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White Paper

Exploring 5G New Radio: Use Cases, Capabilities & Timeline

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5G New Radio for Performance & Flexibility

5G New Radio (a.k.a., 5G NR) is the name for the new air interface being developed to enable advanced 5G services. The radio is a critical component of 5G networks and is fundamental to determining the types of services 5G will be able to support.

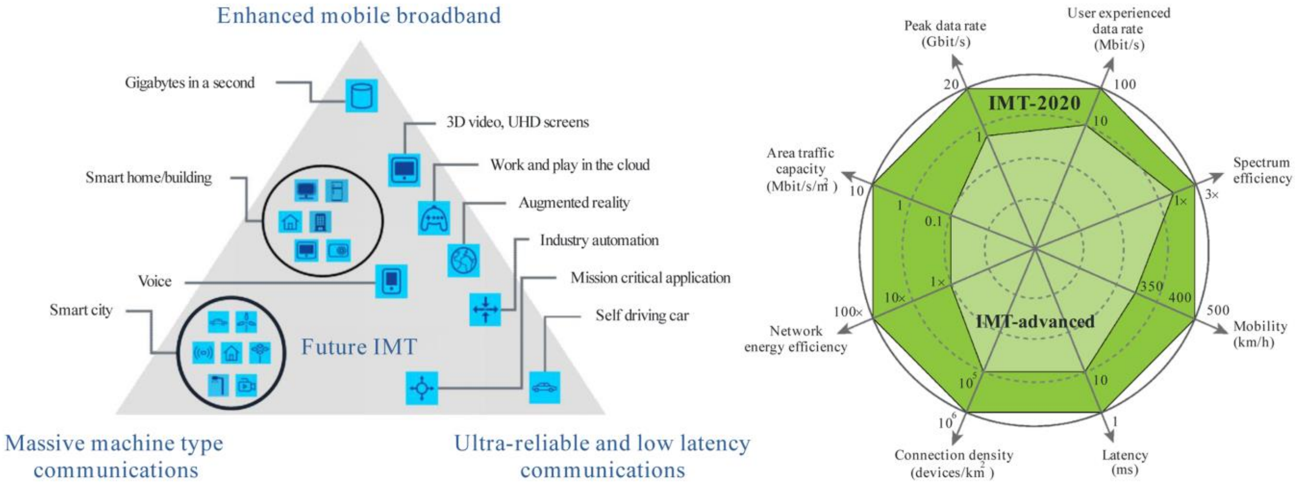
Development of NR is underway, both in R&D labs and in standards. Major industry players are investing substantial sums in research and product design and the first prototype systems are now available for testing and evaluation. In parallel, the global standards body, the 3GPP, is aiming to release its first NR specifications by mid-2018. The objective is to create a scalable air interface that can address the extreme variation of 5G applications and to develop a flexible design that will make 5G NR forward compatible to new service types in the future.

This white paper explores the key features of 5G NR, as understood at this stage of development. It addresses the capabilities NR will use to support diverse performance requirements at a low operational cost, with a focus on nearer-term deployment of enhanced mobile broadband (eMBB), and on how to make 5G NR wireless links indistinguishable from wireline broadband. It also discusses NR features that will enable innovative services and help insert 5G into new industrial value chains.

5G Use Cases & Performance Targets

High-level performance targets for 5G are shown in **Figure 1**. These targets were developed as part of the IMT-2020, the International Telecommunications Union (ITU) initiative to define "5G." They are mapped to three different classes of use case: (1) enhanced mobile broadband (eMBB); (2) massive machine-type communications (mMTC); and (3) ultra-reliable, low-latency communications (UR-LLC).

Figure 1: IMT 2020 Performance Targets



Source: ITU Recommendation ITU-R M.2083-0, September 2015

Each use-case class supports various different services with similar performance requirements – industrial automation and mission-critical communications both require ultra-low-latency, for example – while other services sit on the axes between points of the triangle. These performance requirements are outlined to the right of **Figure 1** and expressed in either absolute terms or relative to LTE Advanced.

The promise of 5G NR is to be able to support a vastly expanded range of service types and be forward compatible to new services that may emerge.

Phased Development of 5G New Radio

It is improbable that all the services envisaged for 5G could be, or should be, deployed at the same time. To operators (and vendors), prioritization is important. There is an industry-wide plan for a phased introduction of 5G in order to enable early launch of 5G services, and to make the development process manageable.

