IEEE 5G AND BEYOND TECHNOLOGY ROADMAP WHITE PAPER

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ABSTRACT

Technologies for 5G and future generations of connectivity, when deployed in the 2020s, will provide higher bandwidth and lower latency than current-generation 4G technology. "5G and Beyond" will enable bandwidth in excess of 100s of Megabits per second (Mb/s) with latency of less than 1 millisecond (ms), as well as provide connectivity to billions of devices. Most importantly, these technologies are expected to enable fundamentally new applications that will transform the way humanity lives, works, and engages with its environment.

The members and societies of IEEE recognize the disruptive nature of technologies enabling the IEEE 5G and Beyond vision, as well as the substantial technical barriers to its realization. Consequently, IEEE is developing a technical community to foster exchange of ideas, sharing of research, setting of standards, and identification, development, and maturation of system drivers, system specifications, use cases, and supported applications. One of the first activities of our IEEE 5G Initiative is the formation of a working group around a future-networks roadmap, with emphasis toward 5G and Beyond technologies and a charter to develop a white paper summarizing the challenges and opportunities in building and sustaining a 5G and Beyond ecosystem. With the release of this white paper, our attention turns to developing a comprehensive IEEE 5G and Beyond Technology Roadmap to help guide operators, regulators, manufacturers, researchers, and other interested parties involved in developing the 5G and Beyond ecosystem. Once released, the IEEE 5G and Beyond Technology Roadmap will be periodically updated with forecasts for three-, five-, and 10-year horizons.

This white paper describes the IEEE 5G and Beyond Technology Roadmap process and summarizes the need for collaboration among all stakeholders in industry, academia, and standards development organizations (SDOs) in undertaking this high-risk engineering challenge. We outline the current telecommunications value chain that will have to adapt to the changes and opportunities that the introduction of 5G and Beyond technologies will bring. Future applications are listed that drive 5G and Beyond requirements to provide societal benefits for education, manufacturing, healthcare, smart grid, entertainment, autonomous cars, and smart cities. We also describe key technology trends that may impact 5G and Beyond design drivers and the design challenges if these technologies are to simultaneously provide wireless communication, massive connectivity, the tactile internet, quality of service (QoS), and network slicing (NS). Finally, the white paper highlights some technology enablers that need to be explored in the creation of the roadmap. Collectively, we think that, with widespread participation, the roadmap process outlined here can reduce some of the technical and engineering risk associated with the migration to 5G and Beyond technologies.

Key words:
3GPP, 4G, LTE, 5G, architecture, artificial intelligence, AI, augmented reality, AR, bandwidth, broadband, business model, cellular, cloud, communications, connected vehicles, connectivity, core network, EAP, edge automation platform, fixed, future networks, fog computing, frugal 5G, IETF, industry verticals, information technology, integration, International Telecommunication Union, internet, Internet Engineering Task Force, internet of things, IoT, ITU, key performance indicators, KPIs, latency, massive connectivity, massive MIMO, merged reality, MR, microwave, millimeter wave, mmWave, mobile, mobile virtual network operators, multiple input/multiple output, native security, network slicing, networking, networks, NFV, OMEC, open multi-access edge cloud, radio access network, RAN, SDOs, self-optimizing networks, sensors, service quality, slice management, software defined networks, SSDN, standard developing organizations, standards, tactile internet, telecommunications, testbed, Third Generation Partnership Project, transport network, value chain, virtual reality, VR, wireless, wireless communications

FUTURE NETWORKS: IEEE 5G AND BEYOND TECHNOLOGY ROADMAP

BACKGROUND AND MOTIVATION

In the last 20 years of the previous century, mobile phones became pervasive among consumers. A new mobile generation has appeared approximately every 10 years since the first 1G systems were introduced in 1982. Mobile phones were originally perceived to be limited to voice communications. The first 2G systems were commercially deployed in 1992, and the 3G systems appeared in 2001. 4G systems were first standardized in 2012. The development of the 2G Groupe Speciale Mobile (GSM) and 3G standards took about 10 years from the official start of the research and development (R&D) projects, and development of 4G systems began in 2001-2002.

In a similar time period, the internet became accessible to the consumer community, as well. Initially, the communication capability of the internet was aimed at text messages; shortly after, access to multiple sites on the web also became available via the internet. The introduction of smartphones and tablets in 2007 and 2010, respectively, transformed the combination of these mobile appliances into instruments that, in addition to enabling voice calls, could navigate the internet and handle photos and video, download, and stream movies, among many other applications. In 2016 alone, about 1.5 billion smart phones were sold, and Cisco forecasted that, by 2019, 80 percent of global internet consumption will be video content. This will amount to a total of about 90,000 petabytes per month by then, with mobile video consumption growing at an estimated compounded annual growth rate (CAGR) of 67 percent versus a 29 percent growth for fixed video consumption in the period 2014-2019. [1]

Some drastic upgrade/conversion of the whole communication infrastructure needs to happen by the year 2020 to support the forecasted growth in the flow of information. It is well known that the ability of a communication channel to carry high-quality audio or video information is directly proportional to the usable frequency bandwidth. This demand for broader channel bandwidth associated with the forecasted growth in the number of communication channel requires the use of higher frequencies above 3GHz where contiguous spectrum can be found to support wider communication channels.

New mobile generations are typically assigned new frequency bands and wider spectral bandwidth per frequency channel (1G up to 30 KHz, 2G up to 200 kHz, 3G up to 5 MHz, and 4G up to 20 MHz). But there is little room for larger channel bandwidths, and new frequency bands suitable for land-mobile radio would overlap with K-band (18 to 27GHz) transmissions of communication satellites.

In addition, the path loss between transmitting and receiving antennas is proportional to the square of the frequency in accordance with Friis equation (Power received is proportional to Power transmitted/f^2). Furthermore, penetration loss, diffraction loss, etc., also increase with increasing frequency. The bands between 6 GHz and 30 GHz are important to consider for increased communication capacity, but, as the operational frequency is increased, the antenna gain at the transmitter and receiver must compensate these losses.

All of the issues related to higher operational frequencies need to be well understood and resolved since the whole system design completely depends on this.

[1] *https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/complete-white-paper-c11-481360.pdf*

Fifth-generation mobile networks or fifth-generation wireless systems, abbreviated “5G,” are the proposed next telecommunications standards beyond the current 4G standards. 5G planning aims at higher capacity than current 4G, allowing a higher density of mobile broadband users and supporting device-to-device, ultra-reliable, and massive machine communications.5G R&D also aims at lower latency than 4G equipment and lower battery consumption, for better implementation of the internet of things (IoT).

The Next Generation Mobile Network (NGMN) defines the following requirements that a 5G standard should fulfill:

- Data rates of 10s of Mb/s for 10s of thousands of users
- Data rates of 100 Mb/s for metropolitan areas
- 1 Gigabit per second (Gb/s) simultaneously to many workers on the same office floor
- Several hundreds of thousands of simultaneous connections for wireless sensors
- Significantly enhanced spectral efficiency compared to 4G
- Improved coverage
- Enhanced signaling efficiency
- Significantly reduced latency compared to Long Term Evolution (LTE)

It is the purpose of this white paper to stimulate an industry-wide dialogue to synchronously address all the facets of the development and deployment of 5G by the year 2020.

1. Introduction

The mobile and fixed wireless industry has enjoyed tremendous growth over the past decades. Indeed, mobile has evolved from a niche technology, embodied by an analog 1G voice system, to a full-fledged internet on the move and end-to-end (E2E) digital 4G system. Now 5G communities—with many R&D, standardization, academia, fora, etc., around the globe—are aiming to fulfill demands (and hype) with a broad set of new technologies and capabilities being developed.

So, what is beyond 5G?

One area will be software defined network/network function virtualization (SDN/NFV) to expand to E2E frameworks with distributed system software to enable all systems from management and control to user equipment (UE). Software-based design (i.e., softwarization) is a transformation that is not expected to be complete in the 5G timeframe. Beyond 5G, the biggest opportunity and challenge will be to finish an overall industry transformation to a software-centric vision, in which commercial off-the-shelf (COTS) network equipment is flexibly and easily designed, implemented, deployed, upgraded, managed, maintained, and programmed using machine learning/artificial intelligence (ML/AI) as part of agility of all lifecycle management of network systems. These are very comprehensive and difficult tasks that will require another decade or so to complete.

Other aspects of beyond 5G systems will be end-user integration and enablement, security, spectral and energy co-efficiency, and the whole area of resiliency (such as maintaining service quality, tolerance to any disruption, etc.) Softwarization in architecture will address many other trade-offs among flexibility, performance, cost, security, safety, manageability, etc.

1.1. NEED FOR A ROADMAP

With so many generations of mobile now deployed globally, the technology is starting to become a commodity and is naturally experiencing market pressure underpinned by shrinking margins and higher deployment costs.

It is useful and timely to pose the question on the future of mobile—a future that goes beyond 5G. Notably, it is important to understand which technology disruptions are required to enable mobile not only to survive but also to thrive in an increasingly competitive technology and business landscape.

