IEEE

International Network Generations Roadmap (INGR)

An IEEE 5G and Beyond Technology Roadmap

Executive Summary

1st Edition

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International Network Generations Roadmap (INGR)

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FOREWORD—*THE WIRELESS TECHNOLOGY AND IEEE NETWORKS ROADMAP HISTORY*

Wireless two-way communications were demonstrated in 1973 but it was not until 1980 that wireless phones became commercially available to consumers. The technology used in the first generation of wireless phones (1G) was 100% analog. This technology was completely adequate for voice communications but it did not allow for any other capabilities. In the 1990s digital technology was introduced with 2G, enabling wireless phones to benefit from communications features readily available on personal computers. Voice communications via wireless phones had to be converted from analog to digital (ADC) in transmission and then converted from digital to analog (DAC) in reception (adding complexity and cost—a small price to pay for the benefit of wirelessly accessing the many communication capabilities readily available). The subsequent wireless generations of 3G, LTE and 4G further enhanced the existing capabilities and added new ones.

Reports in conferences and industry publications in the past five years about the advent of 5G created excitement among consumers and also prompted a vigorous discussion among experts as many new and exciting features were continuously added to the list of 5G capabilities. This realization led a group of experts in 2016 to formulate the concept of generating a "5G" roadmap within the IEEE Future Networks Initiative, with a stated mission to identify short (~3 years), mid-term (~5 years) and long-term (~10 years) research, innovation and technology trends in the communications ecosystem; guide the IEEE community towards maximum impact contributions across its societies and in conjunction with its demand-side and guide the wider industry and standards ecosystem. The outcome was projected to be a live document with a clear set of (accountable) recommendations. Subsequent updates would serve to focus the network industry community in areas of research and industry partnerships.

It quickly became clear that 5G was just the beginning of a new revolutionary way in which communications were going to continue evolving with time. Additionally, the roadmap needed to address the question of "What will be the role of 6G as a follow up and enhancement of 5G?" Therefore, the Future Networks roadmap effort was relabeled in 2018 as the "5G and Beyond" roadmap. These considerations were captured in the Future Networks Initiative white paper published in 2017, which detailed the charter and scope of the 5G roadmap effort. (It can be accessed at this link.)

The 5G-communication revolution continued to expand and it became clear that the transformation occurring in networks introduced by some of the new features opened opportunities well beyond the capabilities of wireless phones, with new networks enabling an era of diversified products no longer limited to wireless phones. In fact, it is likely that many of these new wireless products will be optimally experienced in enclosed environments, like homes, airports, shopping malls, etc. In addition, other features like minimal latency and large bandwidth will revolutionize the overall telecommunication industry, the Internet of Things (IoT), remote medicine, transportation and most aspects of society involving any form of communications. These considerations led to the present rebranding of the Future Networks IEEE roadmap effort as the "International Network Generations Roadmap" (INGR).

The 1st Edition INGR chapters address many aspects of 5G. This edition provides a high-level perspective and projection of how the industry could evolve, with highlights of common needs, the challenges to achieving those needs, and the potential solutions to those challenges as nine initial chapters. This first edition roadmap lays the foundation for the next edition that will include a description and evaluation of 6G and other future enhancements.

KEY WORDS

3GPP, 4G, LTE, 5G, 6G, architecture, artificial intelligence (AI), virtual reality (VR), augmented reality (AR), bandwidth, broadband, business model, cellular, cloud, communications, connected vehicles, robotics, 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, mm-Wave, 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, smart cities, ecosystems, public safety, healthcare, electrical, water and wastewater, hardware, deployment, signal processing, optics, satellite, standardization building blocks, system optimization

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EXECUTIVE SUMMARY

1. INTRODUCTION

Technologies for 5G and future generations of connectivity will be deployed throughout the 2020s and will provide higher bandwidth, massive sensing, higher reliability and lower latency than current-generation 4G technology. 5G 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.***

In the past any transition from one wireless technology to the next was simplistically characterized by the introduction of a new higher frequency spectrum. Since the amount of information that can be wirelessly distributed is directly proportional to the spectrum frequency, it is self-evident that utilization of a higher frequency enables more content to flow through the network. It will be noticed later on that especially with the advent of 5G the transmission of information may be partitioned across multiple frequency bands to overcome bandwidth limitations. In the past, news of frequency transitions occurred somewhat in the background since the attention of the customers was concentrated on what new and better services they were receiving by transitioning from the "N"G generation to the "(N+1)"G generation. After all, why did customers need to worry about how it was done as long as the range of connection distance was covered and the quality of the connections was getting better?

Customers' attention was concentrated on the form factors of smart phones' "look, touch and feel." Any introduction of a new model ignited a spending frenzy among consumers that were willing to actually camp out the night before the introduction of a new model to grasp the new, more attractive and improved smartphone. The end products took center stage in any of these "G" transitions, while the wireless transmission and networking technology powering these devices operated like a "Cinderella" in the background.

However, while this "5G and Beyond" roadmap activity was underway, a major revolution has occurred. Radio, television, multimedia, the Internet of Things (IoT) and other applications have in common some form of wireless distribution of their contents. This basic technology commonality has led to the predictable confluence of all these means of communication into compatible (although not directly comingled) formats with the advent of 4G in a single wireless phone. The last remaining choice left for consumers consisted of selecting the physical format of the electronics appliance. ***In doing so, the capabilities of the networks have kept on increasing in the background so that now new additional and previously unexpected applications are being inspired by the overall "Network," that has now assumed the central role!***

It is clear from the above considerations why the realization of the enhanced role of the Network has led to the renaming of the IEEE Future Networks roadmap effort as the International Network Generations Roadmap (INGR).

Below are examples of these new revolutionary applications heralded with the advent of 5G:

- Next generation mobile immersive media and education
- Realtime surveillance/facial recognition and predictive policing
- Mobile healthcare and monitoring via wearables

- Industrial IoT (IIoT) and autonomous manufacturing
- Smart agriculture (self-driving tractors, drones, field robots)
- Environment monitoring and reporting of on-time deviations from established averages
- Retail asset tracking and real-time inventory, pick, pack and ship logistics
- Remote control of robotics
- Telemedicine
- Smart infrastructure connectivity in home and city
- Possible disruption of traditional communications ecosystem (i.e., new service providers creating new business models)
- Virtual Reality (VR) and Augmented Reality (AR)

The members of INGR teams and multiple IEEE societies recognize the benefits of this transition but also the disruptive nature of technologies enabling 5G, 6G and subsequent future networks, as well as the substantial technical barriers to be overcome for its realization. Consequently, the IEEE INGR effort includes 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 the INGR has been the formation of roadmap working groups, with emphasis toward 5G technologies for the 1st Edition INGR chapters. It is also part of this activity to identify the challenges and opportunities in building a 5G network—keeping in mind any possible compatibility with future networks like 6G. It is expected that the INGR will help guide operators, regulators, manufacturers, researchers, and other interested parties involved in developing future network ecosystems. To build the appropriate foundation for the roadmap effort, the release of this 1st Edition INGR will focus mostly on 5G. The 2nd Edition Roadmap will include additional 6G-specific technologies, as well as a more end-to-end perspective that integrates future network technologies, enablers, and will indicate challenges and technology gaps in the evolution of the networks' industry at three-, five-, and 10-year horizons.

The INGR emphasizes the need for collaboration among all stakeholders in industry, academia, government and standards development organizations (SDOs) in undertaking this high-risk engineering challenge. The current telecommunications value chain will have to adapt and most of all evolve to accommodate the changes and opportunities that the introduction of 5G technologies will bring, ideally in a way that will also be 6G-compatible.

In the following sections future applications are listed that will drive INGR requirements to provide societal benefits for education, manufacturing, healthcare, smart grid, entertainment, autonomous cars, robotics and smart cities, just to name a few. The INGR will also describe key technology trends that may impact 5G and 6G design drivers and the design challenges if these technologies are to simultaneously provide wireless communication, massive connectivity, the tactile internet, quality of service (QoS), multi-access edge cloud (MEC), network function virtualization (NFV), and network slicing (NS) just to mention a few. The INGR chapters will highlight some technology enablers that have **not yet been fully explored** but are critical not just for the success of 5G but also for the achievement of 6G.

Collectively, the INGR members think that, with widespread participation, the roadmap process outlined here can reduce some of the technical and engineering risk associated with the migration beyond 4G and related technologies.

2. WIRELESS COMMUNICATIONS BACKGROUND

In the last 20 years of the previous century, mobile phones became pervasive among consumers. A new mobile generation 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 1991, and the 3G systems appeared in 2000. 4G systems were fully standardized in 2012 even though long-term evolution (LTE) services were already provided in 2010. 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. Several major improvements continued to be made in the past 10 years like 4G LTE, 4G LTE Advanced, and 4G LTE Advanced Pro etc.

