Making 5G NR a reality

Leading the technology inventions for a unified, more capable 5G air interface

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Table of Contents

1 Executive summary

The 5th Generation (5G) of mobile networks is on the horizon and promises to deliver a unifying connectivity fabric that will take on a much larger role than previous generations. It is a new kind of network that will not only interconnect people, but also interconnect and control machines, objects, and devices — a platform for innovations that can enable new services, empower new user experiences, and connect new industries. 5G will significantly enhance and lower cost for mobile broadband services available today on 3G and 4G networks, while also bringing new kinds of services to life, such as enabling mission-critical control through ultra-reliable, low-latency links and connecting the massive Internet of Things.

Making this 5G vision a reality will require a unified, more capable air interface design that will bring new levels of flexibility, scalability, and efficiency to meet the expanding connectivity needs in the next decade and beyond. 3GPP is defining 5G New Radio (NR) that will scale to address diverse 5G services and devices, pushing many limits to deliver not only significantly higher performance but also unprecedented levels of cost, power, and deployment efficiencies. Additionally, 5G NR is being designed to get the most out of every bit of spectrum across a wide array of spectrum regulatory paradigms (including licensed, shared, and unlicensed) and all spectrum bands – from low bands below 1 GHz, to mid bands from 1 GHz to 6 GHz, to high bands known as millimeter wave (mmWave). In order to proliferate 5G to connect virtually anything, anywhere, 5G NR will support a wide range of deployment models from traditional macro to hotspot deployments, as well as new ways to interconnect devices such as device-to-device and multi-hop mesh that will open doors to more opportunities and broaden the mobile ecosystem.

Designing the 5G NR unified air interface is by no means a trivial task. Not only does it need to meet the diverse set of requirements of known use cases, but its foundational design must also ensure seamless forward compatibility with both emerging and future unknown services. To achieve this, the 5G NR design will include flexible OFDM-based waveforms and multiple access techniques, optimized for the various 5G services and deployment types. A new common, flexible 5G NR framework and a self-contained integrated subframe design will allow network operators to more efficient multiplex diverse services on a unified 5G network, while also ensuring 5G NR forward compatibility to future 5G features and services. Moreover, 5G NR will incorporate a plethora of advanced wireless technologies, such as massive MIMO that provides access higher spectrum bands including mmWave, that are key enablers to meeting the extreme variation of 5G requirements

The 5G-connected world is quickly approaching and as we did in 3G and 4G, Qualcomm is leading the way. We have been designing 5G technologies for many years, building upon the long-standing expertise in delivering 3G, 4G, and Wi-Fi, combined with mobile computing solutions. We are inventing technologies to make 5G NR a reality, as well as accelerating the path to 5G NR commercial network launches in collaborations with industry leading network operators and infrastructure vendors. The Qualcomm Research 5G NR prototype systems are being utilized to test, demonstrate and trial our innovative 5G designs across diverse spectrum bands and types. We also announced the Qualcomm® Snapdragon™ X50 5G Modem that will enable early 5G mmWave trials and deployments. In parallel, we continue to lead the way on LTE Advanced Pro advancements that will pave the path to 5G; for example, delivering Gigabit LTE connectivity with our Snapdragon X16 LTE modem and paving the path to 5G Narrowband with our LTE IoT solutions.

2 Ushering in the era of the 5th generation mobile network

For the past 30+ years, mobile networks have evolved to interconnect people in new and better ways. Although this evolution of new features and technologies is continuous, approximately every 10 years a new generation of mobile technologies is introduced that delivers a big leap in performance, efficiency and capability. And now, the world sits at the dawn of the fifth generation of mobile — 5G, a unifying connectivity fabric for a wide range of industries that will bring significant economic and societal benefits.

2.1 From 1G to 4G: interconnecting people

The 1G network based on analog voice communications was first introduced in the 1980s, and for the first time, people were no longer tethered to a fixed telephone. The ability to connect on-the-go had forever changed the way people communicate, work, and play, and it was no surprise that it didn't take too long for these 1G networks to proliferate and evolve.

With mobile telephony quickly gaining momentum, the limitations of 1G analog became clear – the bulky devices, costly service, spotty coverage, and inefficient use of spectrum resources. The transition to digital voice communications drove the very first generational leap from 1G to 2G. The 2G networks, first introduced based on TDMA[1], solved many of the limitations of early 1G networks. 2G also saw the introduction of CDMA[2], pioneered by Qualcomm, bringing significant improvements including over 10x capacity increase in the amount of voice calls that could be supported.

CDMA also became the foundation for 3G with CDMA2000 and WCDMA[3]. While 3G did increase voice capacity, the major paradigm shift was the new CDMA-based technologies that 3G introduced to optimize mobile networks for data services, allowing users to access e-mail, weather, and news on their mobile devices. This transformation established the foundation for mobile broadband that would help usher in the era of the smartphones.

4G LTE[4] brought faster, better mobile broadband, along with a new, simplified all-IP network architecture. It brought a new foundational air interface design based on OFDM[5] waveforms and multiple access (with OFDMA[6] downlink and SC-FDMA[7] uplink). 4G LTE has continued to evolve since then, bringing new technology inventions such as MIMO[8], carrier aggregation, and higher-order modulation to deliver blazing-fast wireless performance, as well as solutions to efficiently grow network capacity to address the surge in data traffic which has grown over 4,000 times in the past 10 years[9].

To put this into perspective, new Gigabit LTE networks that are emerging now can deliver peak rates around 100,000 times faster than the first data-capable 2G network. With the proliferation of 3G and 4G LTE networks, the global mobile broadband connections had surpassed fixed broadband in 2010[10], with over 7 billion mobile connections worldwide today. The economic value generated by the mobile sector continues to grow, and it is estimated that by 2020, it will generate $3.7 trillion[11]. These are just two of

[1] Time Division Multiple Access
[2] Code Division Multiple Access
[3] Wideband Code Division Multiple Access
[4] Long Term Evolution
[5] Orthogonal Frequency Division Multiplexing
[6] Orthogonal Frequency Division Multiple Access
[7] Single-carrier Frequency Division Multiple Access
[8] Multiple Input Multiple Output
[9] Cisco, February 2016
[10] GSMA Intelligence, October 2014; WBIS, October 2014
[11] GSMA, February 2016

the many remarkable milestones that showcase the transformational nature of mobile communications, and these amazing innovations had happened in the short span of just three decades. And it is exciting to see the world is on the cusp of yet another transformation that will expand the role of mobile networks to address the needs of a new wave of emerging use cases. The world is now preparing for a new kind of network - the 5G network.

2.2 5G: a new kind of network for tomorrow's innovations

While the first four generations of mobile networks interconnected people by delivering better voice and faster data services, it is envisioned that 5G will do and connect much more. 5G is a platform for innovations that will redefine a wide range of industries by connecting virtually everyone and everything, from workers and patients to robots and crops, supporting the connectivity needs across a variety of world-changing use cases. 5G will bring together people's worlds to achieve new levels of efficiency that will benefit the entire society. The figure below shows a few example applications that 5G will bring to life.

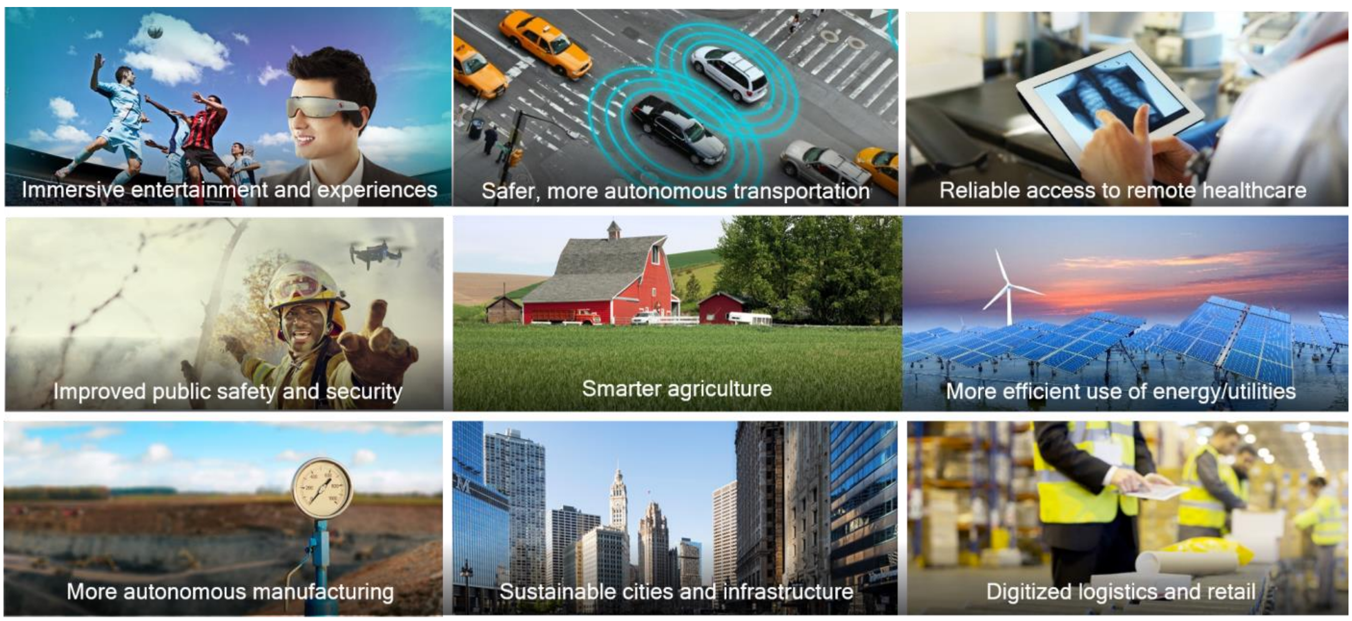

Figure 1: 5G will create new values and redefine a wide range of industries

The potential for 5G is not limited to these use cases, as there are many emerging and new applications that are yet to be completely defined or even known today. Similarly, no one could have imagined the transformations that modern smartphones have created when 4G LTE was initially being conceived in 2004[12]. Thus, 5G is being designed with flexibility and scalability in mind in order to provide this unifying connectivity platform for future innovations. Today, the mobile industry has broadly agreed on and defined three main categories of 5G services: enhanced mobile broadband, mission-critical control, and massive Internet of Things – each driving a very diverse set of requirements.

[12] At the 3GPP workshop on LTE in November 2-3, 2004

Figure 2: 5G is a unifying connectivity fabric for the next decade and beyond

2.3 Scaling across diverse services and devices

5G is envisioned to support a multitude of service and devices, thus it needs to be adaptable to a huge variance of requirements around coverage, throughput, capacity, latency, and reliability, just to name a few. 5G must scale from supporting low-data rate sensors at 10s of kbps to new immersive mobile experiences at multi-Gbps. The figure below shows the multifaceted requirement dimensions that 5G must address with its unifying design.

