THE Next Wave

The National Security Agency's review of emerging technologies

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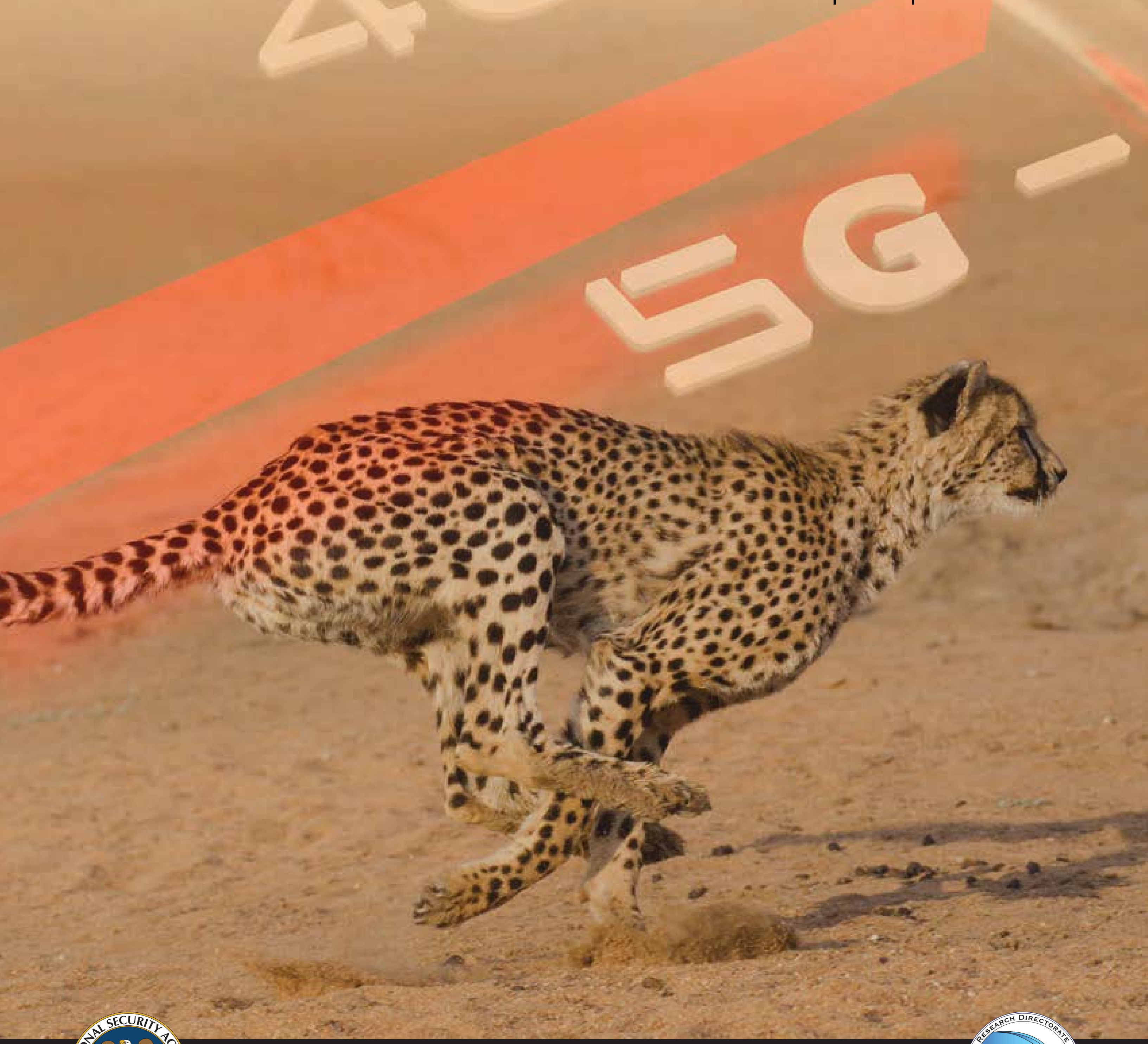

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Editor's column

While the global mobile telecommunications industry has been attempting to keep pace with ever-changing technology and consumer needs, it has not had a strong development roadmap like the International Technology Roadmap for Semiconductors (ITRS). Instead, mobile technology's development has been characterized by multinational companies pushing proposed standards for adoption by international standards bodies. These standards are subsequently adopted in a haphazard, nation-by-nation process. However, consumer desire for faster, more fully featured mobile devices has proven to be as strong a driving force as the ITRS, and has led the industry to roll out generations of new technology on a roughly 10-year basis (approximate dates: 1G - 1981, 2G - 1992, 3G - 2001, and 4G - 2009). This decade-by-decade introduction of new mobile communication technology has led to the common prediction for fifth-generation (5G) mobile to appear around 2020, in keeping with the observed linear cadence.

But why create 5G mobile anyway? The push for 5G is not just a mad rush to keep pace and provide more bandwidth to services that can already stream high-definition video. The Internet of Things (IoT; see TNW Vol. 21 No. 2) is a major driving force (among several) behind technologies being developed for 5G mobile. As personal mobile devices are more enmeshed into machine-to-machine (M2M) communications and the number of IoT sensors explodes, 5G technologies must address several needs: high-speed data rates for many more users, increased density of users, greatly increased simultaneous connections, and reduced latencies. These needs will propel many of the technologies that Dr. Farroha et al. describe in their introduction to 5G article (page 2).

One of those technologies, virtualization, has been instrumental in making efficient use of servers (virtual machine or VM) and computer networking (software-defined networking or SDN). Over the course of continuing improvement to 4G implementations, the networks are evolving into an all-digital Internet protocol packet-switched system. This evolution means that those efficiencies developed for SDN and used in computing can be applied to mobile networking. We can see this application in more depth in the article on 5G virtualization (page 16).

Several markets have already taken advantage of 4G mobile technology, most notably media. This market is expected to expand with 5G as consumer desire for high-resolution video and augmented/virtual reality increases. Automotive, energy, health, and public safety are several areas of M2M that will be greatly enhanced by increased bandwidth and, most importantly, low-latency networks. On 13 December 2016, the US Department of Transportation proposed a rule for vehicle-to-vehicle communication and announced a vehicle-to-infrastructure communication rule to be proposed. The article on 5G and the automotive industry (page 20) provides insight into how this market segment is enhanced by 5G connectivity.

Although mobile technological developments are typically categorized into different generations, each generation covers a vast array of individual technologies and protocols that roll out as they mature. In practice, mobile service providers often work across a range of generations. This is highlighted by the fact that in many cases voice calling is handled by the 3G network while data is handled on the 4G network. Domestically, T-Mobile and AT&T did not enable voice over LTE (VoLTE) until May 2014, and did not meet the International Telecommunication Union (ITU) standard until Verizon launched LTE-Advanced in August 2016.

Many factors can impact the broad global deployment of 5G networks, such as existing technologies, geography, spectrum, and national interests. Some countries may jump to the current network generation while others may delay deployment because their current networks are considered to be "good enough." The decreased per-customer costs of updating networks in densely populated countries makes it more attractive to keep on the leading edge. The increased data rates and simultaneous connections require increased spectrum allocations, which are handled by national regulatory organizations. Several countries, most notably South Korea, have tied their technological identity to the increased connectivity of next-generation wireless technologies. All these factors give rise to a patchwork international environment for 5G implementation.

Current forecasts for the rollout of 5G networks are in the 2020 time frame. Recent news indicates that it may be earlier than that. Samples of Qualcomm's new Snapdragon X50 4G/5G modem that uses the 27.5 gigahertz (GHz) to 28.35 GHz band—part of the spectrum opened by the Federal Communications Commission for 5G—will be available in the second half of 2017. Samsung and KT, one of South Korea's mobile providers, have announced that they will be the first to provide mobile 5G trial service at the PyeungChang 2018 Winter Olympic Games. Undoubtedly, this trial 5G service will not be fully compliant with 5G standards, which have yet to be adopted. However, we should expect things to advance quickly following the Korean introduction of 5G.

RECENT NEWS

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Introducing 5G

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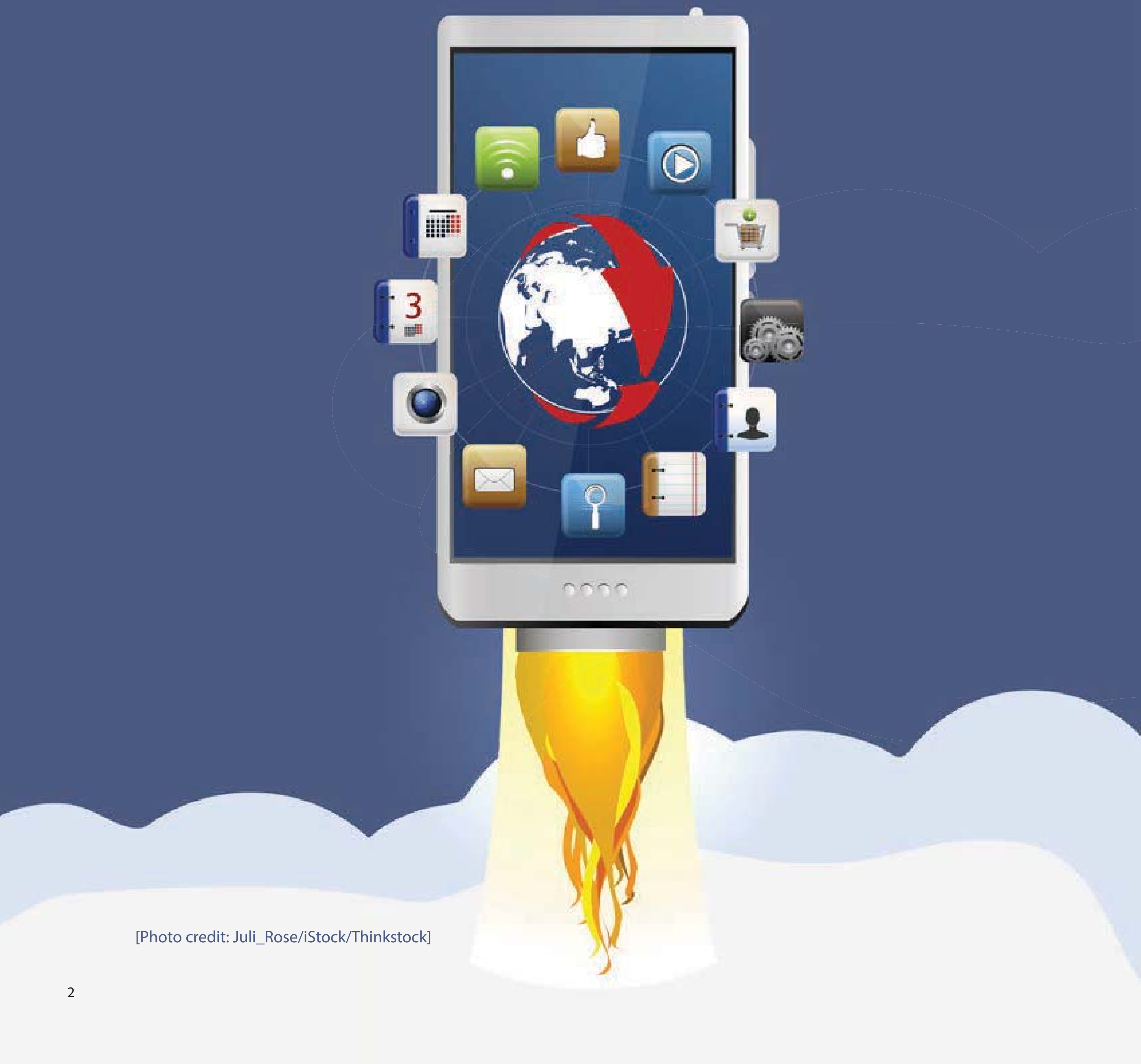