Almost in the same time period, the Internet became broadly accessible to the consumer community. 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. Transmission of attachments, photos, videos, etc., became possible in the subsequent decade. Personal computers connected by cables became the standard way of accessing the Internet. By the end of the 1990s personal computers became capable of wirelessly connecting to the Internet. The introduction of smartphones and tablets in 2007 and 2010, respectively, introduced the combination of all these aforementioned capabilities into single mobile appliances that, in addition to enabling voice calls, could navigate the internet and handle photos and video, download and also stream movies, among many other applications. Since 2016 close to 1.5 billion smart phones were sold each year, and Cisco projected that by the end of 2019 80 % of global Internet consumption will be video content. This amounts to a total of about 90,000 petabytes per month, with mobile video consumption growing at an estimated compounded annual growth rate (CAGR) of 67% versus a 29% growth for fixed video consumption in the period 2014–2019. Voice communications have now become a small contributor to the amount of information traffic over the network!

Some drastic upgrade/conversion of the whole communication infrastructure needs to happen in the year 2020 to support the forecasted growth in the flow of information and various types of applications. 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 3 GHz where contiguous spectrum can be found to support wider communication channels. Worldwide the selection of the frequency range between 3.7 and 4.2 GHz seems to be the most common choice [Figure 1].

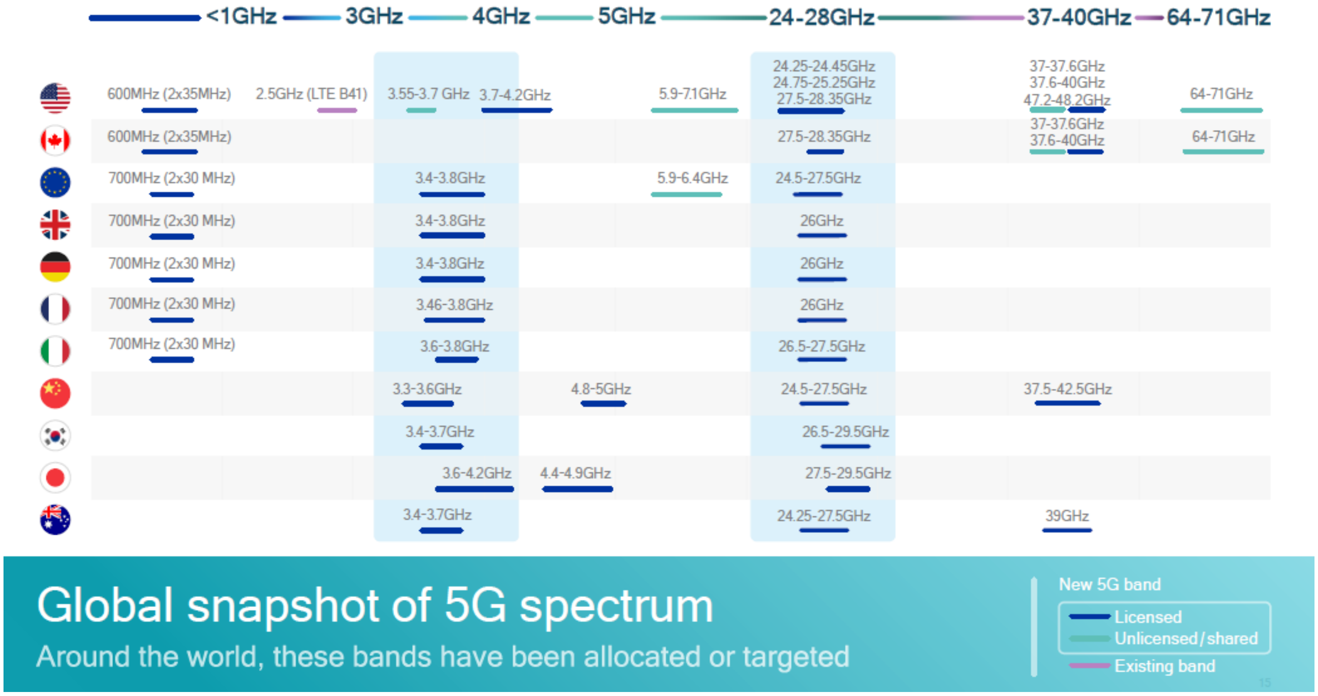

Figure 1. 5G Spectrum Across National Borders

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). At present 5G is aiming at a band of 100MHz frequency range 1 (FR1). In order to deliver this capability at the mobile level the network will need to operate at least above 18-20 GHz. Under these conditions it is also possible to deliver a band of 400 MHz (FR2). Some operators are also advocating taking this frequency range all the way to the mobile user level. But there is little room for new available larger channel bandwidths since new frequency bands suitable for terrestrial cellular radio would overlap with the K bands (18 to 27 GHz) transmissions that are already allocated for communication satellites.

In addition, the path loss in air between transmitting and receiving antennas is proportional to the square or higher of the frequency [Figure 2] 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.

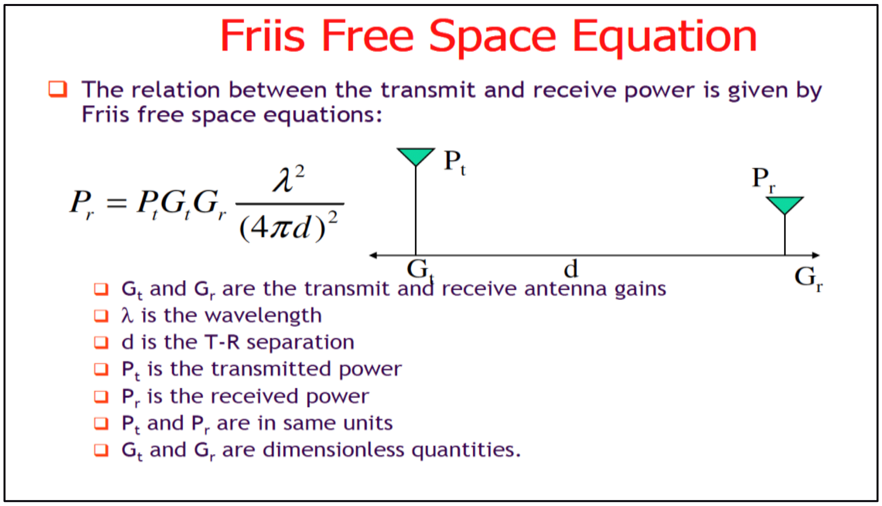

Figure 2. Friis Equation Relates Power, Distance and Frequency

Also, electromagnetic (EM) waves of frequencies above 6 GHz are severely affected by any physical obstacles like walls and trees and weather conditions. These constraints require a complete rethinking of the mobile distribution of communications. For instance, to compensate for the substantial (50% and more) range reduction, arrays of multiple antenna elements arranged in a squared 2D flat surface can emit EM waves in a highly directional mode. Therefore the flow of information can be precisely pointed towards any receiving phone in line of sight (LoS). This technical solution brings back the range of antenna-to-customer communications closer to the 4G ranges. When the position of the phone keeps contiguously changing, the array signal can be electronically steered to accurately track the phone movements. Additionally, when the receiving phone is hidden behind a blocking object it is possible to utilize signals reflected and diffused by surrounding structures to make a LoS connection between the radiating antenna and the receiving phone. All of these issues are related to higher operational frequencies and need to be well understood and resolved since the entire system design completely depends on this.

Here is a simple overview of the target capabilities that will be delivered from this new network generation.

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 research and development (R&D) also aims at lower latency than 4G equipment and lower battery consumption for better implementation of the IoT.

The Next Generation Mobile Network (NGMN) Alliance 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 LTE

3. THE BIG PICTURE: 5G WIRELESS PHONE, WI-FI 5GHZ AND 5G IMT-2020[1] PLATFORM

In the last few years the media and advertising have made ever increasing promises about 5G. Since the letter "G" had been associated in the past with any new wireless phone generation it seems that many of consumers are expecting that most, if not all, of these new capabilities will be imbedded in the next generation of wireless phones.

Even though more powerful wireless phones will indeed benefit consumers with many new capabilities, it is worthwhile to clarify that the features of 5G networks will go well beyond mobile phones.

3.1. 1G TO 4G WIRELESS PHONES

Since the 1980s four main generations of wireless phones have been introduced. Initially mobile voice communication was the main and only goal of wireless phones operating in **1G.**

Beginning with **2G** the information transmitted migrated from analog to digital format and this conversion opened the way for applications beyond voice communications on a wireless phone. On 2G, users could send short message service (SMS) and multimedia messaging service (MMS) messages, although slowly and unreliably. In 1997 the general packet radio service (GPRS) upgrade allowed users to also send and receive email. Accurate models were developed to allow thousands of simultaneous individual telephone conversations. One such model is called time division multiple access (TDMA). In cellular communications the frequency bandwidth is partitioned in multiple channels to allow simultaneous phone conversations to take place. Digital techniques facilitate squeezing more communication channels with lower interference.

