x8 MIMO. In reality the detailed specification work on implementing it in available spectrum is up to five carriers and 4x4 MIMO and is not yet deployed on all networks. As of today, the most advanced networks combine three downlink CA, 4x4 MIMO and 256 QAM and demonstrate close to 1 Gbps peak data rates. Similarly, uplink CA and uplink MIMO have been specified, but only uplink CA has been implemented in active networks, and as of Q1 2017 only in regions of Korea and China.

Besides this stream of continuous evolution for higher data rates, new features are also introduced. This is the case for License Assisted Access (LAA) and enhanced LAA (eLAA) that make use of the 5 GHz unlicensed band as a possibility for bandwidth aggregation, with a licensed band respectively in downlink and uplink.

However, it needed some additions in order to operate in an unlicensed band where other technologies are deployed. Similarly, LTE technology was tailored to address the Internet of Things (IoT) space (Narrowband-IoT introduced in Release 13), or Vehicle-to-Vehicle (V2V)/Vehicle-to-Everything (V2X) in Release 13/14. Another case is the High Power User Equipment (HPUE), which allows a better balanced downlink and uplink coverage in Time Division Duplex (TDD) networks with a 3 dB higher power capability in uplink.

For 5G technology, 3GPP will continue to address new use cases via evolution of the LTE technology, but it will also introduce new technology like NR in Release 15. This brings yet another dimension to RF complexity by adding techniques such as millimeter wave (mmWave) spectrum, beam forming capability, higher spectral efficiency waveforms, lower latency, multiple numerology, and non-orthogonal multiple access. These RF functionalities are crucial in the never-ending effort to bring more items that offer flexibility to the networks, to serve more data, to more users, in a number of new use cases.

LTE Features that Contribute to Increased User Equipment (UE) Data Rates

One of the objectives of this paper is to paint the landscape in which we operate. In order to understand the key features that are and will be implemented, it is instructive to review the Shannon-Hartley Theorem on channel capacity in bits per second (see Figure 12).

We dissect the Shannon-Hartley Theorem to directly correlate the key factors that increase data rates with the areas that 3GPP, and the industry as a whole, are working to improve customer satisfaction through increased mobile data rates. Shannon-Hartley states that the capacity of a data link is a function of the number of data streams, bandwidth (spectrum) and channel noise.

$$\boxed{C\ (b/s) = M*B*\log_2(1 + S/N)}$$

C	=	Channel Capacity in bits/second
M	=	# of Channels, the MIMO order, higher M means faster data rate
B	=	Bandwidth, the wider the bandwidth the higher the theoretical data rate can be
S/N	=	the signal to noise ratio

Figure 12. Shannon-Hartley Theorem (simplified version)

To achieve higher capacity or data rates, we need to:

- Increase bandwidth
- Increase MIMO order (M, # of paths)
- Increase the Transmit Power (S)
- Decrease Noise (N) and Improve Receive (Rx) Sensitivity

Of all the techniques available in 3GPP LTE Advanced, the key to getting higher data rates (see Figure 12) is related to four main categories:

1) Increasing network density (S/N)
2) Increasing channel bandwidth using carrier aggregation (B)
3) Utilizing higher order modulation or increasing the number of bits per symbol (S/N)
4) Utilizing MIMO to increase the number of data streams (M)

In the following sections we focus on the fundamentals of what the RF front-end can do to support the features that affect the user equipment and elaborate on the implications of their performance improvement, which will of course be compounded as the networks mature and become more dense over time.

To recap, any combination of increased bandwidth, modulation, and MIMO will result in higher data rates – that is what we see happening in the 2015 to 2020 timeframe to move the industry forward. As a result, there are three LTE Advanced Key Techniques:

- Wider bandwidth via carrier aggregation
- Higher order modulation
- MIMO utilization

Carrier Aggregation (CA)

Increasing Frequency Bandwidth Through CA

LTE allows for channel bandwidth up to 20 MHz per channel. In geographical locations where mobile operators own frequency spectrum in multiple bands or larger bandwidth in one band, 3GPP allows for a combination of those component carriers and in same or separate bands (CA). CA is the combination of up to five channels or component carriers (CC) in the downlink direction and up to three component carriers in the uplink direction. Every 20 MHz channel is comprised of 100 resource blocks, so aggregating channels will allow for increased data rates (see Figure 13).