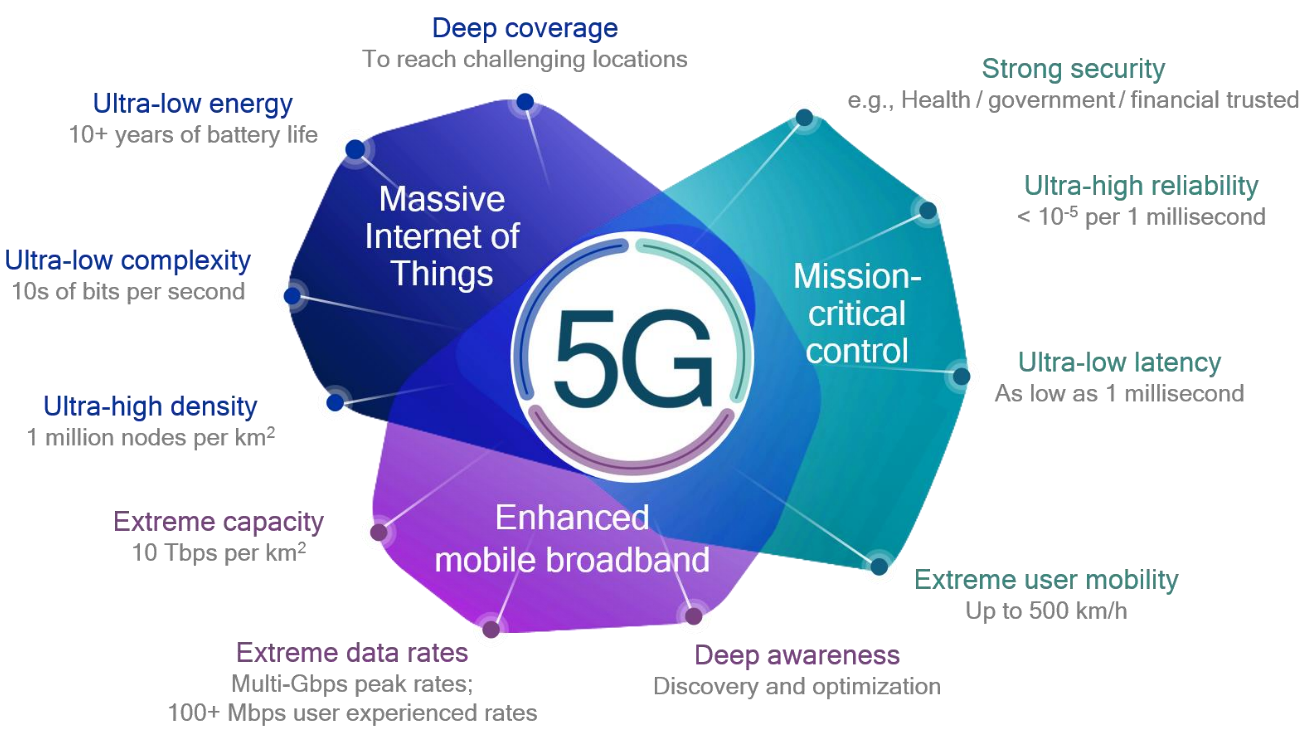

Figure 3: 5G will scale and adapt to a wide range of requirements

To meet these expanding connectivity requirements, 5G is being designed to meet the new IMT-2020[13] performance targets that are being defined by the ITU[14] based on the target 5G service areas. It spells out new requirement dimensions such as ultra-high reliability (e.g., 10^{-5}/1ms) as well as improvements over IMT-Advanced that defined requirements met by LTE Advanced (Release 10). 5G will differentiate itself by delivering the improvements such as:

- 10x experienced throughput – bringing more uniform, multi-Gbps peak rates
- 10x decrease in latency – delivering latency as low as 1 ms
- 10x connection density – enabling more efficient signaling for IoT connectivity
- 3x spectrum efficiency – achieving even more bits per Hz with advanced antenna techniques
- 100x traffic capacity – driving network hyper-densification with more small cells everywhere
- 100x network efficiency – optimizing network energy consumption with more efficient processing

2.4 Getting the most out of a wide array of spectrum

In addition to supporting a wide range of services and devices, 5G will make the best use of a wide array of spectrum available across regulatory paradigms and spectrum bands. Previous generation networks primarily operated in licensed spectrum bands below 3 GHz, 5G will bring the next level of convergence with support for licensed, shared, and unlicensed spectrum from the very beginning. Moreover, 5G will expand spectrum usage to low-bands below 1 GHz, mid-bands between 1 GHz and 6 GHz, and high-bands above 24 GHz, loosely known as mmWave, which will open up vast amount of bandwidths for extreme data rates and capacity that were previously not usable for wide-area mobile communications.

Figure 4: 5G will natively support all different spectrum types

Qualcomm is pioneering spectrum sharing technologies today with various efforts including LTE-U[15], LAA[16], LWA[17], CBRS[18], LSA[19], and MulteFire. 5G will be built to natively support and advance these

[13] ITU Recommendation ITU-R M.2083-0, September, 2015; http://www.itu.int/rec/R-REC-M.2083-0-201509-I
[14] International Telecommunication Union
[15] LTE Unlicensed
[16] Licensed-Assisted Access
[17] LTE Wi-Fi Link Aggregation
[18] Citizen Broadband Radio Service
[19] Licensed Shared Access

technologies as spectrum sharing becomes increasingly important to meeting tomorrow's connectivity needs for faster data rates and increased network capacity by aggregating unlicensed spectrum opportunistically, but also to enable new deployment models, such as enterprise mobile broadband or private IoT networks. Qualcomm is also inventing technologies to deliver robust mobile broadband communications at mmWave spectrum bands with our 5G mmWave prototype system, as well as our 802.11ad Wi-Fi technology operating at 60 GHz.

2.5 Adapting to diverse deployments and topologies

5G will also enable different types of deployments and network topologies. Traditional mobile networks focused on macro coverage and were deployed or managed by MNOs[20], but 5G is envisioned to open doors to new ecosystem players, such as cable operators and vertical service providers, to participate in 5G deployments. However, MNOs' 5G deployments continue to be the backbone for 5G, providing ubiquitous network coverage. Figure 5 shows some of the new deployment models that 5G will support.

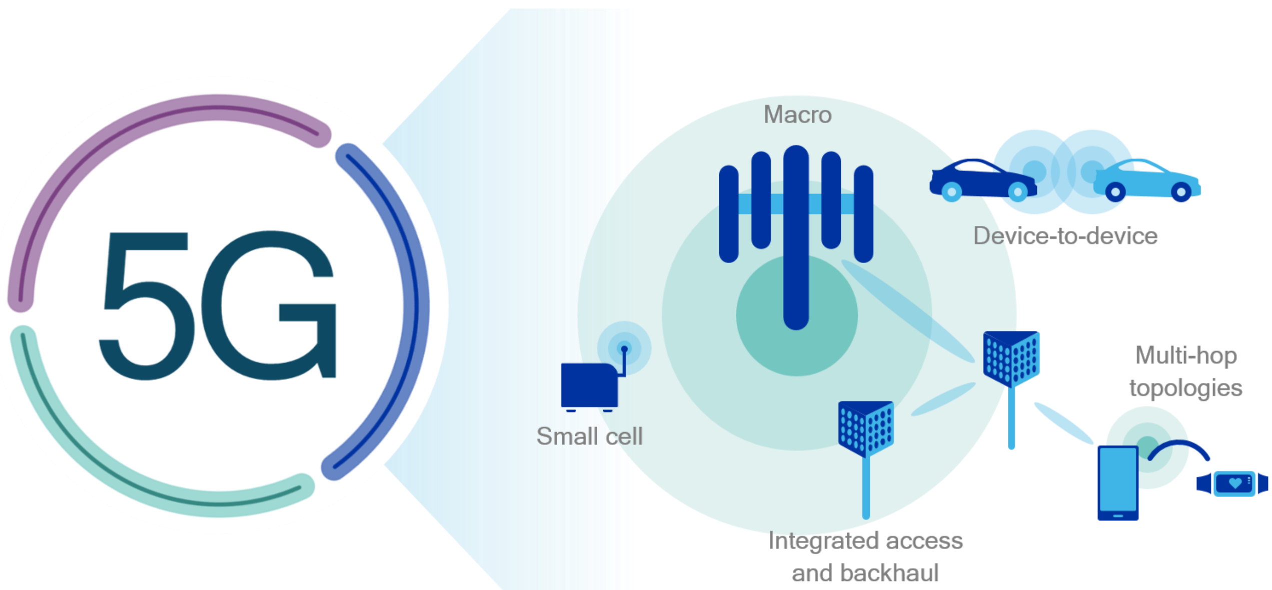

Figure 5: 5G will enable different deployments and topologies

In order to achieve higher connection density and traffic capacity, 5G will continue to drive network densification with more small cells everywhere. Thanks to recent advancements in antenna technologies and more intelligent network management, 5G will bring mmWave technologies to 5G networks, also opening up the opportunity for integrated access and backhaul. The ability to cut the cord on backhaul connectivity greatly simplifies small cell deployments. Moreover, 5G will also build upon C-V2X[21] and LTE Direct to enable ultra-low latency sidelinks and multi-hop mesh. These new ways for 5G devices to connect will extend network coverage further and also enable new types of use cases.

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[20] Mobile Network Operators
[21] Cellular Vehicle-to-Everything

3 Leading the way to a 5G-connected world

Today, the mobile ecosystem is well underway to define, prototype, and test new 5G technologies that will ultimately lead to the commercialization of 5G networks. 3GPP[22], the standard body that overlooked the development of 3G UMTS[23] (including HSPA[24]) and 4G LTE standards, is defining 5G NR – the global standard for 5G New Radio that will ensure the quality, performance, and interoperability of 5G devices and networks. In parallel, the industry is driving LTE to its fullest potential, pioneering many of the 5G technologies and use cases.

3.1 5G NR standardization and timeline

3GPP has started the 5G process with a workshop in September 2015. The 5G NR Study Item was officially kicked off in March 2016, and is expected to evolve into the Release 15 Work Items in March 2017, which will formally define the first 5G NR specification.

The current schedule for the completion of Release 15 specification is estimated for June 2018; however, due to strong industry interest to accelerate standard-based 5G deployments, a proposal has been set forth to accelerate a non-standalone version of 5G NR to December 2017 or March 2018. 5G NR non-standalone operation will utilize an LTE anchor (LTE EPC[25]) for control and mobility management, bringing new capabilities and efficiencies with the 5G NR air interface, while leveraging the existing LTE core network. The proposal also emphasizes interest in not delaying finalization of the 5G NR standalone operation and the new 5G NextGen core network specifications beyond the currently planned date of June 2018.

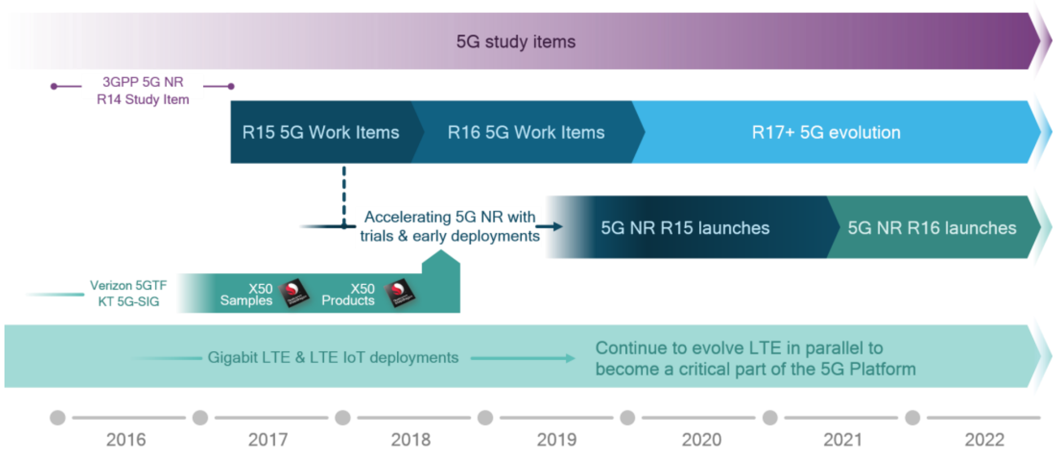


Figure 6: 5G NR standardization timeline

The 3GPP Release 15 5G NR specification will define the features and services for the first phase of 5G NR commercial network launches starting in 2019. The target use cases expected for Release 15 specification include enhanced mobile broadband, with advanced features such as massive MIMO, scalable OFDM numerology, and a new self-contained TDD[26] subframe design. It will support both

22 3rd Generation Partnership Project
23 Universal Mobile Telecommunications System
24 High Speed Packet Access
25 Enhanced Packet Core
26 Time Division Duplex

mmWave bands up to 40 GHz as well as mid/low-bands below 6 GHz. Release 15 is also expected to introduce new low-latency and high-reliability features to enable some mission-critical services. More importantly, Release 15 is establishing the foundation for the 5G NR design, including the waveforms, multiple access techniques and framework. 3GPP Release 16 and beyond will continue to bring new features (e.g., support for bands above 40 GHz, multicast) and introduce new services (e.g., massive IoT).