Initial specifications for NR are expected in mid-2018, as part of 3GPP Release 15. The focus is on enabling fast launch of 5G for enhanced mobile broadband, with trials starting in late 2017, or early 2018, and commercial launch from 2019. In some cases, operators will be able to deploy pre-standard equipment and launch services to customers ahead of this schedule – for example, fixed wireless may be possible from 2017 onward. It remains to be determined, but some UR-LLC and mMTC features may also be included in the first release.

Importantly from an NR perspective, the first phase will provide the foundations for enhancements in later releases. This means that decisions made being now on fundamental aspects of NR – such as waveform, frame structure and error correction – will have a profound and long-term impact on the evolution of NR and future 5G services. The industry is, therefore, now in *the* critical phase of 5G development.

New capabilities will be introduced with later 3GPP releases. Release 16 specifications are scheduled for the end of 2019, with ongoing iteration of 5G NR expected in subsequent years. As has been the case in the specification of 2G, 3G and 4G, the first release will be the start of a decade-long development cycle.

Spectrum for NR

Any discussion of radio technologies must include spectrum. Broadly speaking, 5G can be thought of as targeting spectrum between 1-3 GHz (the classic mobile bands), between 3-6 GHz (emerging mobile bands), and above 6 GHz (the centimeter-wave [cmWave] and millimeter-wave [mmWave] bands). The intent is to create a radio interface that can scale across this vast frequency range. This makes NR fundamentally different, and more ambitious, than prior generations.

In the sub-6 GHz bands, 5G will typically target new spectrum in the first instance – for example, the C-Band or 700 MHz in Europe, 3.5 GHz in China, or 4 GHz in Japan – and then re-farmed 2G/3G/4G spectrum over time. Spectrum in these lower bands is relatively constrained, but these frequencies are critical to coverage, and to deliver wide-area services. It is expected that operators will be able to reuse existing cell site infrastructure (towers, power supply, upgraded backhaul, etc.) to enable rapid 5G deployment at manageable cost.

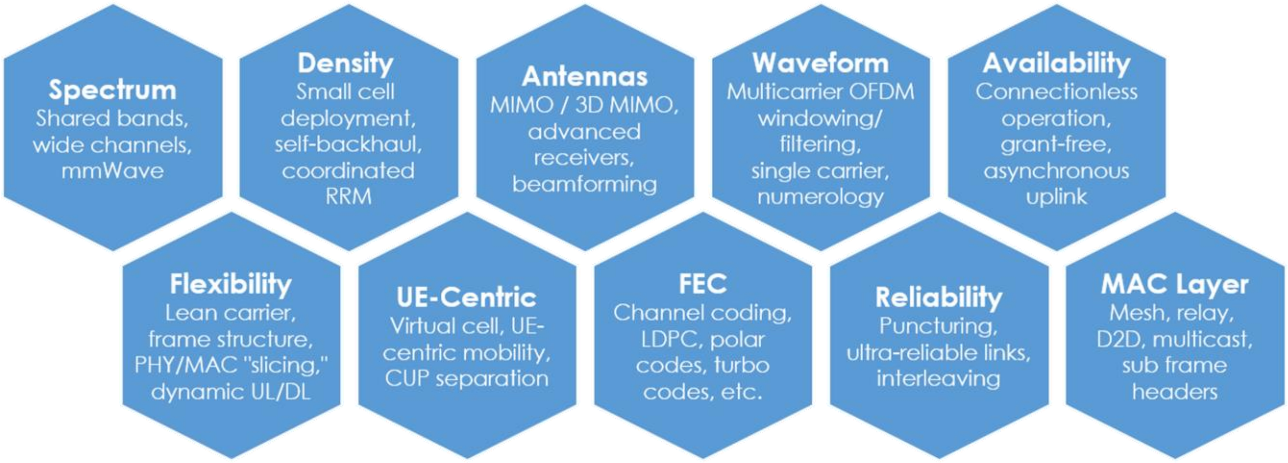
The higher frequencies are also of great interest to 5G because of the vast amount of spectrum available in the cmWave and mmWave bands (often several hundred MHz of contiguous spectrum). Some of the first 5G deployments may be in these bands, particularly for small cell and fixed wireless access applications – for example, the 28 GHz band is attracting attention in the U.S. and other progressive markets.

Spectrum-sharing between different operators, and different radio systems, is increasingly important, and lightly licensed and unlicensed spectrum will be important in 5G NR. Initiatives in the 4G-LTE world, such as MulteFire and LTE-LAA in unlicensed spectrum, and the Citizens Broadband Radio Service (CBRS) in the licensed shared-access 3.5 GHz band, provide a foundation for shared spectrum in 5G.