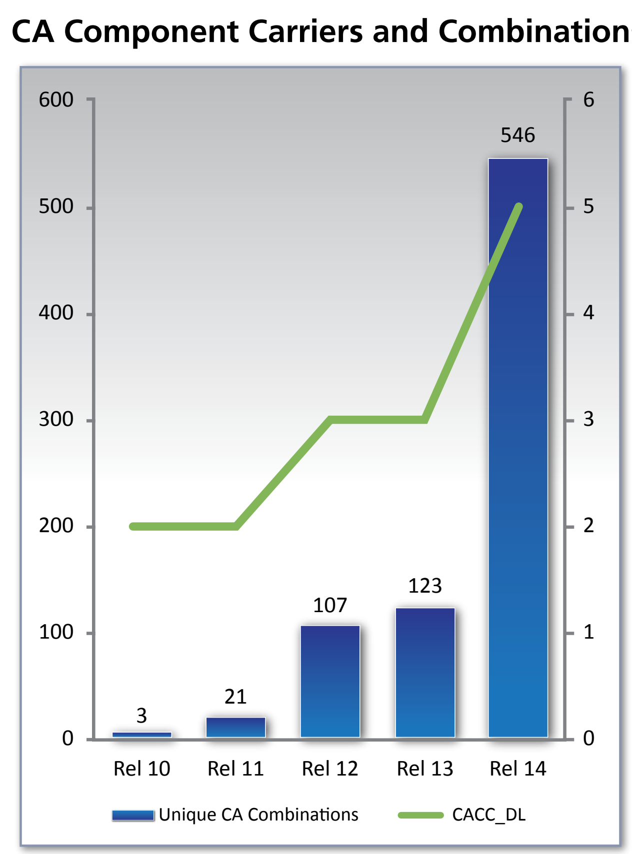


Figure 13. LTE Advanced Pro – UE Features Growing in Complexity

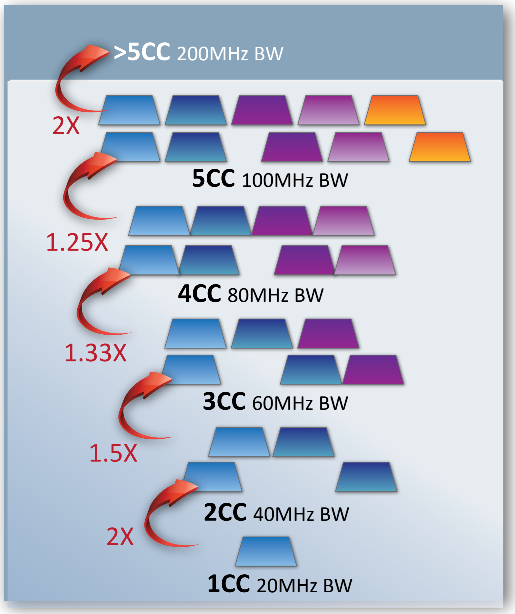


Figure 14. Data Rate Impact of Increasing CA

Carrier Aggregation (CA- 2 ➡ 5 CC downlink/uplink)

One of the fastest ways for mobile operators to implement higher data rates for enhanced mobile broadband service is enabling CA. In doing so, operators can widen the transmission bandwidth for any one user by utilizing different spectrum bands or by separating channels in the same band that they own in any regional area and coupling them together. This effectively allocates the simultaneous use of these different bandwidths (sometimes across multiple bands) to grant more total spectrum to a single user for enhanced data rates and a better user experience. In 3GPP Release 10, CA is recognized as critical for increasing network efficiencies, as well as peak and average data rates for each user. It also leverages the optimum trade-off between user experience and network capacity. CA is a process where a primary component carrier (PCC) that is typically allocated, is supplemented by additional secondary component carrier (SCC) – and sometimes more supplemental downlink carriers (see Figure 14) – in order to increase the total available transmit and receive bandwidth, effectively "widening the pipe" to increase instantaneous data rates for that single user.

However, absent the sharing of bands, separate frequency channels must be owned by the same network operator in order to coordinate CA in present implementations. This aggregation occurs by the simple addition of each of the component carrier bandwidths. As long as it is supported in the terminal and in the network, users can benefit almost immediately with double or triple the available bandwidth.

Implementation details of CA are dependent on the specific region and carrier or mobile device leading to an ever increasing number of CA combinations in each 3GPP releases as shown in Figure 13.

The first implementation of CA is primarily in the downlink direction, meaning aggregated carrier components are simultaneously transmitted as multiple data streams from the remote radio head of the base station and received in the user equipment. This is what people typically mean when they describe CA benefits. The 3GPP standards allow for up to two component carrier CA in uplink direction as well, and is currently specifying 3 uplink CA, thus increasing data rates from user equipment to cloud.

Current state-of-the-art LTE networks are now transitioning from two component carrier to three component carriers in downlink. Skyworks forecasts that by 2018, two component downlink CA will be available in a plurality of the networks, with advanced networks moving towards four and five component carrier downlink CA. There is even activity to extend CA up to 32 component carriers, as well as the use of the unlicensed spectrum, or LAA as an adjunct. The result will be increased capacity and data throughput in the networks. This is the growth in complexity we discussed earlier. The same LTE bands are supported in the RF front-end, however now there are more simultaneous receive operations that effectively increase downlink data rates. The proliferation of downlink CA is the biggest driver for improved receive sensitivity and creating explosive demand for diversity receive modules on receive paths.

Modulation (Bits per Symbol)

Increasing Modulation and Coding Complexity [Quadrature Phase Shift Keying (QPSK) to 16-64-256 Quadrature Amplitude Modulation (QAM)]

3GPP LTE allows for the use of complex modulation schemes to increase the number of bits per symbol or data density. This technique is designed to increase the spectral efficiency of that bandwidth, effectively increasing data rates in bits/Hz. We can think of "spectrum" as land – a limited and globally shared resource. More complex modulations increase occupancy on that land. With the same channel bandwidth, increasing the modulation (bits per symbol) will increase data rates. Termed higher order modulations, it was defined in 3GPP's Release 12 (Spring 2015) to be a maximum of 256 QAM for the downlink, and 3GPP's Release 14 (expected Spring 2017) to support a maximum of 256 QAM for the uplink.

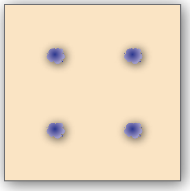
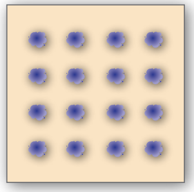
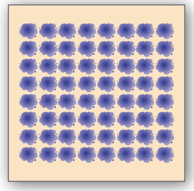
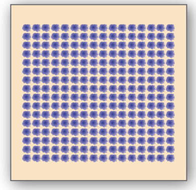
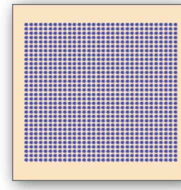
Modulation	QPSK	16 QAM	64 QAM	256 QAM	1024 QAM
					
States	4	16	64	256	1024
Bits / Symbol	2	4	6	8	10
Downlink	Mandatory			Optional	Future
Uplink	Mandatory		Optional	Rel 14	

Table 3. Modulation Order and Bit per Symbols

The higher order the modulation, or distinct states, means the faster a certain amount of data block can be transmitted.

As the standard started with modulations of QPSK (2 bits/symbol), and since migrated to 16 QAM (4 bits/symbol), to 64 QAM (6 bits/symbol), and now to 256 QAM (8 bits/symbol), the spectral efficiency is increased by the factor of bits per symbol. This increase in bits/symbol requires a correspondingly higher signal-to-noise ratio (SNR). It is more efficient to transmit data with the highest possible modulation.

In LTE systems, the radio modem actually monitors the signal and will increase or decrease the modulation rate depending on the quality of the received signal. As a result, devices targeting the fastest data rate need to support the highest modulation available in the system.

