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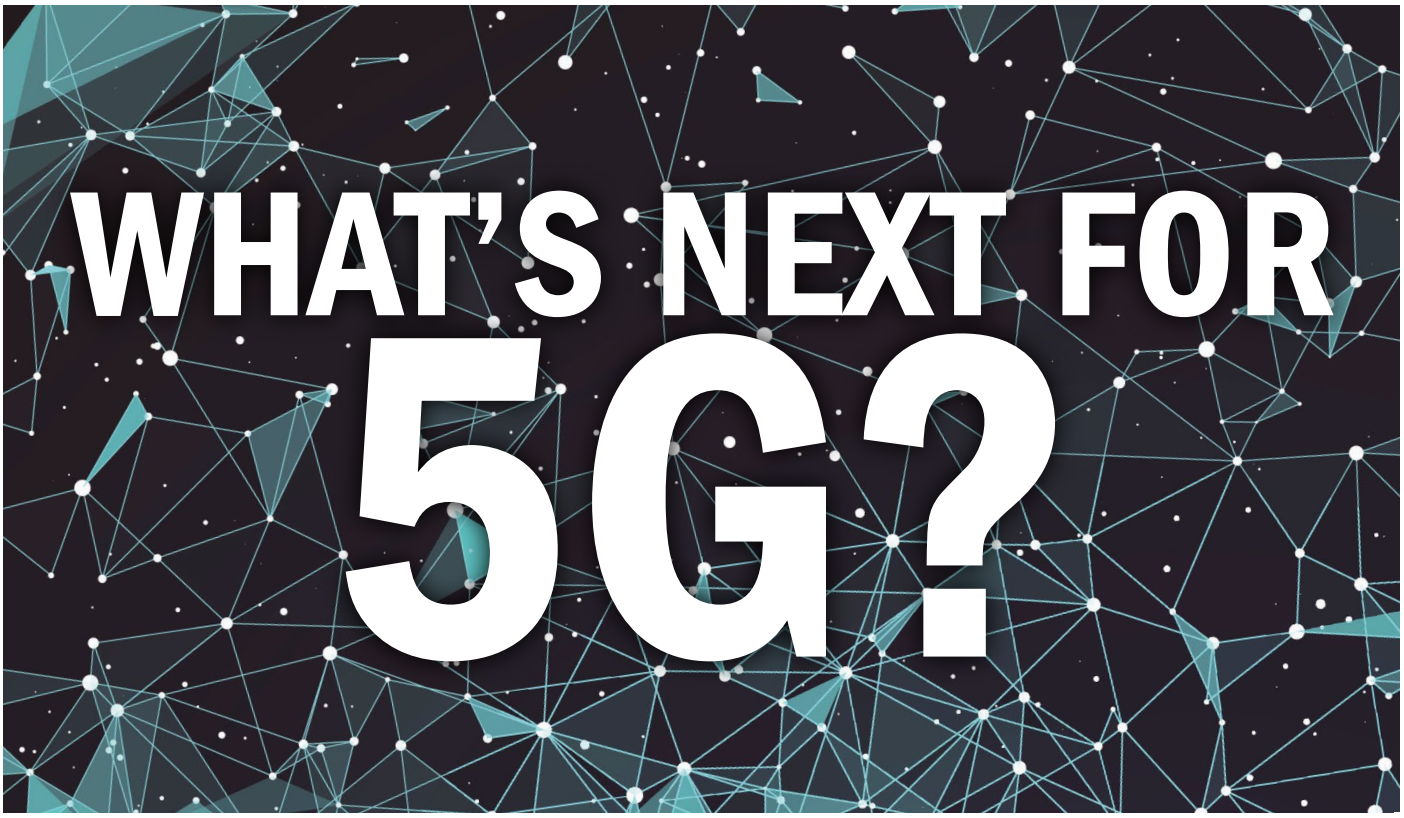

THE $12 TRILLION OPPORTUNITY AHEAD

The 5G vision is a unifying connectivity fabric for a diverse range of services and devices, expanding mobile technology from more than 5 billion humans to trillions of things, disrupting virtually every industry. With the first global 5G standard now upon us, the industry is one step closer to a 5G "future" that is expected to benefit entire economies and societies. However, a great deal of research and development (R&D) and standards work remains to be done before the full potential of 5G is realized.

In December 2017, the 3rd Generation Partnership Project (3GPP) completed the first phase of the 5G standard—part of Release 15—focusing on a subset of requirements that were essential to the most pressing commercial needs, including an enriched 5G New Radio (5G NR) and new technologies to meet enhanced mobile broadband (eMBB) requirements. The completion of the first 5G standard has, according to 3GPP, "set the stage for the global mobile industry to start full-scale development of 5G NR for large-scale trials and commercial deployments as early as in 2019."