Understanding that technology disruption is tightly coupled to innovation, the aim of this collaborative IEEE technology roadmap development is to outline a technology and innovation vision that is coherent within the telecommunications industry and across a much wider industry stakeholder system. With proper guidance, it is anticipated that 5G and Beyond will be able to unlock the economic benefits outlined in numerous studies.[2]

It is imperative that the entire industry for future networks and massive connectivity participate in this IEEE 5G and Beyond Technology Roadmap activity. Doing so will allow participants to realize critical benefits:

- Optimize investment strategies for R&D
- Enable visibility into future technology trends
- Concentrate efforts toward future solutions so benefits are maximized for the industry
- Contribute to and be informed of common perspectives in a timely way to address the shared needs and challenges faced in the evolution to the future state
- Be aligned with pre-competitive solutions that can be implemented in collaborative environments, as well as in the competitive domain
- Explore unique innovations to provide potential solutions where it serves individual stakeholders within industry to do so
- Leverage R&D costs through resulting collaborations and partnerships or benefit from the results of enabled research activities
- Provide valuable input to the formulation of standards

Developing a timeframe of projections for when introductions of new technologies may be needed also will convey important benefits:

- Provides necessary lead time for equipment and interface development
- Allows time for solutions to be modeled and tested
- Enables research opportunities to be explored and funded

[2] *European Commission, "5G deployment could bring millions of jobs and billions of euros benefits, study finds," https://ec.europa.eu/digital-single-market/en/news/5g-deployment-could-bring-millions-jobs-and-billions-euros-benefits-study-finds.*

1.2. Roadmap process

To this end, the community realized in mid-2016 that there is a need and opportunity to develop an orchestrated vision on the wireless connectivity ecosystem. The IEEE 5G Initiative was, hence, introduced under the auspices of IEEE technical activities with an inception meeting in August 2016, in Princeton, New Jersey, in the United States. In addition, an important workshop was held in conjunction with IEEE GLOBECOM 2016, where the vision was articulated in public and contributors were encouraged to input to the growing roadmap ecosystem.

Based on these workshops and a broader community consultation, a working methodology had been established. In essence, the focus of this IEEE technology roadmap is to identify key needs, challenges, and potential solutions/areas of innovation. The aim is to build partnerships and collaborations among an industry community, be inclusive of all sectors of the wireless community, and be driven by industry trends/drivers. The objective is to update it periodically; notably, a set of progress reports are to be routinely produced and distributed to the industry at large.

1.3. White paper structure

This white paper presents the elements of the 5G industry from current to future state and builds the case for a roadmap effort. It is structured as follows:

- Section 2 presents the scope and charter.
- Section 3 describes the various 5G stakeholders.
- Section 4 focuses on the state of operations (i.e., how the ecosystem functions today).
- Section 5 presents important industrial and consumer use cases that cannot be enabled by today's networks.
- Sections 6 and 7 discuss the resulting technical design drivers and design challenges, respectively.
- Section 8 exposes today's technology enablers and solutions, addressing several key drivers/challenges.
- Section 9 draws conclusions for consideration as the IEEE 5G and Beyond Technology Roadmap effort begins.

2. Scope and Charter

2.1. Focus topics

The IEEE 5G and Beyond Technology Roadmap effort focuses on identifying technical needs and possible solutions that would enable the transformation of the wireless connectivity ecosystem. Near to mid-term, the initiative will support 5G development efforts; however, mid to long-term developments will remain completely agnostic to specific SDOs. The translation of the findings is left to the respective standards communities, as well as business analysts.

IEEE Roadmap topics must relate to the wireless connectivity ecosystem and will emphasize the actual technology building blocks and architecture, the application and service opportunities, and the underpinning value chain. The 2017 IEEE roadmap working groups reflect these topics:

- Applications and Services
- Hardware
- Massive multiple input, multiple out (MIMO)
- Millimeter Wave (mmWave)
- Edge Automation Platform (EAP)
- Security
- Standardization Building Blocks
- Testbed

2.2. ROADMAP TIMEFRAME

The near-term plans are to engage with the ecosystem to get a clearer picture on the exact roadmap, develop a stable version of a working plan to establish the roadmap, draft a white paper based on the agreed content, and then release a first edition of the table of contents for a comprehensive interactive IEEE 5G and Beyond Technology Roadmap document.

The mid-term plans (Q4 2017/Q1 2018) are to engage the roadmap working groups to develop the IEEE 5G and Beyond Technology Roadmap; engage with the wider ecosystem (horizon scanning, interviews, etc.) for input and perspectives; and synchronize with other 5G activities (standards, education, etc.)

The long-term plans are to track technologies that could impact the telecommunications ecosystem in the next 10-20 years and update the working document every 12-24 months.

2.3. ROADMAP CHARTER

Based on horizon scanning, interviews, and expert knowledge, the mission of the IEEE 5G and Beyond Technology Roadmap working groups are to identify short (~3 years), mid-term (~5 years) and long-term (~10 years) research, innovation, business, and technology trends in the communications ecosystem. This will enable the development of a concrete innovation and engagement roadmap guiding the community toward maximum impact in the telecommunications industry, its demand-side industries, and the wider industry and standards ecosystem(s).

The outcome shall be a living document with a clear set of (accountable) recommendations; the document shall be updated annually and be developed in conjunction with the other working groups.

3. ECOSYSTEM STAKEHOLDERS

There are several classes of stakeholders that will participate in or be affected by the emerging next-generation networks: end users, application developers, service providers (e.g., telecom, cable operators and content providers), equipment manufacturers, component suppliers (e.g., silicon, III-V integrated circuits and antennas), technology innovators (e.g., academics and inventors), governments and standards bodies, such as the IEEE Standards Association (IEEE-SA), Third Generation Partnership Project (3GPP), and International Telecommunication Union (ITU). This roadmap will engage all stakeholders in a collaborative, consensus-driven process to identify specific technology trends in each of their sectors and estimate how they will evolve in the future.

Many of these stakeholders participate in the technology standards development process to develop the interoperability specifications and process guidelines that will be used in the near future to roll out these next-generation networks and services. New stakeholders are continually emerging (e.g., automotive manufacturers, medical equipment suppliers, etc.). The IEEE technology roadmap effort, thus, will seek to include all that are known, as well as (hopefully) new, unexpected stakeholders.

Dependencies and linkages throughout the wireless-industry community also compel the IEEE technology roadmap working groups to include representatives from throughout the industry landscape outlined in Section 4, as well as the R&D community that includes universities, national labs, and industry consortia.

3.1. Industry Interactions

The IEEE roadmap effort will include a series of meetings over the course of several years to gather stakeholders to assess current business/technology/societal trends and project such trends into the future. A principal class of participant in this exercise will be the suppliers of equipment to consumers (e.g., IoT or IoT devices, medical devices, smartphones, and automobiles) and service providers (e.g., telecom, cable operators, and content providers) for the implementation of the complex networks necessary to deliver services in an inexpensive robust, secure, and private manner.

This roadmap process will also include interaction with other industry verticals such as automotive, healthcare, and entertainment and will incorporate those vertical-specific requirements while developing IEEE standards for 5G and Beyond technologies.

3.2. Recognition of Other Efforts

Standards that follow research findings will be a crucial enabler for economic delivery of next-generation network services. This is because of their demonstrated ability to spur innovation and leverage a wide range of talent and expertise not limited by the boundaries of academic institutions, corporations, or governments. These standards necessarily will be of a wide range; hence, no one SDO will be the exclusive supplier of standards in these markets. Several organizations in addition to the IEEE will contribute, including (but not limited to) the Internet Engineering Task Force (IETF), ITU, and 3GPP. This roadmap will attempt to build a comprehensive list of such organizations and their standards, along with attempting to illustrate their synergies and overlaps.

IEEE is collaboratively engaging with regional experts and standards bodies. As part of this collaboration, the IEEE Communications Society is developing a “Frugal 5G” concept to provide next-generation network infrastructure technology efficiently to specific geographical locations, driven by experts from the Telecommunications Standards Development Society India (TSDSI) community.

4. TODAY'S 5G LANDSCAPE

4.1. (SIMPLIFIED) VALUE CHAIN AND BUSINESS MODEL

The established cellular industry value chain can be summarized as follows:

- Component manufacturers—At the beginning of the value chain are component manufacturers that gear up for the manufacturing of billions of components for mobile and millions for base stations and backhauling links. These pertain to the production of chips, batteries, casings, smart/SIM cards, and antennas, among others. While volumes are large in these segments, margins are tight, as competition is high.
- Vendors/integrators—The above components are being assembled using components from in-house or third-party manufacturers. This vendors ecosystem is then utilized by the operators to build the telecommunications system.
- Network operators—These companies own the spectrum and telecommunications infrastructure and provide the calling and data service to consumers. They procure into their vendor supply chain and sell to consumers via stores and/or online. Mobile virtual network operators (MVNOs) have also appeared over the years, mainly under the pressure of regulation. In this case, an MVNO would use the physical infrastructure and spectrum of an operator in a wholesale arrangement.
- (Telecommunications) service providers—The ecosystem that provides services for managing the telecommunications infrastructure is referred to as service providers. Naturally, the operators are best suited to be service providers, but there are other players, too.
- Users—Finally, there are the end users who utilize the networking technologies. These are consumers, as well as businesses/industries.

There are also two other important constituents:

- Standardization—Standards are at the root of the telecommunications industry's success of global interoperability. Standardization takes place at several levels. Requirements are established by the ITU; the technology is standardized by SDOs such as the 3GPP and IEEE, and the spectrum usage is agreed upon by the ITU and at the World Radiocommunication Conferences (WRC).
- Equipment testing—Developed and deployed telecommunications equipment needs to be tested against claimed functionalities and agreed standards. Testing of the equipment is paramount.

The business models and value chains are well established. In the upstream, the supply chain starts with the component providers that are procured by the vendors. The vendors have a business-to-business (B2B) relationship to operators and are being procured by them. The operators then run and service the network that incurs costs but also yields revenues. In the downstream, the operators engage with customers in a business-to-consumer (B2C) relationship in-store or online. The consumers are billed monthly; the network infrastructure is being procured on 5–10 year cycles.