It is also notable that efforts such as KT-SIG[27] and VZ-5GTF[28] are developing specifications to target early 5G mmWave trials for the 2018 Winter Games and fixed wireless access deployments, respectively, ahead of 2019 to accelerate learning at these higher frequency bands. To enable these early 5G activities, Qualcomm announced the Snapdragon X50 5G modem in October 2016, which is expected to begin sampling in the second half of 2017, and to be in products by 2018. The learning from taking on the challenge of integrating new mmWave technology into commercial devices and networks will help to accelerate the finalization of the 5G NR standard and usher in 5G NR networks and devices.

3.2 The path to 5G includes a strong LTE foundation

What role will 4G have in the 5G connected world? The answer is quite simple – it is absolutely foundational to the 5G vision. LTE is continuing to evolve in parallel with the efforts around 5G. In fact, LTE is already pioneering many of the technologies that will be the foundation for 5G. For example, Gigabit LTE is paving the path to 5G fiber-like mobile broadband by leveraging advanced LTE technologies such as carrier aggregation, advanced MIMO, higher-order modulation, and the use of unlicensed spectrum. Moreover, LTE IoT (including NB-IoT[29] and eMTC[30]) is delivering the foundational technologies for the massive Internet of Things, which Narrowband 5G will expand upon in Release 16 and beyond. And similarly, new LTE technologies, like C-V2X being introduced as part of Release 14, are providing an early glimpse into 5G automotive mission-critical services.

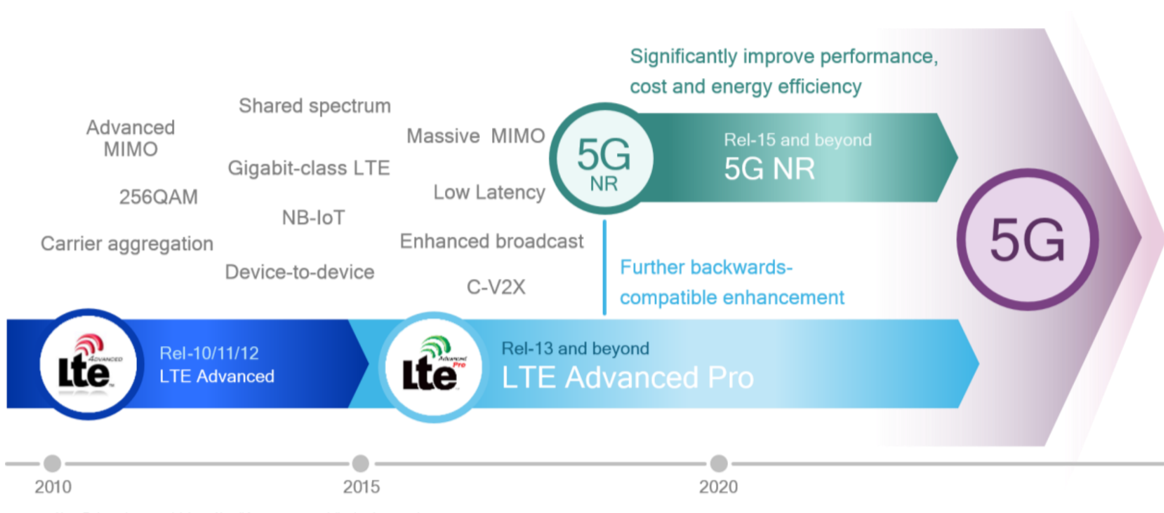


Figure 7: The path to 5G includes a strong LTE foundation

[27] KT Special Interest Group
[28] Verizon 5G Technical Forum, http://www.5gtf.org/
[29] Narrowband IoT
[30] Enhanced Machine-type communication

3.3 A phased 5G rollout that fully leverages LTE investments

5G will expand upon the dual-connectivity framework that was first introduced for LTE to support simultaneous links and aggregations across 5G, 4G, 3G, and Wi-Fi in a multi-connectivity framework using multi-mode devices. Not only will this enable a better, more seamless user experience, but it will also play an important role in enabling early 5G deployments. LTE will become an essential pillar for the 5G experience, as it will provide a complementary wide coverage layer for nascent 5G networks which will have a limited local and global footprint during the early years of 5G deployments.

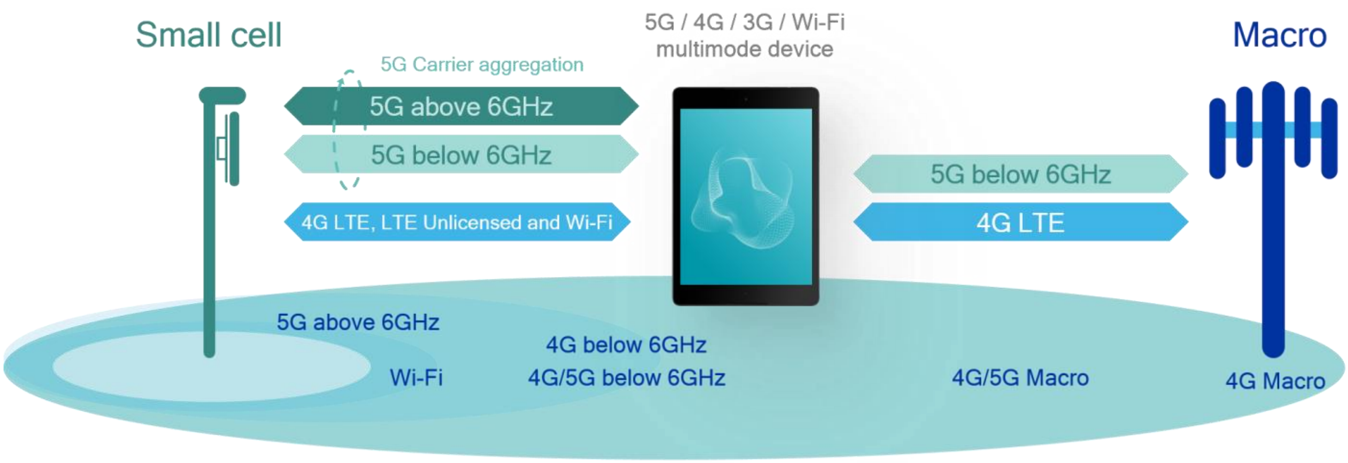


Figure 8: Multi-connectivity is an integral part of the 5G design

3.4 A global effort to get more spectrum for 5G

Beyond standardization, the mobile industry is also working with regulators around the world to make the necessary spectrum resources available to meet 5G's requirements. As pointed out earlier, 5G will make use of diverse spectrum types and bands. The efforts to identify and allocate 5G spectrum have already begun in many countries, and the momentum so far has been strong. Here is a brief summary of the progress made to-date as of November 2016:

- *United States (US):* the Federal Communications Commission (FCC) is driving key spectrum initiatives to enable 5G across low, mid, and high bands. In the low-band, the FCC is conducting the world's first voluntary incentive auction of the 600 MHz band. For the mid-band, it has opened up 150 MHz in 3.5 GHz CBRS bands for sharing. And in the high-band, about 11 GHz of spectrum (28 GHz, 37-40 GHz, and 64-71 GHz) has been made available for mmWave applications, with additional candidate bands identified for IMT-2020.
- *European Union (EU):* the European Commission (EC) has identified pioneering spectrum bands of 700 MHz, 3.4-3.8 GHz, and 24.25-27.5 GHz, with the full set of 5G spectrum bands to be agreed on by end of 2017. It has laid out an action plan in September 2016 that targets to deploy 5G across Europe by 2020, with at least one major city per country supporting 5G, and full deployment across all urban areas and major terrestrial transport paths by 2025. Early technical trials are expected to start in 2017 and pre-commercial trials in 2018.
- *China:* the initial focus is on sub-6 GHz spectrum bands, with approved trials in 3.4-3.6 GHz, but also looking at other opportunities such as 3.3-3.4 GHz and 4.8-4.99 GHz. There are also

activities in identifying mmWave bands, initially 24.25-27.5 GHz, and longer term targeting 27.5-29.5 GHz as well.

- *South Korea:* early 5G is planned for the higher mmWave bands, focusing on 28 GHz (similar to the 28 GHz band in the US and Japan). This is driven by the combined KT-SIG/VZ-5GTF effort, targeting trials at the 2018 Winter Games, with the possibility to use the same band for early 5G deployments afterwards. In addition to 28 GHz, Korea is also looking at opening 37.5-40 GHz.
- *Japan:* there is a strong focus on both sub-6 GHz and mmWave bands, including 3.6-4.2 GHz, 4.4-4.9 GHz, and 27.5 GHz-29.5 GHz.
- *Australia:* the current 5G focus is on sub-6 GHz, primarily in 3.4-3.7 GHz, while also identifying potential mmWave bands.

4 Designing 5G NR unified air interface

At the heart of 5G is a new, more capable, unified air interface - 5G NR. It will not only significantly enhance mobile broadband, but will also enable new services such as mission-critical control and massive IoT. 5G NR adopts an optimized OFDM-based family of waveforms and multiple access, as well as a common, flexible framework that enables efficient service multiplexing and provides the forward compatibility required to futureproof 5G. This section explores these key foundational elements that are integral to the 5G NR air interface design. 5G NR will also incorporate a plethora of advanced wireless technologies that will bring new levels of performance and efficiency. The next section (Section 5) will explore these advanced techniques with a focus of key features being defined as part of 3GPP Release 15. It is important to note that the Release 15 specification for 5G NR is not expected to be frozen until 2018, but key decisions are already made during the study item phase that turns into the work item phase in March 2017. Therefore, the 5G NR design elements presented below represent Qualcomm's view based on current status in 3GPP.

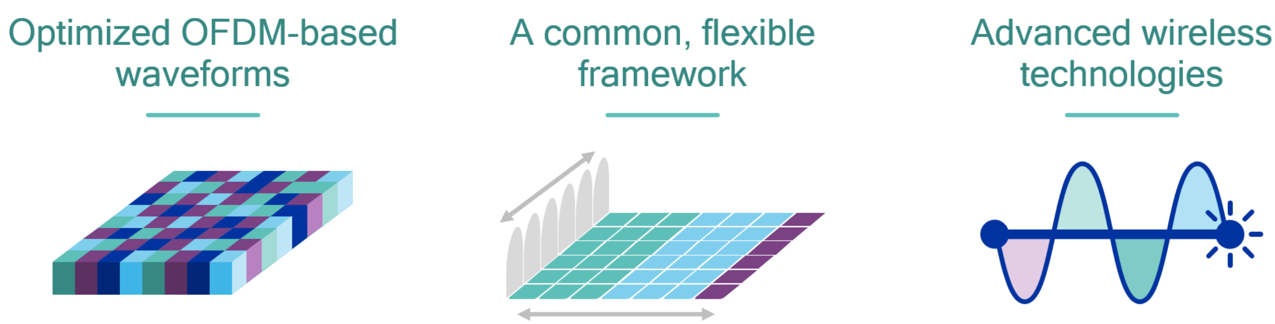


Figure 9: 5G NR foundational design elements

4.1 Optimized OFDM-based waveforms and multiple access

One of the foremost decisions for designing a unifying 5G air interface is the choice of radio waveform(s) and multiple access technique(s). Not only will they need to deliver high performance at low complexity, but they must also be capable of supporting (and multiplexing) all the envisioned 5G use cases efficiently. Qualcomm Research has been designing the new 5G air interface for many years, and has published a detailed analysis on the different waveform and multiple access techniques that were considered. This whitepaper will provide a summary of this, but the complete research can be found in the 5G Waveform & Multiple Access Techniques Whitepaper.