A Unified Air Interface

To scale across a wide range of performance requirements, spectrum bands and deployment scenarios, operators require an air interface that is highly configurable. A unified air interface is important to economies of scale in R&D, manufacturing, deployment and operation. 5G NR will be made up of several foundation technologies, some of which can be grouped into sets of enablers, as shown in **Figure 2**.

Figure 2: Enablers for 5G NR



Source: Heavy Reading

These enablers are indicative of the wide range of technical inputs – typically the result of years of R&D investment – that are part of NR development. Multiple antenna systems and beamforming, for example, are critical techniques for improving spectral efficiency, cell-edge performance and end-user performance where multipath effects are high, and particularly at higher frequencies. Similarly, the separation of the control plane and user plane, already introduced in LTE, is expected to take on a much more important role in 5G and, over time, will enable UE-centric mobility and virtual cells.

Spatial reuse of spectrum in the form of densification is the biggest opportunity for capacity gain. 5G NR should address the major deployment challenges of small cells with support for self-backhaul and build on extensive work on interference management/cancellation in LTE to support co-channel deployments. Other technologies, such as mmWave, are unfamiliar to mobile operators, but will be an important contributor to small cell networks, using wide channel widths and MIMO to sustain high-capacity links. (For more on this, see the Heavy Reading white paper Exploring the Potential of mmWave for 5G Mobile Access.

And, as discussed below, a major design target of 5G NR is forward compatibility: the ability to upgrade a radio interface to support new capabilities without having to redesign the radio itself. Flexible numerology, frame structure and "lean radio" concepts are at the heart of this.

Note also that these building blocks are intended to help create a radio interface that will make 5G NR suitable not only for diverse services, but also for diverse deployments – from dense indoor, to wide-area macro, to vehicle communications, to low-power Internet of Things (IoT) environments and more.

Flexible Air Interface for 5G NR

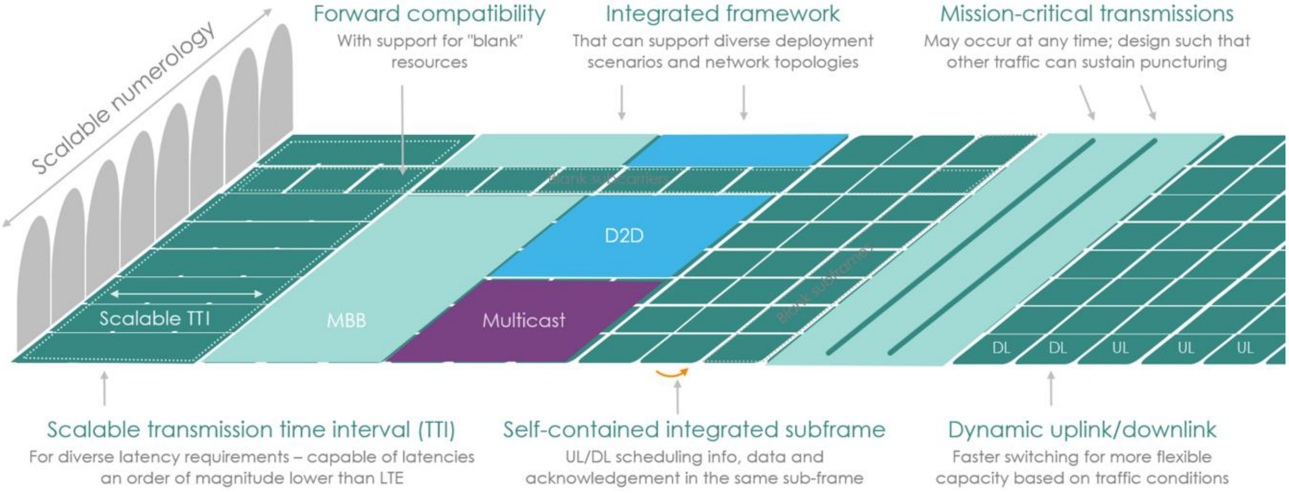
There is widespread support for OFDM to remain the preferred waveform and modulation scheme in 5G, and a view that it has the attributes to effectively support many of the envisioned 5G services. There is a strong knowledge base on how OFDM performs (from 4G-LTE, WiFi, etc.) and a wide range of modeling tools to support development and operation in 5G NR.

At the time of writing, it has not been confirmed by the 3GPP that OFDM will be selected; other waveforms have been proposed and remain under consideration, and there is the potential that additional single-carrier waveforms may be introduced for very low-band spectrum, and that single-carrier waveforms (based on OFDM) will be used on the uplink, particularly in power-limited scenarios.

Nevertheless, although some of the details about how exactly to implement it remain open (e.g., filtering vs. windowing), OFDM has broad support and is likely to be selected. (For more on this, see 5G Waveform & Multiple Access Techniques).