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The evolution of modern cellular communications has been marked by a series of technology generations. Although the technology itself tends to evolve continuously, a new generation of standards marks a revolutionary step forward, with a substantial increase in system requirements to drive fundamentally new applications. With fourth-generation (4G) networks now widely deployed, the industry has turned its sights on "the next big thing." Fifth-generation (5G) networks are expected to enable a seamlessly connected society in the time frame beyond 2020 for both people and things, including vehicles, homes, smart cities, sensor networks, and the power grid. While the Long-Term Evolution (LTE) standard will continue to evolve and play a critical role in the wireless ecosystem, 5G represents an opportunity to architect a new system that is fundamentally different without the constraint of backward compatibility with existing technologies.

What is 5G?

Although there are as yet no standards for 5G mobile networks, a number of key technology trends have emerged. This article describes seven major technology trends that will pave the way to the next generation of 5G networks.

- **New Flexible Radio Access Technology (RAT):** A new, non-backward-compatible RAT will be defined for 5G that is distinct from previous generations, such as 4G LTE and its evolution. New multiple access schemes under consideration include various modified Orthogonal Frequency-Division Multiplexing (OFDM)-based solutions with improved spectral efficiency. The new RAT must be flexible enough to accommodate a variety of traffic types with often conflicting radio requirements. The concept of a unified air interface has been proposed for multiplexing multiple physical layer (PHY) regions with different characteristics [e.g., transmission time interval (TTI), subcarrier spacing] on a contiguous block of spectrum [1, 2, 3]. Spectrum for the new RAT will include existing bands below 6 gigahertz (GHz), as well as new centimeter-wave (cmWave) and millimeter-wave (mmWave) bands in the 6- to 100 GHz range [4]. The new RAT must also support significantly reduced latency, with as low as 100 microsecond (μs) transmission time interval (TTI) at the PHY for the ultra-reliable and low-latency communications (URLLC) use case [5]. Lastly, to further improve spectral efficiency, full-duplex transmission schemes have been proposed, potentially allowing the same time-frequency resources to be used for uplink and downlink transmissions simultaneously [6].
- **Virtualization:** Software-Defined Networking (SDN) and Network Function Virtualization (NFV) are two key architecture concepts in development to support the flexibility and mobility demands of the 5G network infrastructure [7, 8, 9]. Virtualization of network functions, which were traditionally implemented in hardware, will pave the way for commercial telecommunications operators and service providers to introduce new features and integrate new standards releases at an accelerated rate. NFV enables providers to move toward a decentralized network to increase flexibility, pushing core functions toward the edge to reduce latency, and virtualizing those functions on cloud-based servers. The proposed Cloud Radio Access Network (C-RAN) architecture, a specific use case of NFV applied to the RAN, uses a pooled architecture of baseband resources to increase scalability, physical layer flexibility, and spectral efficiency [7, 10].
- **Millimeter Wave (mmWave) Communications:** The term mmWave refers to carrier frequencies in the International Telecommunication Union (ITU) extremely high-frequency (EHF) band, from 30 to 300 GHz. Within the context

of 5G, the term has recently been loosely used by industry to refer to the higher frequencies from 6 to 100 GHz that are under consideration for new mobile spectrum [11, 12]. mmWave technologies are becoming an increasingly attractive solution to the problems of frequency reuse, cell density, raw data throughput, and antenna array size. This has led to a synergy between mmWave, small cell deployments, and massive multiple-input, multiple-output (MMIMO) techniques [13, 14].

- **Massive Multiple-Input, Multiple-Output (MMIMO) Techniques:** MMIMO is a new concept in antenna arrays that provides a number of advantages over traditional MIMO arrays currently deployed in 4G networks. Traditional MIMO arrays use only a few antenna elements (i.e., 2 to 16), whereas MMIMO uses a large number of elements in the array, currently considering a range of 128 to 512 at a minimum. Highly directional beamforming to multiple users simultaneously allows for increased user density and higher aggregate cell throughput [15]. So-called hybrid MMIMO has also been proposed; it combines beam steering with array processing techniques, such as spatial multiplexing, to increase single-user throughput [16].
- **Heterogeneous Networks (HetNets):** HetNets expand the mobile access network capacity by coordinating small cells with larger macro cells or offloading traffic to wireless local area network (WLAN) access points. There are two types of heterogeneity: 1) various cell sizes (e.g., macro, pico, femto) and 2) heterogeneous RATs [e.g., third-generation (3G), 4G, 5G, WLAN]. Small cells may include femto, pico, and micro cells, which can range in capacity from less than 10 to several hundred simultaneous active users. While HetNet deployments have already been introduced in 4G networks, network densification through the aggressive deployment of small cells is expected to increase significantly in future 5G networks [17, 18].
- **Native Machine-Type Communications (MTC) Support:** 5G networks are expected to incorporate a new model for connectivity specifically designed for MTC [19]. With the significant increase in connected machines over the last several years, a new 5G standard is seen as a prime opportunity to ensure new RATs can efficiently support a large number of connected devices with their own unique access constraints. Two categories of MTC are discussed: 1) general MTC and 2) vehicle-to-everything (V2X) MTC. General MTC devices have a few unique design and deployment considerations—namely, lower bandwidth needs, stringent power budgets, and relaxed latency requirements. V2X MTC devices, in contrast, require low-latency communications, out-of-coverage networks, and limited operation on a subscription-free basis [20].
- **Device-centric Architectures:** New network architectures will focus on a uniform quality of experience (QoE) for the user device, in contrast to traditional base-station-centric architectures. A number of new device-centric approaches are under consideration: decoupling the user plane and control plane, decoupling the uplink and downlink, and device-to-device communications [4, 21]. Another novel proposal is the user-centric cell or virtual cell model, which uses distributed beamforming and decoupled user/control planes to create a virtual cell around each user [2, 3]. Because the virtual cell follows the user, QoE variations are reduced and the cell-edge problem is mitigated. New device-centric architectures may significantly alter the traditional concept of cell handovers or eliminate it entirely.

Many of these technologies are already being added to the evolution of existing technologies beyond 4G, such as LTE-Advanced Pro [22].

In 2015, there was a significant increase in industry activities surrounding 5G networks. Major standards bodies, including the ITU and the Third-Generation Partnership Project (3GPP), reached important milestones in the early development of the eventual 5G standards. In September, the ITU published its vision for 5G networks [19]. The vision for International Mobile Telecommunications for 2020 and beyond (IMT-2020) defines three future-looking, high-level use cases for 5G:

- **Enhanced Mobile Broadband (eMBB):** This is generally a human-centric use case driven by the exponential increase in demand for mobile access to multimedia content, services, and data.

The eMBB use case will come with new application areas and requirements that go beyond existing mobile broadband applications for improved performance and increasingly seamless user experience. This use case covers a range of scenarios, including wide-area coverage and localized high-throughput spot coverage, which will have different requirements.

- **Massive Machine-Type Communications (mMTC):** This use case is characterized by a large number of connected devices typically transmitting a relatively low volume of nondelay-sensitive data. Devices are intended to be low cost and have a very long battery life.
- **Ultra-Reliable and Low-Latency Communications (URLLC):** This use case is characterized by stringent requirements for latency, throughput, and availability. Examples include wireless control of industrial manufacturing processes, remote medical surgery, distributed smart grid automation, and transportation safety [e.g., vehicle-to-vehicle (V2V) or vehicle-to-everything (V2X) communication]. Many companies have referred to this use case as critical MTC (cMTC) or ultra-reliable MTC (uMTC). However, based on the ITU definition in [19], this use case is not strictly limited to MTC applications.

It is important to consider that the applications that will use 5G technology do not necessarily correspond to a single use case but are more accurately described as a combination of multiple use cases. Figure 1 illustrates some examples of currently envisioned 5G applications and their relationship to these three IMT-2020 use cases [19]. Figure 2 illustrates eight key capabilities identified by ITU for IMT-2020 and their relative importance to the same three use cases [19]. Furthermore, additional future use cases are expected to emerge but cannot be accurately predicted (i.e., what will be the "killer app" in 2025?). Therefore, it is desired that 5G standards will provide the flexibility to adapt to new use cases.