Based on this research, the OFDM family is the right choice for 5G enhanced mobile broadband and beyond. This is notable, as this will make 5G the first mobile generation that will not be based on a totally new waveform and multiple access design. Instead, 5G NR will build upon OFDM, which both LTE and Wi-Fi use today, to adapt to meet the extreme variation of 5G requirements. Key benefits of the OFDM family that make it ideal for meeting 5G requirements are:

- *Low complexity:* it enables low-complexity receivers (e.g., mobile device), even when scaling to wider bandwidths – lowering device cost.
- *High spectral efficiency:* it allows for low-complexity MIMO implementation that can add more data streams easily – getting closer to Shannon's limit.
- *Low power consumption:* it can support single-carrier waveforms that have smaller power variations – optimizing PAPR[31] for uplink transmissions to deliver more power-efficiency.
- *Frequency localization*: OFDM allows for enhancements such as windowing/filtering, which can effectively minimize in-band and out-of-band emissions – critical for 5G service multiplexing.

The OFDM family can also efficiently coexist with other waveforms and multiple access schemes in the same framework; for example, supporting asynchronous, grant-free transmissions (e.g., RSMA[32]) for connecting the IoT and enabling mission-critical control communications.

4.1.1 Scalable OFDM numerology with scaling of subcarrier spacing

Today, LTE supports carrier bandwidths up to 20 MHz with mostly a fixed OFDM numerology - 15 kHz spacing between OFDM tones or sub-carriers[33]. 5G NR, on the other hand, will introduce scalable OFDM numerology to support diverse spectrum bands/types and deployment models. For example, 5G NR must be able to operate in mmWave bands that have wider channel widths (e.g., 100s of MHz). It is critical that the OFDM subcarrier spacing is able to scale with the channel width, so the FFT[34] size scales such that processing complexity does not increase exponentially for wider bandwidths.

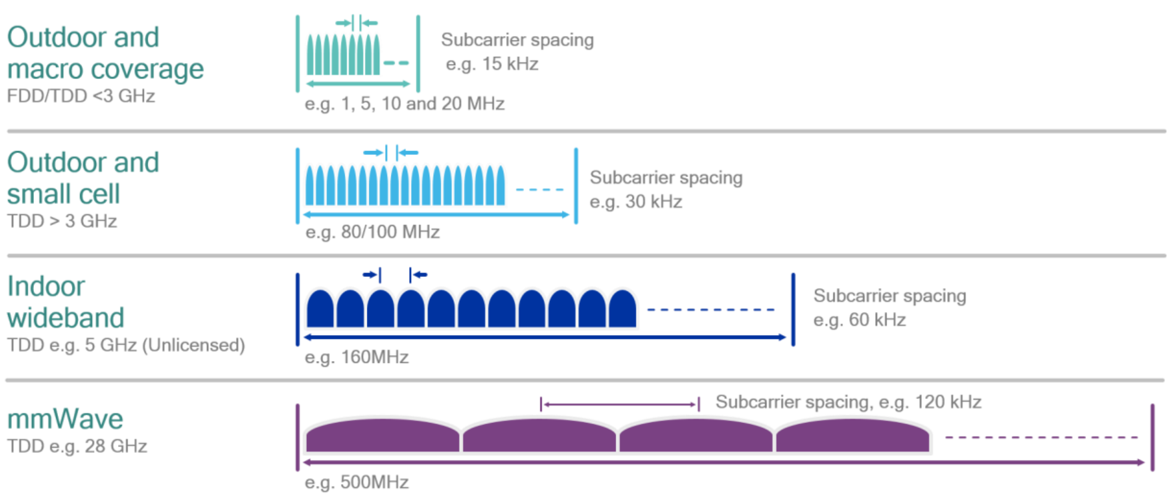


Figure 10: Example usage models, channel bandwidths, and subcarrier spacing

[31] Peak-to-average power ratio
[32] Resource Spread Multiple Access
[33] Some exceptions, e.g. NB-IoT as defined in 3GPP Release 13 can support single-tone transmissions at 3.75 kHz subcarrier spacing
[34] Fast Fourier Transform

In addition to supporting different channel widths for different/scalable deployment types, as seen in the above figure, 5G NR is also being designed to accommodate different numerologies in the same deployment – allowing services that use different bandwidths to efficiently multiplex in the integrated framework. For example, using scalable numerologies, smaller sub-carrier spacing provides larger cyclic prefix which can be used to support broadcast service (see Figure 11), in the same carrier. The 5G NR unified air interface will also allow carrier aggregation across numerologies, such as aggregating mmWave and sub-6 GHz carriers to bring more robust and higher performance connectivity.

4.1.2 Enabling efficient services multiplexing with windowed OFDM

In order to efficiently support multiplexing of 5G services, both in-band and out-of-band emissions must be kept to a minimum, so that services being transmitted on adjacent frequency channels do not interfere with one another. OFDM allows for waveform post-processing, such as windowing in the time domain or filtering in the frequency domain, to improve frequency localization. Figure 11 below showcases different 5G services, utilizing different 5G NR OFDM numerologies, multiplexed on the same frequency channel.

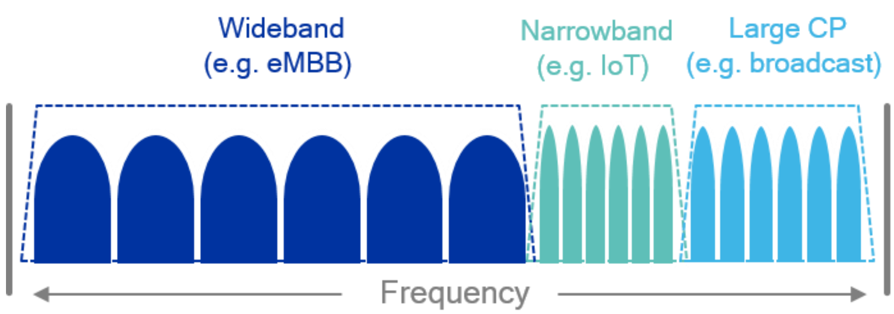


Figure 11: 5G NR will efficiently multiplex different services

Qualcomm is proposing CP-ODFM[35] with WOLA[36] windowing for 5G NR to meet this requirement. Extensive analysis and lab experiments have shown its ability to substantially increase frequency localization by effectively suppressing in-band and out-of-band emissions as shown below. Windowed CP-OFDM is a proven implementation that has been widely deployed in LTE systems today, and is recommended over alternative OFDM-based approaches, such as FBMC[37] and UFMC[38], which add complexity while only bringing marginal benefits. Further details on these alternative approaches are available in the Qualcomm Research Whitepaper previously mentioned.

[35] Cyclic-Prefix OFDM
[36] Weighted Overlap Add
[37] Filter Bank Multi-Carrier
[38] Universal Filter Multi-Carrier

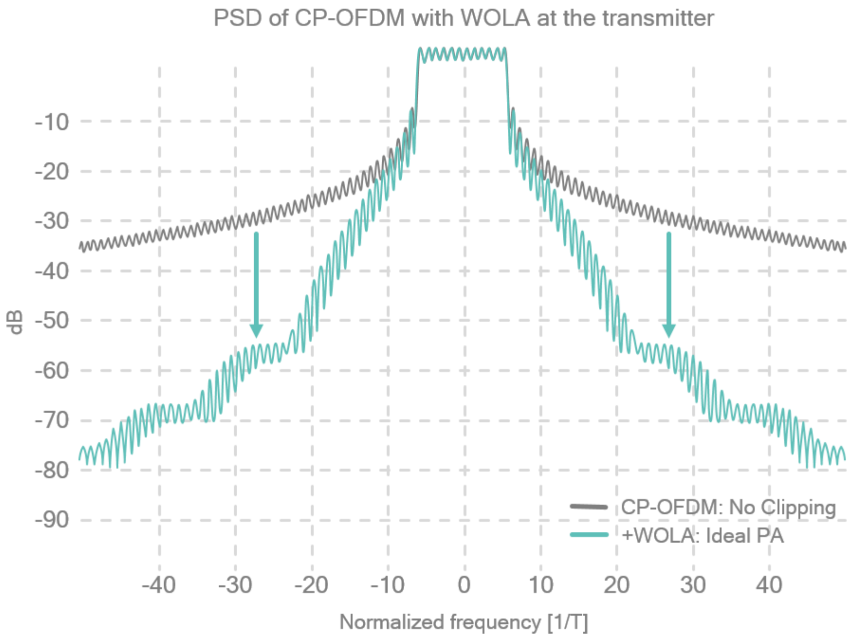


Figure 12: OFDM with WOLA windowing can substantially increase frequency localization[39]

4.1.3 Addressing 5G diverse services and deployments

While it is generally agreed upon by 3GPP member companies that OFDM-based waveforms and multiple access will be heavily utilized in 5G NR, the exact waveform and multiple access implementation is still under discussion. There are multiple OFDM variants being considered for the different 5G use cases and deployments. The following is a summary of Qualcomm's proposal:

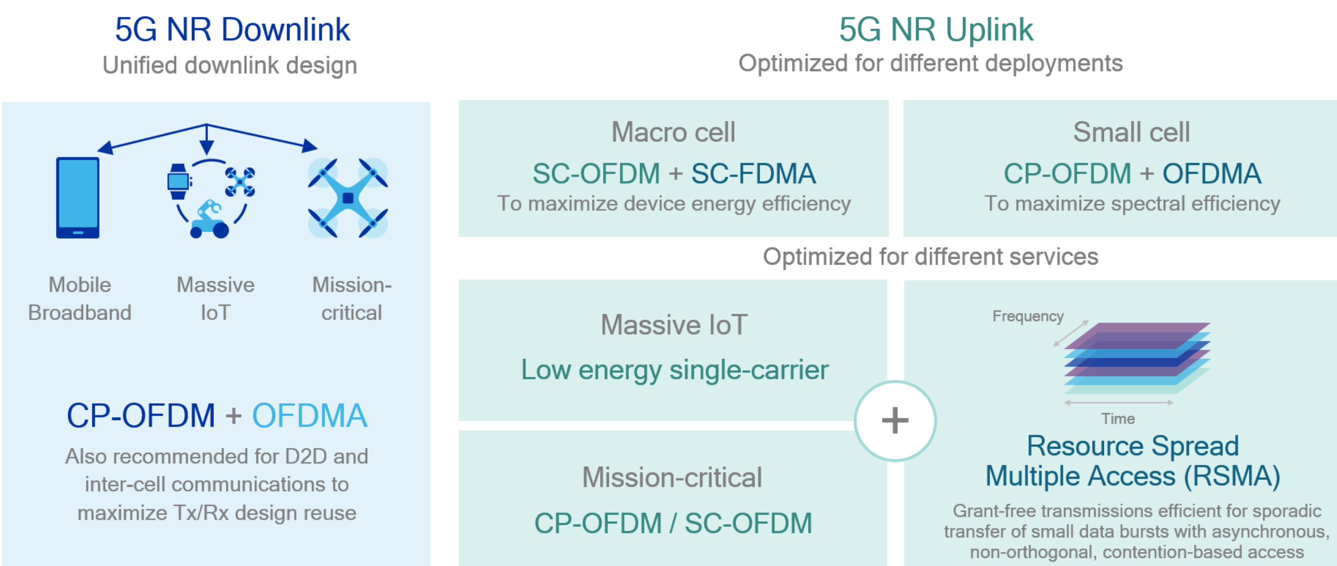


Figure 13: 5G NR waveform and multiple access design proposal

[39] Source: Qualcomm Research; assumptions: 12 contiguous data tones, 60 symbols per run, 1000 runs. CP length is set to be roughly 10% of the OFDM symbol length. For Tx-WOLA, raised-cosine edge with roll off α≈0.078 is used.