Figure 3 shows many of the key features of a new unified air interface based on OFDM. One important characteristic is "flexible numerology," which refers to the ability to configure parameters of the radio interface according to the service.

Figure 3: Unified 5G Radio Interface



Source: Qualcomm

The first degree of flexibility is the ability to scale sub-carriers in 15 kHz, 30 kHz, 60 kHz, 120 kHz units. This in turn maps to flexible channel widths, which can scale according to frequency, spectrum availability and use case – for example, a 20 MHz carrier is suitable for outdoor macro networks in spectrum below 3 GHz, whereas at higher frequencies it would be appropriate to expand to 80 MHz, 160 MHz or even 500 MHz channel widths.

This allows for a natural scaling of cyclic prefix – for example, a wide-area 20 MHz macro carrier would have an extended cyclic prefix, whereas an indoor small cell deployment at 5 GHz or, say, 28 GHz would have a correspondingly large bandwidth and short cyclic prefix. A benefit of this is the ability to scale complexity to wider bandwidths – for example, using 500 MHz channels and a sub-carrier spacing of 15 kHz, the FFT processing would require unreasonable processing (and therefore high power consumption), whereas a larger sub-carrier spacing of 120 kHz with a shorter cyclic prefix would be optimal.

A second degree of flexibility is in the time domain, with a scalable transmission time interval (TTI). The idea is to adjust the TTI according to the latency requirement of the service in question – for example, to meet the 1 ms link requirement, a correspondingly short TTI will be needed, yet for high spectral efficiency longer TTIs are optimal and suit services, such as video streaming, that are less latency-sensitive. Ideally, short and long TTIs should be supported on the same radio at the same time, and use TTI bundling schemes to increase the efficiency of low-latency, short-packet services.

The integrated framework shown in **Figure 3** refers to the ability to use flexible numerology and PHY/MAC configurations to support multiple modes of operation in the same network, transmitted on common frequencies – for example, classic macro-cellular WAN, multicast/broadcast and mesh/relay use cases could be supported on the same network infrastructure.

To efficiently support ultra-reliable services (for example, public safety or autonomous vehicles), the intent in 5G NR is to offer mission-critical services the ability to "puncture" the radio network and be allocated dedicated resources immediately. That is to say, mission-critical services should be able to reliably claim resources from nominal traffic in as short a time as possible for the duration of the transmission. Mechanisms to achieve this remain challenging and underdeveloped, but are a focus of ongoing R&D. The objective is to support this capability on a common infrastructure rather than build dedicated networks for these services.

Forward compatibility refers to the ability to add capability to the radio carrier at a later date without replacing the radio or impacting existing services. Cellular technologies have not, historically, been very good at this. The intent in NR is to support a wide range of as yet undefined services over a long period, making it important that NR can "upgrade" as new requirements emerge.

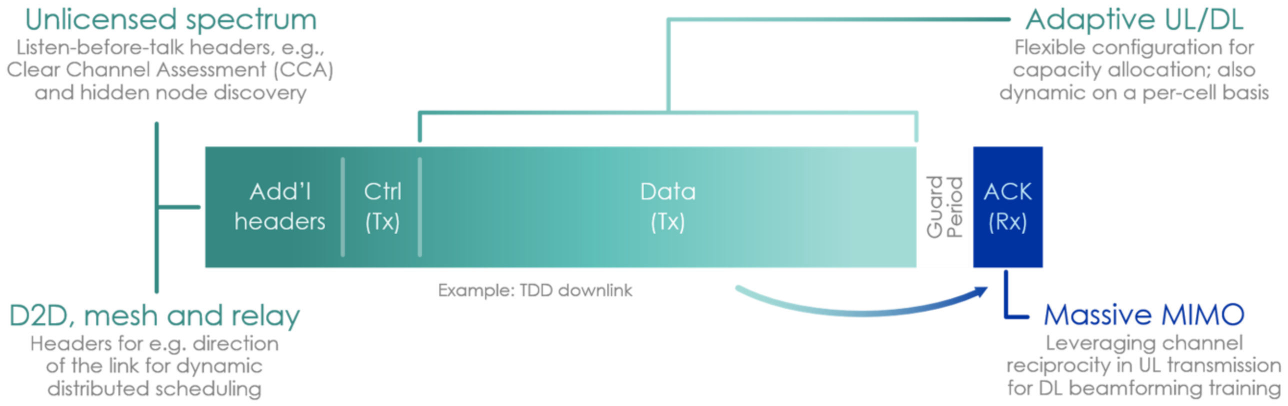
The proposed solution is to use blank sub-frames and blank sub-carriers, so that capabilities such as new headers or multiplexing schemes can be added to the radio interface later. This is to ensure that 5G will be able to meet the needs of diverse application developers from 2025 onward – i.e., for services and processes not yet invented!