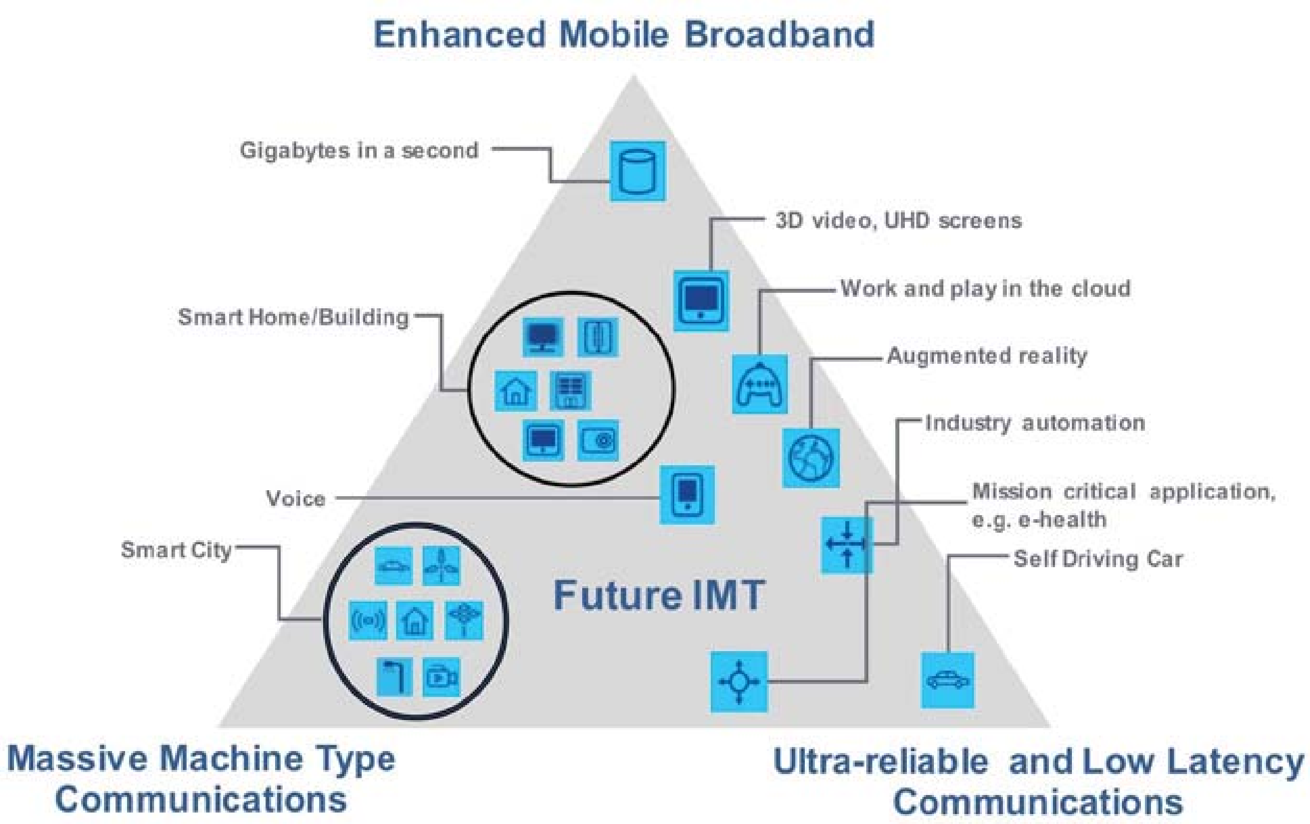

FIGURE 1. 5G use cases as defined by ITU for IMT-2020 [19].

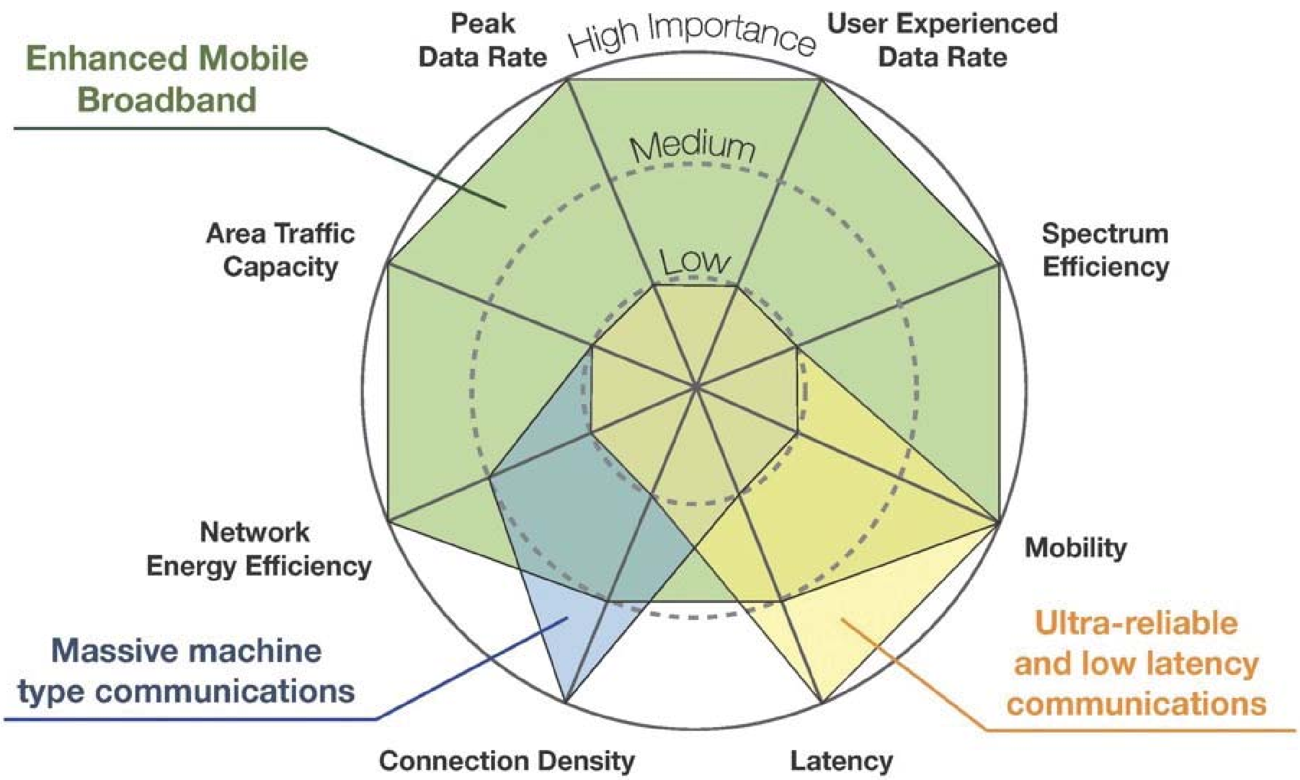

FIGURE 2. Eight key capabilities and their relative importance to 5G use cases [19].

5G Standardization

Development work toward 5G is well under way. Standards bodies are actively working on new 5G mobile technologies to be deployed in the 2020 time frame. This section summarizes the activities and corresponding 5G development timelines for three major standards bodies: ITU, 3GPP, and the Institute of Electrical and Electronics Engineers (IEEE).

Standardization in ITU

ITU is the United Nations agency responsible for promoting worldwide improvement and rational use of information and communication technology. Its members include industry, academia, and standards organizations from more than 190 member nations. The ITU Radiocommunication Sector (ITU-R) works toward worldwide consensus in the use of terrestrial and space radiocommunication services, including mobile communication technologies. Although compliance with ITU-R recommendations is not mandatory, they nevertheless have a high degree of adoption worldwide and hold the status of international standards [23].

International Mobile Telecommunications framework

ITU-R Working Party 5D (WP 5D) is responsible for overall radio aspects of terrestrial mobile systems, referred to as International Mobile Telecommunications (IMT). The purpose of IMT is to provide high-quality mobile services with a high degree of interoperability worldwide. Since 2000, the ITU has developed the IMT standards framework in a manner that parallels cellular generations from an industry perspective. Although ITU-R WP 5D defines the requirements for IMT, it does not develop the actual radio technologies. Rather, candidate radio technologies are submitted for inclusion by external standards bodies, such as 3GPP and IEEE. For this reason, ITU-R WP 5D maintains strong cooperation with the major global standards bodies.

The first family of standards derived from the IMT concept (IMT-2000) aligned with 3G cellular. Radio technologies accepted into IMT-2000 included 3GPP Wideband Code-Division Multiple Access (WCDMA), 3GPP2 cdma2000, and IEEE 802.16 [i.e., Mobile Worldwide Wireless Interoperability for Microwave Access (WiMAX)]. The next generation of IMT standards (IMT-Advanced) aligned with 4G cellular. Radio technologies accepted into IMT-Advanced included 3GPP LTE-Advanced and IEEE 802.16m [i.e., Wireless Metropolitan Area Network (WMAN)-Advanced].

Timeline for IMT-2020

In 2012, ITU embarked on a program to develop "IMT for 2020 and beyond," setting the stage for emerging 5G research activities around the world. The program has since adopted the name IMT-2020 and forms the framework for the next generation of mobile broadband standards. The timeline for the development of IMT-2020 is shown in figure 3 [24]. The IMT 2020 timeline will essentially follow the same process used in the development of IMT-Advanced.