For downlink transmissions, 5G NR networks can benefit from the simplicity of having a unified waveform and multiple access design across all services and deployments. Qualcomm's recommendation is to adopt CP-OFDM[40] with windowing, which is heavily utilized in LTE systems today, combined with OFDMA[41] multiple access. As covered earlier, this established approach meets 5G requirements for high spectral efficiency, low complexity and efficient MIMO implementation, while providing a solution for OFDM frequency localization. Alternative OFDM-based approaches add complexity in the form of radio design and multiplexing, with marginal benefits in realistic implementations. The same design is also recommended for device-to-device and inter-cell communications, allowing for maximum transmitter and receiver design reuse.

For uplink transmissions, 5G NR will deliver different waveforms and multiple access optimized for different deployments.

- *Macro cell wide-area deployments:* A single-carrier OFDM-based waveform, SC-OFDM[42], and multiple access, SC-FDMA[43], can deliver smaller peak-to-average power variations (i.e., lower PAPR) suitable for battery-operated devices – utilized in LTE systems today.
- *Small cell local-area deployments:* Spectral efficiency is a higher priority than PAPR, making CP-OFDM and OFDMA (as used in downlink) the right choice.

As well as optimized uplink waveforms and multiple access for difference use cases:

- *Low-throughput IoT use cases:* 5G NR can consider low-energy single carrier waveform such as SC-FDE[44] or GMSK[45] optimized for low through-put, narrowband implementation. Additionally, new techniques such as RSMA can enable grant-free uplink transmissions (OFDMA requires scheduling of data transmissions to maintain orthogonality) that are more efficient for sporadic transfer of small data bursts.
- *High-reliability, low-latency Mission-Critical use cases:* Grant-free RSMA uplink transmissions can also facilitate mission-critical services defined by small data bursts that may occur at any time and must be transmitted as soon as data is available (i.e., cannot afford waiting to be scheduled). In this case, CP-OFDM and/or SC-OFDM waveforms can be utilized so that the mission-critical services can be efficiently multiplexed with other 5G services (e.g., mobile broadband) through a concept called traffic puncturing that will be discussed in more detail later in this whitepaper.

4.2 A flexible framework with forward compatibility

Supporting the wide range of 5G services and devices requires more than optimized waveforms and multiple access. 5G NR is being designed with a flexible frame structure to efficiently multiplex diverse 5G services and provide forward compatibility for future ones. This equates to flexibility not only in the frequency domain, as discussed earlier with scalable OFDM numerology, but also in the time domain. The 5G NR framework will be able to support the diverse services, features and deployment scenarios envisioned for 5G. Some high-level features of this new flexible framework are described in this section.

[40] Cyclic Prefix Orthogonal Frequency Division Multiplexing – also with time-domain windowing as common in LTE systems today
[41] Frequency Division Multiple Access
[42] Single-carrier Orthogonal Frequency Division Multiplexing
[43] Single-carrier Frequency Division Multiple Access
[44] Single-carrier Frequency Domain Equalization
[45] Gaussian Minimum Shift Keying

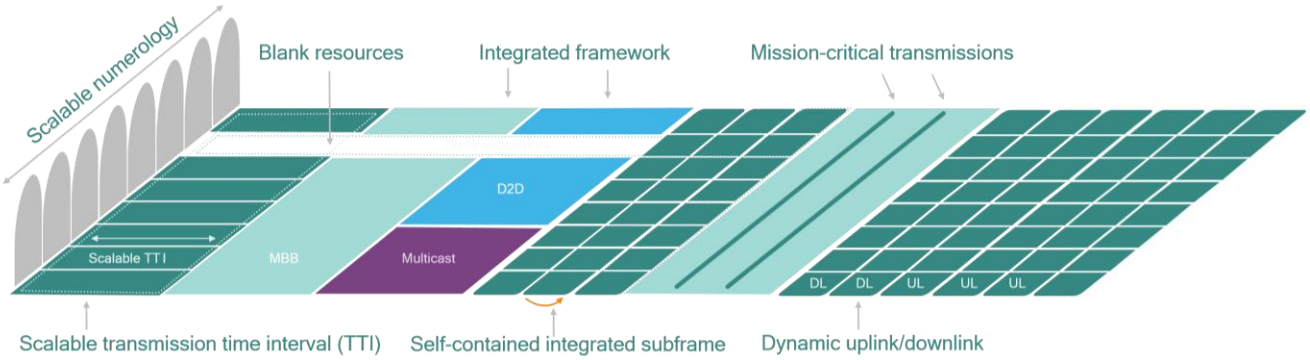


Figure 14: Scalable framework that can efficiently multiplex envisioned and future 5G services

4.2.1 Scalable Transmission Time Interval (TTI)

In the time domain, 5G NR will enable scalability to latencies much lower than what's possible in today's LTE networks. Today, LTE supports a fixed TTI of 1 ms. In the LTE evolution path, there is an ongoing Work Item on latency reduction in 3GPP. Though the technical details are still under discussion, the design target for one-time transmission latency is 8 shortened TTI (sTTI, 1.14ms) with 143 µs sTTI. To better support service with long latency requirement, the 5G NR flexible frame structure is being designed with TTI that will scale up and down, depending on specific service requirements. This flexibility allows the air interface to optimize for lower latencies using shorter TTI (e.g., 100s of µs) or trading off for higher spectral efficiency for delay-tolerant use cases with a longer TTI.

In addition to a scalable TTI, 5G NR will also support service-aware TTI multiplexing on the same frequency that allows transmissions with different TTIs to start on integer symbol boundaries instead of a subframe boundary (i.e., 1ms). For instance, a high-QoS mobile broadband service may choose to utilize a 500 µs TTI instead of a standard, LTE-compatible 1ms TTI/subframe, while another latency-sensitive service further shortens its TTI to just 2 symbols (e.g., ~140 µs). Instead of requiring the second, latency-sensitive transmission to wait until the beginning of the next subframe (i.e., 500 µs later), it can begin as soon as the previous transmission is completed, on the symbol boundary, thereby eliminating a waiting period. As shown on the right hand side of Figure 15, symbols across different 5G NR numerologies are designed to align at the symbol boundaries, which is critical for this efficient multiplexing of long and short TTIs.

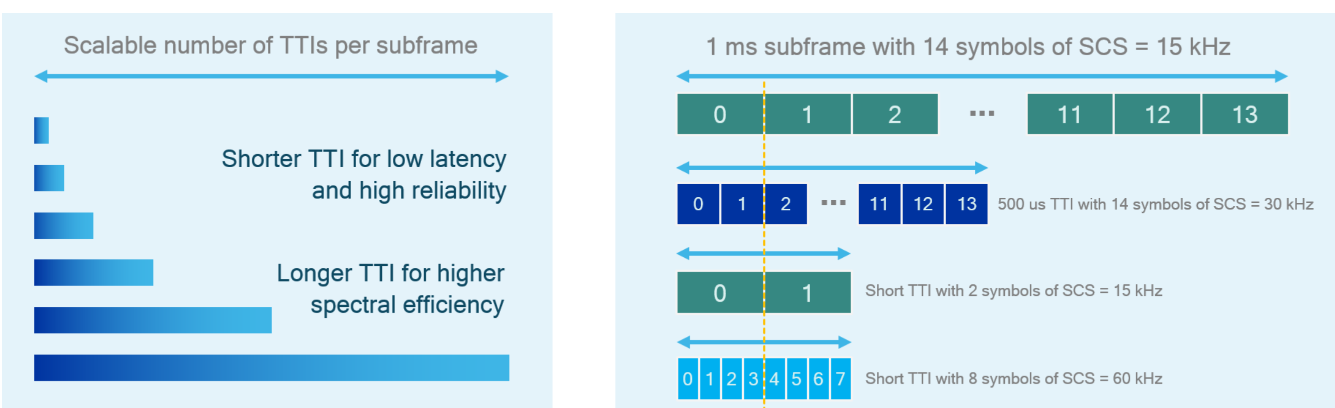


Figure 15: Scalable TTI for diverse latency and QoS requirements, also enables efficient TTI multiplexing

4.2.2 Self-contained integrated subframe

The self-contained integrated subframe is another key enabler for lower latency, forward compatibility, and many new 5G NR features. The lower latency is achieved by having the data transmission and its acknowledgement all contained in the same subframe. Figure 16 shows an example of a TDD downlink-centric subframe, where data transmission is from the network to the device and the acknowledgement is sent by the device back to the network in the same subframe. With the 5G NR self-contained integrated subframe, each TTI is now a modular transaction (e.g., DL grant → DL data → Guard Period → UL ACK) that gets completed within that time period.

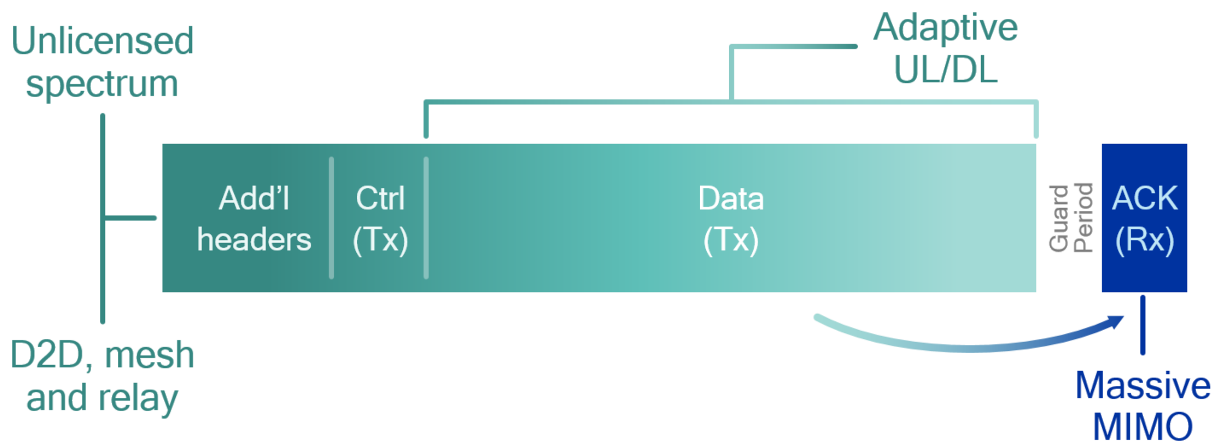


Figure 16: Self-contained integrated subframe design (e.g., TDD downlink)

The modular aspect of the self-contained integrated subframe design also allows for different types of subframes to be multiplexed for new services that are introduced in the future. This, along with the ability for the 5G NR framework to support blank subframes and blank frequency resources, enables a forward-compatible 5G NR design for easily adding future features/services to be deployed in the same frequency in a synchronous and asynchronous manner.

The subframe can also contain additional headers that can be used to provide additional information for the transmission. For example, operating in unlicensed spectrum requires typically requires the support LBT[46] to ensure fair sharing across different users. These LBT headers, sent by the network, are used by downlink devices to assess channel availability for data transmission. And when used in device-to-device communications, these headers can indicate the link direction and provide scheduling information for the directly connected devices.