4.2. COMMUNICATION TECHNOLOGIES AND NETWORKS

The above-discussed ecosystem delivers an E2E communications system that is based on a range of technology components below. Evolution of mobile and cellular technologies have witnessed enhancement and optimization to various parts of the E2E communications systems over generations (e.g., 1G, 2G, 3G, 4G, and 5G), but, largely, these have been categorized into UE, radio access network (RAN), core network (CN) and applications network (e.g., IP multi-media subsystem). In particular, evolution to 5G networks will involve enhancements to various components of the network including new air-interface, virtualization, cloud RAN, SDN, and NS technologies.

4.2.1. MOBILE

The construct of the mobile network has undergone substantial transformations over past years, but its segments largely remained unchanged. From a segment point of view, there is the mobile phone (in SDO language, referred to as "UE"). The UE connects to the base station (referred to as "evolved node B" or "eNB"). The base stations connect to form the RAN. These, in turn, connect to the CN, which exits into the wider internet via the serving and packet gateways.

One of the transformational changes was an E2E internet protocol (IP) architecture that allowed the mobile network to be treated like any other internet network. It has been hugely beneficial to the uptake of applications in the mobile space but also a serious challenge for the telecommunications ecosystem from a business point of view.

Latest technology changes that are of substantial impact are the introduction of cloud-RAN functionalities, where a remote radio head is connected to a cloud server via a fronthaul. Centralizing some of the radio functionalities in a cloud close to the wireless edge has shown substantial cost savings and performance improvements. However, this still comes at a cost, as 5G will require a fronthaul bandwidth that is very expensive to provide. Possible solutions, as well as other challenges, are discussed below.

4.2.2. FIXED

Fixed network elements play an instrumental role in the connectivity ecosystem but less so than in the past in the context of cellular systems. It is interesting to note that the interest of a native usage of fixed networking assets is surging in the context of 5G.

4.2.3. (CONVERGED) CORE NETWORK

The core network aggregates the user traffic (via the user plane) and manages these data flows (via the control plane). While the user plane infrastructure has not been changed much over the years in design, much of the control functionalities have been virtualized. That is, the evolved packet core (EPC) can have its functions placed anywhere and even migrated via containers in real time from one part in the network to another. The virtual EPC (vEPC) approach is seen as a viable way forward, also, since it allows to "thin" the core-networking infrastructure and bring packet gateways closer to the edge.

4.2.4. TRANSPORT NETWORK

The transport network, often being all-optical, is responsible for carrying the data traffic E2E between the operators' packet gateways. It carries traffic from internet service providers (ISPs) and other data sources. It must be dimensioned to cater for the increased data traffic coming from wireless systems. In addition, if 5G is to offer slicing capabilities, then slicing ought to be offered in the wider transport network, too; otherwise, benefits of slicing will be eroded.

5. ENVISAGED FUTURE APPLICATIONS

The above networking technologies have been driving applications and services. Indeed, up until 4G networks, the applications were driven by available network capabilities. However, with the emergence of a new generation of over-the-top (OTT) applications, they will define and drive the 5G network capabilities.[3]

OTT applications have changed the service providers' business models, limiting them to just being a bit pipe and, thereby, creating new independent application platforms. 5G networks—with the capabilities of NS, latency, and ultra-broad bandwidth—can help service providers to create new application platforms to enable the next generation of applications and develop new business models. Video streaming and IoT-based applications are the current "killer applications," and these applications, mixed with the virtual/augmented reality capabilities, will create opportunities across several verticals.

5.1. APPLICATIONS IN INDUSTRY VERTICALS AND THEIR NEEDS

It is also interesting to note that most of the needs of the applications can be served with the current networks; however, the element of human interaction (or lack of it) demands guaranteed latency and makes most of the 5G requirements critical. The following table presents some emerging applications and services for which 5G will be a pivotal enabler.

Table 1. Emerging applications and services enabled by 5G

Verticals	Drivers	Enablers	5G requirement
Education	• Remote delivery • Immersive experiences	• Video streaming • Augmented reality/ • Virtual reality	• Large bandwidth • Low latency
Manufacturing	• Industrial automation	• Massive IoT networks	• High connection density • Ultra reliability • Low power consumption
Healthcare	• Remote diagnosis and intervention • Long term monitoring	• Video streaming • Augmented reality/ Virtual reality • Embedded devices, advanced robotics	• Low power • High throughput • Low latency
Smart Grid	• Intelligent demand/ supply control • Powerline communication	• IoT sensors and networks	• High reliability • Broad coverage of network • Low latency
Entertainment	• Immersive gaming and media industry • Multimedia experience at 4k, 8K resolution	• Video streaming • Augmented reality/Virtual reality	• Large bandwidth • Low latency

[3] *ITU-T Technology Watch Report, "The Tactile Internet,"*
https://www.itu.int/dms_pub/itu-t/oth/23/01/T23010000230001PDFE.pdf

Verticals	Drivers	Enablers	5G requirement
Automotive / Autonomous Cars	• Collision avoidance • Intelligent navigation and transportation systems	• Vehicle-to-vehicle (V2V), • Vehicle-to-infrastructure (V2I) and other intelligent transport systems (ITS)	• Large bandwidth and low latencies (< 5 ms) and high connection reliability (99.999%)
Smart Cities	• Connected utilities, Transportation, Healthcare, Education and all amenities	• Massive IoT networks • Automation • Cloud infrastructure • Artificial intelligence	• Large bandwidth • High throughput • High connection density • Low latencies

Possible future extensions and verticals might include the following:

- Aerospace
- Ocean
- Threat response
- Mobile platform
- Terrestrial and distributed computing (cloud/IoT-fog)

The bandwidth and the latency requirements of applications based on the mobility are mapped in the following graph from GSM Association (GSMA) Intelligence.

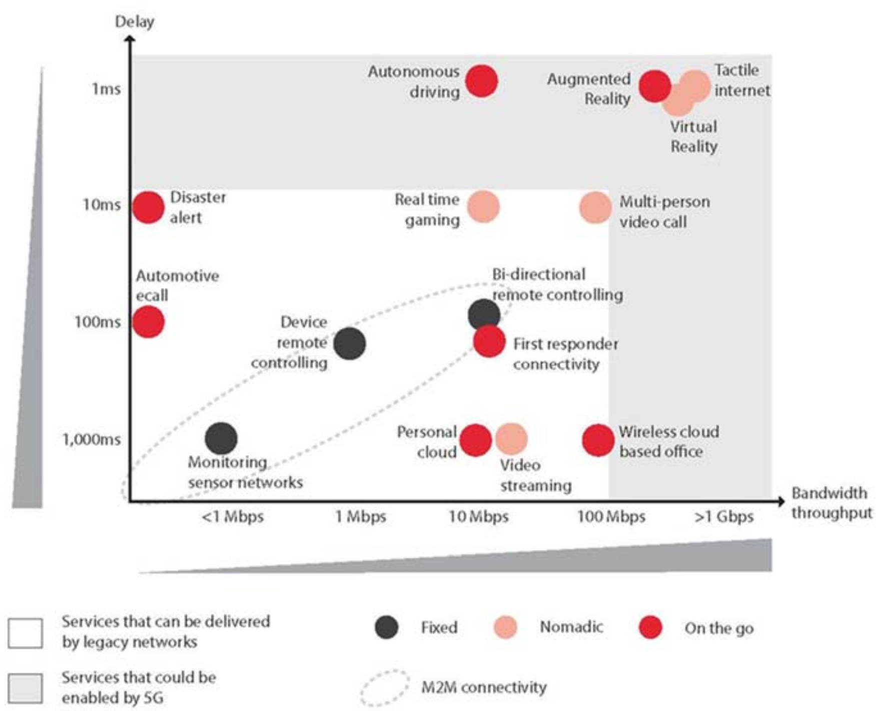

Figure 1 Bandwidth and latency requirements of new applications[4]

[4] *© GSMA Intelligence 2017. Figure 1 used with kind permission from GSMA. https://www.gsmaintelligence.com/research/?file=141208-5g.pdf&download*

5.2. NEW TECHNOLOGIES AND INDUSTRY ENABLERS

There are several new technologies that are becoming mainstream and enabling the next generation of applications. Though many of these enablers have been in industry for a long time, there are some new applications that are applying these technologies and generating business value. Key enablers and their impact on 5G are as follows:

- Robotics and drones—Industrial automation and healthcare will be two main areas where advancements in robotics will play a major role. Furthermore, an important use case for 5G will be drones and autonomous aerial vehicles (UAVs). For instance, in the future, UAVs will deliver products and perform surveillance, disaster relief, etc. Currently, the ecosystem is exploring the use of 4G networks to enable complex flight operations that are safe (e.g., avoid collisions with buildings, airplanes, and each other). 5G enhancements will further enable UAV deployments that, in turn, will disrupt many current business practices.[5]
- Virtual/augmented reality—A new set of end-user devices enabled with virtual-reality capabilities, augmented reality (with digital view on a physical view), and haptic feedback are becoming popular with education, gaming, and real-world simulations. These devices are wirelessly connected and need low latency and high reliability to enable real-time experiences.
- AI—Advances in deep learning have allowed for very complex algorithms being applied in everyday applications. This has been made possible due to the petabytes of data generated by networks and services on the internet and otherwise. AI will drive applications like autonomous cars, robotics, automation, and several intelligent applications on mobile devices. AI will also be the key driver for self-optimizing networks (SON) that will allow 5G networks to respond to issues of congestion, failures, and traffic spikes.