In **3G** the migration from digital to packet switching began in 2000. This approach divides the data to be transmitted into packets transmitted through the network independently. In packet switching there was no longer an exclusive connection. This meant that instead of one line being dedicated to a single communication session at a time, packets from multiple competing communication sessions shared network links. Overall 3G communicated at a much faster rate and could transmit greater amounts of data than 2G. This meant that users could make video calls, share files, surf the Internet, watch TV online and play online games on their mobiles for the first time. With 3G, cell-phones were no longer just about calling and texting, they became the hubs of social connectivity

In March 2008, the ITU Radiocommunication Sector (ITU-R) released new standards for **4G** including faster connection speeds and mobile hotspots. These standards were groundbreaking at the time, and it took years for actual cellular networks to catch up with the technology.

Short for "long term evolution", **LTE** is an improvement over its 3G predecessor, but not substantial enough to qualify as a new generation despite what the name seems to indicate. Think of LTE as a clever workaround that allowed cellular networks providers to advertise "4G speeds" without actually reaching the minimum 4G standards. Nevertheless, phones typically displayed 4G LTE.

[1] *International Mobile Telecommunications-2020 (IMT-2020 Standard)*

The goal of LTE was to increase the capacity and speed of wireless data networks using new digital signal processing (DSP) techniques and modulations that were developed around the turn of the millennium. A further goal was the redesign and simplification of the network architecture **to an IP-based system with significantly reduced transfer latency compared to the 3G architecture**. As a result the LTE wireless interface is incompatible with 2G and 3G networks, so that it must be operated on a separate radio spectrum.

Finally, the initial introduction of 4G in 2013 was done using frequencies spanning from 700 MHz to 2.5 GHz and brought the bandwidth to the 20 MHz standard level and could in theory support speeds up to 100 Mbps. 4G is an all-IP packet switched network that is incompatible with 2G and 3G networks.

Under 4G, users can experience better latency, higher voice quality, easy access to instant messaging services and social media, quality streaming and faster downloads.

It is clear from the above considerations that mobile phone networks have migrated with time far from the initial offering of voice communications, and added a multitude of new capabilities.

3.2. Wi-Fi 5 GHz

How is 5G different from previous generations? The first workable prototype of the Internet became functional in the late 1960s. Internet technologies continued to grow in the 1970s after transmission control protocol (TCP) and Internet protocol (IP), or in short TCP/IP, were invented. These protocols defined a set of standards for how data could be transmitted across multiple networks. Voice communication was never the goal of this project.

Commercial Internet service providers (ISPs) began to emerge in the very late 1980s. The online Internet world then took on a more recognizable form in 1990, when the World Wide Web was invented, as the most common means of accessing data online in the form of websites and hyperlinks became available.

Wired connection to the Internet with personal computers, via phone lines and subsequently via higher speed lines, was the typical method of accessing email and Internet sites in the 1990s.

Wi-Fi was invented to eliminate wired connections to the Internet and it was first released for consumers in 1997. This was due to the work of a committee that created IEEE 802.11, consisting in a set of standards that defined communication protocols for wireless local area networks (WLANs). Following this milestone, a basic specification for Wi-Fi was established, allowing two megabytes per second of data to be transferred wirelessly between devices. This sparked a development in prototype equipment (routers) to comply with IEEE 802.11, and in 1999, Wi-Fi was introduced for office and later for home use.

The Wi-Fi frequency of 2.4 GHz was selected among the industrial, scientific and medical (ISM) radio bands; the operating range is 50–150 feet and a typical channel is 20 MHz. Most importantly, ISM frequencies do not require a license and are therefore much cheaper to obtain than cell phone frequencies! As an example, garage door openers and microwave ovens work on this precise unlicensed frequency.

Once the Wi-Fi signal leaves your mobile device at home is gets wirelessly connected to a router. From the router the signal travels through a variety of physical media like copper wires and coaxial cables to a specific website where the desired information is retrieved. The signal may also undergo more complex routes spanning from Wi-Fi towers to satellite [Figure 3].

Figure 3. Wi-Fi Router Connects Computers and Cell Phones to Internet

About 10 years ago the speed of accessing the Internet began to slow down as the amount of traffic continued to grow due to the increasing number of users simultaneously online, and also due to the increasingly larger size of attachments, photos and videos transmitted.

As previously indicated the ISM frequency of 2.4 GHz with a bandwidth (BW) of 20 MHz was used to carry the wireless signals for distances up to 50–150 ft.

The advent of digital and high-definition TV (HD TV) pushed consumers to upgrade to coaxial cables or direct satellite TV. Under these conditions, a second ISM band of 5 GHz began to be implemented around the year 2009. Most routers nowadays carry both frequencies.

3.3. 5G International Mobile Telecommunications IMT-2020 Platform

The ITU-R has defined three main uses for 5G. They are enhanced mobile broadband (eMBB), ultra-reliable low latency communications (URLLC), and massive machine type communications (mMTC). Only eMBB is deployed in 2019; URLLC and mMTC are several years away in most locations.

eMBB uses 5G as a progression from 4G LTE mobile broadband services, with faster connections, higher throughput, and more capacity

URLLC refers to using the network for mission critical applications that require uninterrupted and robust data exchange.

mMTC would be used to connect to a large number of low-power, low-cost devices, which have high scalability and increased battery lifetime in a wide area. 5G technologies will connect some of the 50 billion connected IoT devices. Most will use the less expensive Wi-Fi. Smart cities will monitor air and water quality through millions of sensors, giving them insights needed to provide a better quality of life. Many cars will have a 4G or 5G cellular connection for many services. Note that autonomous cars do not require 5G since they have to be able to operate where they do not have a network connection. While remote surgeries have been performed over 5G, most remote surgery will be performed in facilities with a fiber connection, usually faster and more reliable than any wireless connection.

In order to increase the amount of information that can be transmitted using the 5G network many service providers have acquired spectral frequencies of 20 GHz or above.

3.4. Summarizing the Multiple Facets of "5G"

The fundamental innovation of 5G lies in the fact that the entire infrastructure acts as a cohesive platform for innovative applications and is tuned to flex with demand by providing services tailored to their unique characteristics. While the infrastructure may encompass discrete components from multiple vendors and heterogeneous wireless networks, it is designed to be a fully programmable and an interoperable framework both in the core and radio resource management.

This smart network infrastructure and an enhanced ability to support exponential scale for connectivity open the doors to innovative applications across a variety of markets, such as connected cities, smart agriculture, smart manufacturing, connected healthcare, virtual reality, and autonomous vehicles.

Many discussions about the adoption of spectral frequencies equal or exceeding 10 GHz have been reported. It is progressively more difficult for an electromagnetic wave exceeding frequencies of 8–10 GHz to penetrate physical objects. Even though wireless distribution of information by means of these frequencies is possible—although in a very complicated manner—these considerations indicate that the most likely utilization of these frequencies will be primarily carried via cable of fiber optics or even satellites to routers located inside homes, airports, shopping malls or similar facilities. Most likely frequencies of 20 GHz or above will not be practically used for wireless phones since the practical range may be limited to only 2000 ft (i.e., "How many Wi-Fi towers would be required to obtain coverage similar to 4G-LTE?").

So, consumers that hear about the adoption of millimeter waves in 5G should not expect that these frequencies would be practically viable for 5G wireless phones in general.

It goes without saying that the complexity and the cost of the electronics components and circuits will go substantially up, so the question is "What are the mobile consumers willing to pay for these enhanced capabilities?"

In few words, the term "5G IMT 2020" defines a highly flexible interoperable wireless platform and it is not to be intended as a new standard exclusively aimed at a new generation of wireless cell phones!

This concept has not been fully communicated to the consumers that are still looking at 5G as their next wireless phone.

3.5. The New Telecommunication Industry

In the past 10 years new ways of delivering information to consumers have begun to lay down the foundations of a completely new telecommunication industry. As an example, in August 2008, for the first time ever, every minute of every event of the Summer Olympic Games was streamed online in high definition. This event proved that the Internet was capable of scalable, reliable broadcast of high-quality video. Since then, new streaming technologies have been tested that promise even better performance. However, since any new entrepreneur can obtain access to the communication network, it is anticipated that 2020 will see a transformation of the communication industry as multiple new (and powerful) players will fight for market share in which content and ease of use will be the driving factors. In the end, streaming services that will offer the best and broadest content libraries will likely own the roadmap to success.