The IMT-2020 program is well under way, with a number of key milestones completed. In September 2015, ITU published its vision of the 5G mobile broadband connected society [19]. This document defined three high-level use cases for 5G, described earlier in this article, which have already been widely adopted by 3GPP and industry in general. In the next phase, the 2016–2017 time frame, ITU-R WP 5D will define in detail the performance requirements, evaluation criteria, and methodology for the assessment of the new IMT radio interfaces. It is anticipated that the time frame for proposals will be focused in 2018. In the 2018–2020 time frame, independent, external groups will evaluate proposals and the definition of the new radio interfaces to be included in IMT-2020 will take place. ITU-R WP 5D also plans to hold a workshop in late 2017 to discuss the performance requirements and evaluation criteria for candidate technologies for IMT-2020, as well as to provide an opportunity for presentations by potential proponents for IMT-2020 in an informal setting. The whole process is planned to be completed in 2020, when a new draft of the ITU-R recommendation with detailed

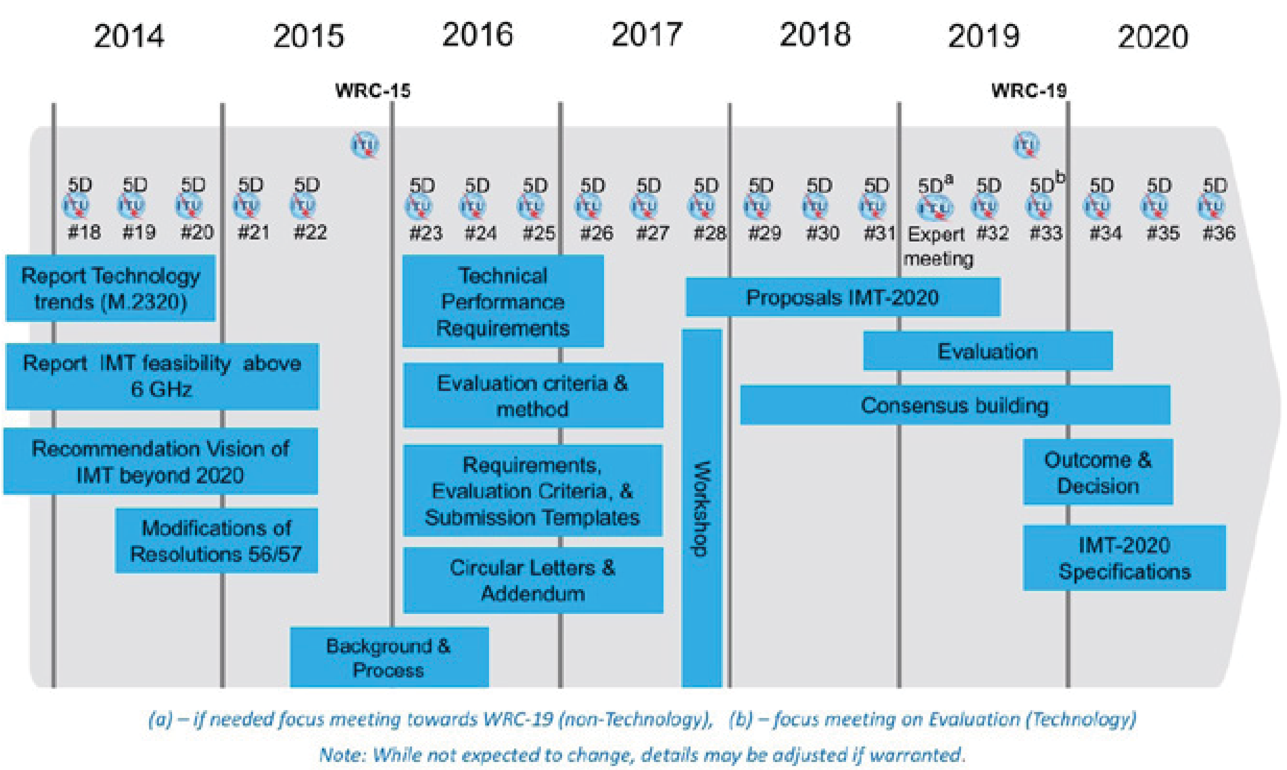

FIGURE 3. Detailed timeline and process for IMT-2020 in ITU-R [24].

specifications for the new radio technologies will be submitted for approval within ITU-R [24].

Standardization in 3GPP

3GPP is the international standards body responsible for the development and maintenance of major second-generation (2G), 3G, and 4G cellular standards. The purpose of the organization is to produce interoperable cellular communications standards, as well as studies and reports that define 3GPP technologies. The following technologies are currently maintained and evolved by 3GPP:

- Global System for Mobile Communications (GSM), General Packet Radio Service (GPRS), and Enhanced Data Rates for GSM Evolution (EDGE);
- Universal Mobile Telecommunications System (UMTS), WCDMA, High-Speed Packet Access (HSPA), and HSPA Evolution (HSPA+); and
- LTE, LTE-Advanced, and LTE-Advanced Pro.

These 3GPP technologies are constantly evolving through a series of backward-compatible releases. Since the completion of the first LTE and Evolved Packet Core (EPC) specifications, 3GPP has become the focal point for mobile systems beyond 3G. Therefore, 3GPP is expected to be a critical player in the development of 5G, and their timeline will have a direct influence on the timeline of the emerging 5G market.

3GPP is currently defining a new 5G RAT and corresponding network architecture. These are being developed within 3GPP under the working names "new radio (NR)" and "next-generation (NextGen) architecture," respectively [25]. In October 2016, 3GPP announced that the new 3GPP system will officially be known by the name "5G" from Release 15 onward [26]. Some initial standardization steps that have been taken to date include the following:

- **SMARTER study item:** In March 2015, 3GPP Technical Specification Group (TSG) System Aspects (SA) began a study item on technology enablers for new 5G services and markets, known as the SMARTER study item [27]. The objective of this study was to develop high-level use cases and identify the related high-level potential requirements to enable 3GPP network operators to support new services and markets in 5G. Phase 1 of the SMARTER study item was completed in March 2016; results are documented in 3GPP Technical Report (TR) 22.891 to be included in Release 14 [28]. A total of 74 use cases were identified. This work prompted four building block studies that grouped the use cases into families with common requirements: massive Internet of Things (IoT), critical communications, eMBB, and network operation. The building block studies were completed in June 2016; results are documented in 3GPP TRs 22.861, 22.862, 22.863, and 22.864 to be included in Release 14 [29]. The results of the SMARTER study will form the basis for a work item to define normative stage 1 requirements for the next-generation 5G system. The work item is scheduled for completion in March 2017; results will be documented in 3GPP Technical Specification (TS) 22.261 to be included in Release 15 [29].
- **Study item on channel model for frequency spectrum above 6 GHz:** The first 5G study conducted by TSG RAN focused on developing new channel models to support high-frequency spectrum from 6 GHz to 100 GHz. The models consider a variety of scenarios including urban, rural, and indoor, as well as the impact of line-of-sight (LOS) versus non-LOS (NLOS). The study was completed in June 2016, and results are documented in 3GPP TR 38.900 to be included in Release 14 [30].
- **Study item on architecture for next-generation system:** In December 2015, 3GPP TSG SA approved a study item to design a system architecture for the next generation of mobile networks. The new architecture will support at least the new 5G RAT(s), the evolution of LTE, and non-3GPP access types and will minimize access dependencies. The study considers new approaches such as NFV and network slicing. The study item was scheduled for completion in December 2016; results will be documented in 3GPP TR 23.799 to be included in Release 14 [31].
- **Study item on scenarios and requirements for next-generation access technologies:** In December 2015, 3GPP TSG RAN approved a study item to develop deployment scenarios and requirements of next-generation access

technologies. The study identifies 12 deployment scenarios that are more diverse than those originally envisioned for legacy RATs, such as LTE and its predecessors. It also identifies key performance indicators (KPIs) and other requirements for 5G NR. The bulk of the study was completed in September 2016 to provide guidance to the ongoing technical work being performed in the RAN working groups. However, the study item will remain open until March 2017 to match the IMT-2020 timeline and ensure all IMT-2020 requirements are captured. Final results are documented in 3GPP TR 38.913 to be included in Release 14 [32, 4].

- **Study item on NR access technology:** In March 2016, 3GPP TSG RAN approved a study item to develop the 5G NR access technology capable of meeting the broad range of use cases defined for 5G. The study seeks to develop a single technical framework capable of addressing all usage scenarios and requirements defined in TR 38.913 for eMBB, mMTC, and URLLC, with an emphasis on forward compatibility. The study is scheduled for completion in March 2017; results will be documented in 3GPP TR 38.912 to be included in Release 14 [1].

5G standardization activities in 3GPP will continue through 2020 and beyond, as described next.

Emerging 3GPP standardization timeline

In March 2015, 3GPP announced a tentative standardization timeline for 5G based on the ITU work plan timeline for IMT-2020 [33]. Since then, a more detailed timeline has come into focus as study items have commenced and completed, and as the 3GPP TSGs coordinate for the initial release of 5G. The timeline shown in figure 4 is a composite from multiple sources.