6. DESIGN DRIVERS AND KEY TRENDS

The traditional drivers for the cellular ecosystem were cost, both capital expenditure (CAPEX) and operational expenditure (OPEX) reductions, coverage (stimulated by government contracts during spectrum auctioning/assignment), and reliability (the system has to work dependably from a consumer point of view). As of late, other drivers have emerged or are perceived to be important:

- Value creation—With B2B playing a prominent role in 5G, there is an opportunity to focus on creating value in the industries.
- Service-level agreements (SLAs)—The ability to offer SLAs, particularly in the B2B setting, is proving valuable.

To keep up with the applications and design drivers, some transformations in the ecosystem need to be invoked. Some examples are discussed below[6] [7].

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[5] *http://www.sandiegouniontribune.com/business/technology/sdut-qualcomm-drones-att-cellular-lte-remote-navigation-2016sep07-story.html*

[6] *M. Dohler, T. Mahmoodi, M. Lema, and M. Condoluci, "Future of Mobile," EuCNC 2017.*

[7] *X. Lu, M. Lema, T. Mahmoodi, and M. Dohler, "Downlink Data Rate Analysis of 5G-U (5G on Unlicensed Band): Coexistence for 3GPP 5G and IEEE802.11ad WiGig," European Wireless 2017.*

6.1. From key performance indicators (KPIs) to perception of KPIs

With decreasing cell sizes and increasing traffic demand, it will become increasingly difficult to offer satisfactory designs on rates, outage, or delay. Therefore, the IEEE 5G and Beyond Technology Roadmap initiative advocates for a fundamental change in the design approach where systems are not designed and regulated based on the measured KPI but on the perceived KPI.

Rate is an example of measured versus perceived KPI. In future 5G systems, the majority of the capacity will be provided via some high-capacity small cells using, for example, mmWave technologies. However, providing ubiquitous radio frequency coverage to satisfy such capacity increases is both technically challenging and economically prohibitive. One possible solution is to use predictive analytics on different metrics, such as user data usage behavior, user movement behavior, or speed of movement. As an example, that would allow one to implement enhanced caching techniques that provide service continuity in the case of a coverage hole and buffer the "to-be-watched" streaming video until the next access point is reached. Several disruptions are needed, however, with the most notable being that the application layer needs to communicate with lower layers to execute the best strategy. Strategies based on the use of SDN result in QoS management that can be further enhanced with predictive analytics to provide accurate, on-demand resource allocation.

6.2. Atomized and decoupled architecture(s)

The breakdown on the increase of wireless capacity over the past three decades indicates that smaller cell sizes are the biggest contributor. This, in turn, translates to more heterogeneous architectures that have to be managed in a novel way. The 3GPP has proposed to decouple control and user planes (CP and UP, respectively) via phantom cell approaches. However, the latest research has shown that further enhancements in the small-cell features can lead to massive improvements in the UP transmission. Cell selection based on the reference signal received power (RSRP) result in imbalance problems, since the downlink (DL) coverage of a macro-cell is much larger than that of a small cell.

One strategy that can address this problem and bring some fairness to the uplink (UL) is the cell range extension (RE). However, recent studies have shown that using high RE offsets increases the DL interference levels. Alternatively, a full decouple of UL and DL allows similar UL fairness while reducing the RE interference problem in the DL. Prior art has shown performances with much higher throughputs and, above all, smaller UL outages. Continuing this trend, a challenge will be to design a completely decoupled architecture (i.e., decoupled in CP/UP and UL/DL), enabling ultra-low latency and ultra-reliable communications. Work shows that to enable complete, flexible transmissions in both CP and UP, centralized architectures with low-latency fronthaul connections maximize the performance improvements.[8]

6.3. Thinning of the core network infrastructure

Scalability in 3GPP architectures is greatly limited by the physical infrastructure of the CN. For instance, a typical operator in a country like the United Kingdom has only a handful of packet gateways (PGWs) to serve the entire country's mobile traffic. The CN is, in fact, an artifact of pre-internet times, as it was introduced in 2G because none of the operators believed that there would ever be a general internet capable of carrying the voice traffic. Thirty years on, the CN is still used and, thereby, greatly limits the scalability

[8] *M. Lema, T. Mahmoodi, and M. Dohler, "On the Performance Evaluation of Enabling Architectures for Uplink and Downlink Decoupled Networks," IEEE GLOBECOM Workshops, December 2016, pp. 1–6.*

of the wireless edge, which, because of above discussions, limits the rates to be delivered. Capitalizing on this insight, as well as recent trends to virtualize the enhanced packet core (vEPC) functionalities, the next step should be to push the entire cellular CN system to the edge—first, into the emerging Cloud-RANs, and, later, into the edge devices. Important to note is that the CN fiber infrastructure could be leased (or, in the long term, even sold) to ISPs; in return, more CN fiber capabilities can be leased when needed. This approach would allow to scale and, importantly, to significantly decrease the E2E delay between operators.

6.4. 3GPP-AS-A-CONTROL-SYSTEM

At any time, the IEEE 802.11 standards' link capacity has always been one to two orders of magnitude higher than 3GPP link capacities. At the same time, it is well established that the ratio between control and data packet sizes is about one to two orders of magnitude in typical communications systems. Based on this observation, the IEEE roadmap team suggests exploring if combining the best of both worlds allows one to achieve prior unseen performance gains. Notably, one needs to research the architectural and protocol approach to have 3GPP act as a control channel/system for all wireless systems available globally. Going well beyond today's licensed assisted access (LAA), cellular would be responsible to coordinate various IEEE 802.11™ "Wi-Fi®" and other systems to ensure best possible link performance while offering mobility/roaming, as well as billing. This work is already gaining increased interest in the context of fixed and mobile converged networks in 5G, where the broadband forum and the 3GPP architectures are merged to obtain the best of each technology.

6.5. SELF-DESIGNING CELLULAR SYSTEMS

With advances in AI, software defined radio/networks (SDR/SDN), and robotics, there is no reason why the cellular system could not adapt its own design and deployment. While research on best possible technology solutions can still be conducted by humans, future cellular systems should be able to scout the publication/innovation databases, extract the most promising solutions, self-upgrade these (using SDR/SDN), and/or self-deploy them (using autonomous drones, for example). This would allow the standardization cycles to be shortened from years to days, if not minutes. Bringing the principal of SDN to the mobile CN can deliver the similar benefits in terms of agility and evolvability as it has delivered to data centers.

7. DESIGN CHALLENGES

To enable the key trends, some significant design challenges need to be overcome. A few of these challenges are summarized in this section.

7.1. THE WIRELESS ROADMAP

5G is envisioned to support a broad range of use cases, including enhanced mobile broadband (eMBB), massive IoT, and mission-critical control. These use cases have diverse requirements, ranging from high capacity and data rate for eMBB, to low latency with high reliability for mission-critical control. To ensure spectrum availability, 5G must be able to operate on diverse spectrum types and bands, including licensed, shared, and unlicensed, and from sub-6GHz to mmWave. A key challenge of 5G designs is how to deliver a highly capable and scalable air interface to effectively support various use cases and spectrum requirements. In addition, unforeseen use cases and requirements may emerge; another challenge of 5G design is, thus, to allow continued technology evolution with forward compatibility.

The critical components for wireless considerations are summarized as the following:

- Spectrum flexibility, to support devices in operating on diverse spectrum types and bands
- Scalable air interface, to support the wide range of anticipated end points
- Adaptable, forward-compatible air interface, to support future requirements and evolutions in technology

The vision for 5G air interface consists of a highly scalable and forward-compatible platform based on orthogonal frequency-division multiplexing (OFDM). This enhanced OFDM design enables efficient multiplexing of services within a carrier and supports scalable numerology and transmission time interval (TTI) to satisfy diverse bandwidth and latency requirements. In addition, a self-contained, integrated TDD subframe design is supported. This allows the completion of a data transaction, including signaling, data transmission, and acknowledgment or negative acknowledgment (ACK/NAK) within a sub-frame, while providing the flexibility to support various features such as unlicensed access, dynamic uplink/downlink allocation, and massive MIMO. This design reduces latency for packet delivery, response to service request, and air interface procedures. Its "self-contained" nature also enables forward compatibility when combined with OFDM blank subframes and sub-carriers.

As part of utilizing the mmWave frequencies, the air interface supports analog/hybrid beamformed devices that are capable of quickly identifying the best beam directions and maintaining the beamformed link in a robust fashion. Discrete Fourier transform spread OFDM (DFT-s-OFDM) is also supported in the air interface to operate effectively in link-budget-limited use cases such as mmWave uplink.

Additional key 5G features include multi-user massive MIMO, which delivers high capacity and allows the support of macrocell coverage even in the mid bands (e.g., 3.3 to 3.8GHz), and advanced low-density parity-check (LDPC) coding that offers high performance, efficiency, and scalability for eMBB and other advanced use cases. 5G will natively incorporate these and many other innovative techniques to meet the diverse requirements.

The 3GPP is standardizing the 5G air interface system referred to as new radio (NR) and next-generation core (NGC) network. The Rel. 14 study item focused on NR design recently completed. Rel. 15 is now underway. This includes the NR work item for non-standalone (NSA), which relies on an LTE anchor to operate and complete by the end of 2017 and 5G NR standalone (SA) scheduled to complete in mid-2018. Additional NR features and enhancements will be defined by 3GPP Rel. 16 and beyond.

7.2. MASSIVE CONNECTIVITY

This section on massive connectivity presents the characteristics of machine-to-machine communications. To support the communications of a massive number of machines/devices, the challenges to the future 5G network impose changes to traditional person-to-person communication networks, as discussed below. The proliferation of IoT devices in the upcoming years inevitably demands massive connectivity for wireless communication systems. The ever-increasing number of connected, machine-to-machine (M2M) type communications devices is characterized by low-complexity transmission, sporadic traffic pattern, ultra-low power consumption nature, high reliability, and low latency.