At present, telecommunications firms and enterprises are still trying to determine what the "killer apps" for 5G will be. In fact the advent of 5G will likely enable introduction of new kinds of applications never considered before. One such candidate is augmented reality/virtual reality (AR/VR). This technology may be critical in further developing gaming and immersive performance participation. The low latency and high-volume communication in real time may be well suited for sport viewing (and even betting) as another example of 5G applications.

Looking further out, telecommunication companies are starting to target manufacturing, healthcare, retail, transportation and education as favorable 5G applications. As more information is collected at the “edge” it will progressively be more convenient to store and manipulate information close to the locations were sensors are located, as opposed to moving information back and forth from remote data centers. By enabling techniques allowing data aggregation and processing at the edge, it is possible to achieve both bandwidth savings and reduced latency.

In summary, 5G is very much in the “build and discovery” phase right now. However, the 5G platform has been designed to address and harmonize an unprecedented number of capabilities. As people come to truly understand its capabilities and limitations, the next generation of solutions based on 5G will continue to be introduced, one by one, in the next decade.

It is the purpose of the INGR roadmap to stimulate an industry-wide dialogue to synchronously address all the facets of the development and deployment of 5G in a well-coordinated manner, starting with the year 2020 and going beyond.

4. Roadmap Motivation

Due to the revolutionary transformation of the network and the wealth of new capabilities that will be caused by the insertion of 5G and beyond technologies, the IEEE community realized in mid-2016 the 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 technology needs, challenges, potential solutions and 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 of the “5G and Beyond” has evolved in 2019 to the present INGR roadmap with the goal of generating a vision of the technology needs and possible solutions required for the successful creation of this brand new network; periodical updates monitoring the progress of this roadmap program will be routinely produced and distributed to the industry at large.

4.1. Roadmap Methodology: History and Successes

The roadmap methodology was introduced and adopted as far back as 1991 by the semiconductor industry. Until 1997 participation in the National Technology Roadmap for Semiconductors (NTRS) was limited to organizations in the United States. Government, industry and university researchers constituted the representatives of technology working groups (TWGs) that generated the roadmap chapters. During that time the roadmap was mostly outlining the evolutionary progress of scaling down dimensions of semiconductor devices fabricated with the planar process invented in the late 1950s with consequent improvements in density, performance and cost. However, in the second half of the 1990s it became clear that some fundamental limits were going to be reached in the second half of the subsequent decade. It was then anticipated that the magnitude of the problems was so great that no single company or region had the knowledge or the resources to solve them. In order to overcome these problems it was proposed to extend the participation of the NTRS membership to representatives from Europe, Japan, Korea and Taiwan. The World Semiconductor Council (WSC) approved this proposal in 1998 and the new International Technology Roadmap for Semiconductors (ITRS) was created. In a little less than 15 years, one by one all the problems were solved at regular time intervals and by 2011 the new and completely refurbished manufacturing technology and a new architecture of vertical FinFET devices had been solidly introduced into high volume manufacturing.

Could this methodology be successfully applied to the conversion of Future Networks to "5G and 6G"?

4.2. Roadmap Evolution: From ITRS to IRDS

Since the mid-80s the pace of the Electronics Industry had been controlled by the rate at which integrated device manufacturers (IDMs) could introduce standard logic and memory products into manufacturing; system integrators were therefore left with only a few options on how to customize their systems with these standard components openly available to anybody. However, the introduction of the iPhone and the iPad in the second half of the past decade changed the model of the whole electronics industry. In both cases the processors that constituted the "heart" of the products had been designed by the system integrator itself and fabricated by a foundry without having to rely on IDMs! Suddenly, any new system design was now completely under the control of the system integrators. The requirements of the electronic industry had evolved from a bottom-up to a top-down driven approach. Under these conditions the roadmap process was no longer exclusively dictated by the semiconductor industry, but it had become a shared effort between system integrators and semiconductor manufacturers. This realization led to the reorganization of the roadmap (ITRS 2.0) in 2014–15; during this process it became clear to move the roadmap effort under a much broader umbrella. On May 2016 IEEE announced the new International Roadmap for Devices and System (IRDS).

This roadmap evolution exemplifies the fact that a live and meaningful roadmap needs to evolve and adapt to any vibrant and ever-changing ecosystem in order to avoid becoming obsolete.

5. INGR: SCOPE AND STRUCTURE

The International Network Generations Roadmap effort focuses on identifying ***technical needs*** and ***possible solutions*** that would enable the transformation of the wireless connectivity ecosystem. The roadmap has a 10-year outlook. This time span is divided in 3-, 5-, and 10-year range (short, mid and long-term). The developments will remain completely agnostic to any specific standards developing organizations (SDOs). Near to mid-term, the initiative will support 5G development efforts; the translation of the findings is left to the respective standards communities, as well as business analysts. Long term will emphasize the compatibility with 6G.

INGR 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 INGR team is constituted of 15 working groups:

1. Applications and Services
2. Deployment
3. Edge Automation Platform (EAP)
4. Energy Efficiency
5. Hardware
6. Massive MIMO
7. Millimeter Wave (mmWave) and Signal Processing
8. Optics
9. Satellite
10. Security
11. Standardization Building Blocks
12. System Optimization
13. Testbed
14. Connecting the Unconnected (CTU)
15. Artificial Intelligence/Machine Learning (AI/ML)

The activity of the TWGs is coordinated and monitored by the INGR Leadership Team that meets on an almost weekly basis. Overall roadmap coordination is performed by the Project Coordinators. Each of the TWGs is responsible to generate a chapter of the roadmap document.

6. From Roadmap to Implementation

The roadmap methodology identifies technology needs and possible solutions. It also lays out a timetable by which different parts of the ecosystem need to be evaluated firstly by research organizations (~10 years), secondly when (~5 years) feasibility of the best solutions needs to be evaluated by development consortia (typically) and finally when (1–3 years) actual industry implementation needs to occur. In order to seamlessly accomplish these three different phases it is necessary to involve industry participation from the very beginning.

Involving industry participation in all the TWGs and in addition by scheduling regular meetings to communicate any new information to the industry participants and to receive their feedback will accomplish this goal.

7. Challenges Associated with Establishing the INGR as the Reference Document for 5G and 6G Networks Development and Deployment

By definition a roadmap process starts by identifying technology needs and possible solutions required to reach implementation into manufacturing. Once this is done the roadmap process (of any type) needs to define key parameters that unequivocally characterize the fundamental elements enabling introduction of this new technology into manufacturing; subsequently key milestones towards reaching the deployment phase are identified; finally a timetable forecasting how numerical values of key parameters are evolving as a function of time is created. Once this timetable of key parameters is generated it is the role of the roadmap process to monitor their progress in time towards reaching manufacturing. This implies that multiple possible solutions need to be monitored as a function of time to identify the most successful one.

The semiconductor industry adopted the roadmap methodology about 30 years ago. As the industry evolved so did the roadmap, and vice versa. This symbiotic relation weaved the roadmap methodology into the very foundation of the semiconductor industry. Moore's Law, first enunciated as far back as 1965 and later on revised in 1975, established the goal of doubling the number of transistors every two years. This rhythm of technology introduction provided an easy target for the whole industry to aim for. To this day, the leaders of the semiconductor industry are still marching at a pace close to this.

Moore's Law: such a reference does not exist, at present, in the wireless industry.

The wireless industry has never benefited from a real roadmap methodology. New technology generations simply identified by a numerical value in front of the letter "G" have been introduced without a completely clear definition, they were just better than the previous one (e.g., 1G, 2G, 3G and 4G).

The question then arises: How can a timetable for "5G and 6G" be generated? Let's analyze the key elements leading to the construction of such a roadmap timetable.

1. The pace of the cell phone industry has been mostly characterized by the introduction of new phone models endowed with new features at **6 to 12 months** intervals.
2. Furthermore, the wireless phone industry has transitioned from one generation to the next in about **10-year intervals**. The technical item that most closely correlates with this time interval is the introduction of a new spectrum bandwidth with any new wireless generation.
3. It is absolutely necessary for TWGs constructing the INGR roadmap to identify key technical items that can be tracked on **a yearly timetable** across the 15 chapters in order to synchronize

and then monitor the progress of research and development, leading to a well identifiable time of introduction into manufacturing.

4. In addition, the advent of "5G" is heralded by multiple industries (some already existing and some completely new), each advertising different features of what "5G" is supposed to provide. In the past, traditional telecommunication companies took care of the deployment of any new cellular generation. A merge, or at least a compatibility, of multiple capabilities supported, requested and heralded by completely different industry players that have never cooperated with each other make the deployment of a "5G' network an unprecedented challenge. ***This has never happened before!***

   Most of the existing wireless industries will be converging on 5G; these include radio broadcasting, television, streaming movies, Internet, voice, data, email, just to mention a few. In addition, new industries like self-driving automobiles, autonomous manufacturing, IoT, VR and many more are also converging on 5G.

   How can all of them harmoniously operate side by side in the same network?