Frame Structure & Self-Contained Sub-Frame

The frame structure is critical to the flexibility, and forward compatibility, of 5G NR. In previous generations of mobile air interface, a frame is associated with a fixed TTI and transmits separate ACKs/NACKs for each packet, which in turn generates a relatively long Hybrid ARQ roundtrip time (8 ms in LTE). This determines the lower bound of service latency, restricting the ability to meet certain use cases or deploy innovative architectures such as cloud RAN.

The proposed solution in NR is the self-contained sub-frame design shown in **Figure 4**. The idea is to include link data and ACKs on the same sub-frame as the payload to speed up processing (e.g., on the downlink) and make efficient use of channel reciprocity for MIMO in TDD systems. The sub-frame can be configured to support a single interlace where latency and/or single-user efficiency is critical, and multiple interlaces where latency is less important but multi-user capacity is critical. This is made possible by improvements in chipset processing, which are becoming capable of the real-time computation needed to multiplex different service streams.

Figure 4: Self-Contained Sub-Frame Design



Source: Qualcomm

There are other benefits to the proposed new sub-frame design. Faster, more flexible, resource allocation is one important feature. The idea is that dynamic UL/DL switching in TDD systems allows capacity to be allocated according to prevailing demand for services and according to resource use across the system. In small cell networks, for example, it may be better to allocate more capacity to uplink traffic for one particular cell, and more capacity to downlink on another. This could have particular use in self-backhauled small cell scenarios where there is a need to allocate resources, dynamically, to either the access or backhaul link.

Additional headers could also be added to the sub-frame to support new modes of operation, such as device-to-device and mesh or relay communications (which also leverage integrated backhaul capabilities) and to support operation in unlicensed, or shared access, spectrum where airtime is shared with different radio systems. This ability to add new headers is key to making 5G flexible relative to historical designs, where adding capability post-specification has resulted in suboptimal implementations.

The sub-frame design outlined in **Figure 4** seems to be widely supported in the industry – although, as with other aspects of NR, it remains subject to discussion and debate in the standards development process.

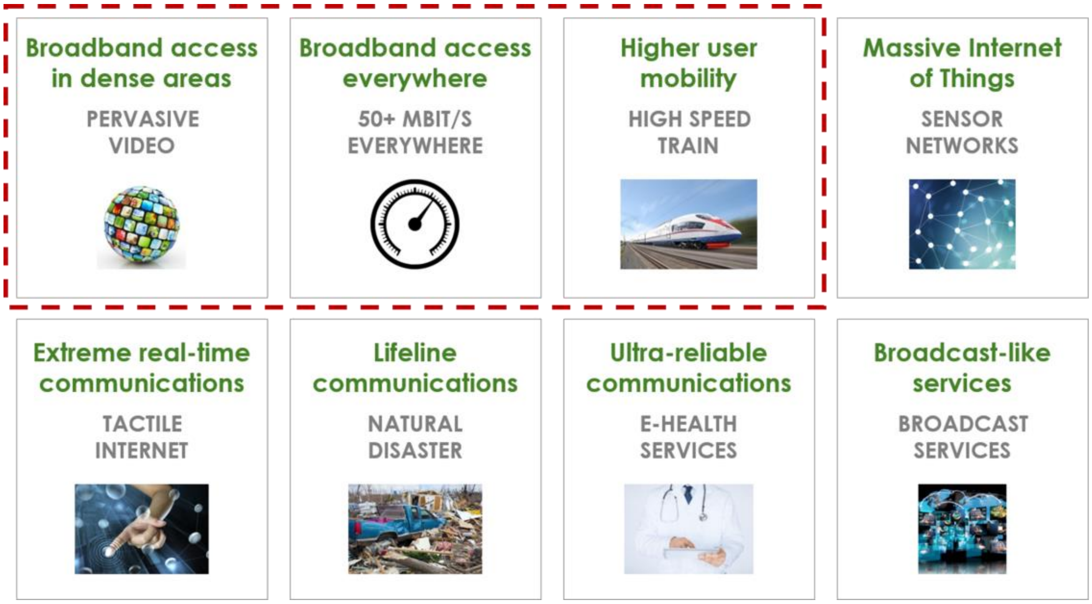
Designing for Enhanced Mobile Broadband

5G is intended to support a wide range of services; however, the first commercial use of the technology is expected to be for enhanced mobile broadband (eMBB) and fixed wireless access services. It stands to reason, therefore, that broadband optimizations (within the parameters of the unified air interface) will be useful and that 5G NR "profiles" will emerge for these services.