To meet these challenges, 5G is expected to experience fundamental changes as compared to traditional cellular networks, which have been designed in a less-scalable, network-centric manner and have been mainly targeted for human being-involved applications. 5G will need to provide new ways of connecting billions of devices, including new network architecture, new air interface technologies, and new spectrum. As a result, the future 5G network architecture will enable a more scalable, user-centric design. NS segments the network to support customized connectivity for various M2M services or business segments. New medium access control (MAC) and physical layer (PHY) protocols that allow for massive wireless access are also under extensive R&D. Recent progress in non-orthogonal multiple accesses (NOMA) manages to support more devices using the same resource simultaneously and the system performance in terms of throughput and spectral efficiency. Furthermore, device-to-device (D2D) underlay communications, either with the aid from base station (BS) or without, can also help with the massive connectivity due to the close proximity. In addition, underlay D2D uses the same spectrum as other D2D or cellular users, helping increase the spectral efficiency.

Additionally, by taking the advantage of big data analysis on M2M traffic, context-aware communication can be used to remove redundancy in the message. For example, hundreds of environmental sensors may send the highly correlated data in the same geographic area to an access point. By analyzing this correlation, only a few selected devices may allow communication that not only shrinks the contention period but also improves energy efficiency.

7.3. THE TACTILE INTERNET

Mobile communications networks of today have successfully connected a vast majority of the global population. After creating the "mobile internet" connecting billions of smart phones and laptops, the focus of mobile communications is moving toward providing ubiquitous connectivity for machines and devices, thereby creating the IoT.

With today's technological advancements in mobile communications, the stage is being set for the emergence of the "tactile internet," which has been defined as "a network or network of networks for remotely accessing, perceiving, manipulating, and controlling real or virtual objects or processes in perceived real time by humans or machines" by the IEEE P1918.1™ standardization working group. Currently, the conventional internet embodiments are widely used for content delivery (voice telephony, text messaging, file sharing, etc.) The tactile internet will underpin the internet of skills, which, in turn, will provide a true paradigm shift from content delivery to remote skill-set delivery, thereby introducing novel use cases and, hence, revolutionizing every segment of the society.[9] [10] [11] [12] [13]

Key elements for the tactile internet are:

- Physical real-time interaction (humans and machines access, manipulate, and control objects in perceived real-time)
- Ultra-responsive infrastructure for remote control

[9] *M. Dohler et al., "Internet of Skills, Where Robotics Meets AI, 5G and the Tactile Internet," EuCNC 2017.*
[10] *ITU-T, "The tactile internet," ITU-T Technology Watch Report [Online]. Available: https://www.itu.int/dms_pub/itu-t/oth/23/01/T23010000230001PDFE.pdf*
[11] *G. Fettweis, "The Opportunities of the Tactile Internet—A Challenge for Future Electronics," http://www.lis.ei.tum.de/fileadmin/w00bdv/www/fpl2014/fettweis.pdf*
[12] *M. Simsek, A. Aijaz, M. Dohler, J. Sachs, and G. Fettweis, "5G-Enabled Tactile Internet," invited submission to IEEE Journal on Selected Areas of Communication (JSAC), SI on Emerging Technologies, vol. 32, no. 3, pp. 1-14, 2016.*
[13] *M. Dohler, T. Mahmoodi, M. Lema, and M. Condoluci, "Future of Mobile," EuCNC 2017.*

- Emerging applications by bringing control and communication into one network

With 5G, an additional breakthrough is soon to happen, as the latency of communicating over the wireless network will become low enough to enable an E2E, round-trip delay from terminals through the network back to terminals of approximately 1-10 ms (or less)[14]. This is the response of human tactile to visual feedback control. The wireless communications network can then become the platform for enabling control of real or virtual objects in many situations of life. Almost no area of economy will be left untouched, with examples being healthcare, automotive, education, manufacturing, smart grids, and many more. To make this happen, many open research challenges must be tackled.

One of the key technological challenges for the realization of the tactile internet lies in the combination of communications, control, and computing systems into one shared infrastructure. By taking the 5G system as the underlying wireless network, together with its softwarization and virtualization, a (bi-directional) real-time control loop must be integrated to enable the anticipated real-time control together with a highly computationally efficient computing capabilities at the edge of the network—for example, in an open mobile edge cloud (OMEC) now referred to as an EAP. The tactile internet must overcome the fundamental limitation of the finite speed of light to guarantee real-time physical interaction. To achieve this, the tactile internet must support ultra-responsive connectivity through edge intelligence.

In addition, unlike the conventional internet embodiments, the tactile internet provides a medium for remote physical interaction in real time, so that humans or machines cannot distinguish between locally executing a manipulative task and remotely performing the same task across the tactile internet. This requires the exchange of haptic information. Haptic information refers to either tactile or kinesthetic information, or both. Therefore, codecs for the haptic information for both humans and machines must be precisely defined, as is targeted by the IEEE P1918.1 Tactile Internet Working Group.[15]

7.4. NEGOTIATING SERVICE QUALITY

Foreseen use cases for next-generation communications are expected to request a large diversity of service-quality requirements. This diversity includes much higher end-user data rates and cell-level throughputs than today's networks to meet the enhanced mobile broadband (eMBB) requirement and satisfy an ultra-reliability, low-latency connection (URLLC), as well as to serve a massive number of devices for machine-type communications (mMTC)—all three in possibly extreme interpretation. Highlights for these considerations include:

- 5G network needs to support multiple QoSs for a variety of services, as opposed to current networks that are purpose-built for a limited set of QoSs.
- A network slice management and orchestration layer can support QoS management by evaluating the current network slices performance and orchestrating necessary resource changes in virtual network functions (VNFs) in different domains (RAN, CN, and transport) to meet the required QoS.
- Effective E2E negotiation of QoS would require application and service awareness to be built at various network points of presence.

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[14] *NGMN, "5G White Paper, 2015,"* *https://www.ngmn.org/uploads/media/NGMN_5G_White_Paper_V1_0.pdf*
[15] *X. Liu, M. Dohler, T. Mahmoodi, and H. Liu, "Challenges and Opportunities for Designing Tactile Codecs from Audio Codecs," EuCNC 2017.*

- A rich set of real-time data streams from various points of presence are key to leverage powerful analytics, using machine learning and AI.

Two major implications are supporting required QoS for applications/services and supporting various levels of QoS (e.g., premium) among various tenants on the network. Different use cases will request artificial combinations, either mutually excluding or overlapping, of these requirements to be met simultaneously for multiple tenants. In addition, the tenants' business- and end-customer service contracts will vary over time and network service area and will request guaranteed performance levels and isolation from each other.

While today's purpose-specific, stand-alone (or purpose-built) CNs may meet some of these requirements, the diversity of requirements over service quality, time, and region suggest a much more flexible, scalable, and agile network architecture and implementation than today. The concept of NS will support this in an efficient manner. Several definitions of NS exist, which all have the agile deployment of multiple logical networks-as-a-service (NaaS) on the same underlying network infrastructure in common. The concept of NS needs to be naturally included in a future network architecture and deployment. NS will require a resource pool of physical resources as common infrastructure and virtual network functions running on parts of this infrastructure.

Service-centric network slice management and orchestration will then instantiate, manage, and terminate E2E (logical) network slice instances on demand, by tailoring network-slice blueprints or templates and allocating necessary virtual and physical resources and functions from the pool.[16] An E2E network slice is defined from the device/terminal through to the IP interface of a different network and will include (radio) access, transport, and core network along with operational and business support system functions. Network slice management and orchestration can include administration of multi-vendor, -technology, and -operator scenarios, including roaming and SLA cooperation. Network slice instantiation should also consider the choice of placing network function either in the edge cloud or the centralized/remote cloud. Proximity data centers would be key enablers for realizing an EAP, in order to support some local break out (e.g., low latency, content serving).

5G could offer the promise of realizing true E2E subscriber quality of experience by bringing in subscriber and application awareness to several functional areas in the network (instead of just being in the CN). The service quality negotiated in SLAs needs to be guaranteed and fulfilled throughout the operational lifetime of the network slice instance. Network slice management and orchestration will take care of allocation of physical (e.g., antennas, storage, computation, transport bandwidth, etc.) resources and instantiation of virtual network functions (e.g., protocol layer implementations or parts thereof) for each network slice. Powerful predictive and semantic analytics, including machine learning and AI, will help to assure the service quality for all concurrently operating network slices. Such streaming data input from available input sources across all mentioned parts of the network, including support and business data, needs to be analyzed and the information therein to be leveraged to optimize operations and guarantee service quality for the tenants and fair access for end users.

[16] P. Schulz *et al.*, "*Latency Critical IoT Applications in 5G: Perspective on the Design of Radio Interface and Network Architecture,*" in *IEEE Communications Magazine*, vol. 55, no. 2, pp. 70-78, February 2017

7.5. E2E SLICE MANAGEMENT

NS is an E2E concept covering all network segments.[17] [18] It enables the concurrent deployment of multiple logical, self-contained, and independent shared or partitioned networks on a common infrastructure platform. From a business point of view, a slice includes a combination of all the relevant network resources, functions, and assets required to fulfill a specific business case or service. This includes operational support system (OSS), business support system (BSS), and software development and information technology operations (DevOps) processes. From the network infrastructure point of view, NS instances require the partitioning and assignment of a set of resources that can be used in an isolated, disjunctive, or non-disjunctive manner for that slice. Currently, NS refers to the managed partitions of physical/virtual network resources and network physical/virtual and service functions that can act as an independent instance of a connectivity network and/or as a network cloud. (Network resources include connectivity, computing, and storage resources.)