The higher order modulation requires better SNR in order to accurately receive the signal. As shown in Table 3, as the density of the constellation goes up, it becomes more challenging to determine the digital character of the symbol versus others in the presence of significant noise and interference. This can be understood visually as it is more and more difficult to distinguish between the different points in the constellation. This SNR is a function of the radio environment, nearby sources of signal interference and emissions noise, as well as the intrinsic performance of the radio itself. The low noise amplifier (LNA) in the user equipment receiver must have the absolute lowest noise figure, so that its own noise contribution is minimized, and the linearity must be maximized for enhanced robustness against both in-band and out-of-band interferers. This challenging dynamic range of the LNA must be maximized in co-design with the filter for both in-band insertion loss and out-of-band attenuations for optimal reception. On the transmit side, the power amplifier (PA) must similarly minimize its own contributions to degrading SNR by having extremely low in-band emissions and noise levels, as well as a minimum of distortion at the high end of output power amplitudes to avoid further intermodulation-related in-band distortion that impacts error vector magnitude (EVM). The wider dynamic range of the PA also needs to maintain excellence in these factors while maximizing efficiency and minimizing the direct current (DC) consumption required to deliver this performance.

MIMO Order

MIMO Order (2T2R, 4T4R Systems)

Higher order MIMO is another technique used to increase the bandwidth of mobile devices, increasing throughput and providing a more satisfactory mobile broadband service. Through the use of multiple independent LTE data streams being simultaneously transmitted, MIMO helps to increase peak data rates. MIMO involves the sending and receiving of more than one data stream on a single radio channel at the same time through the use of multiple antennas for both transmit and receive functions. MIMO signals benefit from reduced signal interference. The radio environment for each of the data streams to the receiver is improved by coding, multiplexing, diversity and antenna array gain.

The MIMO order represents a number of independent information streams that can be sent or received and it is directly equivalent to the number of antennas involved. In describing MIMO systems, it is standard to talk about the number of base station transmit antennas and the number of user equipment receive antennas. For example, 2x2 MIMO means there are two transmit antennas on the base station and two receive antennas on the phone.

LTE devices are now required by standard to functionally operate as 2x2 MIMO devices in downlink where there are two active receive antennas in the user equipment. Within one to two years, mobile operators will start to support increased data rates by the addition of two more simultaneously active receive antennas. Manufacturers will deploy 4x4 downlink MIMO (four transmit, four receive MIMO) that will add substantial enhancements to the data path. The trade-off is additional complexity and content by two additional receive paths, but this is outweighed by the improvement in downlink data rates.

Although conceptually 4x4 MIMO is applicable in all bands, by applying the rules of physics we see that higher frequencies enable the use of smaller antennas. This may be a deciding factor in using 4x4 MIMO for higher frequency LTE bands.

There are three main antenna configurations used for LTE devices: SISO, 2x2 MIMO and 4x4 MIMO.

SISO: Single input, single output has only one stream and uses one antenna on the phone. This is the default case for LTE uplink and a majority of use cases.

2x2 MIMO: Two input, two output MIMO is implemented with two antennas on the base station and two receive antennas on the phone. This is the default case for downlink and is a potential for emerging uplink applications. There is also the case when two antennas are available in antenna diversity schemes and are used where there is only one stream transmitted (see Figure 15).

4x4 MIMO: Four input, four output MIMO uses four receive antennas at the device. This feature is being implemented in flagship platforms in 2017-18 timeframe. 4x4 MIMO in the downlink is usually applied to the higher frequency bands where four antennas can most easily fit in the phone, since the higher frequency antenna structures are smaller than lower frequency antennas (see Figure 15).

MIMO (2x2 ➡ 4x4)

As an example, if four downlink data streams are transmitted from the base station (eNodeB) and four separate antennas are used for reception at the user equipment handset, then this 4x4 downlink MIMO link will be able to support two times the data rates of a 2x2 downlink MIMO link (two antennas at the eNodeB and two antennas at the user equipment). The application of MIMO requires higher SNR to function adequately.

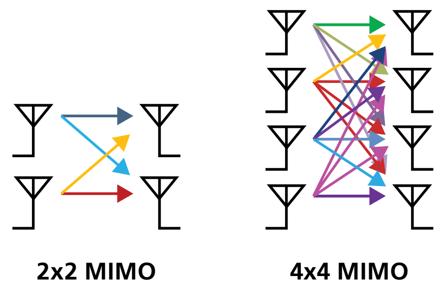


Figure 15. Examples of 2x2 and 4x4 MIMO

In US-based carrier Sprint's 2015 summary of their B41 network capability when applying 4x4 MIMO for the downlink, the carrier demonstrated large increases in throughput across a wide signal-to-interference-plus-noise ratio (SINR) range. It showed improved data rates of 50% to 60% at cell edge through SNR gains and diversity gain, and leveraging sufficient SNR to improve throughput 45% at mid-cell, and 22% to 38% at cell center (Sava, 2015). Similar studies by Orange in 2012 indicated a 60% increase in average throughput in upgrading from 2x2 to 4x4 downlink MIMO (Landre, El Rawas, & Visoz, 2012), and more recently SK Telecom indicates a 42% average throughput increase with 4x4 MIMO versus 2x2 (Kim, Choi, Kim, & Park, 2016). A study on the T-Mobile network in the U.S., published on January 2017, corroborates the findings of improved downlink data rates enabled by 4x4 MIMO.

This technology of packing more bits into the existing spectrum is extremely attractive to the operators who are required to pay so much for the fundamentally limited resource of the available spectrum. The increase of throughput throughout the cell and improvement all the way to the critical cell edge user experience is part of the reason behind the rapid adoption of 4x4 MIMO on the downlink of higher tier handsets.

Key Insights

MIMO benefits have been demonstrated on live networks and show data rate improvement

Putting It All Together to Increase Peak and Typical Data Rates

Now that we have the tools to increase data rates, we need to see how these can be combined in multiple ways to achieve our objective.

First, it is helpful to understand that each factor described earlier has a multiplying effect. For any given MIMO or modulation order, doubling the bandwidth will double the data rate. If we have the same modulation order and bandwidth, then extending to 4x4 MIMO versus 2x2 MIMO or alternatively going from 2x2 MIMO versus SISO will double the data rate. Second, at any given bandwidth or MIMO order, increasing the modulation from QPSK to 16 QAM or from 16 to 256 QAM will double the data rate.