   However, the ITRS and then IRDS could forecast 5, 10, and 15 years out with what was going to happen in the semiconductor industry. These roadmap efforts then would plan accordingly, stimulate preparation of the infrastructure, and then monitor the progress of practical deployment and implementation of the new technology. This was possible since all the key research and industry players had learned since the 1990s how to work with each other in a cooperative environment without compromising any of their competitive advantages**.**

   This is not presently the case for the INGR roadmap effort, since it is establishing itself in this challenging role for the very first time. The roadmap is unfolding while a multiplicity of the necessary components are simultaneously unfolding under the assumption of initial introduction of "5G" starting with the year 2020!

8. USEFUL DEFINITIONS OF THE WIRELESS ROADMAP

Normally a well-defined spectrum and a well-defined useable frequency range characterized each of the past wireless generations. Both of these were higher than the ones used by the previous generation. Small numerical differences existed among the values of these frequencies from one region to another and were determined by local regulations, but in each location the frequency range was unequivocally defined. As time went by, the request for more information to be carried compelled service providers to "spread" the information across multiple frequencies (e.g., older generations acquired a different role).

With respect to 5G, the desire to maximize the amount of information (of any type) carried by means of wireless technology is introducing the concept of simultaneously utilizing multiple frequencies up front (i.e., spectrum harmonization). It is clear to the specialists that each of these frequencies have specific requirements and applications, but for the time being they are all bunched under a **"5G" umbrella**. Therefore, it is imperative to overcome this confusion by introducing a nomenclature capable of differentiating among these frequencies as the very first step of the process.

In addition, deployment of some of the proposed frequencies may take a much longer time than anticipated and it may be therefore advantageous to separate them under the **"6G" umbrella**.

8.1. 5G BAND NOMENCLATURE

1. **Low-Band**

   This band includes all the frequencies below 1GHz. It should be mentioned that a low band at 600 MHz has already been assigned to one carrier; in this case the spectrum blocks are only ~20 MHz.

2. **Mid-Band**

   The range of new wireless frequency proposed for typical mobile phones is **3.7–4.2 GHz**. As stated before, regional adjustments may be required. At present two possible ways of utilizing the 500 MHz frequency range are under discussion. Under one proposal, different organizations would utilize channels of 20 MHz as completely separate entities in accordance with past allocation methodologies. The other proposal recommends to "share" the full 500 MHz range among all users and establish a mechanism that allocates flexible portions of the bandwidth according to some algorithms based on utilization requirements during the time of the day and a set of priorities. It is clear that the latter would provide a much better performance to users if appropriately managed. As mentioned before, spectrum harmonization will be employed.

3. **High-Band**

   Propagation of wireless frequencies in excess of about 6 GHz are extremely affected by obstacles and weather conditions. These wireless frequencies may however be utilized with some precautions within buildings or in any space that is not crowded with multiple standing constructions. In this approach it may be suitable to carry the information via cable or via "line of sight" (LoS) means up to the location where it is wirelessly distributed at a different frequency. Other distribution methods are under discussion. Three different ranges are presently under discussion. Refer to Figure 4.

   a) The first spanning from 24.25 GHz to 24.45 GHz offers a band of 200 MHz.

b) A second possible range is available from 24.75 GHz to **25.25 GHz** offering a band of 500 MHz.

c) Finally, a third range is available from 27.5 GHz to 28.35 GHz with a total band of 850 MHz. It should be noted that a block of 800 MHz of band available at 28 GHz has already been allocated to a carrier.

Nomenclature	Frequency Range	Available Band
Low-band	600–705 MHz	20 MHz
Mid-band	3.7–4.2 GHz or share the 500 MHz spectrum with intelligent resource sharing	20 MHz
High-band	24.26–24.45 GHz	200 MHz
	24.75–25.25 GHz	500 MHz
	27.5–28.35 GHz	850 MHz

Figure 4. Low, Mid and High Band at a Glance

8.2. THE CASE FOR 6G AND BEYOND

It should be pointed out that many frequency bands spanning from 28 GHz to 90 GHz (and beyond) are also under consideration.

This spectrum has already been extensively used for decades, mostly for satellite communications [Figure 5]. In this case, the issue is not feasibility but how to apportion some specific slivers of this spectrum for 5G specific applications.

It seems beneficial to assume that the need for larger allocations of BW will be necessary in the future as new applications (like holographic communications) will require a huge amount of bandwidth to carry the necessary volume of information required. It is therefore useful to keep this concept in mind so that construction of the next network could be done in the near future in such a way that it could conveniently accommodate for new capabilities in the more distant future without having to completely tear down one network to build the next one.

Frequency	Low	High
	GHz	GHz
C	3.7	4.2
Ku	12	18
K	18	26
Ka	26	40
V	40	75
W	75	110

Figure 5. Satellite Bands

9. THE INGR TECHNOLOGY WORKING GROUPS ORGANIZATION

Originally nine working groups were formed in 2018. As time went by and as a better understanding of 5G continued to progress, it became necessary to extend the number of TWGs to 15. Some of the groups are completely formed and have provided 1st Edition chapters while others are still in white paper development. The full 15 chapters will be provided in the 2nd Edition of the INGR.

This 1st Edition of the INGR expects a broad variety of readers with different levels of knowledge of these TWG topics. It is therefore desirable to provide the readers with the skeleton of an overall structure of the INGR. (This structure may evolve as the INGR develops, but for the time being will be valuable for many readers.)

The overall 5G ecosystems can be summarized into four categories, as follows: (Note that each TWG topic also indicates if it is a 1st Edition INGR chapter or white paper.)

1. ***Access: This group describes how the users are able to reach the network***
   - 9.1 Massive MIMO (chapter)
   - 9.2 mmWave and Signal Processing (chapter)
   - 9.3 Hardware for mmWave (chapter)
   - 9.4 Energy Efficiency (white paper)
2. ***Networks: This group describes how the networks are interconnected***
   - 9.5 Edge Automation Platform (chapter)
   - 9.6 Satellites (chapter)
   - 9.7 Optics (white paper)
3. ***System and Standards: This group describes system standards and testability***
   - 9.8 Standardization Building Blocks (chapter)
   - 9.9 Testbed (chapter)
   - 9.10 System Optimizations (white paper)
4. ***Enablers and Users: This group represents all the elements that enable deployment, assure functionality and security and address impact on society and environment***
   - 9.11 Deployment (chapter)
   - 9.12 Applications and Services (chapter)
   - 9.13 Security (chapter)
   - 9.14 Artificial Intelligence and Machine Learning (AI/ML) (white paper)
   - 9.15 Connecting the Unconnected (CTU) (white paper)

9.1. MASSIVE MIMO

Vision and Goals

The use of a large number of antenna elements, known as Massive MIMO, is seen as a key enabling technology in the 5G wireless ecosystems. This vision will carry on to 6G as well. The intelligent use of the multitude of antenna elements unleashes unprecedented flexibility and control of the physical channel of the wireless medium. Through Massive MIMO and other techniques, it is envisioned the 5G wireless systems will be able to support high throughput, high reliability, high energy efficiency, low latency, and an Internet-scale number of connected devices.

Massive MIMO and related technologies will be deployed in the mid-band (sub 6 GHz) for coverage, all the way to millimeter-wave bands to support large channel bandwidths. It is envisioned Massive MIMO will be deployed in different environments: frequency-division duplex (FDD), time-division duplex (TDD),, indoor/outdoor, small cell, macro cell, and other heterogeneous network (HetNet) configurations. Accurate and useful channel estimations remain a challenge in the efficient adoption of Massive MIMO techniques, and different performance-complexity tradeoffs may be supported by different Massive MIMO architectures such as digital, analog, and/or digital/analog hybrid.

Massive MIMO opens up a whole new dimension of parameters where the wireless applications or other network layers may control or influence the operation and performance of the physical wireless channel. To fully reap the benefits of such flexibility, latest advances in AI and ML techniques will be leveraged to monitor and optimize the Massive MIMO sub-system. As such, a cross-layer open interface can facilitate exposing programmability of Massive MIMO through techniques such as NS and (NFV. Finally, security needs to be integrated in the design of the system so the new functionality and performance of Massive MIMO can be utilized in a reliable manner.

The Massive MIMO WG will be based on the following frameworks:

a) Framework for large number of active users with massive connectivity.
b) Framework for high spectral efficiency and energy efficiency with high user density and emerging applications having the strong need of QoS guarantees.
c) Big Data management
d) Cost-effective, reliable, and scalable implementation for Massive MIMO
e) Machine-type communications and low complexity transceiver design
f) PHY design for millimeter-wave massive MIMO systems
g) Analog and digital hybrid precoding design
h) Secure communications for massive MIMO systems
i) The integrating of machine learning into massive MIMO systems

The 3GPP cellular architecture will be used as a reference, while future architecture evolution such as network slicing will be considered. Under the different network architectures, these are the envisioned applications and services as follows: Energy and utilities, industry and manufacturing, public safety, healthcare, public transport, media and entertainment, automotive, financial services, agriculture, and tactile applications.