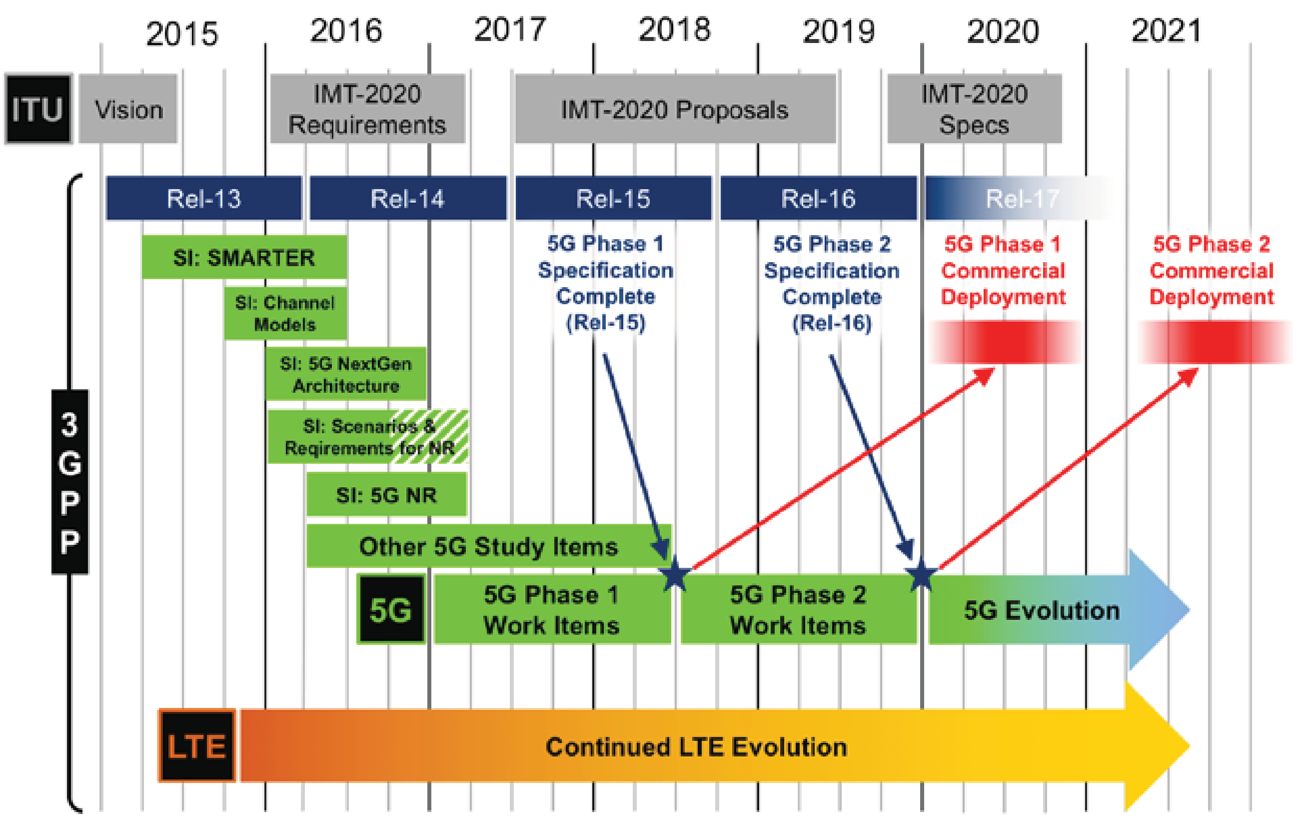

FIGURE 4. Emerging 5G standardization timeline for 3GPP. (Figure is a composite from [34] and [35] that includes additional data from various sources.)

The initial 5G study items in TSG SA and TSG RAN commenced in 2015 and 2016, as described previously. These initial 5G study items will be included in 3GPP Release 14. This work is carried out in parallel with ongoing LTE work. At the 3GPP plenary meeting in June 2016, the TSGs agreed on a work plan for the first release of 5G in 3GPP Release 15, including a clear work division between the TSGs [25].

5G work items were scheduled to begin in December 2016 for TSG SA and March 2017 for TSG RAN. The Phase 1 5G work items will fall into Release 15, with planned completion in June 2018. Additional 5G study items will continue during Release 15 in support of Phase 2. Subsequently, the Phase 2 5G work items will fall into Release 16, which will be completed around December 2019 in time for the final submission to ITU for IMT-2020. Phase 1 commercial deployments are expected to begin in 2020, followed by Phase 2 deployments in the 2021–2022 time frame. However, early pre-5G mmWave deployments may emerge in limited markets, such as South Korea or the United States, before 2020.

For example, Verizon Wireless has announced its plans to pilot a 28-GHz mmWave deployment in the United States for fixed wireless applications starting in 2017 [36]. To support this effort, the Verizon 5G Technology Forum (V5GTF)—an industry consortium led by Verizon—published an open radio interface specification in July 2016 [37]. The Verizon specification uses an OFDM-based PHY similar to time-division LTE (TD-LTE) with enhanced beamforming for operation in 28 and 39 GHz mmWave spectrum. However, with the initial focus on fixed wireless, the first release does not support user mobility. The Verizon specification can be considered pre-5G in the sense that it supports new mmWave capabilities beyond 4G but does not address all the use cases and associated requirements for 5G. The Verizon specification is expected to be incompatible with the eventual 3GPP 5G standard, potentially leading to market fragmentation [38].

3GPP phased approach to 5G standardization

3GPP TSG RAN will take a two-phased approach to developing the new 5G RAT [35]. The Phase 1 standard will define a new, non-backward-compatible 5G RAT. A subset of prioritized features and use cases will be addressed in Phase 1 to allow for early commercial deployments targeted for the year 2020. The Phase 2 standard will implement the full set of features and use cases necessary to meet the requirements for 5G. An initial proposal will be submitted to ITU as a candidate radio interface technology for IMT-2020 by the June 2019 submission deadline. The Phase 2 standard will later form the final submission around December 2019. The Phase 1 standard will be designed for forward compatibility with Phase 2 [35]. Forward compatibility means that Phase 1 must be designed from the beginning to optimally accommodate all of the features and use cases expected to be added later in Phase 2, even though those features are not yet fully implemented. Although the forward-compatibility requirement may sound straightforward, it represents a fundamental shift from the normal 3GPP standardization process, which historically has focused on a series of backward-compatible releases.

While prioritization of features between the two phases has been a topic of much debate, it is clear that the 5G Phase 1 standard will support tight interworking with LTE to simplify initial rollout. The phased approach and tight interworking with LTE means that elements of the LTE system architecture may persist in 5G deployments for some time to come. This implies that current and future work on LTE, LTE-Advanced, and LTE-Advanced Pro networks and technologies may have direct applicability to eventual 5G network deployments.

Standardization in IEEE

Initial 5G standards activities within the IEEE suggest that they do not intend to be a direct competitor with organizations like 3GPP on the radio interface between the RAN and the user equipment. Instead, IEEE has begun developing complementary technologies to support other communications requirements within the 5G ecosystem. In 2016, IEEE established two new working groups related to 5G: IEEE 1914 and IEEE 1918.

IEEE 1914 is the Next Generation Fronthaul Interface Working Group. This working group is currently developing two standards: the 1914.1 standard for packet-based fronthaul transport networks and the 1914.3 standard for radio over Ethernet encapsulations and mappings [39, 40]. These standards focus on the fronthaul interface within the RAN between baseband units (BBUs) and remote radio heads (RRHs) to support novel RAN architectures like C-RAN, and antenna techniques like MMIMO and coordinated multi-point (CoMP) transmission and reception. The projected completion dates for these standards are August 2018 for 1914.1 and October 2017 for 1914.3.

IEEE 1918 is the Tactile Internet Working Group. This working group is currently developing the 1918.1 standard, which defines a framework for the Tactile Internet [41]. The purpose of this framework is to establish a basis for the rapid development of the Tactile Internet as a 5G and beyond application, with the expectation of additional IEEE 1918 standards to follow. The projected completion date for the 1918.1 standard is October 2018.

With respect to IMT-2020, IEEE may seek to expand the role of WLAN in 5G as a complementary radio interface for next-generation HetNets. In September 2016, the IEEE 802.11 working group sent a liaison statement to 3GPP TSG RAN and TSG SA inviting them to consider the use of IEEE 802.11-based WLAN in unlicensed spectrum as a complementary means of meeting the performance requirements of IMT-2020, potentially leading to inclusion in a joint submission to IMT-2020 [42]. This approach would be a logical extension of the increasing level of interworking between LTE and WLAN in recent standards releases. WLAN is already widely used in 3GPP networks for high data rate offloading.

Recent enhancements in radio-level interworking have increased the efficiency of these networks. Enhancements include LTE-WLAN Aggregation (LWA) and LTE WLAN Radio Level Integration with IPsec Tunnel (LWIP) in 3GPP Release 13, with further enhancements in 3GPP Release 14. Although 3GPP declined to make a decision at the September 2016 plenary meeting, the concept of a potential joint submission could represent a novel approach to IMT-2020. In contrast, previous generations of IMT saw IEEE in competition with 3GPP, with the submission of the IEEE 802.16 WiMAX family of standards to IMT-2000 and IMT-Advanced as a direct competitor in the 3G and 4G markets.

Conclusion

This article provided an introduction to major technology trends in the emergence of next-generation 5G mobile networks. These networks are expected to see initial commercial deployment starting around the year 2020. Early 5G standardization activities in the ITU, 3GPP, and IEEE were addressed.

For further information on the latest developments in 5G, the interested reader is directed to the following resources. ITU publications for IMT-2020 can be found on the IMT-2020 web page [24]. Notable documents include the ITU vision for IMT-2020 [19] as well as the technical performance requirements for IMT-2020 (scheduled for completion in February 2017). The 3GPP web site (www.3GPP.org) is the most direct source for 3GPP-related technical information. 3GPP press releases provide high-level summaries of ongoing standards activities and often include links to more detailed further reading. The latest versions of the 3GPP TR and TS documents mentioned in this article can be accessed there as well. Information on the IEEE 1914.1, 1914.3, and 1918.1 standards can be found in the approved project authorization request (PAR) documents [39, 40, 41] and the corresponding working group web pages. Lastly, the Verizon mmWave specification is available on the V5GTF website (www.5GTF.org). This pre-5G specification defines layers 1 to 3 of an open radio interface using a document structure similar to that of LTE.