As mentioned previously, data rate is usually quoted as the peak data rate, which is obtained by multiplying the effect of the highest supported bandwidth, MIMO order and modulation. For example, an LTE phone with 2x2 MIMO and a single 20 MHz channel with 64 QAM has a peak downlink data rate of 150 Mbps. In uplink at a default of 16 QAM and SISO the data rate is 50 Mbps for 20 MHz signal. If we take that same structure and then start to layer CA where we increase the spectrum by adding two, three or up to five component carriers, we can achieve significantly higher downlink data rates (see Table 1 in previous section). We can extend that further by adding in 4x4 MIMO to achieve double the data rate. As evidenced in these tables, there is a lot of flexibility in how the device and the network can employ the 3GPP features to deliver the highest data rate to the user. Looking at 3GPP Release 14, we can see a combination using five component CA, 4x4 MIMO, and 256 QAM to achieve maximum theoretical data rate of 2 Gbps in the downlink. For the uplink, we can achieve 300 Mbps if we use three component CA, SISO antenna and 256 QAM. LTE specification classifies the phone in terms of their downlink and uplink capability and this is signaled to the networks. This capability is reported to the network as categories and specifies the number of carriers, MIMO layers, and modulation order that the phone supports together with the required peak data rate.

Again, this discussion is around the theoretical peak data rate available. We have seen before that the typical data rates are 10 to 100 times lower in normal instances. The typical user is not usually located directly next to a base station, instead are initiating calls from inside buildings, or from other locations where obstacles attenuate the wireless signals. Even with these complications, it is easy to see that in the near future, users will enjoy much higher data rates through improvements in both the user equipment and the network's ability to deliver high-speed data.

Figure 16 shows the trade-offs in data rate by the three main LTE techniques in relation to the user distance to the base station: Aggregated Bandwidth, Modulation Order and MIMO Order.

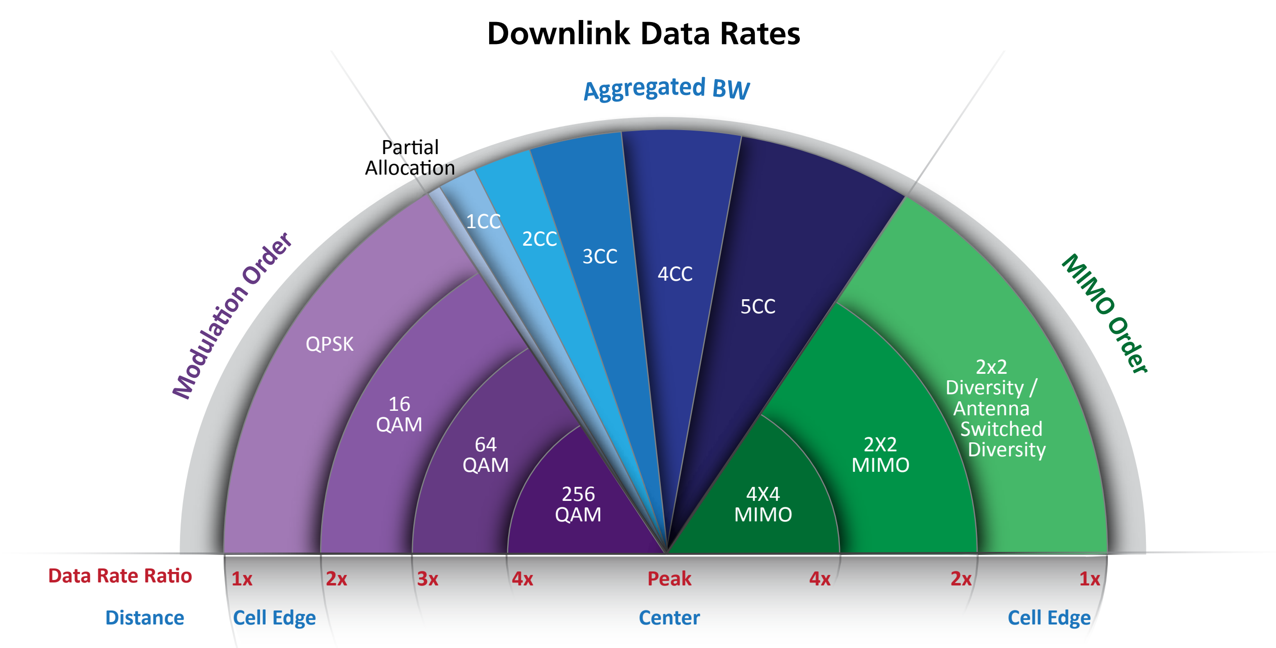


Figure 16. Impact of Modulation, Bandwidth and MIMO to Downlink Data Rate as a Function of Distance to Cell Center

The center of the axis is the highest data rate – close to the base station. Looking at modulation, you can see that it starts with the highest order modulation at the area closest to transmitter at eNodeB. The device will progressively reduce modulation in order to maintain radio link. That means that in typical conditions (inside a building), or in a moving car, you will have lower data rates than when you are in line-of-sight outdoor conditions.

Similarly, MIMO orders will transition from 4x4 in ideal conditions to lower orders in order to save the link. The cell edge condition is one often used by mobile operators to connote the lowest acceptable range of data rates for consumers. Those two categories are inversely related to distance from the eNodeB.

The impact of aggregated bandwidth in terms of data rate versus distance is less related to distance. There are some small changes due to modifications in combined transmit power, but within first approximation, almost the entire cell radius can be covered with any number of component carriers.

We can do a similar analysis for the uplink direction – the user equipment transmitting back to the base station. We can come up with similar diagram, with a few small changes (see Figure 17).

For example, while 256 QAM in uplink is allowable, it has not yet been adopted in mainstream LTE. Same with 2x2 MIMO. While it has already been standardized with two paths uplink CA, we are just starting to see deployments this way. This is one area where current deployment differs from the emerging 5G Radio Access Technologies (RAT). In 5G, the ratio of downlink to uplink data is intended to be more symmetrical so you can expect more uplink and higher order modulation in 5G systems.

In the uplink scenario, modulation rates and MIMO order will decrease with distance from the center of cell. There is a more pronounced reduction as more uplink CA component carriers are added, due to reduced transmit powers when aggregating transmit paths as the user equipment has a limited power and must distribute it evenly on each carrier.

One future impact that will be seen on the user's side is the movement to add additional power classes to have higher transmit power, known as HPUE techniques.

These techniques will effectively increase transmit power at user equipment by 3 dB, thus expanding the radius of cell coverage by 20%.