9.2. MMWAVE AND SIGNAL PROCESSING

Vision and Goals

The Millimeter-wave and Signal Processing (MMW-SP) Working Group of INGR examines improvements in current millimeter-wave architectures, hardware capabilities and signal processing techniques to enable the 5G systems to achieve the 3GPP Release 15 requirements for massive mobile broadband (eMBB), and for Release 16 requirements for ultra-reliable low-latency communication (URLLC) and massive machine-to-machine (MM2M) use cases. The WG will translate the requirements for these drivers and describe technical challenges that should be addressed to support the growth of 5G applications within the 3-, 5-, and 10-year timeframes. This first edition will provide a high-level perspective and projection of how these topics will evolve to address the needs of the 5G ecosystem and later on will provide a perspective on 6G ecosystem needs. The top-level challenges to achieving these goals and the potential solutions to those challenges will be highlighted.

The use of millimeter-waves is a key enabler to address the ever-increasing demand for bandwidth to transfer Gbps of data across the mobile network. In the prior 4G-LTE era, to achieve higher data-rates, each iteration of hardware added modest bandwidths of ~20 MHz at a time through Carrier Aggregation (CA) from generation to generation. In the below 6 GHz (Mid-Band) 5G, a similar approach can be taken to add bands between 2 and 6 GHz and utilize techniques like Massive MIMO to increase system capacity. At millimeter-waves, there is much less spectrum congestion; with available bandwidths ranging from 400 MHz to as wide as 2 GHz available at center frequencies of 28 GHz or at 39 GHz.

The implications of millimeter-wave spectrum include shared license access possible to reduce cost, and cognitive radio for shared spectrum with satellite or radar. However, there are different propagation models and new architectures for directional and adaptive beam steering to realize solutions to overcome attenuation, blockage, and high-power consumption.

If successful, millimeter-wave 5G systems will support and enable new use case scenarios that include VR with high data rates, Autonomous Driving with vehicle-to-everything (V2X) low latency communications and autonomous robots for factory automation and drone deliveries.

Over the next three years, the initial deployments of 5G hardware will, at first, grow rapidly for mid-band and more slowly in high-band (millimeter-wave). Within 5 years, there will be more high-band deployments as the cost of millimeter-wave infrastructure comes down. Within a decade, the attention will turn towards defining 6G with potential use of high millimeter-wave bands (70- to 300-GHz) for another 10× improvements in data rates with low latency.

9.3. HARDWARE FOR MMWAVE

Vision and Goals

Data rates up to 10 Gb/s over 400 MHz wide channels for millimeter-wave links operating in optimal link conditions will become necessary for implementation of communications to automobiles and other mobile platforms for which size, weight and power restrictions are essential. Expansion of services through extensive broadband mesh networking will be required also.

Implementation of cost-effective energy-efficient mobile millimeter-wave handsets able to capitalize on ubiquitous reach of close-by base stations and mesh-networked continuously powered mobile nodes will be essential. Data rates up to 10 Gb/s for mobile links over 400 MHz wide channels (including spectrum harmonization techniques) with global connectivity through base stations and augmented computing resources from fixed servers when operating conditions need to be optimized. For handsets, data rates up to 1 Gb/s with similar or better energy effectiveness available than with present lower-speed systems will be required. Significantly expanded support for new applications and always-on connectivity will be of paramount importance.

The WG will examine improvements in 2018 hardware capabilities required before ultra-broadband millimeter-waves fixed “last-mile” links, mobile handsets, mesh-enabled radios and base stations can reach commercial viability and open ultra-high-bandwidth low-latency applications in mobile virtual reality, robotics, and automated manufacturing can be realized. The WG will translate the requirements for these drivers into hardware needs, including increases in complexity and processing required for fixed links, mesh-enabled radios and base stations, radio architectures that balance spectral and power efficiency. The WG will summarize the resulting hardware requirements, including improvements in efficiency, linearity, cancellation techniques, semiconductor technologies, and integration for fixed links, mobile handsets, mesh-enabled radios, and base stations. Finally, the WG will estimate timelines needed to achieve these objectives. Unfulfilled promises of millimeter-waves 5G links will be incorporated into 6G requirements.

9.4. EDGE AUTOMATION PLATFORM

Vision and Goals

During the past 20 years multiple functions have been distributed across the cloud network in a multiplicity of data centers and other similar structures. Performance requirements dictated by the users have stimulated an almost spontaneous creation of a hierarchical system based on actual utilization.

In particular, the distribution of network functions across the data center tiers is now, more than ever, governed by the performance (e.g., latency, jitter, predictability) requirements dictated by the respective end-user service flows, balanced against the cost to perform computations. Control and management of network functions, along with that of underlying resources are also distributed across the respective Cloud tiers; effectively resulting in an empirically constructed “hierarchical control system” that distributes compute and intelligence across the time and space continuum.

The non-deterministic variance expected with future service flows, along with network functions distributed across different cloud tiers potentially under different jurisdictions (the user cloud and access cloud, for example, may be operated by different providers), dictates the need for a common underlying architecture pattern that enables “stitching” of disparate cloud systems through east-west and north-south interfaces with use of open application programming interfaces (APIs). This system must distribute compute and intelligence across both time and space continuums using a recursive control pattern, which is governed by local policies and federated against global business goals.

Foundational to the success of this new system is flexibility to dynamically stitch distinct functional stacks for the respective cloud tiers using modular functional units (Network Function Components), which are self-sufficient (e.g., for self-contained operation), while contributing to the continuum (e.g., for cross tier control and intelligence).

To accomplish these aggressive technical goals a comprehensive strategy towards an edge automation platform is essential. This means that the network and cloud operators must position themselves for evolved and functionally demanding services specified to support 5G related deployments. Optimal support meeting service level agreements (SLA) definitions and budgets for these services classes requires appropriate functional distribution across different time periods and geographies. The term “functions” here refers to switching and connectivity, compute, store, virtual network functions, and applications.

In order to produce a successfully operational network it is mandatory that EAP establish a strong linkage with other INGR TWGs such as Applications and Services, Security and Testbed.

9.5. SATELLITE

Vision and Goals

Satellite systems are expected to play an important role in future 5G systems. The topics considered in this document as key aspects towards future state for mobile satellite systems are as follows:

a) Applications Domains and Use Cases,
b) Reference satellite network architectures,
c) Antennas,
d) Waveforms,
e) Machine learning applications and AI,
f) NFV/SDN,
g) Optical techniques for links,
h) Integrated protocols and interfaces,
i) QoS/QoE,
j) Security, and
k) Standardization.

The undeniable advances of both fiber and terrestrial mobile are impacting linear video broadcast, which has been the strongest market for satellite communication up till now, displacing it with individually delivered content steered by return link analytics. The analytics are effective and help to adapt the content to the users in a quasi-addictive manner that straight linear media cannot match. Particularly, younger users (for instance, the "Millennials") watch much less traditional TV (and rarely have fixed phone lines).

One can envisage a wide range of scenarios for what happens next. While it is not possible to elaborate on all of them here, one may elucidate several bounding outcomes for them, as follows.

1. The first bounding outcome is that growth in data demand (driven largely by video customized to individual users, steered by analytics) is so extreme (current growth rates exceeding 30%/year) as to render it unacceptable to not be connected, even when remote or moving. We may call this the "broadband" scenario"; the "high throughput satellites" and upcoming large (>100s of satellites) constellations address this scenario. Most of the uses cases defined by ITU belong to the eMBB scenario.
2. A second bounding outcome is the mMTC IoT, where ultimately nearly everything has a small radio periodically sending data (i.e., status or readings), resulting in large volumes across large areas such that satellites must augment terrestrial wireless connections. The satellite solutions required for this are not very different from those of the "broadband" scenario above, although for the most affordable IoT "things" one would want to use the lower frequency satellite bands, such as C-band and below. One key aspect of this scenario is its diverse nature, when it comes to types of devices, data and location, etc. For instance, one might connect all wild and domestic animals over 50 kg in mass, or, e.g., all public and private vehicles, all major civil installations, all homes, and possibly all people.

Satellite solutions are uniquely positioned to provide a solution to the proposed 5G networks, by integrating 5G terrestrial network solutions with the 5G-satellites/non-terrestrial networks. The 5G needs is framed in increasing user access and demand. The anticipated rollout of the 5G terrestrial network will also need to address both mobile users and stranded/fringe users. The satellite industry is poised to leverage existing satellite network architectures to meet the need of extending the 5G networks.