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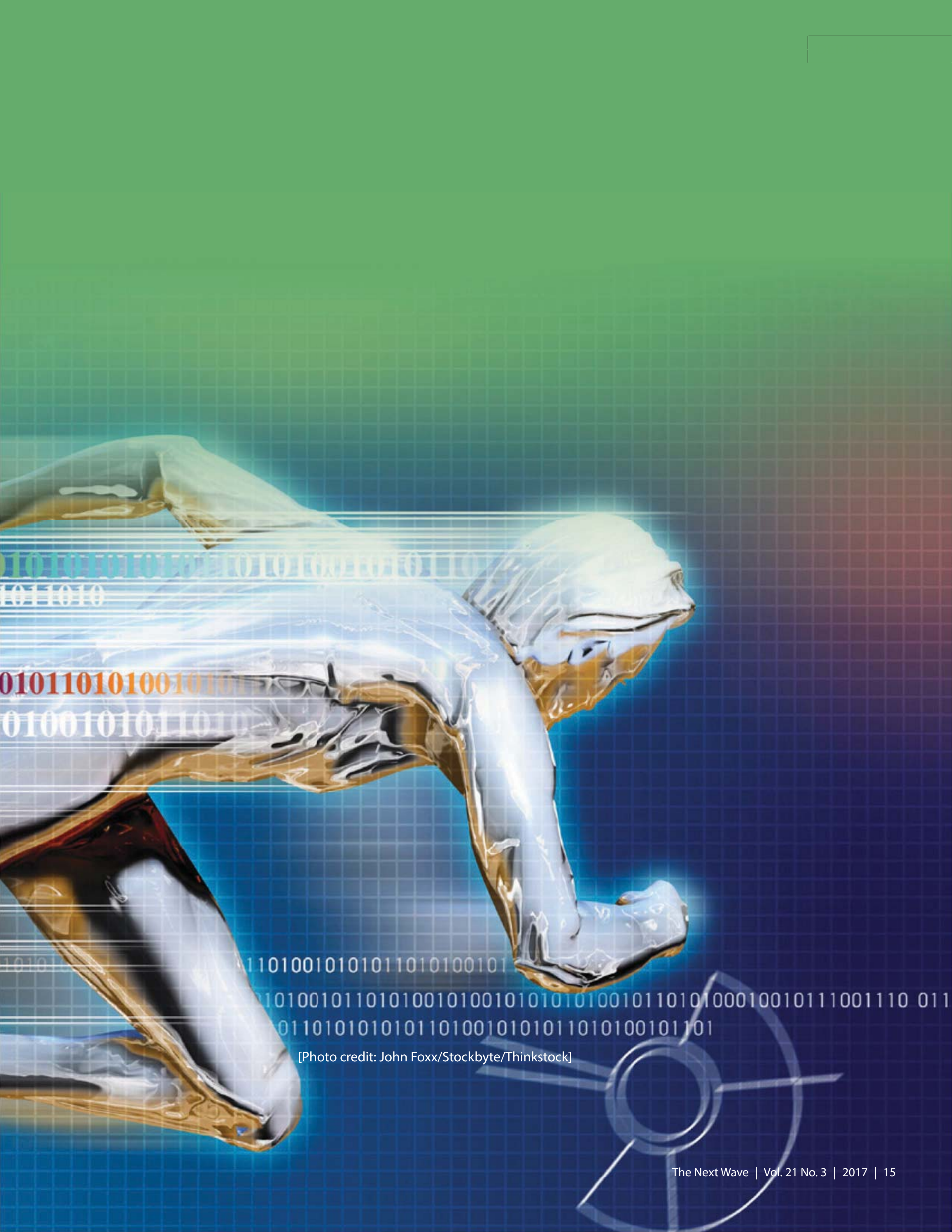
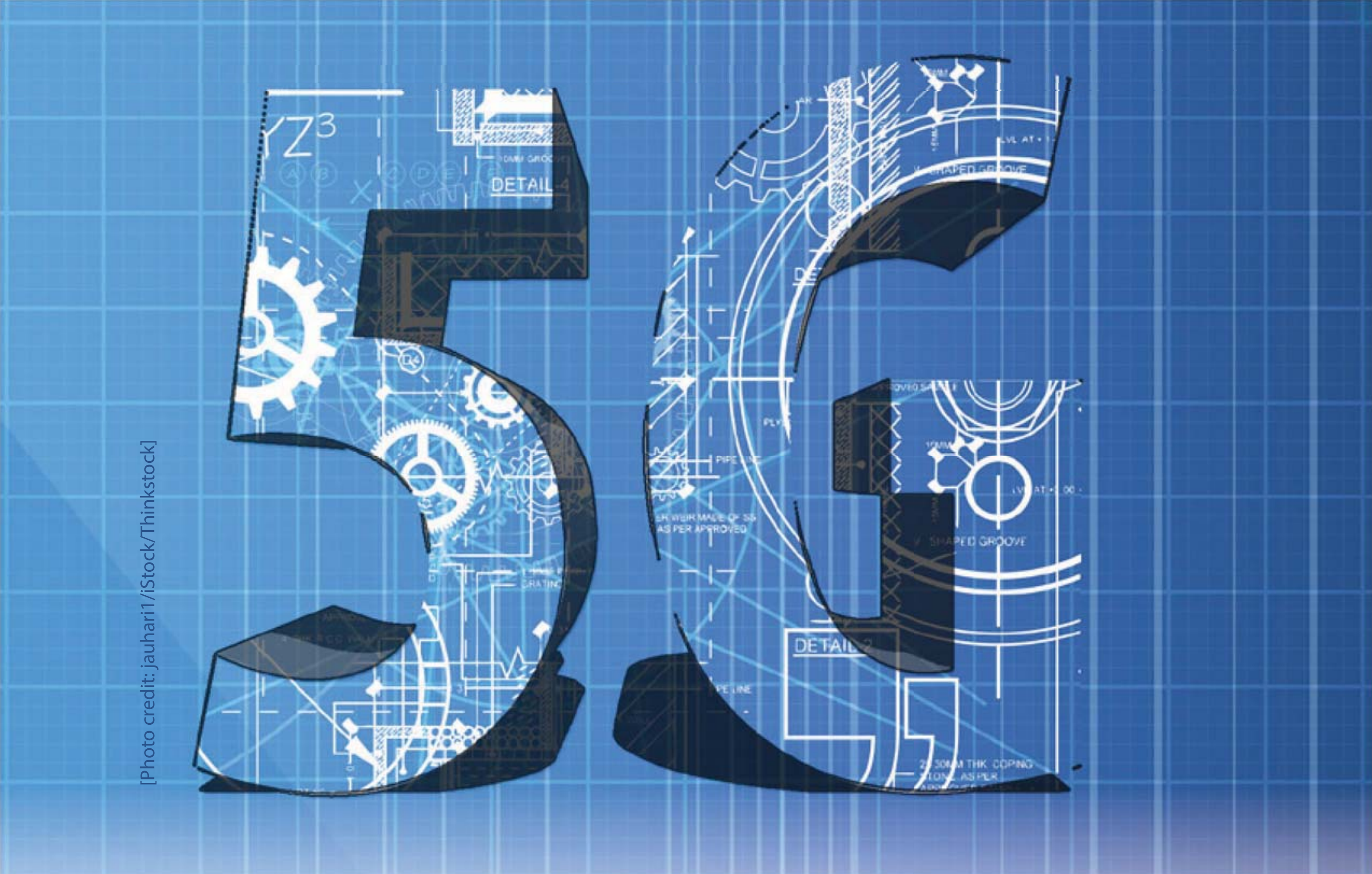


[Photo credit: John Foxx/Stockbyte/Thinkstock]



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Virtualizing the 5G Architecture

Staff Writer

Virtually changing the 5G architecture

Virtualization is set to play a major role in the evolution of the fifth-generation (5G) core network. According to industry experts, 5G will use software-centric networking technologies such as software-defined networking (SDN) and network functions virtualization (NFV), and will be natively cloud based. If correct, this will represent a major transition in system architecture and will require much greater collaboration across the networking ecosystem. The push to incorporate more cloud- or software-based components is driven by the need for greater flexibility and scalability to respond to the demands of radio access technologies that offer more bandwidth, reduced latency, and stringent quality of service (QoS) requirements. The new 5G core network must be adaptable and better equipped to handle various devices and manage capacity in near-real time. Mobile network operators see the advances in cost and efficiency that virtualization brings to other market segments and will use the emerging 5G technology to determine if these same advances can benefit the mobile market [1, 2].

SDN and NFV are two key architecture concepts in development to support the flexibility and mobility demands of the 5G network infrastructure. Virtualizing network functions that were previously implemented in hardware will allow providers to introduce new features and integrate new standards at a faster rate. SDN/NFV provides an avenue for providers to decentralize their networks, thereby increasing flexibility and reducing latency. Two areas where SDN/NFV will benefit 5G networks, and in some cases even fourth-generation (4G) mobile technology, are network slicing and cloud-radio access network (C-RAN).

Network slicing

Network slicing would promote end-to-end mobile network virtualization by "slicing" the network into virtual channels. These virtual channels would be autonomous and encompass a set of resources—physical or virtual—including bandwidth on a network link, processing capacity of servers, processing capacity of network elements, as well as operations support system (OSS) and business support system (BSS) processes. Operators could then use these channels to dynamically devote the appropriate network resources to create a "lane" in the network specifically designed for a particular use or service. This would accommodate the many use cases being put forth for 5G. The operator-led Next Generation Mobile Networks (NGMN) Alliance has sought to define categories of 5G use cases (i.e., service types) that have distinct performance characteristics and commercial potential. In a 2015 white paper, the NGMN listed eight application categories for 5G [3, 4, 5]:

1. Broadband access in dense areas,
2. Broadband access everywhere,
3. Higher user mobility,
4. Massive Internet of Things,
5. Extreme real-time communications,
6. Lifeline communications,
7. Ultra-reliable communications, and
8. Broadcast-like services.

Each of these service types demand different network requirements that are determined by the types of traffic being sent and even the types of devices sending the traffic. For example, someone downloading cat videos will not have the same bandwidth or low latency requirements as a doctor in Los Angeles performing surgery virtually on a patient in Mumbai. The end-to-end notion of network slicing could be key to 5G's ability to effectively accommodate all of these disparate use cases.