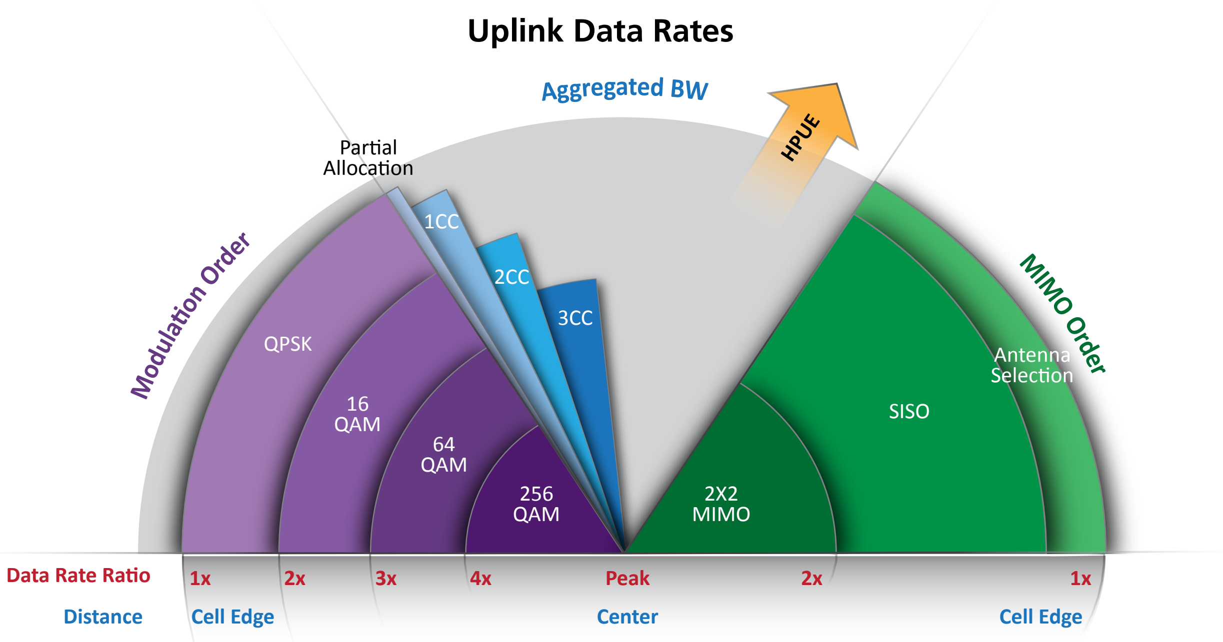


Figure 17. Impact of Modulation, Bandwidth and MIMO to Uplink Data Rate as a Function of Distance to Cell Center

Application Examples of Premium and Value Tier Solutions

As a recap, we have come to understand that the data revolution is just starting. A virtuous cycle, more precisely a data flywheel effect is in play, where a robust network with capable devices will draw more consumers to utilize more data, regardless of socioeconomic circumstances. Clearly, the RF front-end circuitry is becoming more complex in order to deliver the superior results that global consumers demand. While the content may differ slightly depending on whether it is a premium flagship model or value tiered device, the trend for improved data rate experience is influencing the complexity of the front-end.

Figure 18 is a simplification of content contained in tiered devices. To understand it, it is useful to gather insights into current market trends. LTE data throughput is happening on the downlink and uplink directions in the network. In the premium tier, extremely high levels of integration are seen on the transmit side, LTE receive diversity path, LNAs and antenna management functionality. In the near future, additional 4x4 MIMO receive path content will be necessary. This premium tier tends to favor a global stock keeping unit (SKU) approach, where almost all required functionality is included with reduced number of product variants. This tier also has a tendency for being the first to adopt and/or specify the most advanced 3GPP features supported by advanced LTE networks. They typically lead value tier original equipment manufacturers (OEMs) features and functionality by one or two generations.

In the value tier, the same trend is occurring, but with slightly different levels of integration and complexity. The value tier tends to specify more dedicated regional SKUs that are more cost focused than the premium tier. While the partitioning is slightly different, it is still a far more advanced system than was contemplated even one or two prior generations. In 2017, the value tier will support multiple CA combinations and a higher order modulation, with a portion of the more advanced devices beginning to support 4x4 MIMO.

Key Insights

LTE Advanced Features Such as 5CC CA, 4x4 MIMO, and Higher-order Modulation are Capable of Providing Data Rate Improvement by 10-100x Compared to Current Performance