eMBB Performance Targets

Mobile broadband itself incorporates quite a range of services. **Figure 5** shows some of the high-level use-case categories identified by the operator-led Next Generation Mobile Networks Initiative (NGMN) in its 5G White Paper. Three of the categories, highlighted in red, cover eMBB services: high-speed access in dense areas (offices, stadiums, urban centers, etc.), broadband everywhere (suburban, rural and road network) and high-speed mobility (trains, planes, etc.). Each of these scenarios has different performance requirements.

Figure 5: 5G Use-Cases Categories



Source: NGMN, Heavy Reading

Performance targets associated with a selection of MBB use-case categories are shown in **Figure 6**. Note that these are system performance targets (as opposed to end-user targets) for connection density and throughput, and do not include latency, availability, etc. Note also that these targets are aspirational and may not be achieved in initial deployments.

In practice, dense urban and stadium-style use cases are likely to dominate early mobile broadband deployments. Specific configurations (or profiles) are likely to emerge for these types of networks that incorporate factors such as channel width, sub-frame configuration, antenna count, coding and duplexing schemes.

Figure 6: Selected MBB Performance Targets for MBB

Use Case Category	Connection Density	Traffic Density
Broadband access in dense areas	200-2,500 per km^2	DL: 750 Gbit/s per km^2 UL: 125 Gbit/s per km^2
Broadband access in a crowd	150,000 per km^2 (30,000 per stadium)	DL: 3.75 Tbit/s per km^2 (0.75 Tbit/s per stadium) UL: 7.5 Tbit/s per km^2 (1.5 Tbit/s per stadium)
Mobile broadband in vehicles (cars, trains)	2,000 per km^2 (500 active users per train x 4 trains, or 1 active user per car x 2,000 cars)	DL: 25 Gbit/s per train, 50 Mbit/s per car UL: 12.5 Gbit/s per train, 25 Mbit/s per car

Source: NGMN

MIMO & Beamforming

In many mobile broadband service scenarios, substantial gain can be achieved through greater use of multiple antenna systems. In mmWave access, for example, very high numbers of antenna elements can be used to take advantage of short wavelengths, and to enable beam-forming and beam-tracking, typically over short distances.

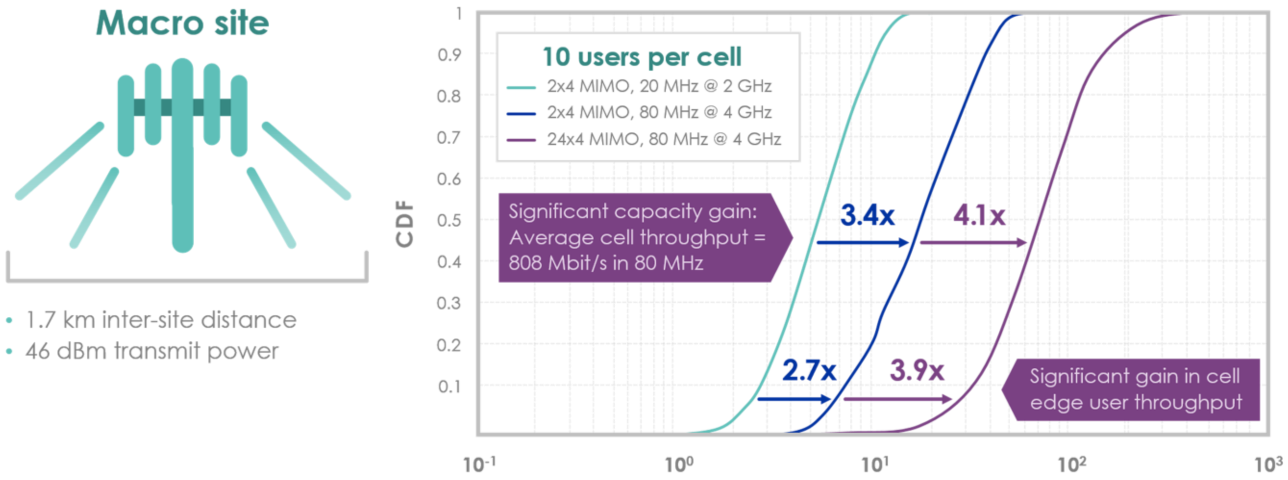
At sub-6 GHz frequencies, different factors are in play. It is common to use 2x2 MIMO in LTE, and a number of vendors are investigating higher-order MIMO systems – sometimes known as full-dimension MIMO, because of the ability to steer beams in vertical as well as horizontal directions – in LTE Advanced networks. Vodafone, for example, showed an eight-antenna base station at Mobile World Congress 2016.