However, although this Release 15 standard represented a major milestone in meeting the 5G

vision and in the ultimate 5G system architecture, it was merely the tip of the 5G iceberg. Whereas Release 15 will serve to accelerate eMBB deployments for 2019 and establish the underlying architecture for future innovation, the second phase of 5G coming in 3GPP Release 16 and beyond will focus more on expanding 5G NR to new use cases and new directions. In short, the next phase of 5G will bring a rich roadmap of advanced technologies that will not only continue to enhance/evolve mobile broadband, it will expand 5G networks to achieve the vision of a unifying connectivity fabric across diverse services:

- **eMBB services** will expand and strengthen conventional mobile broadband, ushering in higher capacity, multi-Gbps speeds, lower latency, coexistence with existing standards, and support for advanced technologies such as massive Multiple Input Multiple Output (MIMO) technology.

- **Massive IoT services** will intelligently connect virtually anything, anywhere with cost- and power-optimized 5G technology that is foundational to supporting the coming IoT reality, which will be teeming with connected devices and sensors.

- **Mission-critical command-and-control services**, where failure is not an option, will benefit from the deployment of new ultra-reliable low-latency communications (5G NR URLLC), particularly in applications such as smart cities, smart grids, the industrial IoT, robotics, and intelligent transportation systems (ITSs).

THE FORTHCOMING 5G OPPORTUNITY

According to *The 5G Economy*, an independent study from IHS Markit, Penn Schoen Berland, and Berkeley Research Group (commissioned by Qualcomm), 5G's full economic benefit should be realized around the globe in 2035, when a broad range of industries—from retail to education, transportation to entertainment, and everything in between—could produce up to $12.3 trillion worth of goods and services enabled by 5G mobile technology. In that same timeframe, the global 5G mobile value chain alone will generate up to $3.5 trillion of economic output and support 22 million jobs.

The first phase of the long-term 5G reality, based on the Release 15 standard, is expected to address about a third of that opportunity—particularly eMBB use cases that will leverage 5G connectivity for better and new mobile experiences (and thus drive consumer adoption of 5G devices). Realizing the full potential of 5G relies on further invention and innovation in Release 16 and beyond. Addressing the $12.3 trillion figure, The *5G Economy* study points to the immense opportunity remaining in the areas of massive IoT ($3.6 trillion), and mission-critical services ($4.3 trillion).

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With the first standard complete and a lot of attention and hype being paid to 2019 deployments, it may seem that that the heavy R&D work and standards development of 5G is in the rearview mirror—but nothing could be further from the truth. In fact, the bulk of the $12.3 trillion opportunity still lies ahead, as mobile networks expand and cellular technology spreads into new areas (new use cases, new verticals, new entities, new types of deployments). We've only begun to explore how 5G NR will extend to new industries, ecosystems, and business models.

ESSENTIAL USE CASES AND NEW VERTICALS ON THE 5G HORIZON

The next wave of 5G NR technologies—propelled by 3GPP Release 16 and beyond—will push forward the broad vision of 5G, taking

mobile networks to new places, enabling new use cases, and expanding the utility of mobile technology. Essential work on these next-generation technologies is already starting to be performed, such as the use of 5G spectrum-sharing technologies for greater mobile broadband performance, extending 5G into new types of deployments such as private networks for industrial IoT, enabling 5G NR-based Cellular Vehicle-to-Everything (C-V2X) technology for autonomous driving, and more. Following are some of the key ongoing efforts to extend 5G into its future and realize the full 5G opportunity.

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The Utilization of Unlicensed Spectrum and Emerging Spectrum-Sharing Paradigms. The importance of spectrum availability in wireless communications—and particularly 5G communications—can't be overstated. Although licensed spectrum remains a priority, the use of all possible spectrum types is necessary to efficiently and consistently deliver multi-gigabit connectivity and expand 5G into new deployment types, and that includes shared and unlicensed spectrum. *Shared spectrum* refers to the simultaneous usage of a region's radio frequencies by several independent entities, whereas *unlicensed spectrum* refers to frequencies not licensed by the government to any entities; rather, it is publicly owned and doesn't require a licensing fee.