The self-contained subframe also plays an integral role in enabling advanced 5G NR antenna techniques, such as massive MIMO. In the downlink, in order for a transmitting cell to more efficiently direct RF energy to a device, it needs to continuously evaluate link quality and make necessary beamforming adjustments. The feedback mechanism is provided by the transmission of common uplink burst, which carries uplink control information (e.g., the ACK) and the uplink sounding reference signals. More accurate and timely knowledge of downlink channel can be obtained at the base stations thanks to the channel reciprocity, which enables the use of uplink sounding reference signal for downlink channel estimate in a TDD

[46] Listen-Before-Talk

system. Note that in addition to the uplink control information and sounding signals, common UL burst can also be used to carry time critical data, e.g., TCP ACK.

A downlink-centric subframe can be generally divided into three main components – a downlink control burst, a downlink data burst, and an uplink control burst that follows a guard period. An uplink-centric subframe has a similar structure, with similar downlink and uplink control bursts at the beginning and the end of the subframe, but with an uplink data burst that follows a guard period. This is illustrated in Figure 17. This design reduces downlink and uplink control channel interferences by requiring all control bursts to be transmitted in the same direction across neighboring cells, thereby allowing more robust link direction switching. The dynamic configuration of downlink- or uplink-centric subframes increases overall network efficiency and capacity by allowing faster switching based on network traffic conditions.

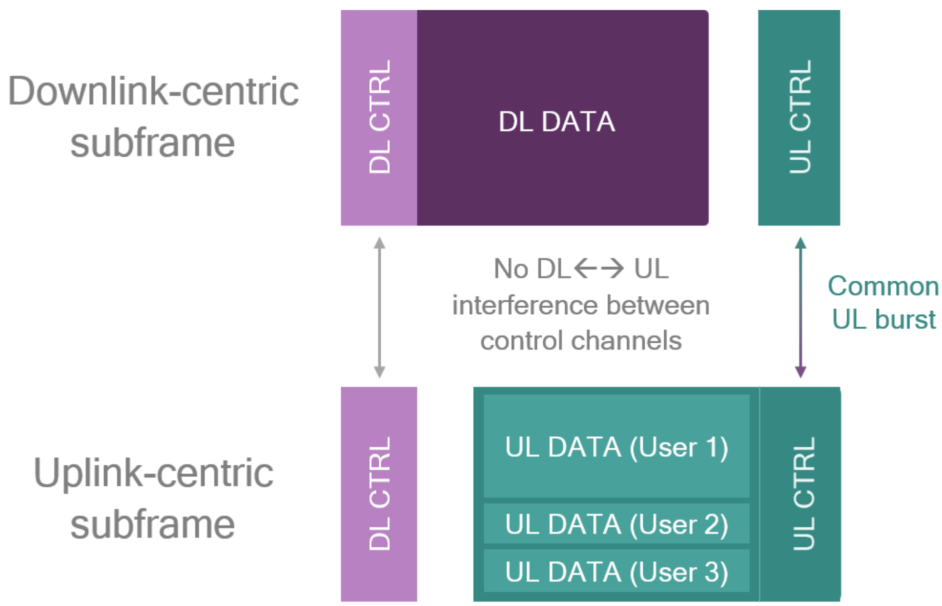


Figure 17: Downlink- and uplink-centric self-contained integrated subframe

4.3 Delivering additional benefits with the new 5G network architecture

The 5G NR air interface is just one component of the overall 5G innovation platform, and many enhancements will also come with the new 5G NextGen core network. It is being designed to work seamlessly with 5G NR to bring new levels of flexibility, scalability, and efficiency. And just like 5G NR, the NextGen core network will also need to adapt to meet the diverse set of requirements driven by the different 5G services with the ability to dynamically orchestrate services. For instance, the NextGen core network will leverage virtualized network functions to create optimized network slices for a wide range of services hosted on the same physical network, and each network slice can be configured independently to provide end-to-end connectivity with 5G NR that is optimized for the application's needs. In addition to allowing more efficient resource allocation and utilization, the 5G NextGen core network will also deliver enhancements such as enabling flexible subscription models and dynamic creation of services that are especially beneficial for connecting the wide range of new services and devices.

5 Advanced wireless technologies to enable diverse services

5G NR will bring many new inventions across a diverse set of services. This section will highlight some of the key technologies that will allow 5G NR to achieve new levels of performance and efficiency. The focus will be on Release 15 features for enhancing mobile broadband with a brief summary of some key features being envisioned for mission-critical control and massive IoT.

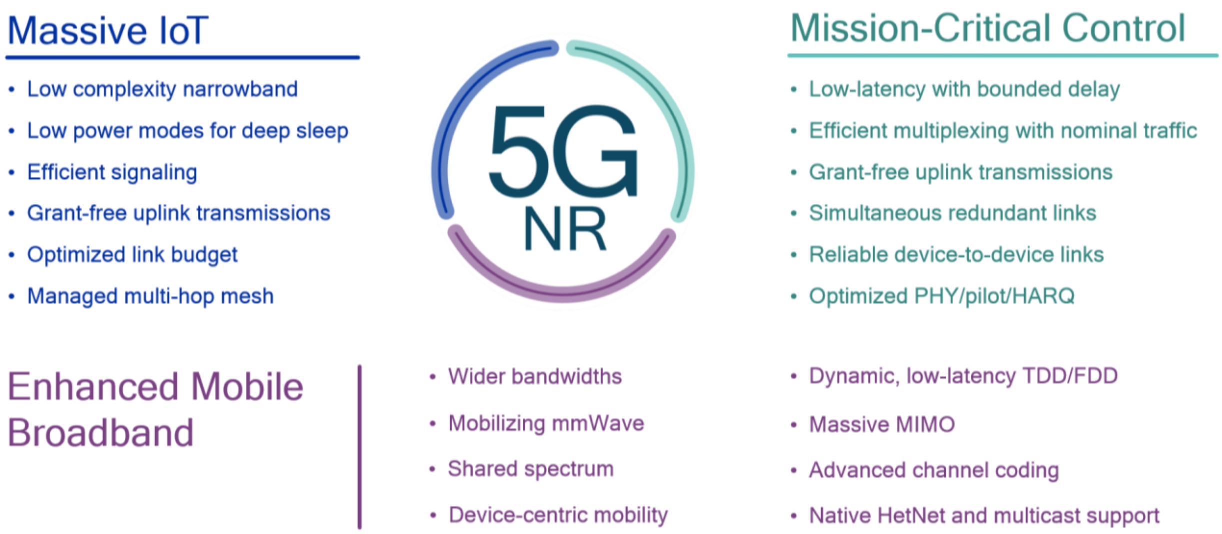


Figure 18: 5G NR design inventions across diverse services

5.1 Enhancing mobile broadband with new levels of performance and efficiency

5G enhanced mobile broadband is ushering in the next era of immersive experiences that will require new levels of performance and efficiency, including higher throughput, lower latency, more capacity, higher mobility, and more uniformity at a lower cost. Qualcomm is at the forefront of driving many new technology inventions that will make fiber-like wireless broadband a reality. This is exemplified by our sub-6 GHz prototype system that tracks 3GPP progress closely and demonstrates our innovative 5G NR designs. It is an end-to-end system that is capable of delivering multi-Gbps throughput at low latency, achieved through a highly efficient FFT implementation, wider carrier bandwidth (e.g., 160 MHz), higher-order modulation, advanced channel coding, and a self-contained integrated subframe design. The prototype is initially designed to operate at 3.5 GHz, but is capable of scaling to other frequencies. The following subsections highlight many of the new 5G NR technologies that will enable next-generation mobile broadband services.

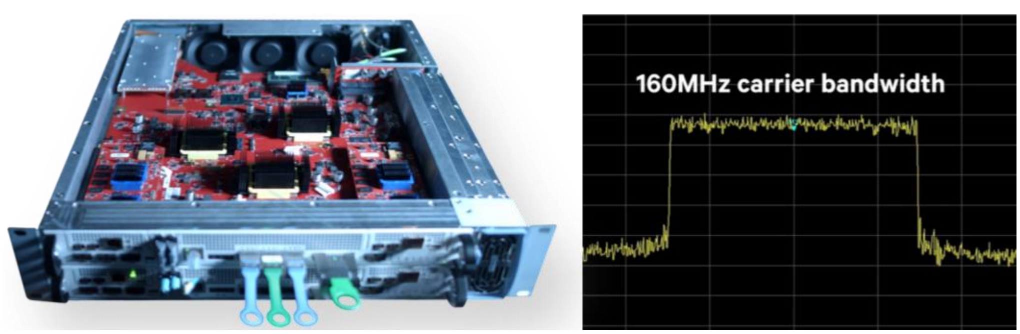


Figure 19: Qualcomm sub-6 GHz prototype system demonstrating wider carrier bandwidth

5.1.1 Gigabit LTE is an essential pillar for the 5G mobile broadband experience

Just like previous mobile generational transitions, the proliferation of the new 5G NR networks is unlikely to happen overnight. For this reason, Gigabit LTE and multi-connectivity will be essential to the viability of delivering seamless Gigabit-class connectivity during the early years of 5G, and multimode solutions are expected to play an important role in ensuring a smooth 5G transition. As an example, a mobile network operator may initially deploy 5G mmWave hotspots to address the immediate capacity needs in hyper-dense urban areas (e.g., at a stadium or in downtown city center), and leverage the existing Gigabit LTE networks to provide seamless 4G/5G mobility support and wide area coverage.

Today, we are delivering Gigabit LTE by pioneering many new LTE Advanced Pro technologies. We are evolving carrier aggregation to achieve wider bandwidths (e.g., 80 MHz), extending LTE into shared and unlicensed spectrum (e.g., LAA), supporting higher-order modulations (e.g., 256-QAM), and leveraging many more antennas (e.g., 4x4 MIMO) than before. As of November 2016, we have announced the first commercial mobile device that supports Gigabit LTE, powered by Snapdragon X16 Gigabit LTE modem.

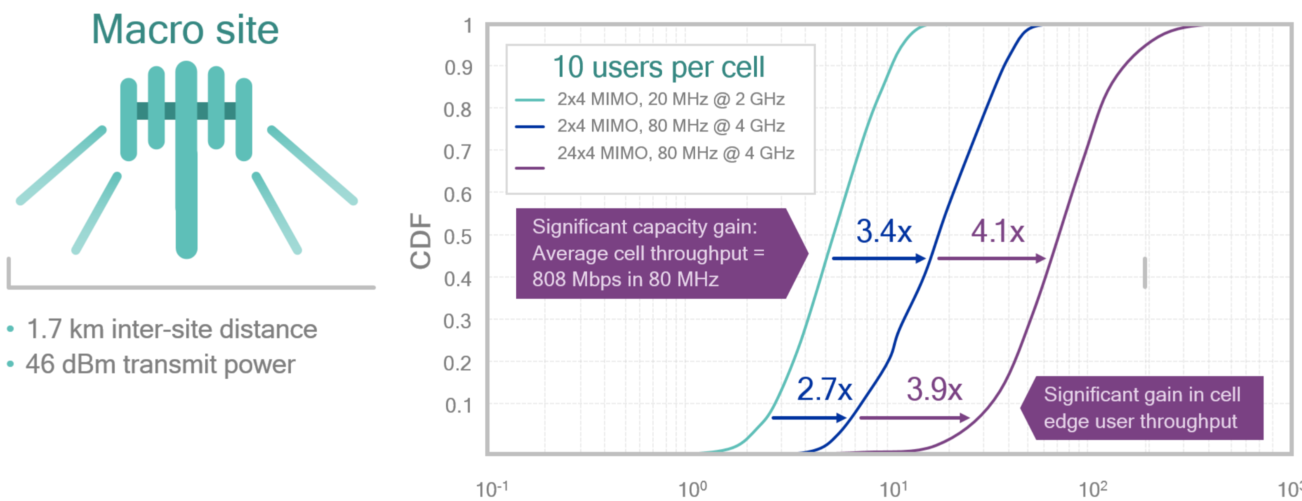
5.1.2 Massive MIMO to bring increased capacity and a more uniform user experience

One key innovation area in wireless communications is in advanced antenna technologies. By using more antennas intelligently, one can improve both network capacity and coverage. That is, more spatial data streams can significantly increase spectral efficiency (e.g., with MU-MIMO[47]), allowing more bits to be transmitted per Hertz, and smart beamforming can extend the reach of base stations by focusing RF energy in specific directions. In LTE today, networks are evolving from 2x2 to 4x4 MIMO, with even more antennas in sight. However, there is an intrinsic limitation on how many antennas one can realistically fit onto a device, especially at lower frequencies where the antennas are large due to longer wavelength. But one way to further increase capacity without adding more device antennas is to have more antennas in the base stations.