Additionally, MIMO technology is one of the main technology enablers to increase terrestrial mobile spectral efficiency and the reliability of the transmissions. Generally, a rich scattering environment as observed in Rayleigh channel conditions known from terrestrial mobile communications guarantees a de-correlation of the propagation paths such that spatial multiplexing can be applied. However, such channel properties are usually not observed in satellite communications because the majority of applications encounter a LoS signal portion.

In summary, the WG believes that Satellite and terrestrial systems have been developing independently, making the integration very difficult so far. To achieve seamless, integrated terrestrial-satellite architecture, it is crucial to adopt a common air-interface that favors the combination with MIMO schemes and is robust to the adverse effects that arise in both satellite and terrestrial environments. Currently, satellite communication systems are based on single-carrier waveforms and mainly use single input, single output (SISO) schemes. To allow interoperability between satellite and terrestrial systems, it would be desirable to employ a multi-carrier waveform in the space segment. Standardization activities and efforts undertaken by ETSI, the 5G Infrastructure Public Private Partnership (5G PPP) and 3GPP will serve as an opportunity to foster collaboration between terrestrial and satellite stakeholders, which is crucial to make progress towards the design of a 5G satellite component. In this sense, it is envisaged that within three years the integration of satellites into the 5G architecture will have an impact on routing and buffering algorithms, allowing ameliorating latency. The convergent architecture may increase the ground segment complexity, requiring more gateways and more complex handover mechanisms.

9.6. Energy Efficiency

The Energy Efficiency (EE) Working Group (WG) is dedicated to ensuring awareness, resources, and proper linkages are captured and disseminated in a meaningful way to enable the most pragmatic (and therefore minimal) utilization of energy and associated carbon footprint for global communications networks. Ideally, all industry stakeholders will come to realize the importance of a highly concerted focus on optimizing energy efficiency/utilization at every level (i.e., from component to system to network) as a critical area as early in the development/deployment/standardization processes as possible to maximize positive results when deployed at all scales (i.e., from edge or small cell to the full network and utility levels).

9.7. Optics

Customer expectations of next generation communications solutions include higher speeds, shorter latency, and shorter response times for not only the 5G radio links but also for the full end-to-end network itself.

New applications, which demand low latency, will drive a significant change in the architecture of our telecommunication networks. Those key 5G drivers will create new market opportunities for optical fiber communications and photonic networking systems.

9.8. STANDARDIZATION BUILDING BLOCKS

Vision and Goals

With the advent of every new generation of wireless networks the capabilities of technologies expand and economic conditions change, resulting in an increasingly broader standardization scope. While progressing from generation to generation it becomes evident that we are shifting away from a carrier-centric paradigm.

The primary objective of the Standardization Building Blocks (SBB) Roadmap is to illustrate the "master timeline" for the standardization of the wireless communications technologies. Accordingly, the scope of the SBB includes the following:

- Depicting the value chain of the global system integrator SDOs
- Illustrating the effort of relevant alliances that drive standardization
- Overlaying core technology standards onto the technology roadmaps

The complexity of the task can be better understood by considering that the ecosystem related to future networks needs to be considered from multiple angles. In the SBB roadmap chapter, we list the standards bodies from relevant realms (Figure 3 in the SBB chapter) and Industry Alliances (Section 3), and open source activities. We also show how their activities are related to one another.

9.9. TESTBED

Vision and Goals

Testbeds are critical part of transition into 5G networks and complement the standards that are developed. Giving the ever increasing complexity of next generation of communication systems and skyrocketing development costs, the importance of publicly available testbeds is quickly becoming critical for researchers and developers to get access to state-of-the-art infrastructures in order to prototype and validate their ideas. Lessons learned from various experiments help to ratify the standards. The testbeds also help as catalyst for deployment of advanced wireless systems. Hence it is essential to have experimental testbeds where functional and end-to-end testing can be performed. The Testbed WG will help collaborate and interact with various existing testbeds and make those available to IEEE 5G community. This Testbed WG will collaborate with the vendor community, research community and will expand upon the existing testbeds.

Some of the goals of the Testbed WG will be functional testing, rapid prototyping, proof-of-concept covering various 5G characteristics at different layers, and also supporting various 5G specific applications such as IoT, tactile internet, and augmented reality. This WG will inventory types of testbeds available in various parts of the world and will serve as facilitator for setting up a federated testbed that will provide access to IEEE community to get access and run experiments. In order to fuel the testbed evolution, the Testbed WG would continue to hold workshops and go over various 5G use case scenarios.

In addition to informing the community on the capabilities and usage modalities of existing testbeds, the workgroup also aims to solicit contributions and promote discussion on the future experimental platforms as well as to facilitate discussions on co-development and co-deployment of future experimental platforms.

The roadmap development initiative focuses on the short-, medium-, and long-term goals as described below:

1. Short Term (3 years)—Develop a bank of data sets from each of the participating testbed and pilot roll-out programs regarding technical challenges and relevant statistics and provide access to the R&D community to this data. This includes propagation data from private/public networks (if available) as well as connectivity demand patterns.
2. Medium Term (5 years) —Build up expected performance benchmark for beyond 5G networks and work closely with standardization building block roadmap WG. Propose new network architectures or key performance indicators (KPIs) for 6G, etc., exploiting the learning from the federation of testbeds.
3. Long Term (10 years) —Testbed standards become fully established

9.10. System Optimization

The Systems Optimization roadmap WG has been formed to explore various approaches to manage complexity of future systems with non-traditional design and operational methodologies. One of the first uses of self-optimizing or self-governing systems came about in cellular radio systems, with the SON capabilities specified by NGMN and 3GPP for optimization of resources across heterogeneous access networks. These systems, however, are based on static policies and are limited in functional scope that addresses 3GPP RAT only. The System Optimization WG is exploring use of emergence to address full stack self-organizing systems, i.e., multi-layer and multi-domain organization and optimization of multiple functional stacks comprising of heterogeneous radio resources (e.g., 3GPP and non 3GPP RAT), fixed access and transport resources (e.g., optical wavelengths), and compute and store infrastructure resources contributed by disparate providers.

9.11. Deployment

The Deployment Working Group (DWG) is a forum for information sharing and discussion among stakeholders in the emerging 5G and beyond economy. The goal of the DWG is to help inform the wireless industry about the tactical challenges of deployment in and around public right of way—including private properties adjacent to the public right of way affected by local government zoning/planning. The DWG will also highlight the particular needs and perspectives of local governments and municipal agencies where applications for deployment of wireless communications facilities will be reviewed and permitted.

9.12. Application and Services

Vision and Goals

The Applications and Services WG promotes a smart city focus as an example that is flexible, extends across end-to-end ecosystems, and caters to different stages of priorities, resources, and technologies. Smart Cities represent an interconnected sustainable ecosystem, which itself consists of the integration of multiple ecosystems that links people, places and things to promote economic development, quality of life, and attractiveness for residents, businesses, and visitors.

The Applications and Services WG roadmap development initiative complements other initiatives such as the ITU Focus Group on Technologies for Network 2030 (FG-NET 2030)[2] or Network 2030. This focus

[2] *ITU Focus Group on Technologies for Network 2030 - https://www.itu.int/en/ITU-T/focusgroups/net2030/Pages/default.aspx*

group intends to study network capabilities to support forward-looking scenarios such as extremely fast response in critical situations and high-precision communication demands of emerging market verticals.

A successful roadmap will articulate a clear set of goals and objectives for beyond 5G evolution, adoption and commercialization across various industry products and application services. The first 3–5 years will be primarily focused on 5G adoption/commercialization for applications and services. Additional considerations include power optimization and efficiency improvement initiatives, especially those that support sustainable power and energy harvesting[3].

The roadmap development initiative focuses on the short term, medium term, and long term as described below:

1. Short Term (3 years) —Cities experiment with new applications and services. The emerging ecosystem will be constituted of a mixture of proprietary and new standards as firm compete for market share.
2. Medium Term (5 years) —As time progresses the smart city market shakeout will begin as the most successful solutions will be adopted, winners and losers will start to emerge. The smart city deployments will begin to concentrate towards a smaller group of proven solutions. Technologies become more standardized as an integration of new ecosystems emerge.
3. Long Term (10 years)—Concentration of proven smart city solutions will become de-facto the integrated city ecosystem. Practically proven standards will emerge as the victors and will expeditiously facilitate even more combinations of deployments.

An important characteristic of any futuristic network is that it should be intuitive, address user demands, and it must be easily manageable. Stakeholders should be able to develop, deploy, and maintain applications and networks easily. Standards should complement each other and solutions should be aligned with the underlying strategy so that application services can be dynamically created, configured and deleted to maximize user experience.