NS considerably transforms the networking perspective by abstracting, isolating, orchestrating, softwarizing, and separating logical network components from the underlying physical network resources. As such, they enhance the network architecture principles and capabilities. The establishment of slices is both business-driven, as slices are the support for different types and service characteristics and business cases, and technology-driven, as slices are a grouping of physical or virtual resources (network, compute, and storage) that can act as a sub network and/or as a cloud. A slice can accommodate service components and network functions (physical or virtual) in all of the network segments: access, core, and edge/enterprise networks.

Network operators can use NS to enable different services to receive different treatment and to allow the allocation and release of network resources according to the context and contention policy of the operators. Such an approach using NS would allow a significant reduction in operations expenditures. In addition, NS makes possible softwarization, programmability, and the innovation necessary to enrich the offered services. Network softwarization techniques may be used to realize and manage NS. NS provides the means by which the network operators can provide network programmable capabilities to both OTT providers and other market players without changing their physical infrastructure. NS enables the concurrent deployment of multiple logical, self-contained and independent, shared or partitioned networks on a common infrastructure. Slices may support dynamic multiple services, multi-tenancy, and the integration means for vertical market players (such as the automotive industry, energy industry, healthcare industry, media, and entertainment industry, etc.)

In order to implement and use network slice functions and operations, there is a clear need to look at the complete lifecycle management characteristics of NS solutions based on the following architectural tenets:

- Underlay tenet—support for an IP-based underlay data plane the transport network uses to carry that underlay
- Governance tenet—a logically centralized authority for all of the network slices in a domain
- Separation tenet—slices may be independent of each other and have an appropriate degree of isolation from each other
- Capability exposure tenet—allow each slice to present information regarding services provided by the slice (e.g., connectivity information, mobility, automaticity, etc.) to third parties via

[17] *http://5g.ieee.org/tech-focus/march-2017/towards-5g-network-slicing*
[18] *M. Lema et al., "5G Case Study of Internet of Skills: Slicing the Human Senses," EuCNC 2017.*

dedicated interfaces and/or application programming interfaces (APIs) within the limits set by the operator

In pursuit of solutions for the above tenets with the relevant characteristics within the context of 5G networking, there is a need to address the following challenges and outcomes:

- A uniform reference model for NS that describes all of the functional elements and instances of a network slice (it also describes shared non-sliced network parts)
- Slice templates that can provide the design of slices to different scenarios
- NS capabilities that include efficient slice creation with guarantees for isolation in each of the data/control/management/service planes
- NS operations that would include slice lifecycle management including creation, activation/deactivation, protection, elasticity, extensibility, safety, sizing, and scalability of the slicing model per network and per network cloud for slices in access, core, and transport networks, slices in data centers, and slices in edge clouds.
- Efficient enablers and methods for integration of the above capabilities and operations

The IEEE 5G and Beyond Technology Roadmap will look into the challenges associated with achieving potential solutions for network slice management. As a start, the working group will do a gap analysis of the existing trends and solutions in NS management and how it can be applied to 5G-specific architecture and applications.

8. TECHNOLOGY ENABLERS AND SOLUTIONS

This section first presents examples of technology enablers and solutions that will be explored more fully as part of the IEEE roadmap effort to address above use cases and technology requirements:

- Network applications interface
- Native security
- E2E network embodiments
- Management orchestration policy
- Testbeds

The section then explores enabling capabilities, or "building-block solutions," which will provide roadmap potential solutions to evolve the industry by resolving challenges and satisfying current and future needs:

- Massive MIMO
- mmWave/microwave/physical electronics
- EAP

The above list will be expanded for the actual IEEE 5G and Beyond Technology Roadmap document, and the topics will be addressed in significantly greater depth.

8.1. Technology Enablers

8.1.1. Network Applications Interface

The new-generation applications across verticals are evolving quickly, based on user and business need, and there are several requirements toward 5G networks. The challenge is with the varied requirements from applications, and there is no "one-size-fits-all" approach. Some vertical applications might need better throughput; whereas, others might need low latency. 5G networks need to be designed to optimally deliver the capabilities through simple and open APIs.

The 5G network application interface (NAI) should provide the means to do service orchestration in real time, dynamic provisioning, activation and termination of resources, and to easily manage service policies. The following are some of the requirements to be considered while designing these layers:

- Policy controls to handle dynamic bandwidth requirements
- Service orchestration for NS based on the applications demand
- Contextual intelligence based on the data in the network and an intelligence layer built around it (useful for augmented and virtual reality)
- Hyper location information for IoT applications
- Online charging and payment integration based on real-time usage of resources

The 5G NAI layer should be carefully designed to ensure that it provides options to enable new business models for service providers and help them make a strong business case for investment in 5G networks.

8.1.2. Native Security

It is imperative to embed security functions from the very beginning while the 5G architecture is being defined and standardized. Security requirements need to overlay and permeate through different layers of the 5G systems—namely physical layer, network layer, and application layer—as well as different parts of an E2E 5G network. Since the 5G network is fundamentally based on SDN and NFV, many of the challenges and opportunities applicable to SDN/NFV networks would be applicable to 5G networks, as well. In that respect, 5G security needs to pay attention to additional security requirements, such as SDN controller security, hypervisor security, orchestrator security, cloud security, API security, and open source security, as well as security under multi-tenancy settings.[19]

SDN/NFV-based 5G networks will need to investigate additional threats compared to non-virtualized networks at different parts of the network and recommend additional controls that are needed. The Security Working Group in European Telecommunications Standards Institute (ETSI) has published a problem statement document that highlights some of the key security areas that need to be investigated. NGMN and 3GPP have been developing security requirements for 5G networks, as well. In addition to security challenges and opportunities associated with SDN/NFV networks, 5G networks should emphasize security challenges and opportunities for various parts of the networks. These infrastructures include RAN, EAP, and NS. Inclusion of cloud RAN (virtual RAN) and separation of data plane and control plane will need to include additional security measures introduced by distributed denial of service (DDOS), resource exhaustion at the RAN, and infrastructure sharing. EAP is needed to support delay-sensitive applications and provide an SLA on up to less than 1 ms delay; this introduces additional vulnerability

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[19] *B. Han et al., "Security Trust Zone in 5G Networks," ICT 2017.*

since security contexts get stored at the edge of the networks and keys are exchanged between the security proxies at the edge and core of the network.

The IEEE 5G and Beyond Technology Roadmap Security Working Group will conduct a gap analysis of existing security requirements for 5G networks by surveying other standards such as 3GPP, NGMN, and ITU devise various security use cases for a variety of 5G-based applications; and investigate additional security requirements for 5G networks. The security working group will also come up with a threat taxonomy and propose potential mitigations controls. This working group will collaborate with the related IEEE 5G and Beyond Technology Roadmap working groups for applications, EAP, and testbed, in order to define a set of 5G-related experiments that can be carried out as proofs of concept.

8.1.3. E2E NETWORK EMBODIMENTS

From an operational point of view, 5G will be enabled by a proper E2E architecture. The different views of such an architecture will be explored in the IEEE 5G and Beyond Technology Roadmap and only briefly discussed here:

- Functional view—the functional blocks and interfaces, regardless of each function block's location within the network and regardless of the resources used (this is a purely logical view of the architecture)
- Resource view—the resources that the different network components make use of (this includes physical and virtual resources, along with repositories for network functions (NF) and service templates)
- Topology view—the topology of the network (this differs from the functional view in that the topology depicts the way in which physical and virtualized network resources are interconnected)
- Deployment view—depicts the different possible locations of functional blocks (this also includes the possibility that a functional block may be deployed in different locations)

8.1.4. MANAGEMENT ORCHESTRATION POLICY

5G is an opportunity to achieve a flexible, efficient, scalable, and programmable network toward a "Telecommunication 5.0" era. A new platform (NFV/SDN) will enable flexible and programmable networks and functions.[20] The new capabilities include in network service (INS) content integration, capability exposure (e.g., EAP). New networking (NS) will support more elegantly vertical and customized third-party virtual networks. New functions via control plane/user plane (C/U) separation are composed of converged control plane and distributed user plane. New protocols aim to optimize mobility management, session management, QoS, etc. As such, the most unique focus of the envisioned E2E 5G network architecture is NS[21] that will:

- Provide differentiated services with isolated networks
    - eMBB, mIoT, and critical communication
    - Requirements are largely different or even in conflict

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[20] *ETSI NFV ISG (2012), Network Functions Virtualization. http://portal.etsi.org/portal/server.pt/community/NFV/367*
[21] *3GPP TR 23.799 V14.0.0 "Study on Architecture for Next Generation System" http://www.3gpp.org/ftp//Specs/archive/23_series/23.799/23799-e00.zip*

- Bring new opportunities in a cost-effective approach
  - Enable services for verticals, such as healthcare, industry, and public safety
  - Customized enterprise services

The slicing orchestration function, being the "heart" of management and orchestration (MANO), should provide the control/management information to the transport layer for proper mapping of the slice, as well.

8.1.5. TESTBED SERVICE CAPABILITIES

While 5G network mostly focuses on various functional components like virtualized RAN, virtualized core networks, and various application services such as IP multimedia services, there are other components in the network such as orchestrator, SDN controllers, data collection and analytics, and SFV that act as enablers to provide 5G-specific services. Roadmap projects will continue to explore these areas beyond traditional RAN and core components in the network. In this respect, the IEEE 5G Initiative will collaborate with other standardization working groups such as ETSI/NFV, open source communities such as open platform network virtualization (OPNFV), the Linux Foundation, and the Open Day Light Forum for alignment.