By continuing to evolve FD-MIMO[48] that was first introduced in LTE Advanced Pro, 5G NR will support massive MIMO that can utilize an even larger number of antenna elements, supporting up to 256 as currently defined. The 2D antenna arrays are capable of 3D beamforming in both the azimuth and elevation plane, and test results have shown significant gains in both capacity and cell edge user throughput - key to bring a more uniform mobile broadband user experience.

Massive MIMO is also a key enabler for opening up the higher frequency bands in the sub-6 GHz spectrum. With intelligent beamforming and beam-tracking, it is possible to reuse existing cell sites (e.g., at 2 GHz) and transmit power for new macro cell networks that operate at higher frequencies (e.g., at 4 GHz). Figure 20 shows an over 4x improvement in average capacity going from a 2x4 MIMO to a 24x4 massive MIMO setup, and almost the same level of throughput enhancements for users at the cell edge.

[47] Multi-User MIMO
[48] Full-Dimensional MIMO



Source: Qualcomm Technologies, Inc. simulations; Macro-cell with 1.7km inter-site distance, 10 users per cell, 46 dBm Tx power at base station, 20MHz@2GHz and 80MHz@4GHz BW TDD, 2.4x Massive MIMO

Figure 20: Massive MIMO increases capacity and cell edge performance

5.1.3 Mobilizing the mmWave to bring extreme capacity and speeds

5G NR will not only enable the use of higher frequencies in the 3 to 6 GHz band for macro/small cell deployments, but it will also open up new mmWave opportunities for mobile broadband. The abundant spectrum available at these high frequencies is capable of delivering extreme data speeds and capacity that will reshape the mobile experience. However, mobilizing the mmWave comes with its own set of challenges. Transmissions in these higher bands suffer from significantly higher path loss as well as susceptibility to blockage, while meeting the power and form-factor requirements of mobile devices has also proven to be challenging. Thus, traditional mmWave implementations have been limited to mostly stationary applications such as shorter-range wireless docking, enabled by technologies like 802.11ad that operates in the 60 GHz band.

With the recent advancements in signal processing and antenna technologies, the idea of mobilizing the mmWave is no longer out of reach. By utilizing a large number of antenna elements in both the base station and the device, along with intelligent beamforming and beam-tracking algorithms, 5G mmWave can provide increased coverage, reduced interference, and a continuous connectivity experience even for NLOS[49] communications and device mobility. Moreover, 5G NR will also leverage multi-connectivity with 5G sub-6 GHz and/or Gigabit LTE to improve overall link robustness and to help achieve faster system acquisition. Additional design considerations have also been incorporated to enable easy deployment of dense mmWave small cells, such as with the support for integrated access and backhaul.

Qualcomm has been at the forefront of mmWave technologies. Having commercialized 802.11ad 60 GHz chipsets for mobile devices, Qualcomm is also developing and testing early mmWave prototype that operates at 28 GHz band today (scalable to other frequencies). With wider bandwidths, it can easily deliver extreme data rates, but more importantly, it supports robust mobility and handovers that are made possible with our intelligent beamforming and beam-tracking algorithms. Field tests and simulations have shown line-of-sight coverage of ~350 meters and non-line-of-sight coverage of ~150 meters in a dense urban deployment. Paving the path to commercializing 5G mmWave, we have also recently announced

[49] Non-Line-of-Sight

our first 5G mmWave modem, the Snapdragon X50, which will become available starting in second half of 2017 to enable early 5G mmWave trials and commercial fixed wireless deployments.

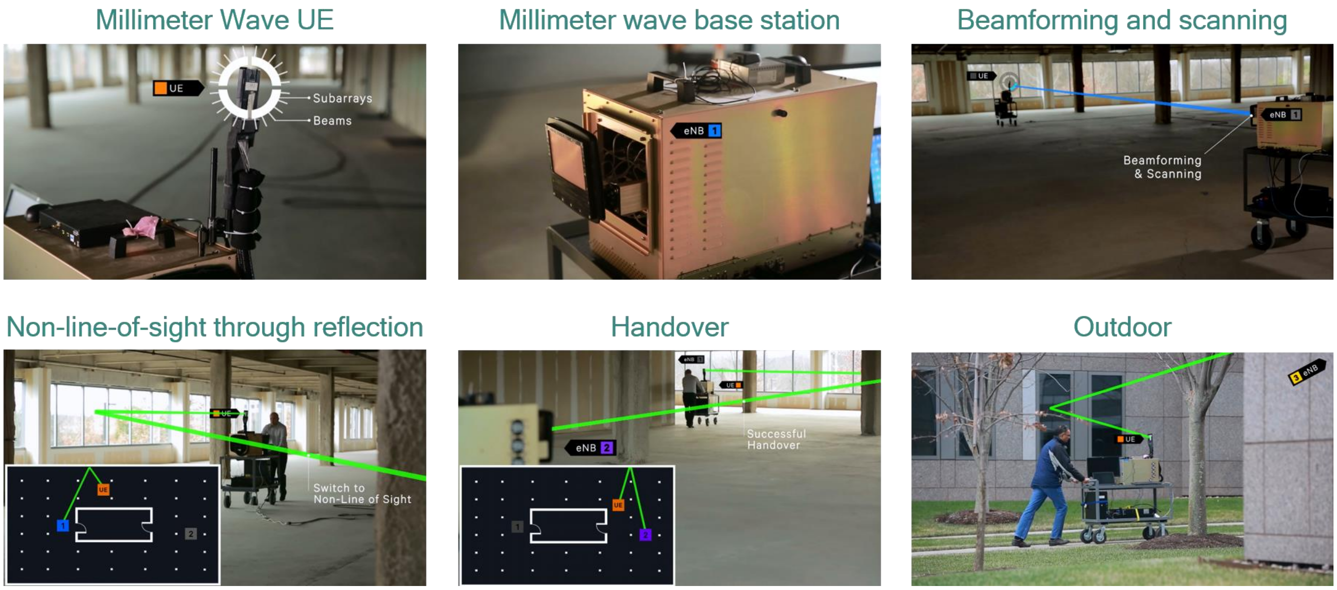


Figure 21: Qualcomm mmWave prototypes demonstrating NLOS operation and mobility

For more detailed analysis on how mmWave can enable 5G mobile access, please refer to the Heavy Reading Whitepaper.

5.1.4 Spectrum sharing techniques to unlock more spectrum, extend the 5G network

Access to shared and unlicensed spectrum will extend 5G into a wider range of deployments and create opportunity for innovations. It will enhance mobile broadband deployments anchored in licensed spectrum by aggregating spectrum for extreme bandwidths (e.g., LAA), but also expand to new types of deployments such as enhanced local broadband and IoT verticals (e.g., MulteFire). 5G NR is designed to natively support all spectrum types, and through forward compatibility, it has the flexibility to take advantage of new spectrum sharing paradigms. Today, we are pioneering spectrum sharing technologies such as LTE-U, LAA, LWA, CBRS, LSA, and MulteFire, and 5G NR will expand on these LTE technologies and innovate around new spectrum sharing paradigms. One example of this is to further enhance LAA to support wider bandwidths based on the new 5G NR numerologies, allowing even more efficient use of unlicensed spectrum to achieve higher capacity.

5.1.5 Advanced channel coding design to deliver faster speeds at lower complexity

With new kinds of mobile broadband services emerging, such as immersive Virtual Reality, there is a need for the 5G NR air interface design to deliver even higher performance and efficiency than what's possible in today's LTE networks. This calls for a new channel coding design that can more efficiently deliver multi-Gbps throughput, especially using larger coding block sizes that are suitable for mobile broadband traffic profiles, while at the same time improving the existing performance envelope relative to LTE Turbo codes. On this front, Qualcomm has led the industry harmonization of adopting an advanced LDPC channel coding scheme, which can provide full rate compatibility with incremental redundancy (IR) HARQ, flexibility for blocklength scaling and fine rate granularity. An example of the performance is illustrated below in Figure 22. The new codes can provide significant efficiency gain over LTE Turbo codes, and the easily parallelizable decoder design can be scaled to achieve higher throughput at low complexity and latency. LDPC codes can also provide an effective forward-compatible architecture for mission critical and massive IoT traffic, since the same LDPC codes or even modified LDPC codes can efficiently re-use the hardware from mobile broadband services yet still further enhance latency, reliability, and performance needed by new services.

For very small blocklengths such as 80 bits or less, which are often used in physical control channels, Qualcomm has shown that alternative coding designs such as Polar Codes[50] as well as enhancements to TBCC[51] can be employed to improve the performance relative to LTE. Polar codes in particular can exhibit slightly better performance when compared to TBCC as shown in Figure 22, and as a result of this observation the industry has converged upon using Polar codes for the physical control channels in 5G NR mobile broadband services. The channel coding schemes for the control channels of mission-critical and massive IoT services are still under study.

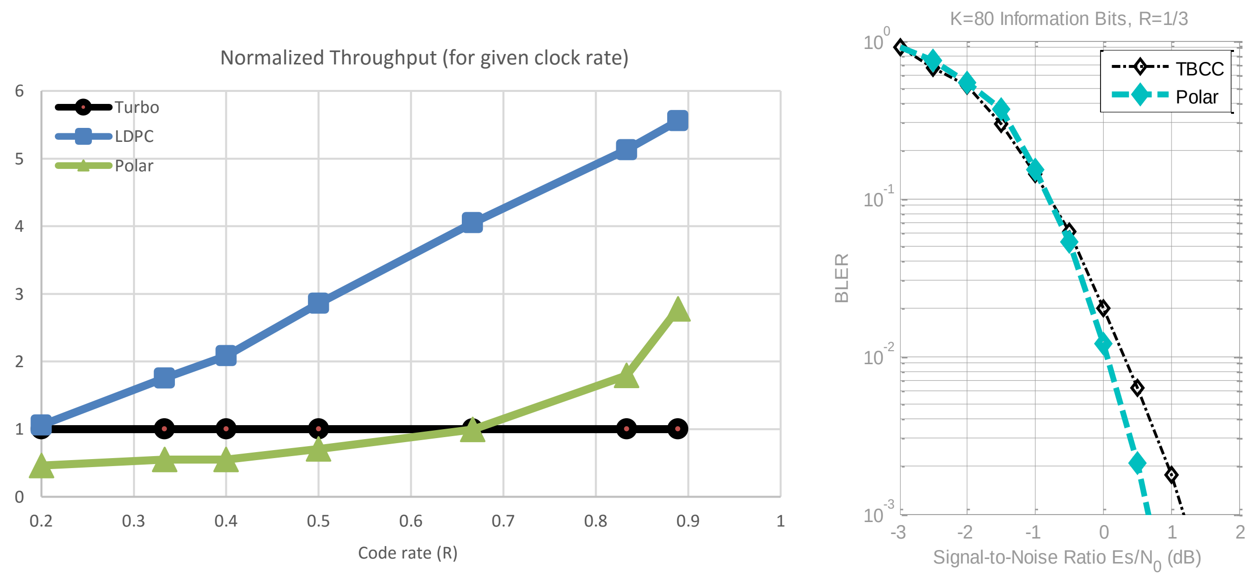


Figure 22: Channel coding performance at large data blocklengths (left) and small control blocklengths (right)

5.1.6 Device-centric mobility to improve energy and overhead efficiency

In addition to downlink-centric mobility, 5G NR will consider uplink- or device-centric mobility that allows the device to send out periodic reference signals for the access network to monitor, and with this information, the network can trigger cell reselection or handover based on the uplink signal strength measurement. This offloads the device from monitoring and processing reference signals from all nearby cells, thereby decreasing both signaling and processing overhead. This is in contrast to LTE, where device mobility is driven by a more overhead-heavy process that involves the device measuring the signal strength of a downlink reference signal sent by the access network, which requires overhead processing on the device. To optimize even further, the 5G network will also reduce the amount of broadcasts.