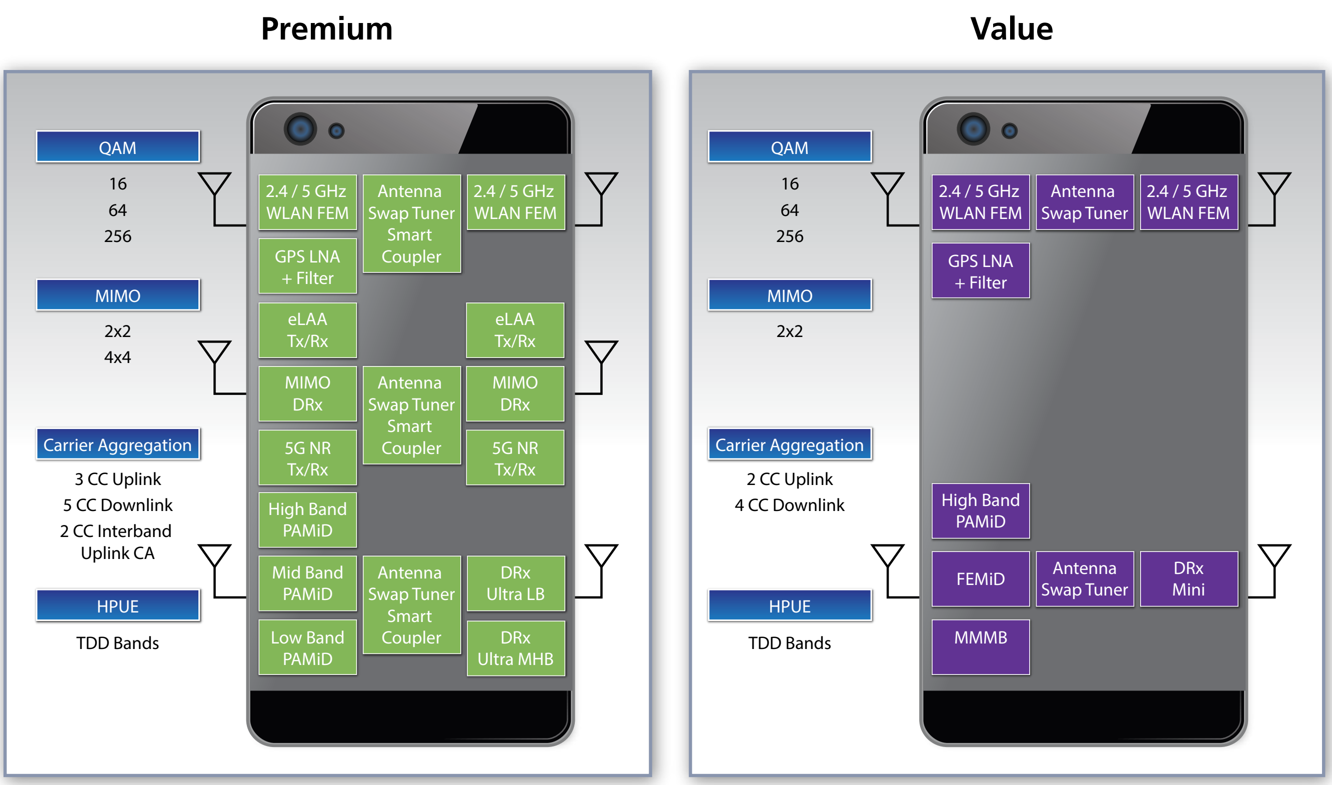


Figure 18. Application Examples

What's Next: Preparing for 5G New Radio Networks and Devices

Figure 19 is a good depiction of a 5G ecosystem. One way to comprehend the 5G ecosystem is to break it up into segments based on frequency. There are two main areas that will capture the attention of network operators, device manufacturers and system solution providers such as Skyworks. First, there will be significant activity in the sub-6 GHz frequency domain. Both 4G LTE as it is currently practiced, and 5G NR will be deployed concurrently in spectrum below 6 GHz. Second, the devices, techniques, and general radio protocols will be very familiar to those addressing this segment of the market. In other words, below 6 GHz we expect the same look and feel with respect to the RF content with allocations for additional content to meet new bands and 5G features.

So far, 3GPP has decided to tether 5G NR to the existing 4G LTE environment. As such, we do not expect standalone 5G NR devices to exist in the market for quite some time. The implication here is the framework for mobile devices remains on a steady track, albeit with some increased functionality, for the new 5G.

Another implication not readily discernible is that the backhaul network will need to increase capacity to cover all the front haul increase in data.

Most of the recent 5G headlines have focused on mmWave spectrum and the introduction of new techniques like beam forming to overcome the higher path losses at these higher frequencies. As with any new technology in its infancy, there are many unknowns regarding the business and usage case, which is compounded by new commercial technology deployments.

Despite the unknowns, we see 5G NR usage cases centered around small cell densification in fixed wireless application as the most likely outcome. This aligns with the views proposed by many of the advanced LTE mobile network operators, with Verizon Wireless being a very strong advocate. Due to the differences in mmWave radio transmission and the sub-6 GHz ecosystem, Skyworks believes the business case for high-bandwidth mmWave fixed wireless communications is the correct focus for initial deployment of 5G NR.

Currently, there are many obstacles to overcome that would prohibit mmWave deployment in consumer devices as a first step in the technology roadmap. These include battery life, beam tracking and management, and radio propagation challenges, to name a few.

Another way to think about the differences between the sub-6 GHz and the mmWave ecosystems is to think about the area coverage. Sub-6 GHz frequencies are used in the macro and small cell densification networks to provide users with data rates approaching and exceeding multiple Gbps covering a large geographical area. Millimeter wave deployments are targeting several tens of gigabits per second data rates in close proximity to small cell base stations with very narrowly focused beams, hence the fixed wireless application.

Mobility applications from mmWave devices will come much later, after the initial deployments have proven successful. Technology barriers for beam tracking and SNR still need to be overcome to achieve a feasible resolution.

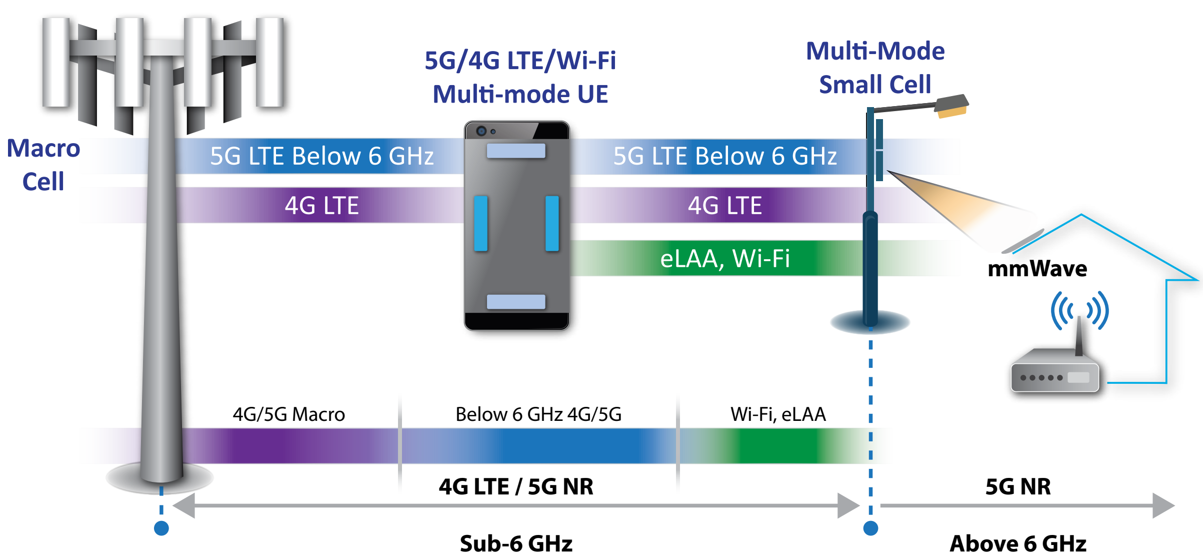


Figure 19. Skyworks' Vision of the 5G Ecosystem

SKYWORKS

Spectrum in 5G

In addition to the key LTE features, another important aspect to consider over the next several years is the availability of spectrum and new bands, which will be utilized to deploy some of these new techniques. A quick survey of the proposed bands indicates a preponderance of new TDD spectrum becoming available globally in the 3 to 6 GHz range (LTE sub-6 GHz) for both LTE Advanced Pro and 5G NR phase 1. For 5G NR phase 2, the intention is to utilize mmWave frequencies with much larger bandwidth for new 5G applications.