Testbeds comprise a critical enabler of 5G evolution and complement the standards that are developed. Lessons learned from various experiments help to ratify the standards. The testbeds also help as catalysts for deployment. Hence, it is essential to have experimental testbeds where functional and E2E testing can be performed. The IEEE 5G and Beyond Technology Roadmap Testbed Working Group will help collaborate with the existing 5G testbeds. The testbed working group will interact with various existing testbeds and make those available to the IEEE 5G community. This testbed working group will also collaborate with the vendor community and the research community and will expand upon the existing testbeds. Some of the key deliverables from the testbed working group will be functional testing, rapid prototyping, and proof-of-concept, covering various 5G characteristics at different layers and also supporting various 5G-specific applications, such as IoT, internet of skills, tactile internet, and augmented reality. This working group will inventory types of testbeds available in various parts of the world and will serve as a facilitator for setting up federated testbeds that will provide access to the IEEE community to get access and run experiments. In order to fuel the testbed evolution, the testbed working group would continue to hold workshops and go over various 5G use-case scenarios.

8.2. BUILDING-BLOCK SOLUTIONS

The building blocks toward a successful 5G system are briefly discussed in this section. They fit into the respective architecture parts and enable a flexible 5G system.

8.2.1. MASSIVE MIMO

MIMO technology has been considered a vital approach to improving spectral efficiency for wireless communications systems over the past 20 years. In 4G systems, the number of the antennas supported at the base station (BS) cannot be larger than 64 and, thus, the performance gain from MIMO is quite limited. For 5G systems and beyond, to further improve spectral efficiency and energy efficiency, a new technique named as large-scale antennas has been proposed to serve multiple users in the same time-frequency resource. Massive MIMO uses hundreds, if not thousands, of antennas.[22] [23]

However, technical challenges escalate as the number of antennas at base stations increases. Firstly, the performance gain from massive MIMO largely depends on the accuracy of channel state information (CSI), which is used for precoding design, modulation and coding scheme decision, and signal demodulation. Therefore, channel estimation accuracy is critical for MIMO realization. Traditional MIMO utilizes orthogonal pilot sequences to acquire CSI. However, this approach encounters great difficulties in the massive MIMO case.

Network operators spend as much as half of their operating expenses on energy costs. As the number of RF chains at a basestation increase to support 5G massive MIMO, the energy costs are likely to go up. There will be a need to create adaptive power management systems. During low usage periods, by using adaptive radio network designs perhaps enabled by machine learning, will significantly lower operator costs and CO_2 emissions. [24]

Although many researchers have studied massive MIMO techniques, how to apply them into high-speed scenario and how to achieve a low complexity yet accurate channel estimation and detection remain big research challenges. Furthermore, system layer views and applications, such as cell virtualization or cell shaping, will require further attention.

8.2.2. MMWAVE/MICROWAVE/PHYSICAL ELECTRONICS [E.G., TRANSMITTERS, RECEIVERS, AND ANTENNAS]

The U.S. Federal Communications Commission (FCC) has freed approximately 30 times more bandwidth at millimeter-wave frequencies than is available at cellphone bands for commercial use. Millimeter-wave spectrum would allow orders of magnitude greater throughput, opening important application spaces such as virtual reality, in which what a user sees is relayed as high-definition video back to a server, processed, and augmented with high-definition overlays sent back to the user, all in real time. Applications like this cannot be supported without the availability of instantaneous bandwidths of 500 MHz (or even wider) and low latencies that cannot be achieved at current cellphone bands. Additional advantages include reducing the need for carrier aggregation and reducing the need to be as spectrally efficient so that modulation waveforms with lower complexity can be used (i.e., 256QAM instead of 1024 QAM).

However, mmWave hardware for 5G has unique challenges and required characteristics as compared to hardware for below-6-GHz operation. The following examples of challenges are identified for 5G mmWave hardware with some suggested solutions and standards that will apply. More detailed discussions of these topics will be addressed in the IEEE 5G and Beyond Technology Roadmap.

- While existing mmWave technology can come close to the transmission efficiency possible below 6 GHz on a J/bit basis if beamforming is utilized to reduce power levels needed, this is still not enough to support the greatly increased data rates envisioned in a practical mobile commercial telecommunications system. Possible solutions include improving current devices, developing new devices, and developing better measurement and modeling tools to characterize those devices and design more efficient transmitters.

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[22] *https://massivemimo.eu/*
[23] *"An Overview of Massive MIMO Technology Components in METIS", by Gábor Fodor, Nandana Rajatheva, Wolfgang Zirwas, Lars Thiele, Martin Kurras, Kaifeng Guo, Antti Tölli, Jesper H. Sørensen, and Elisabeth de Carvalho, IEEE Communications Magazine, Volume: 55, Issue: 6, pp 155-161, 2017.*
[24] *Ali Yazdan et al., "Energy Efficient Massive MIMO," IEEE Microwave Magazine, Vol. 18, No. 5, July/August 2017*

- Many semiconductor technologies offer complementary advantages at mmWave frequencies (*e.g*. SiGe, GaN, GaAs, CMOS), but the technical difficulties and costs associated with integrating these are currently prohibitive. Possible solutions include heterogeneous integration.
- The complexity of beam forming and speed of signal processing in mmWave systems is significantly higher than below 6 GHz.
- Free-space path loss at mmWave operating frequencies
    - Possible solutions include high-density femto/pico cells, beamforming arrays, scalable and massive array concepts, and conformal antenna integration.
    - Related hardware needs include sensitive low-power receivers with robust immunity to interference; low-cost, compact integrated antenna arrays; new conformal materials for antennas; efficient, low-cost active and passive devices (e.g., combiners, phase shifters, filters, and other passives); and large-signal measurements at mmWave frequencies.
    - Semiconductor technologies considered include SiGe, GaN, GaAs, CMOS, heterogeneous integration, and wafer-level packaging.
    - Potential standards activities include the following: IEEE 287™, *IEEE Standard for Precision Coaxial Connectors (DC to 110 GHz)*; IEEE P1770™, *Draft IEEE Recommended Practice for The Usage of Terms Commonly Employed in the Field of Large-Signal Vector Network Analysis*; and the development of IEEE P1785™, *IEEE Frequency Bands and Waveguide Dimensions,* and others[25].
- Multi-user support of base stations
    - Possible solutions include time division multiple access (TDMA), hybrid architectures with subarrays, mmWave MIMO technologies, code division multiple access (CDMA), and frequency division multiple access (FDMA).
    - Related hardware needs include high-power mmWave amplifiers; integrated high-order phase shifters; new active antenna technologies; and measurement traceability for dynamic free-field modulated signals.
    - Potential standards activities include IEEE P149™, *Draft IEEE Recommended Practice for Antenna Measurements*; IEEE 1720™-2012, *IEEE Recommended Practice for Near-Field Antenna Measurements*; and others
- Indoor coverage – mmWave signals will not penetrate building structures
    - Possible solutions include indoor repeaters and collaboration with gigabit Wi-Fi networks.
    - Related hardware needs include handsets with diversity RF-front-ends that can switch between mmWave, below 6 GHz, Wi-Fi, and Li-Fi networks.

8.2.3. EAP

The 5G-era architectures will require rethinking of all fundamentals (e.g., software, automation, Shannon limit, RT-control, cellular structure, BS, spectrum, AI, core, RAN, edge, complexity, and resilience) in

[25] *Kate Remley et al., "Measurement Challenges for 5G and Beyond," IEEE Microwave Magazine, Vol 18, No. 5, July/August 2017*

terms of service agility and costs. This is to provide services and applications needed to end users in modular and flexible (e.g., software-defined and virtualized) platforms built on common hardware and in closer proximity to them. These considerations lead to the need of a new "edge" definition. Currently, multi-access edge computing (MEC) is being defined by ETSI/MEC, and IoT-based groups are working on infrastructure and connectivity for a broad set of applications under the OpenFog umbrella, moving computation, communication, control, and decision making to the network edge where data is being generated, analyzed, and used for control and management.

Edge computing is a new paradigm in which the resources of a small data center are placed at the edge of the internet, in close proximity to mobile devices, sensors, and end users. Terms such as "cloudlets," "micro data centers," and "fog" have been used in the literature to refer to these small, edge-located data centers. The purpose of EAP is to provide a set of capabilities and infrastructure components to make all of these disparate approaches feasible in a unifying architectural framework.

The MEC industrial specification group (ISG) in ETSI describes the MEC as a natural development in the evolution of mobile base stations and the convergence of IT and telecommunications networking.[26] The purpose of this ISG is to create a standardized, open environment that allows the seamless integration of applications from vendors, service providers, and third parties across multi-vendor MEC platforms to ensure that mobile operators are able to serve the vast majority of their customers. It focuses on offering application developers and content providers cloud-computing capabilities and an IT service environment at the edge of the mobile network. It aims to expand the scope of its work to further investigate the use of edge computing outside a mobile-only access environment under the name of multiaccess edge computing with the same acronym, "MEC."

The OpenFog Consortium was formed in November 2015 and focuses on an open, system-level architecture that extends elements of computing networking and storage across the cloud through to the edge of the network.[27] This approach is particularly suited to IoT systems and accelerates the decision-making velocity. The goal of the OpenFog architecture is to facilitate deployments that highlight interoperability, performance, security, scalability, programmability, reliability, availability, serviceability, and agility.

The Open Edge Computing (OEC) Initiative enables OpenStack, mobile application developers, and cloud operators to deliver significantly reduced E2E computational latencies, higher network resiliency, highly optimized network traffic utilization, and multisite live migration. It is an initiative supported by academia and industry and provides its source code for developing and testing edge-computing platforms.