5G NR will use MIMO extensively. **Figure 7** shows how MIMO can be used to ensure broad coverage for 5G NR in sub-6 GHz spectrum – in this case at 4 GHz, which is close to the bands under consideration for 5G in many markets.

The first plot on the chart shows a 20 MHz channel at 2 GHz, with 2TRX at the base station and 4TRX on the user device. The second plot shows that increasing the frequency to 4 GHz and increasing the channel width to 80 MHz (which is reasonable), but keeping the same number of antennas, generates a 3.4x increase in average cell throughput and 2.7x improvement in cell edge performance. The third plot on the chart shows that if the base station is raised to 24TRX, but the user device, channel width and frequency remain the same, a further 4x improvement in average and cell edge throughput is possible.

A really important consequence of this is that operators will be able to deploy 5G NR base stations on the existing cell site grid to achieve the same sort of coverage as 4G and 3G today, but with significantly better performance. This will reduce the cost to deploy 5G, and without the lead time for new towers, will make rapid deployment possible. This makes the 3-6 GHz spectrum bands attractive to operators seeking to offer wide-area 5G coverage and will be a major driver of deployment.

Figure 7: High-Order MIMO @ 4 GHz Allows Reuse of Existing Sites



Source: Qualcomm

Massive MIMO is a significant engineering challenge. However, base station products are already emerging for LTE Advanced Pro networks that have high antenna counts and provide a useful insight into how this technology would work in practice for 5G NR. For example, one major vendor offers a 128 antenna base station in the same form-factor as a classic eight-antenna panel, and another has announced plans to release such a product in 2017. Both market them as "Pre-5G" base stations.

Another challenge is "3D MIMO." Currently, MIMO systems can transmit beams in the horizontal or vertical axes, but can be used only with flat-panel antennas – which is, by far, the dominant type of antenna today. In 5G, however, where there is a need for deployment flexibility and a drive to ultra-dense networks, there may be demand for 3D antennas (i.e., that can transmit and receive in any direction) and therefore an associated 3D codebook – which, again, remains under development.

High-Density 5G NR – Integrated Access & Backhaul

To meet the system performance targets identified for 5G NR, high-density deployments – perhaps incorporating macro, micro and small cells – will be needed. Het-Net technology is now reasonably well established in advanced 4G-LTE networks; in 5G NR, the opportunity is to address dense deployments in the design phase. There are two key aspects to this: deployment simplicity and interference management.

One of the major challenges in current small cell deployments is backhaul. This often limits where cells can be placed, resulting in sub-optimal radio performance, and if backhaul quality is poor (lossy, jittery, etc.) also limits the efficiency gains achievable from coordinated scheduling. Part of the solution is to design NR to support integrated access and backhaul (a.k.a., self-backhaul) and related mesh and relay capabilities. As the industry learned with 4G-LTE, it is important for this capability to be part of the air interface design phase and not delayed in the interests of expediency.

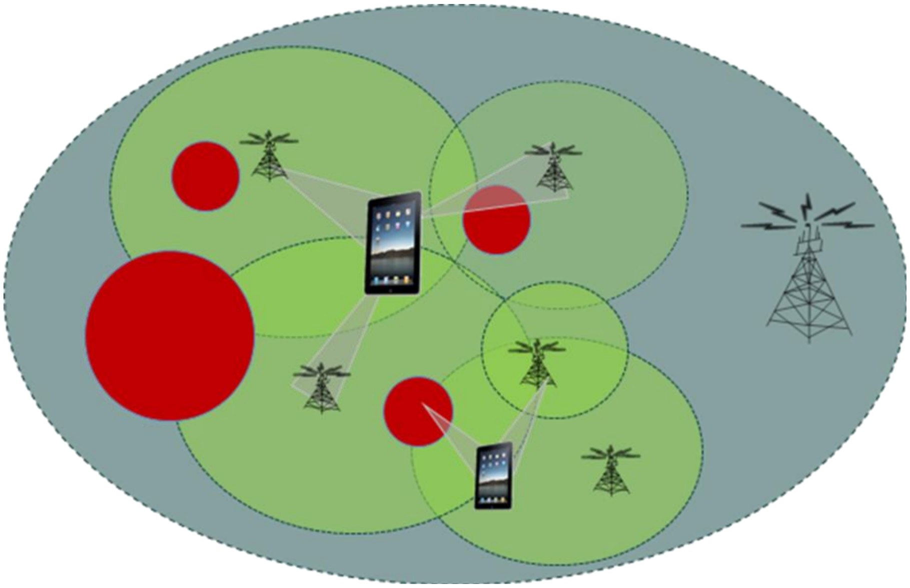
The good news is that integrated access and backhaul, meshing, relaying and device-to-device communication all, to some extent, "come for free" in 5G NR, in the sense that the self-contained sub-frame design (discussed above) supports multi-hop and mesh scenarios natively. This is because from a MAC-layer perspective, if a base station transmits to a user device, or another base station, it is more or less the same thing. Again, however, there is development work to be done on protocols (i.e., headers that will identify a sub-frame as a device-to-device communication), signaling and network management aspects.