The chart shown in Table 4 shows new frequencies being discussed in relation to 5G NR. There are two frequency regions of interest playing an important role in 5G NR. In the 3 to 6 GHz band, there is generally clear spectrum globally in the 3.3 to 3.8, 3.8 to 4.2, and 4.4 to 4.9 GHz region. These bands, which are all based on TDD or unpaired spectrum, generally have wider bandwidth than its 4G predecessors. They will be particularly important in user equipment plans that will use 4G LTE anchors and new 5G NR radio transmissions. In addition to the licensed bands in the 3 to 6 GHz range, it is very likely there will be additional use of supplemental unlicensed bands to squeeze out even more usable bandwidth.

The other aspect of the 5G NR, which is much more revolutionary, will utilize mmWave spectrum. The mmWave bands have the widest achievable bandwidths and are available with some regions offering multiple GHz spectrum. Industry consensus is building around the usage model of mmWave spectrum for fixed wireless applications. Applying mmWave technology to mobile devices will represent a very high technological challenge for the near future.

5G will bring very high capacity and low delay (ultra-low latency) using both sub-6 GHz and mmWave spectrum. In conjunction, we will need to determine how much capacity is needed for backhaul. Network Function Virtualization (NFV) is likely to emerge on last mile links and will leverage more intelligent switching protocols at the network edge.

A key component of the 5G landscape is going to be outdoor small cells. We referred to this earlier as small

Sub-6 GHz Spectrum (MHz)

Region	New F_{LOW}	New F_{HIGH}	Existing F_{LOW}	Existing F_{HIGH}	Existing Band	BW	Total BW
Korea	**3400**	**3700**				**300**	300
EU			2570	2620	38	50	450
	3400	**3800**	**3400**	**3800**	**42+43**	**400**	
Japan			2496	2690	41	194	1494
	3600	**4200**	**3400**	**3600**	**42**	**800**	
	4400	4900				500	
U.S.			2496	2690	41	194	344
			3550	**3700**	**48**	**150**	
China			2300	2400	40	100	790
			2555	2655	41B	100	
	3300	**3600**	**3400**	**3600**	**42**	**300**	
	4400	4500				100	
	4800	4990				190	

Millimeter Wave Spectrum (GHz)

Region	F_{HIGH}	Band	BW	Total BW
Korea	**26.50**	**29.50**	**3.00**	3.00
EU	**24.25**	**27.35**	**3.10**	7.70
	31.80	33.40	1.60	
	40.50	43.50	3.00	
Japan	**27.50**	**29.50**	**2.00**	2.00
U.S.	**27.50**	**28.35**	**0.85**	10.85
	37.00	38.60	1.60	
	38.60	40.00	1.40	
	64.00	71.00	7.00	

Bold values indicate newly introduced frequency ranges with worldwide footprint.

Table 4. Candidate Spectrum for 5G NR

cell densification of the 5G network. These small cells are essential, as mmWave will leverage directional beams in a short range (see Figure 20). A secondary effect of densifying the network with high data rate links is the need to improve backhaul characteristics.

Today, fiber is the backhaul option of preference. However, as networks grow to become more dense with the deployment of small cells, licensed fixed or point-to-multipoint (PMP) mmWave may emerge as the most flexible solution. For example, an operator (leveraging guaranteed QoS with licensed PMP) with a >10 Gbps hub site could aggregate backhaul traffic from multiple base stations. The economics of that scenario improve as more base stations are added progressively with densification.

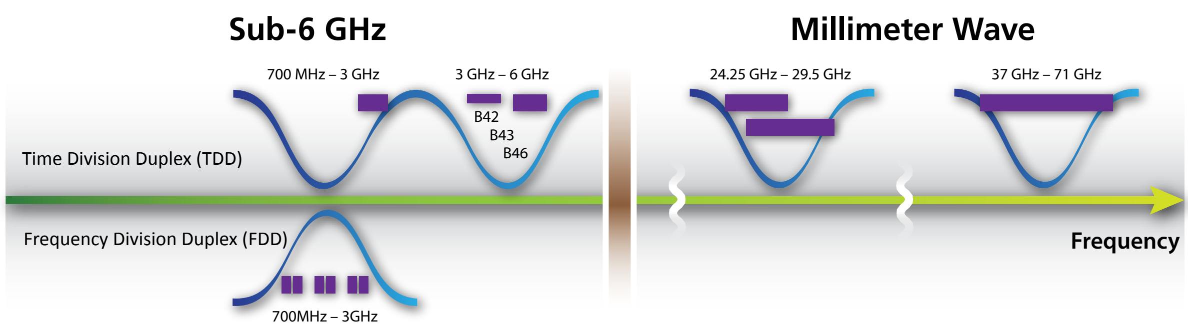
Figure 20. Network Densification Enables Faster Data Rates

Millimeter wave communications technologies in the 60 GHz and 70-80 GHz range for high capacity at the last mile and pre-aggregation backhaul were explored in *'Advanced Wireless and Optical Technologies for Small Cell Mobile Backhaul with Dynamic Software-Defined Management'* (Bojic, et al., 2013).

New Technologies That Are Required to Serve 5G

Table 5 represents existing technology and spectrum, as well as the planned 5G NR spectrum. We mapped those applications to the technologies needed to implement both power and low noise amplifiers, RF switching, filtering, and antenna integration functionality.

One key take away is that the entire new spectrum for 5G NR, whether sub-6 GHz or greater than 6 GHz, are all TDD bands. Due to the fact that they are time division duplex, frequency duplexers are not required to implement a front-end solution. Filtering, as needed, is accomplished in bandpass filters. In the 3 to 6 GHz region, filtering can be accomplished in acoustic, IPD or ceramic technologies. In the sub-6 GHz region, most of the 5G NR activity will be



Product Format Example	FEMiD / PAMiD / DRx	FEMiD / PAMiD / DRx	8T / 8R Antenna Complete Front-end	8T / 8R Antenna Complete Front-end
		Technology		
Power Amp	III-V / SiGe / Bulk CMOS	III-V / SiGe / Bulk CMOS	InP / SiGe BiCMOS / Advanced SOI	InP / GaN / SiGe BiCMOS / Advanced SOI
Low Noise Amp	III-V / SiGe / SOI CMOS	III-V / SiGe / SOI CMOS	Advanced SOI / GaN	SiGe BiCMOS / Advanced SOI
RF Switching	SOI CMOS	SOI CMOS	Advanced SOI	Advanced SOI
Filtering	Acoustic / IPD / Ceramic	Acoustic / IPD / Ceramic	IPD / Ceramic	IPD
Antenna Integration	N/A	N/A	Yes	Yes
Signal Generation	N/A	N/A	Advanced SOI / SiGe BiCMOS	Advanced SOI / SiGe BiCMOS

Table 5. Product and Technology per Spectrum Range

deployed in the 3 to 6 GHz frequency spectrum. In all cases, 5G NR will require a 4G LTE anchor, typically in the below 3 GHz region. In other words, 5G will exist as an overlay to the existing 4G network. Implications are that user equipment will use very similar techniques in both the 4G and 5G NR sub-6 GHz domain. This leads to increased complexity, however the techniques and technology remain essentially the same as our current 4G devices.