Specific objectives of the Application and Services TWG include realizing and deploying a resilient communications network and identifying prioritized areas of deployments with seamless areas of interoperable ecosystems. This should act as a local multiplier of benefits within targeted city clusters or districts. All cities should strive to use technology as an enabler for improved economic development, quality of life, and resource sustainability.

9.13. Security

Vision and Goals

In the past 20 years the amount of telecommunications occurring via wired or wireless lines has exponentially increased. Users of these communication media have gotten accustomed to entrust the most private and valuable information to be freely transmitted by means of these technologies. The prevention of unauthorized access to any information that is transmitted or transferred is therefore of paramount importance. Several disciplines, including emission security, physical security, transmission security and cryptographic security have developed ways of protecting the information content. However, in most cases all of these preventive technologies have been implemented as an afterthought. The INGR Security

[3]*Power Electronics, Brian Zahnstecher, IEEE Perspectives on 5G Applications and Services, March 2018, https://futurenetworks.ieee.org/images/files/pdf/applications/Power-Electronics-111218.pdf*

roadmap is comprised of the following pillars: management and orchestration security, edge security, third party security, data security and privacy and digital forensics solutions for the 5G environment.

The INGR recommends that technologies assuring the highest level of security and privacy must be an integral part of communications from inception. Subsequently security will need to evolve and mature alongside any communication technologies and its applications. As these technologies are integrated into our daily operations, such as smart home to smart cities and critical infrastructures (e.g., smart grids, transportation, etc.), there will be a need to develop security operations at every layer of the communication system governing them. Security technologies will need to support a variety of communication systems spanning from large-scale constrained-environments such as Industrial IoT to individual premises network such as smart home. It is the goal of the standardization process to accomplish at least 30% of deployment in the next three years and to complete full security deployment in five years.

9.14. Artificial Intelligence and Machine Learning (AI/ML)

This topic will be covered by a white paper in the 1st Edition INGR. A full chapter is expected for the 2nd Edition INGR.

9.15. Connecting the Unconnected (CTU)

The arrival of 5G mobile communications in 2020 will accelerate the digitalization of economies and society; however, it is likely to miss over 3 billion users living in remote or rural areas, broadening the "digital divide". The key objective of this working group is to enable everyone in the world to have access to the Internet and participate in the digital society with technologies and system-level solutions. Thus, the CTU WG's objective is to fine-tune 5G and beyond and start positioning 6G with a technical approach for secure, easy-to-use, affordable broadband Internet access for digitally disadvantaged users. This white paper gives a broad summary of what one can expect from the more in-depth roadmap effort for this topic.

10. OVERALL ROADMAP DRIVERS

The roadmap drivers include an assessment of the current industry structure and potential evolutionary paths using a mobility system and services framework. The initial working groups were formed to address key areas of this framework. Areas of considerations include the following:

- Current state of technological developments
- Mobility framework and pillars
- Evolution of current technology generation
  - Interactions within ecosystems
  - Interactions among adjacent ecosystems
- Key enablers, e.g., AI, position determination, cloud
- Vision of 6G

11. GRAND CHALLENGES

The challenges with the INGR include forecasting the needs of the telecommunications industry; combined needs from adjacent sectors; growth of adjacent sectors as a result of the combined communications enhancements; consumer trends and regulatory developments.

Section 7 discussed some of the challenges related to INGR. In earlier technologies such as 4G, the telecommunications ecosystem was primarily involved with the standardization, deployment and performance enhancements. 5G contains new capabilities that introduce the potential for new non-traditional entrants through the core network operations enhancements. Private networks may be deployed from non-traditional actors through open-source deployments. Other industry catalysts include regulatory activities such as shared spectrum and user trends related to applications and services. Traditional industry boundaries may shift and new adjacent industries will emerge with very different demands.

Challenges for the INGR roadmap development include forecasting demands from a telecommunications perspective and from potential adjacent industries. For example, the transportation industries may require additional communications capabilities, e.g., to support connected vehicles. These communications requirements may combine with other adjacent industry requirements, e.g., public safety and healthcare, to further enhance the communications capabilities. This would be difficult to track from a telecommunications industry perspective and would require a broader scope.

Furthermore, improvements in the combined communications capabilities may change the original industries, as there is a potential to either perform activities more efficiently or to introduce new services from existing capabilities. For example, a connected ambulance may be able to support advanced health services through low latency and high-speed imaging capabilities. Usage trends may combine with these developments to increase the difficulty with forecasting long term effects.

12. INGR FUTURE PLANS

The 1st Edition of the INGR lays the framework for key mobility system and services evolution. The initial set of WGs addressed some of the key areas. Future editions will include enhancements from the initial set of WGs and new WGs that address additional areas of the mobility system and services framework. Planned new WGs include AI/ML, Deployment, CTU, Energy Efficiency, Optics, and System Optimization.

13. Acronyms/Abbreviations

Term	Definition
1G–4G	First Generation to Fourth Generation
3GPP	Third Generation Partnership Project
5G	Fifth Generation
5G PPP	5G Infrastructure Public Private Partnership
ACK/NAK	Acknowledgment/negative acknowledgment
ADC	Analog to digital
AI	Artificial intelligence
API	Application programming interface
AR	Augmented reality
B2B	Business to business
B2C	Business to consumer
BS	Base station
BSS	Business support system
BW	Bandwidth
C/U	Control plane / User plane
CAGR	Compounded annual growth rate
CAPEX	Capital expenditure
CDMA	Code division multiple access
CN	Core network
COTS	Commercial off-the-shelf
CP	Control plane
D2D	Device to device
DAC	Digital to analog
DevOps	Development and information technology operations
DFT-s-OFDM	Discrete Fourier transform spread orthogonal frequency division multiplexing
DL	Downlink
DSP	Digital signal processing
EAP	Edge automation platform
EM	Electromagnetic
eMBB	Enhanced mobile broadband
eNB	Evolved node B
EPC	Evolved packet core
ETSI	European Telecommunications Standards Institute
FDD	Frequency-division duplex

Term	Definition
FDMA	Frequency division multiple access
FR	Frequency range
Gb/s	Gigabits per second
GHz	Gigahertz
GPRS	General packet radio service
GSM	Groupe Speciale Mobile
GSMA	GSM (Groupe Speciale Mobile) Association
HD TV	High-definition TV
HetNet	Heterogeneous Network
HIR	Heterogeneous Integration Roadmap
IDM	Integrated device manufacturer
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IIoT	Industrial IoT
IMS	IP multi-media subsystem
IMT	International Mobile Telecommunications-
INGR	International Network Generations Roadmap
IoT	Internet of things
IP	Internet protocol
IRDS	International Roadmap for Devices and Systems
ISG	Industrial specification group
ISM	Industrial, scientific and medical
ISP	Internet service provider
ITRS	International Technology Roadmap for Semiconductors
ITS	Intelligent transport system
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
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
Mb/s	Megabits per second

Term	Definition
MEC	Multi-access edge cloud
MIMO	Multiple input, multiple output
ML	Machine learning
MMS	Multimedia messaging service
mMTC	Massive machine-type communication
mmWave	Millimeter wave
MR	Merged reality
ms	Milliseconds
MVNO	Mobile virtual network operators
NaaS	Network as a service
NF	Network function
NFV	Network function virtualization
NGC	Next generation core
NGMN	Next generation mobile networks
NOMA	Non-orthogonal multiple accesses
NR	New radio
NS	Network slicing
NSA	Non-standalone
NTRS	National Technology Roadmap for Semiconductors
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
R&D	Research and development
RAN	Radio access network
RE	Range extension
RSRP	Reference signal received power
SDN	Software defined network
SDO	Standards developing organization or standards development organization

Term	Definition
SIM	Subscriber identification module
SISO	Single input, single output
SLA	Service level agreements
SMS	Short message service
SON	Self-optimizing network
TCP/IP	Transmission control protocol and internet protocol
TDD	Time-division duplex
TDMA	Time division multiple access
TSDSI	Telecommunications Standards Development Society India
TTI	Transmission time interval
TWG	Technology working group
UAV	Unmanned aerial vehicle
UE	User equipment
UL	Uplink
UP	User plane
URLLC	Ultra-reliable low latency communications
V2I	Vehicle to infrastructure
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-everything
vEPC	Virtual evolved packet core
VNF	Virtual network function
VR	Virtual reality
WG	Working group
WLAN	Wireless local area networks
WRC	World Radiocommunication Conferences
WSC	World Semiconductor Council (WSC)

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IEEE Anti-trust Statement

Generally speaking, most of the world prohibits agreements and certain other activities that unreasonably restrain trade. The IEEE Future Network Initiative follows the Anti-trust and Competition policy set forth by the IEEE-SA.

That policy can be found at https://standards.ieee.org/develop/policies/antitrust.pdf.

FutureNetworks.ieee.org/roadmap

IEEE INTERNATIONAL NETWORK GENERATIONS ROADMAP, 1ST EDITION