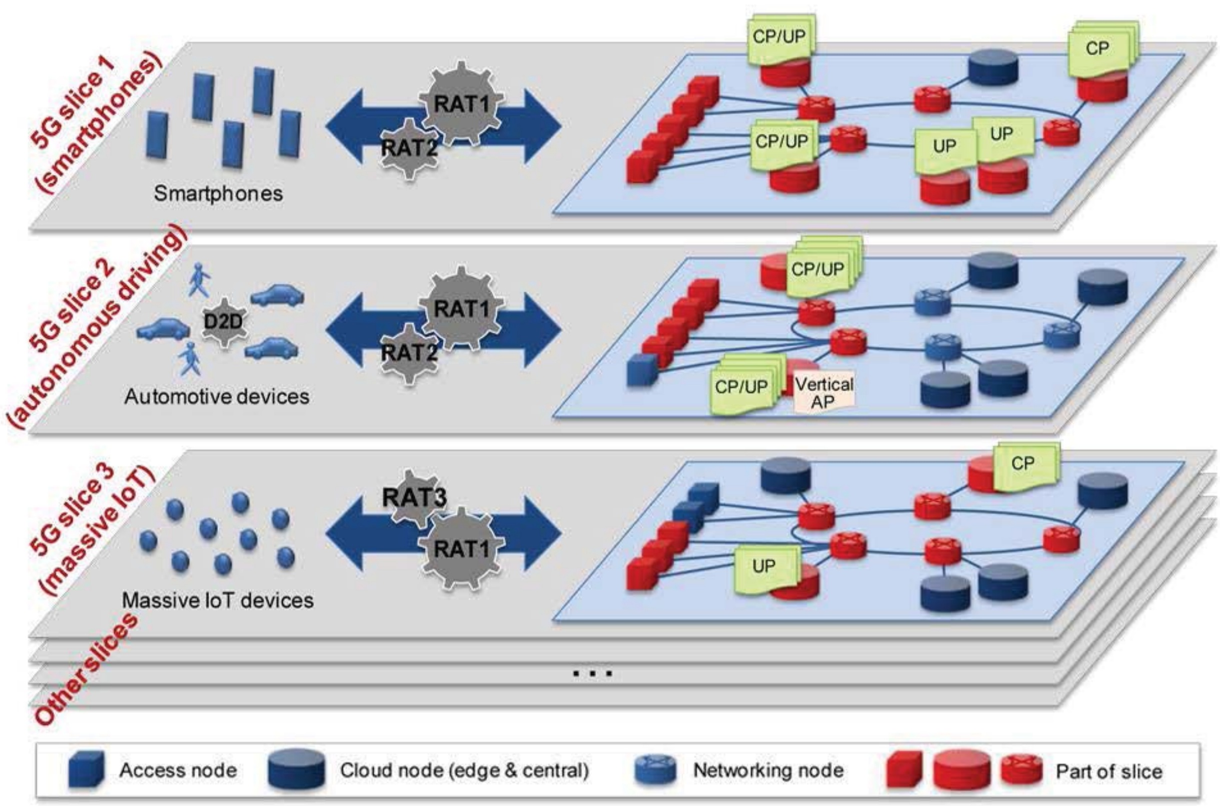

FIGURE 1. 5G's incorporation of SDN and NFV would allow network slices to be created dynamically and deployed as needed to accommodate a variety of scenarios [2].

The Open Networking Foundation, in an April 2016 white paper, called out SDN's ability to support multiple services over a common architecture as a key enabler for network slicing. SDN also allows for slices to be created dynamically and deployed as needed to accommodate a variety of scenarios (see figure 1). Currently, 4G mobile networks prioritize traffic to get a similar effect, but with more rigidity and limitations. However, as 4G networks incorporate SDN and NFV, network slicing will become an option.

C-RAN

There are more than six million base stations (excluding small cells) deployed worldwide across approximately five million different cell sites serving close to four billion users. The surge in demand for connectivity has network operators searching for ways to shrink their network footprint, lower operational expenditures (OPEX), and still meet users' demand for access. C-RAN meets these requirements and has either been implemented or trialed by several operators including Verizon, AT&T, KT (South Korea), and China Mobile. Radio base stations currently depend on special purpose-built hardware deployed at the cell site. The baseband processing unit (BBU) is the part of the RAN that is responsible for managing the radio functions (or all functions that require an antenna). The BBU is one of the parts of the RAN that can be moved to a central location, creating a pool of BBUs to serve multiple base stations. C-RAN aims to centralize and virtualize baseband processing to reduce cell site costs and enable coordinated scheduling of resource blocks across a coverage area [6].

Figure 2 illustrates the evolution from the classic RAN model to a C-RAN setup. On the left, the classic model has the BBU deployed at the cell site connecting to the core network over IP/Ethernet transport. Any coordination between cell sites takes place over the X2 interface, which allows two sites to communicate. In a C-RAN architecture, the BBUs are pooled at a location away from the cell site. Pooling BBUs negates the need for the X2 interface as communications between cell sites now takes place internally. This is one of the reasons for the increased performance in C-RANs. The C-RAN model also makes updating the waveform and protocols easier as it only requires a software upgrade at the centralized BBU and not at each individual cell site

The move to a C-RAN architecture increases the flexibility of the network by allowing providers to, in theory, even change the types of RANs used—from 3G to 4G. For instance, in an area that has a mix of 3G and 4G users, operators can rebalance radio frequency resources by shifting more resources to 4G when 4G

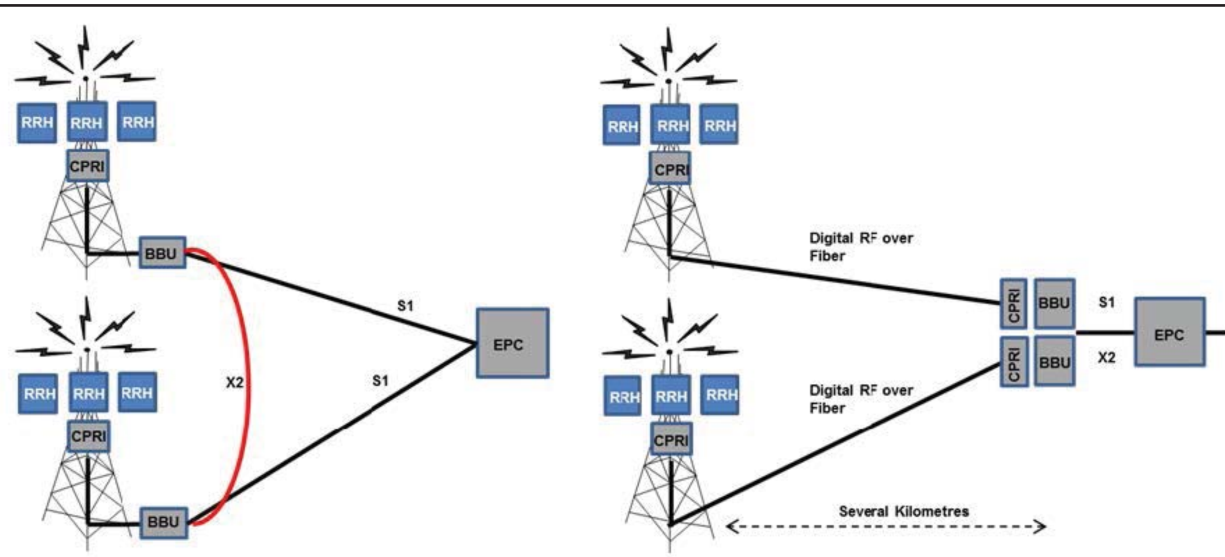

FIGURE 2. Unlike the traditional RAN model (on the left), C-RAN technology (on the right) pools the BBUs at a location away from the cell site offering an increase in performance and simpler upgrade path [6].

users are prevalent in the covered area. This shuffling of resources ensures that there is sufficient capacity for subscribers. C-RAN will also enable RAN-as-a-Service (RaaS), which will allow operators to rent RAN capacity to other operators.

Conclusion

On the face of it, virtualizing the 5G architecture seems like a necessary step towards preparing for the low latency requirements associated with 5G services. However, there are many uncertainties around 5G and a lack of visibility into what 5G will actually become through the standardization process, and at which phase different performance requirements will be supported or required. Phase II, the phase that is expected to meet International Mobile Telecommunication system for the year 2020 (IMT-2020) requirements, is expected in 2020. However, early versions or "pre-5G" offerings could be on the market before the final standard is approved. So, while these pre-5G solutions will have some 5G functionality, they will not field the full complement of improvements offered by an approved 5G system. For this reason, it is unclear to what degree virtualization techniques like C-RAN and network slicing will need to be implemented. It may come down to what the industry leaders in 5G implement in their "pre-5G" networks that will decide what a virtual 5G network will look like and when we can expect to see one.

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5G and the Auto

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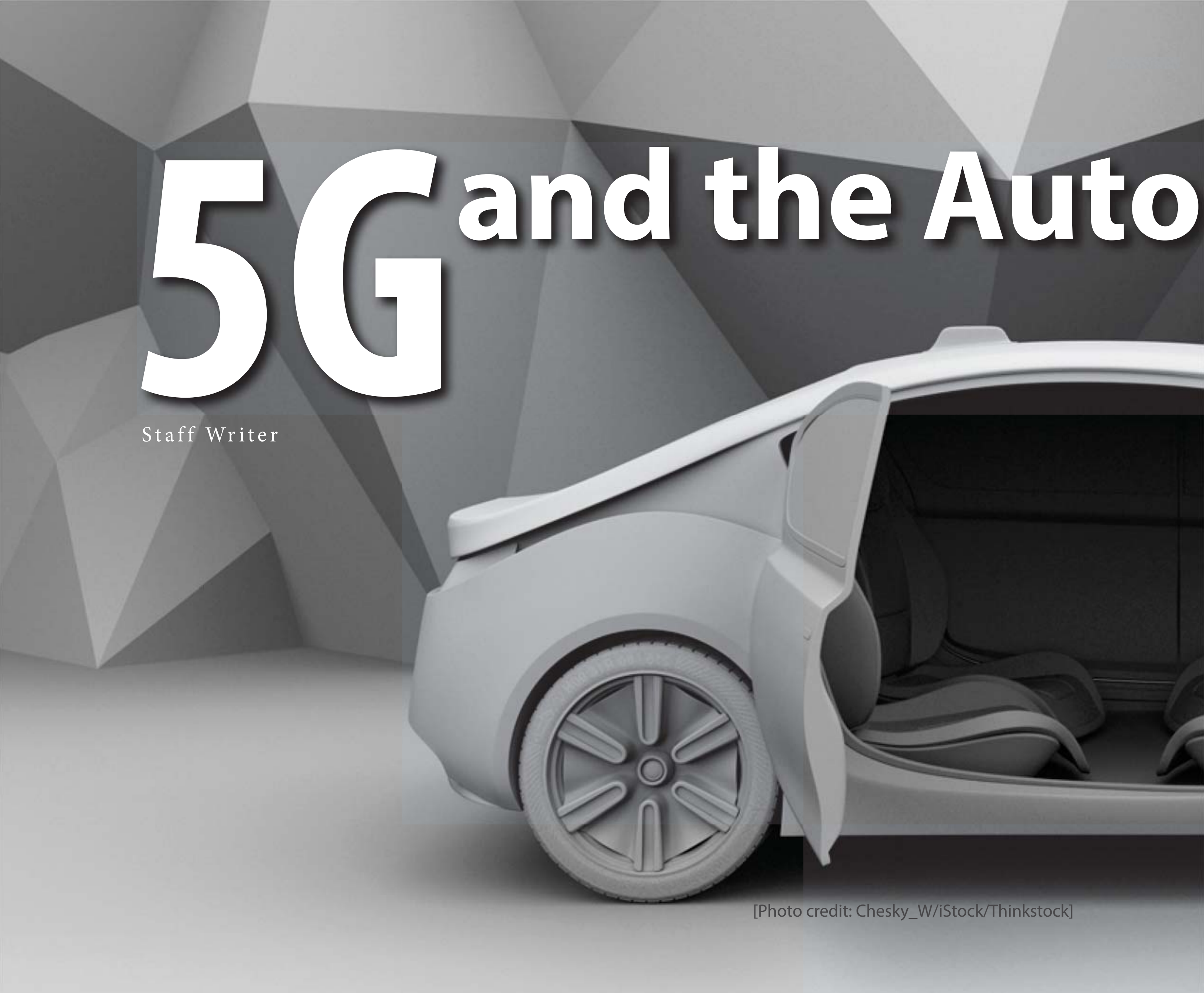