For the 5G mmWave fixed wireless applications, requirements for massive MIMO and multiple beamforming means that transmit and receive functions will most likely be in distributed array formats. As a result, there will be multiple PA streams and multiple receive chain streams to accomplish transmit and receive functionality to fixed wireless devices.

Filter technology for mmWave 5G is likely to be based on transmission line and waveguide cavity technology. Microelectromechanical systems (MEMS) cavity resonators are also an attractive choice to avoid hand-tuning filters and leveraging silicon wafer-based manufacturing approaches. Multi-pole filters suitable for operation at frequencies of 20 to 100 GHz have been demonstrated in *'RF-MEMS based Passive Components and Integration Concepts for Adaptive Millimetre Wave Front-Ends'* (Gautier, 2010).

User equipment PA technology for 5G sub-6 GHz will leverage traditional GaAs heterojunction bipolar transistor (HBT) technology, but it will require some improvement or innovation in dealing with wide bandwidth signals, especially in biasing. Skyworks will leverage its current expertise in Wi-Fi 802.11ac and 802.11ax (up to 160 MHz bandwidth with extremely tough error vector magnitude requirements). Above 6 GHz, we will leverage our experience in System-in-Package (SIP) technology to create antenna front-ends on organic laminates.

Summary: Enabling Gbps in User Equipment

Key Differences between 4G and 5G Radio Interfaces

What changes are required to deploy new 5G radios and how can Skyworks address these new requirements?

4G and 5G radio interfaces impact the RF front-end in several ways: one key way is that 5G phase 1 is not a standalone radio, it is always used in conjunction with 4G LTE. The anchor is 4G LTE technology and 5G sub-6 GHz is a supplement.

Fundamentally, 4G and lower frequency (sub-6 GHz) 5G look the same from an RF front-end point of view and are implemented in similar ways using the same componentry. This means that LTE 4G and 5G phase 1, sub-6 GHz will utilize the same RF front-end, albeit a more complex one than a previous generation.

Uplink MIMO for 4G requires multiple separate data streams driving discrete antenna elements, similar to sub-6 GHz 5G. These antennas are adjusted for relative phase to beam form as needed, but the lower frequency and lower number of antenna elements constrain the overall antenna gain and narrowest beam cross-section. Generally, sub-6 GHz antennas are designed to be omnidirectional for obvious coverage and connectivity/orientation independent performance required in mobile cellular radio environments.

As user equipment develops feature-rich capabilities for the uplink in this direction of uplink MIMO, the multiple transmit of separate data streams to separate antennas starts to look just like the architecture required for 4x4 uplink MIMO.

That is not the case when we compare 4G (sub-6 GHz) to mmWave 5G, as those implementations are quite different and distinct.

Compared with sub-6 GHz implementations (2x2 uplink, 4x4 downlink), mmWave devices will require substantial antenna gain to overcome path loss. This indicates that mmWave front-end will be drastically different than the sub-6 GHz. The mmWave RF front-end will employ multiple transmit/receive streams (8, 16, or higher) to achieve antenna gain, total combined transmit power. The challenges in gain and efficiency will constrain the overall transmit power to lower maximum powers per antenna element and RF path. Generally, this will improve the overall link level requirements for radiated power back to the eNodeB. The large conducted path loss associated with mmWave frequencies means that the design can no longer tolerate long trace lengths between the active circuitry and the antenna radiating element(s).

The good news is that the antenna array has physically shrunk in size with increasing frequency, as the wavelength is inversely proportional to frequency. As a result, the most likely implementation is where the antenna array is integrated into the same package containing the active transmitter and receiver circuits operating at the mmWave frequencies. This tightly integrated package will house active die, which are also highly integrated and support all the required amplification, phase shifting and path switching to properly drive each of the independent antenna array radiating elements. Skyworks has strong capabilities in highly integrated packaging of flip-chipped or Chip Scale Package (CSP) die with dual-sided multi-chip modules. Likewise, Skyworks has experience in dual-sided and ultra-thin stacked packaging approaches required for volume commercial 4G deliveries. Such experience will be required for 5G as well.

Because of the susceptibility of the 5G mmWave antenna array to orientation, connectivity issues could include blockage by user hand/head placement, performance interruption due to line-of-sight obstruction and difficulty penetrating materials such as brick and tinted glass. Therefore, it is likely that more than one antenna array would be needed for a given mobile device form factor. Antenna array switched diversity would be used to select the better option of a choice of two or more arrays in order to overcome these challenges and to maintain the user experience.

The market for wireless communication technology is expanding, and 5G is at the heart of this transformation. Wireless communication has expanded into adjacent segments such as automotive and autonomous driving, machine type communications, smart infrastructure and applications not yet considered. Complexity will continue to increase and finding effective solutions will be the greatest task for wireless technology experts who are bringing connectivity to new market verticals and people around the globe.

At Skyworks, we believe the future for 5G is indeed bright as we continue to drive toward our mission of ***Connecting Everyone and Everything, All the Time***.

AT&T's Perspective on 5G

"New experiences like virtual reality, self-driving cars, robotics, smart cities and more are about to test networks like never before. These technologies will be immersive, pervasive and responsive to customers. 5G will help make them a reality. 5G will reach its full potential because we will build it on a software-centric architecture that can adapt quickly to new demands and give customers more control of their network services. Our approach is simple – deliver a unified experience built with 5G, software-defined networking (SDN), Big Data, security and open source software."

—John Donovan

Chief Strategy Officer and Group President, AT&T Technology and Operations (AT&T, 2016)

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