The use of 5G spectrum-sharing technologies is expected to play an essential role in extending 5G into new types of deployments, such as enhanced local broadband networks and private networks for industrial IoT. 5G NR is poised to evolve and expand upon existing LTE-based spectrum-sharing technologies, such as Licensed Assisted Access (LAA), MulteFire, and Citizens Broadband Radio Service (CBRS):

- ***LAA/LTE-U*** enables the carrier aggregation of licensed and unlicensed spectrum to enable more mobile operators globally to offer gigabit LTE services.
- ***MulteFire*** enables LTE to operate in unlicensed spectrum in a standalone capacity, using only unlicensed spectrum to enable new types of deployments such as neutral host and private Industrial IoT networks.
- ***CBRS*** opened the 3.5 GHz spectrum band in the United States for LTE operation by enabling new wireless entrants to use the spectrum without disrupting the incumbents.

The work to introduce shared/unlicensed spectrum in 5G NR has already been kicked off with an approved 3GPP study item. (Qualcomm, who pioneered the use of unlicensed/shared spectrum with LTE, is leading the efforts on 5G NR Spectrum Sharing.) Beyond expanding and improving upon existing LTE-based spectrum sharing, 5G NR could potentially introduce more revolutionary spectrum-sharing techniques, such as the use of Spatial Domain Multiplexing (SDM) and Coordinated Multi-Point (CoMP), which deliver higher network capacity and user throughput, via tighter coordination. These advanced techniques can deliver significant benefits, including improved spectral efficiencies, higher perceived user data speeds, horizontal and vertical sharing, and guaranteed Quality of Service (QoS). As a result, a higher number of operators will potentially find themselves able to offer fiber-like 5G experiences in a wide range of deployment types.

Private 5G NR Networks for Industrial IoT. Another important focus of the next phase of 3GPP 5G NR will be private 5G networks for industrial IoT. The ability, for example, to run industrial ethernet over a wireless network facilitates reconfigurable factories to increase productivity and flexibility (See Qualcomm video for overview of Industrial IoT use cases.)

The concept of private networks for Industrial IoT is already starting today based on new LTE technologies. 5G NR will introduce new capabilities to open new opportunities in this use case. Private networks are:

- ***Optimized***—The private network can be tailored for specific industrial applications. Examples of such optimization are quality-of-service (QoS) and mobility settings.
- ***Dedicated***—A private, local network is independently managed—free from issues such as sudden, unexpected traffic surges that occur in shared networks. This is beneficial in industrial applications where productivity must be maintained at high and predictable levels.
- ***Readily deployed***—It utilizes licensed/shared/unlicensed spectrum that is readily available, plus a self-contained core network and self-organizing network technologies for easy deployment.
- ***Secure***—LTE and 5G NR provide industrial-grade security inherently built into cellular technologies.

The premier example of new capability that 5G NR will bring in this arena is URLLC with high-reliability (99.9999%) delivering extremely low error rates through higher link reliability and spatial diversity (e.g., CoMP), as well as sub-millisecond latency through the 5G NR flexible slot structure and optimized processing time. 5G NR URLLC provides the ability to run precise command-and-control in high-demand factory automation applications such as autonomous vehicles and motion control, as demonstrated by Qualcomm

recently at Mobile World Congress. Beyond its benefits to industrial networks, 5G NR URLCC is expected to benefit other mission-critical applications, such as autonomous vehicles, remote medicine, and smart grid/energy controls.

Momentum is building around C-V2X—a vital technology for the future of autonomous driving and road safety.

5G NR C-V2X for Autonomous Driving. Momentum is building around C-V2X—a vital technology for the future of autonomous driving and road safety—thanks to its performance and an unprecedented level of collaboration between the automotive and telecom industries. Safety use cases utilizing C-V2X are already being tested today, based on 3GPP Release 14 specifications, with multiple trials already underway. New 5G NR C-V2X technologies coming in Release 16 and beyond promise advanced capabilities for autonomous vehicles while maintaining backward compatibility.

C-V2X encompasses vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), and vehicle-to-network (V2N) operation. C-V2X introduces direct communications operating in ITS bands, combined with network-based C-V2X communications based on existing and future cellular networks, as follows:

- ***Device-to-device***—This direct V2V, V2I, and V2P communication doesn't need to rely on the network for scheduling.
- ***Device-to-network***—This V2N communication uses traditional cellular links to enable cloud services to be an aspect of the end-to-end solution.

Release 16 5G NR will bring high-throughput and URLLC capability into the system and enable advanced use cases for safe autonomous vehicle operation. These include high-throughput sensor sharing, intention/trajectory sharing, wideband ranging and positioning (bird's-eye view), and 3D HD map updates. The potential role of 5G NR–based C-V2X in autonomous driving—wherein the technology will allow vehicles to share their intent for higher levels of predictability—is immense. Such radio techniques complement cameras and sensors used for advanced path planning.