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Industry stakeholders envision 5G as a key enabler that allows network connectivity in vehicles to shift in status from an optional accessory to a core feature that supports not only the individual vehicle, but also communication with other vehicles and sensors that inform traffic, parking, and navigation—while also ensuring passenger safety and data security. For consumers, a connected vehicle provides a growing number of features and services that make the driving experience safer, convenient, and less costly. 5G connectivity will enable information from in-car sensors to continuously be passed to the cloud. By sharing information and alerts about micro-level weather, road temperature, surface conditions, and violent breaking ahead, more efficient and consistent traffic flows will be achieved that reduce congestion and emissions. The aggregated and interpreted data will provide more informed driving information, as well as alert and activate onboard safety systems to prevent accidents [1].

motive Industry

Autonomous vehicles

Autonomous vehicles—also referred to as driverless or piloted vehicles—are predicted to hit the market by 2020, but stable 5G infrastructure will play a key role, according to a white paper by ABI Research [2]. Estimates indicate that 5G latency could be as low as one millisecond (ms) over-the-air, and 5 ms end-to-end, enabling the following automotive use cases:

- Broadband multimedia streaming (driverless vehicles as mobile living rooms).
- Cloud services for vehicle lifecycle management, apps, security, and over-the-air updates (cloud-to-vehicle).
- Capturing or uploading huge volumes of sensor data for real-time traffic, weather, parking, and mapping services (vehicle-to-cloud).
- Cooperative mobility: low latency vehicle-to-vehicle and vehicle-to-infrastructure for active safety and autonomy [redundancy for advanced driver assistance systems (ADAS)] [2].

The current ADAS being delivered on 2016 vehicles already facilitate SAE Level 1 (see figure 1) and are beginning to incorporate features that would be considered Level 2. However, Level 4 and 5 capabilities may not be that far away. In October 2015, Robot Taxi, a joint venture between Japanese mobile Internet company DeNA and vehicle technology developer ZMP, announced that it would offer driverless transportation to about 50 people in an area near Tokyo. Its goal is to commercialize the service by 2020, in time for the Tokyo Olympics [1]. While Robot Taxi is shooting for full automation (Level 5) in time for the games, it is likely that the use of such vehicles will initially be limited to shuttling passengers between Olympic venues. However, this venture is particularly notable because the technology is brand-agnostic and can be retrofitted to any vehicle [4].

Clearly, experimentation with autonomous vehicles is increasing, and 2020 as a date for some form of commercial implementation is certainly feasible from a technology perspective. Probably the best-known self-driving car project belongs to Google, which was started in 2009 and has clocked more than two million miles on public roads to date [5]. However, Google is not alone; Tesla, BMW, Audi, Mercedes, and most recently GM, have all showcased self-driving concept cars and demonstration projects. In mid-October 2016, Tesla announced that all cars currently being produced in their factories would include the hardware needed for full self-driving capability at a level of safety far greater than that of a human driver. However, the company added that the technology first needed to be tested and calibrated via “millions of miles of real-world driving” before the hardware would be activated on consumer vehicles [6]. In addition to traditional car manufacturers, companies such as Uber and Chinese search giant Baidu are also working on autonomous technology and self-driving cars [1].

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* (“system”) monitors the driving environment**						
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	**High Automation**	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

FIGURE 1. SAE Levels of automation. The Society of Automotive Engineers (SAE) has defined levels of automation to clarify what role (if any) drivers have in operating a vehicle while a driving automation system is engaged. These levels are intended to establish a consistent framework that can be used across industries as the dialogue about autonomous vehicles continues. (Figure credit: SAE International J3016 [3].)

The motivations for creating an autonomous vehicle are beyond just technology. It's about reducing emissions through better fuel consumption, as well as addressing the demographic changes of an aging population that increase, rather than decrease, the potential for human error-induced accidents. It's also about leveraging the convergence of the shared economy and urban living, where young and old people no longer feel the need to own a car if there is a cost-effective and convenient alternative, such as Zip Car rentals, or on-demand ride-sharing services such as Uber [1].

Looking forward

Geographical coverage will be a key condition for 5G to have any relevance in the automotive sector. Initial 5G coverage can be supplemented by 4G and Wi-Fi connectivity on phones and other devices while the infrastructure is being built up, but these multimode, multiconnectivity solutions will not suffice for critical automotive use cases relying on the unique capabilities of 5G in terms of latency, reliability, and security [2]. Even once 5G is fully deployed, the adoption of self-driving technology will likely play out differently in the various markets in different regions since the forces shaping it are diverse at both the global and local level [1].

Government and industry cooperation

The continuous progression of ADAS-enabled cars and the gradual adoption of the autonomous vehicle will significantly reduce, and possibly eliminate, the number of crashes. This could, in turn, allow the removal of some regulations that relate to safety considerations, such as crumple zones, bumpers, and airbags. It also means that a review of laws relating to driving age, drunk driving, and speed restriction enforcement may be required, but not until all vehicles are compliant [1].

In September 2016, the US Department of Transportation (DOT) released the Federal Automated Vehicles Policy for highly automated vehicles (HAVs), or those intended to operate at Levels 3 to 5 as defined by SAE. The document—which is currently intended as guidance rather than formal policy—lays out standards for safe design, development, and testing of HAVs before they are commercially sold or operated on public roads. It also proposes guidelines for state governments to ensure a consistent national framework for regulation of motor vehicles with all levels of automated technology [7]. DOT's National Highway Traffic Safety Administration released additional nonbinding guidance in October 2016, outlining best cybersecurity practices for motor vehicle manufacturers and individuals and organizations involved in developing self-driving technology. The guidance aims to make cybersecurity a top priority for the automotive industry and proposes layered solutions to ensure that automated driving systems are designed to take appropriate and safe actions, even when an attack is successful [8].

A challenge yet to be addressed is that, historically, car manufacturers have completely controlled the design and development of vehicles. The advent of computers and software that effectively become the "mind" of the car means that manufacturers could lose control to technology and software companies, and yet still remain liable for any issues or catastrophes related to the car. It also remains to be seen how much and what type of data car manufacturers and network providers would be expected to share to improve overall safety and security of connected vehicles [1].

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FROM LAB TO MARKET

News from the Technology Transfer Program

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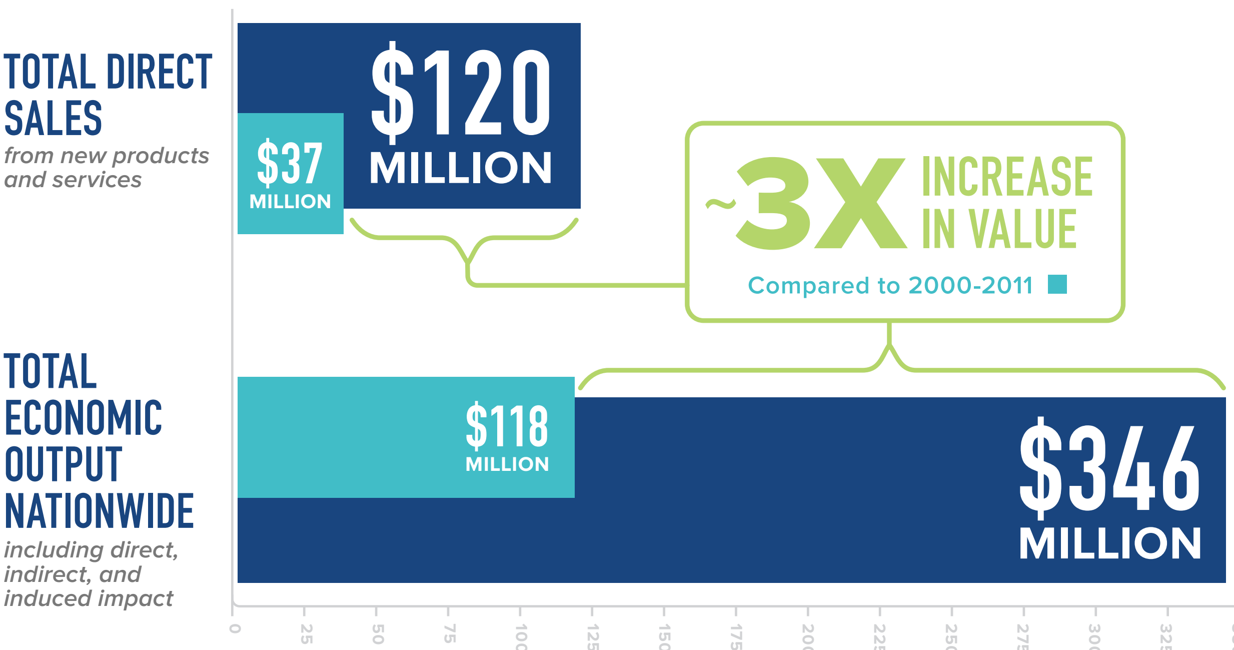

JOBS CREATED
or retained

1,330

SOURCE: *National Economic Impacts from DoD License Agreements With U.S. Industry*, TechLink and UC Business Research Division.

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NSA Technology + Technology Transfer = Economic Growth ⇒ National Security

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