[50] Polar Codes are based on the seminal work from Arikan (IT Transactions 2009, vol 55 issue 7) along with pioneering enhancements to code construction and list decoding from Tal and Vardy (IT Transactions 2010, vol 61 issue 5).

[51] Tail-Biting Convolutional Coding

Instead of sending system information regardless of device presence, the 5G network will only send out minimum system information periodically, and on-demand system information upon requests from devices. The reduction in signaling and processing overhead will enable longer battery life on the devices as well as making the network more energy efficient; in addition, the new device-centric mobility design also contributes to supporting seamless handovers at higher speeds (e.g., up to 500 km/h).

5.2 Enabling new mission-critical services where failure is not an option

5G NR will expand beyond the capabilities and efficiencies offered by 4G LTE to address the requirements of mission-critical control - extreme low-latency, high reliability, high availability, and strong security. As previously discussed, 5G NR is capable of delivering lower latency down to 1 ms by scaling down the TTI, while also providing network reliability and availability through links with guaranteed packet loss within a delay bound (e.g., $< 10^{-5}$ at 1ms), and with multi-connectivity to create redundant links . 5G NR is being designed to allow efficient mission-critical traffic puncturing, so other services can coexist in the same network deployment.

5.2.1 Efficient multiplexing of mission-critical transmissions with scheduled traffic

5G NR is being designed to support mission-critical services that may require the network to allow time-sensitive transmissions to take higher priority over nominal traffic (e.g., mobile broadband). Since these mission-critical transmissions are asynchronous and can occur at any time, they would essentially “puncture” an on-going, scheduled transmission. In order to minimize performance impact, 5G NR is considering enhancement to PHY design, as well as an additional layer of forward error correction coding in the MAC layer, to allow punctured traffic to self-recover without triggering an excessive number of retransmissions. Simulations and extensive analysis have shown this design to be more flexible and efficient than using dedicated, potentially under- or over-utilized frequency resources (e.g., FDM[52]) for mission-critical transmissions.

5.2.2 Providing redundant links to mission-critical devices with multi-connectivity

5G NR will also support redundant connections through multi-connectivity, allowing devices to connect across multiple 5G network nodes, or even 4G LTE or Wi-Fi depending on reliability level needed, simultaneously to enhance reliability. In addition, mission-critical devices can also leverage device-to-device communications to enable direct exchange of real-time information when they are temporarily out of network coverage. The use of a direct link in a multi-connectivity framework is pioneered by C-V2X as part of LTE Advanced Pro, and this concept can be further expanded with multi-hop mesh in 5G NR, where an out-of-coverage device can still transmit to or receive from the network via a neighboring device that is connected to the network.

5.2.3 Cellular Vehicle-to-Everything technologies to enable safer vehicles

C-V2X is a key technology enabler for safer, more autonomous vehicles of the future. It gives vehicles the ability to communicate with each other (V2V), to pedestrians (V2P), to roadway infrastructure (V2I) and to the network (V2N). C-V2X complements the capabilities of evolving ADAS[53] by providing vehicles 360 degree non-line-of-sight awareness, as well as the ability to gather data from further ahead to deliver a more predictable driving experience. 3GPP Release 14 has defined a broad set of use cases, and 5G NR will build upon the existing specification to bring even more enhancements to C-V2X, such as

[52] Frequency Division Multiplexing
[53] Advanced Driver Assistance Systems

additional safety features that will enable the next-generation use cases like high-density platooning and V2X augmented reality.

5.2.4 Real-time command-and-control for cellular drone communications

Cellular connectivity is also playing a key role in safely coordinating drone operations and enabling a growing set of drone use cases within and beyond visual line of sight. With LTE establishing the foundation for mission-critical communications, 5G will bring the required ultra-high reliability, ultra-high availability, and strong end-to-end security for mission-critical drone use cases, when connectivity absolutely cannot fail or be compromised. More specifically, 5G will deliver more uniform throughput, coverage at all relevant altitudes, direct communication, and the ability to simultaneously serve a large number of drones. When the capabilities of 5G come into the picture, we envision fleets of drones flying autonomously, communicating, and adjusting behavior through real-time data inputs and sharing. For example, a team of autonomous drones can collaborate with each other to conduct search and rescue mission – first searching for and finding a lost hiker, then manipulating and lowering a net, and ultimately bringing the hiker to the nearest medical facility.

5.3 Intelligently connecting the massive Internet of Things

In addition to enabling mission-critical services, 5G NR is also being designed to connect the Internet of Things. 5G massive IoT will build upon the foundation established by NB-IoT and introduce new techniques to more efficiently connect the wide variety of IoT devices and services that make the best use of precious network and spectrum resources.

5.3.1 Establishing the foundation for Narrowband 5G with NB-IoT

In order to more efficiently support the large number of IoT devices, Release 13 of the 3GPP standard has defined and introduced NB-IoT, a narrowband technology that lowers device complexity, reduces power consumption, deepens coverage, and enables higher node density deployments. 5G massive IoT will build upon the foundation established by NB-IoT to deliver even more capabilities and higher efficiencies. In the meantime, NB-IoT will continue to evolve in Release 14 and beyond – bringing multiple enhancements such as adding voice support, enabling lower latency, providing location services, allowing device mobility, and supporting broadcast to facilitate efficient OTA (over-the-air) firmware updates. For more detailed information on LTE IoT, please refer to the Paving the Path to Narrowband 5G with LTE IoT Whitepaper.

5.3.2 A more efficient uplink transmission scheme for IoT with RSMA

In order for 5G NR to improve upon NB-IoT's ability to support even higher node density at lower complexity, Qualcomm is proposing a new uplink multiple access design called RSMA. As discussed previously, it is an asynchronous, non-orthogonal, and contention-based access protocol that will further reduce device complexity and signaling overhead by allowing devices, such as a massive number of sensors, to communicate with the network without prior network scheduling.

5.3.3 WAN-managed multi-hop mesh to extend network coverage

Another potential improvement area is for 5G NR to support even wider network coverage for the IoT. To extend coverage to the most extreme locations (e.g., hyper-remote, deep underground), Qualcomm is proposing the support of a new multi-hop mesh architecture that allows out-of-coverage devices to connect directly with devices that can relay data back to the access network. This essentially creates an edgeless network that extends coverage beyond the typical cellular access (e.g., base stations and small cells). This can also lower device power consumption, as an out-of-coverage device can now communicate with another device that is in closer proximity instead of trying to reach an access network that is farther away. In some cases, this can lead to a reduction in device cost, as a remote device (e.g., a water meter) may integrate a lower-cost PA[54], or eliminate the need for a PA altogether. More importantly, the 5G core network will also take on WAN management for both devices in access coverage as well as those supported by the peer-connected mesh network – key to simplify device deployment and management.

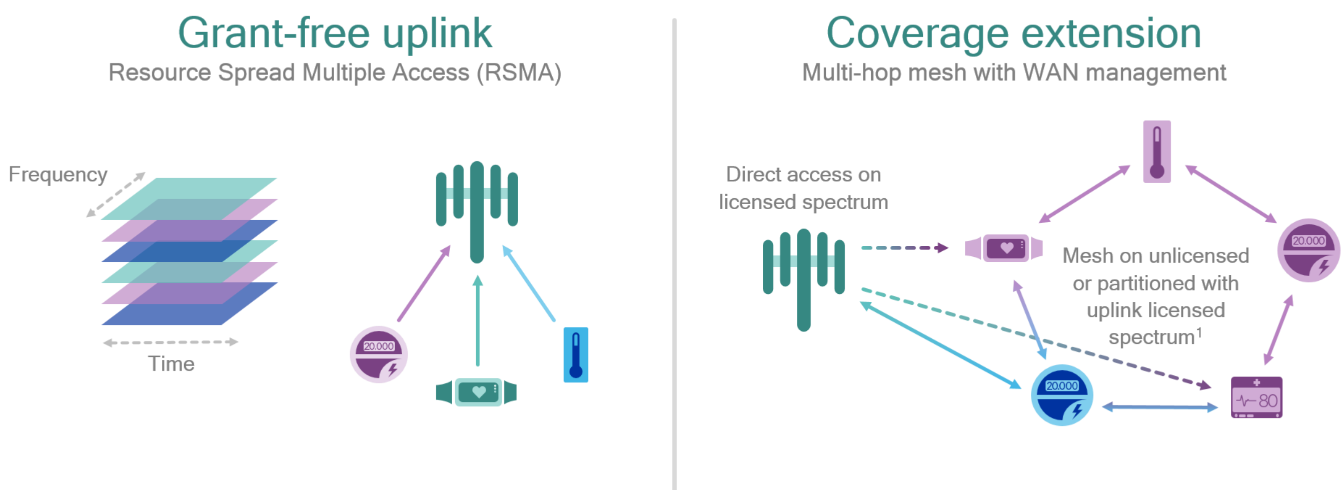


Figure 23: New 5G NR inventions to enable the massive Internet of Things

[54] Power amplifier

6 Conclusion

5G is a unifying connectivity fabric that will expand the value of mobile networks to take on a much larger role than previous generations, empowering many new connected services across an array of world-changing use cases. At the heart of 5G is the new 5G New Radio unified air interface that is being designed to meet the expanding connectivity needs in the next decade and beyond. The current schedule for the completion of Release 15 specification, the first phase of 5G NR, is estimated for June 2018; however, a three-to-six month acceleration in 3GPP schedule is expected due to strong industry interests, which will enable 5G NR commercial network deployments to start in 2019.

This 5G-connected world is quickly approaching and as we did in 3G and 4G, Qualcomm is leading the way. We have a proven end-to-end system approach, which is required to drive new technologies from concept to commercialization at a rapid pace and at a massive scale.

Figure 24: Making 5G a reality with an end-to-end system approach

We are working on many fronts to make 5G NR a reality, collaborating with industry leaders across the entire mobile ecosystem to accelerate the standardization of 5G NR in 3GPP, as well as developing prototypes and testbeds in both mmWave and sub-6 GHz that closely track 3GPP progress and can be used to demonstrate our innovative 5G NR designs. To ensure a timely launch, we are planning and executing on impactful technical trials with our ecosystem partners using our trial platforms to gain early learnings. And we are also accelerating 5G commercialization through our chipset leadership. We have announced our first 5G modem, the Snapdragon X50, that will not only enable early 5G mmWave trials and commercial fixed wireless deployments, but also paves the path to accelerate 5G NR – the global 5G standard that will make use of both sub-6 GHz and mmWave spectrum bands.

To learn more about 5G, please visit:

www.qualcomm.com/5G