To unify these diverse activities and provide a jointly designed open EAP architecture will build on the work of the IEEE 5G and Beyond Technology Roadmap EAP Working Group that has been initiated within the IEEE SDN and 5G initiatives. The mission of the EAP working group is to identify a roadmap for plans of proofs of concept, research, and collaborative efforts to help prevent fragmentation at the edge architectures.

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[26] *ETSI, "Mobile Edge Computing A key technology towards 5G", ETSI White paper No. 11, Sept. 2015, available: http://www.etsi.org/images/files/ETSIWhitePapers/etsi_wp11_mec_a_key_technology_towards_5g.pdf*

[27] *OpenFog, "OpenFog Architecture Overview", White paper, February 2016 ,available: https://www.openfogconsortium.org/wp-content/uploads/OpenFog-Architecture-Overview-WP-2-2016.pdf*

9. CONCLUSIONS

Migration from 1G to 4G has been facilitated by the availability of readily usable or at least known technologies that required a limited amount of development. The migration from the operating frequency of 800MHz of 1G to the 1800MHz range of 4G did not have a major influence on signal propagation properties in air. The migration to digital technologies, introduction of new, more efficient protocols, and the extensive coverage provided by deployment of repeaters were the main contributors to enhanced performance. However, the use of frequencies beyond 6GHz will impose drastic restrictions on signal propagation distance. Furthermore, the inability of signals to circumvent obstacles will progressively become an even greater problem as higher frequencies are under consideration for future generations.

The IEEE 5G Initiative is mobilizing across industry, academia, R&D organizations, application developers, and the standards, policy and regulatory communities globally to enable the historic transformation promised by 5G and future generations of connectivity.

5G is not just an evolutionary upgrade of the previous generation of cellular, but it is a revolutionary technology envisioned that will eliminate the bounds of access, bandwidth, performance, and latency limitations on connectivity worldwide. 5G has the potential to enable fundamentally new applications, industries, and business models and dramatically improve quality of life around the world via unprecedented use cases that require high data-rate instantaneous communications, low latency, and massive connectivity for new applications for mobile, eHealth, autonomous vehicles, smart cities, smart homes, and the IoT.

Network migration to picocells and other more elaborate schemes presently under consideration will drastically depart the deployment of 5G from any previous generation. Will the ecosystem be compelled to adopt a frequency for outside communications different to the one used inside buildings? Definition and implementation of 5G will have to answer these questions for the very first time and will represent a fundamental inflection point that will redefine wireless communications. It is the goal of the IEEE 5G and Beyond Technology Roadmap to bring these issues to the front and provide a path for the communication industry to successfully and expeditiously herald the foundation of the communication world of the 21st century.

It is critical that the entire future networks and massive connectivity industry participate in this IEEE 5G and Beyond Technology Roadmap activity. All ecosystem stakeholders will benefit from a common perspective to address the future needs and challenges faced in the evolution to future state. Because of the dependencies and linkages throughout the wireless industry community, it is imperative that the IEEE 5G and Beyond Technology Roadmap working groups include representatives from component manufacturers, suppliers, integrators, network operators, service providers, and end users, as well as the R&D community, which includes universities, national labs, and industry consortia. These working groups are Standardization Building Blocks, mmWave, EAP, Massive MIMO, Applications and Services, Security, Hardware, and Testbed (Figure 2).

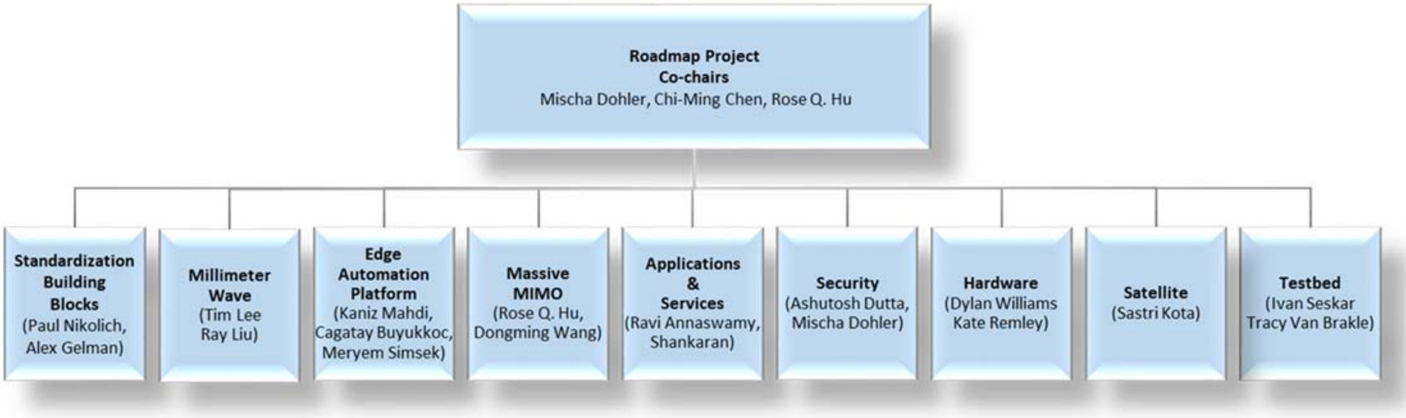

Figure 2 IEEE 5G and Beyond Technology Roadmap Working Groups

This white paper shall serve as the initial launch point for the IEEE 5G and Beyond Technology Roadmap. It identifies the first main thrusts of technology and will hopefully start a lively and fruitful discussion to sharpen the view and generate further versions of the IEEE 5G and Beyond Technology Roadmap in regular time intervals. We will be coordinating with the relevant roadmap activities that include the IEEE International Roadmap for Devices and Systems (IRDS)[28] and the IEEE Heterogeneous Integration Roadmap (HIR).[29]

Our intent is to engage all 5G stakeholders within academia, industry, and government, in order to provide a holistic picture that includes many points of view for the potential benefits, challenges, and technical solutions that will enable the 5G revolution. We invite you to get involved. Please visit https://5g.ieee.org/ to learn how to engage.

[28] *IEEE International Roadmap for Devices and Systems, available at IRDS: http://irds.ieee.org/*
[29] *IEEE Heterogeneous Integration Roadmap, available at http://cpmt.ieee.org/technology/heterogeneous-integration-roadmap.html*

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12. ACRONYMS/ABBREVIATIONS

Term	Definition
1G-4G	First Generation to Fourth Generation
3GPP	Third Generation Partnership Project
5G	Fifth Generation
ACK/NAK	Acknowledgment/negative acknowledgment
AI	Artificial intelligence
API	Application programming interface
B2B	Business to business
B2C	Business to consumer
BS	Base station
BSS	Business support system
CAPEX	Capital expenditure
CDMA	Code division multiple access
CN	Core network
COTS	Commercial off-the-shelf
CP	Control plane
C/U	Control plane / User plane
D2D	Device to device
DevOps	Development and information technology operations
DFT-s-OFDM	Discrete Fourier transform spread orthogonal frequency division multiplexing
DL	Downlink
EAP	Edge automation platform
eMBB	Enhanced mobile broadband
eNB	Evolved node B
EPC	Evolved packet core
ETSI	European Telecommunications Standards Institute
FDD	Frequency-division duplex
FDMA	Frequency division multiple access
GHz	Gigahertz
GSMA	GSM (Groupe Speciale Mobile) Association
HIR	Heterogeneous Integration Roadmap
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IMS	IP multi-media subsystem
IoT	Internet of things
IP	Internet protocol
IRDS	International Roadmap for Devices and Systems
ISG	Industrial specification group
ISP	Internet service provider
ITS	Intelligent transport system
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardization Sector
KPI	Key performance indicator
LAA	Licensed assisted access
LDPC	Low-density parity-check
LTE	Long-term evolution
M2M	Machine to machine
MAC	Medium access control
MANO	Management and orchestration

MEC	Multi-access edge cloud
MIMO	Multiple input, multiple output
ML	Machine learning
mMTC	Massive machine-type communication
mmWave	Millimeter wave
MR	Merged reality
MVNO	Mobile virtual network operators
NaaS	Network as a service
NF	Network function
NFV	Network function virtualization
NGMN	Next generation mobile networks
NGC	Next generation core
NOMA	Non-orthogonal multiple accesses
NR	New radio
NS	Network slicing
NSA	Non-standalone
OEC	Open edge computing
OFDM	Orthogonal frequency-division multiplexing
OMEC	Open mobile edge cloud
OPEX	Operational expenditure
OPNFV	Open platform network virtualization
OSS	Operational support system
OTT	Over the top
PGW	Packet gateway
PHY	Physical layer
PoC	Proof of concept
QoS	Quality of service
RAN	Radio access network
RE	Range extension
RSRP	Reference signal received power
SDN	Software defined network
SDO	Standards developing organization or standards development organization
SIM	Subscriber identification module
SLA	Service level agreements
SON	Self-optimizing network
TDD	Time-division duplex
TDMA	Time division multiple access
TSDSI	Telecommunications Standards Development Society India
TTI	Transmission time interval
UAV	Autonomous aerial vehicles
UE	User equipment
UL	Uplink
UP	User plane
URLLC	Ultra-low reliability low latency connection
V2I	Vehicle to infrastructure
V2V	Vehicle to vehicle
vEPC	Virtual evolved packet core
VNF	Virtual network function
WRC	World Radiocommunication Conferences
WG	Working group

13. APPENDIX

13.1. ANTI-TRUST STATEMENT

The IEEE 5G Initiative follows the anti-trust policy set forth by the IEEE-SA. That policy can be found at https://standards.ieee.org/develop/policies/antitrust.pdf.