Automated network management in the context of NR is particularly important. For example, devices need to be able to select the "best" frequency or sub-channel on which to transmit based on the prevailing utilization of neighboring channels, and this would be practically impossible without automation and "self-learning." There is an argument that where 5G NR uses wider channels – say 100 MHz, or several hundred MHz – it would be somewhat easier to allocate a sub-channel for a backhaul or mesh communication than it would be with a 20 MHz LTE channel, and that this should make integrated high-density deployments simpler. This is, to some extent, a fair comment; however, even in this case the respite may only be temporary as demand continues to increase.

High-Density 5G NR – Virtual Cells

A key aspect of high-density radio networks is resource and interference management. There are many aspects to coordinating resources and transmissions in a given coverage area, and this remains very much subject to study and improvement. One very interesting concept that emerges from the new coordination schemes under evaluation for 5G NR is the so-called "virtual cell" or "no-cell" network. This is also sometimes known as UE-centric mobility. The concept is outlined in **Figure 8**.

Figure 8: Virtual Cell & UE-Centric Mobility



Source: Heavy Reading

Classically, in a mobile network a user device attaches to one particular cell that provides service. As the device moves, the network executes a handover to a neighboring cell, which takes over the provision of service. This model started to evolve with the introduction of dual connectivity for HetNets in LTE Advanced – essentially, this means a primary serving cell is supported by a secondary cell to boost user-plane throughput. The same model will be important in 5G networks, both in multi-RAT scenarios where a device is connected to 5G and LTE radio bearers simultaneously, and in pure 5G environments where the device is connected to a <6 GHz radio for control and coverage and >6 GHz radios for capacity.

This can evolve further to model where the device is not connected to primary cell, but is served, according to prevailing load, by a number of different radios distributed across the coverage area. In this scenario, the UE exists in a virtual cell composed of diverse transmissions selected to optimize performance of the device. Scheduling resource use at the sub-frame level across this type of radio access network is obviously very complex and requires more R&D; however, the potential is compelling because, in principle, it can generate greater spectral efficiencies.

Evolution of 5G NR

This paper has argued that the development of 5G NR is now in a critical phase. Decisions made in 2016 and 2017 on NR design will have profound, long-term implications for 5G itself, and for the services and business cases it can support. The good news is that the industry has a solid base of experience to work with, particularly in the form of LTE Advanced Pro (a.k.a., Release 13), which pioneers the use of technologies, architectures and use cases that will be mainstream in 5G.

Development of 5G NR is also not a one-time endeavor that will result in a capable, but static technology. To a much greater extent than ever before, the industry is creating a framework that is extensible and will evolve. In the first instance, it will deliver a tightly specified air interface for deployments and use cases, such as broadband access, that have immediate commercial application. However, it will also include flexibility to add functionality that will make NR forward compatible with as-yet-unknown new requirements, driven by new services and new business models.

About Qualcomm

Qualcomm Incorporated (NASDAQ: QCOM) is a world leader in 3G, 4G and next-generation wireless technologies and chipsets. For more than 30 years, Qualcomm ideas and inventions have driven the evolution of digital communications, linking people everywhere more closely to information, entertainment and each other.

Qualcomm has been investing in 5G research and development for many years. At Mobile World Congress in February 2016, Qualcomm did a live demonstration of their 5G mmWave prototype, operating at 28 GHz. The demonstration showcased adaptive beamforming and beam-tracking techniques to enable robust and sustained broadband communications under line-of-sight (LOS) and non-line-of-sight (NLOS) RF channel conditions and device mobility.

In addition, Qualcomm has been able to use the technologies it has developed and is developing for Wi-Fi and 4G LTE as a starting point for its work in 5G. For example, the company has a 60 GHz Wi-Fi (802.11 ad) device chipset with a 32 antenna element array suitable for mobile form factors.