The use of C-V2X technology also can potentially extend to the optimization of mobile/cellular networks for coordinated operation and control of drones, enabling a growing set of use cases within and beyond the operator's visual line of sight.

5G NR Massive IoT. IoT is upon us, and future cellular networks will need to scale to connect a massive number of IoT devices and address an extreme variation of requirements across a wide-range of low-power, wide-area IoT use cases. LTE IoT was first introduced in 3GPP Release 13 as part of the LTE Advanced Pro platform to tackle the challenges of connecting low-power, low-complexity devices to the wide-area mobile network, and more than 50 global operators have deployed or committed to deploy LTE IoT networks (source: GSA NB-IoT and LTE-M: Global Market Status, March 2018).

These LTE IoT technologies—enhanced machine-type communications (eMTC) and narrow-band IoT (NB-IoT)—are continuing to evolve in 3GPP Release 14 and beyond to address tomorrow's massive IoT needs as an essential part of the 5G scalable platform that will connect a broad swath of consumer and enterprise IoT applications. These optimizations to cellular/mobile networks are giving machines, devices, sensors, and objects the ability to connect and communicate remotely, reliably and securely, from virtually anywhere, at any time.

To enable LTE IoT technologies in 5G NR spectrum, the first phase of 5G NR massive IoT in Release 16 will support the in-band deployment of eMTC and NB-IoT technologies, so that 5G NR IoT can fully leverage LTE IoT investments. In addition, the LTE IoT technologies will be core

network agnostic—meaning that the new 5G core network can be deployed with an LTE IoT RAN.

Release 16 and beyond will also bring further potential enhancements to both LTE IoT and 5G NR IoT, including non-orthogonal multiple access (NOMA), to improve network capacity, efficiency, and device density. NOMA—already an approved 5G NR study item in Release 15—is a multiple access technology that is well suited for the higher connection density and increased efficiency requirements for 5G Massive IoT. Other potential new technologies in Release 16 and beyond include grant-free uplink transmissions to increase device power efficiency and multi-hop mesh networking to increase coverage.

5G URLCC and Massive IoT technologies are also expected to play an essential role in the Internet of Medical Things, bringing a trusted, always-on medical-grade connectivity network to global health care. Massive IoT addresses the growing needs of many low-power, wide-area medical use cases.

5G NR Integrated Access and Backhaul for Small Cell Deployments. A major new technology coming in the first phase of 5G, with commercial deployments expected in 2019, is the use of mmWave spectrum bands for mobility applications to meet increasing mobile broadband needs and emerging use cases. Advanced 5G NR mmWave technologies are overcoming the challenges and complexities of these higher frequency bands to deliver robust mobile broadband communications at multi-Gbps data rates in real-world mobile environments (see Qualcomm's over-the-air mmWave mobility testing).

The wide bandwidths of spectrum available at higher bands—up to 800MHz and even beyond (1GHz and more)—open up not only the potential to utilize the spectrum for mobile broadband access in small cells, but also as backhaul to simplify small cell deployments. As antennas continue to evolve and network management becomes more dynamic and intelligent, mmWave technologies bring new opportunities for integrated access and backhaul—

and a move away from expensive traditional fiber backhaul. Transformed concepts of backhaul connectivity will lead to the simplification of easy/low-cost small cell deployments. This densification will lead to better coverage for 5G NR mmWave access, introducing a new sense of immediacy for consumers, enhancing media consumption, enabling immersive virtual/augmented reality (VR/AR), and streamlining access to rich information.

THE 5G FUTURE IS TAKING SHAPE

New technologies are poised to expand the mobile ecosystem and vastly expand the financial opportunities inherent in our collective 5G future; 5G NR builds upon these, with more capability, efficiency, and scale, while fully leveraging all LTE investments made through tight interworking and backward compatibility. At Mobile World Congress (MWC) 2018, Qualcomm demonstrated a few of these advanced 5G technologies for the next phase of 3GPP's 5G NR standard, showcasing the company's continued leadership in developing the foundation for the 5G future.

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As we embark on the technological advancements of 3GPP Release 16 and beyond, a lot of work lies ahead. Now is not the time to become complacent. Although many of the use cases described in this article are already in place with 4G LTE—for example, LTE IoT and C-V2X—5G will build upon LTE's foundation and radically shape the landscape, introducing massive scale and connecting trillions of things. For that reason, the industry needs to devote the same energy to Release 16 that it applied to accelerating the first phase of 5G NR for eMBB. Doing so will lead to myriad new opportunities for the mobile ecosystem. That's the future that still lies ahead.